IFR statistical department

World Robotics
Service Robots

2024 incl. Mobile and Medical Robots

Statistics, Market Analysis and Case Studies

World Robotics Service Robots 2024
incl. Mobile and Medical Robots

World Robotics 2024 – Service Robots
incl. Mobile and Medical Robots

Produced by VDMA Services GmbH, Lyoner Str. 18, 60528 Frankfurt, Germany.

The service robot statistics is carried out by the IFR Statistical Department.

Chapter 3 is co-edited by Dr. Werner Kraus, Head of the Research Division “Automation and Robotics”, Dr. Birgit Graf and Kevin Bregler, in cooperation with other scientists, all at Fraunhofer Institute for Manufacturing Engineering and Automation IPA, Stuttgart (Germany).

The cover and the editorial are sponsored by Stäubli WFT

Assisting in statistics data collection, text and charts processing: Dr. Anne Jurkat, IFR Statistical Department

We express our most sincere gratitude to all partners!

Dr. Christopher Müller
Director
IFR Statistical Department

Tel: +49 69 66 03-11 91
E-Mail: statistics@ifr.org
Internet: http://www.worldrobotics.org

Suggested citation: Müller, Christopher; Kraus, Werner, Graf, Birgit; Bregler, Kevin (Eds.): World Robotics 2022 – Service Robots, IFR Statistical Department, VDMA Services GmbH, Frankfurt am Main, Germany, 2022.

Short citation: World Robotics 2024 – Service Robots

ISBN 978-3-8163-0766-2

Foreword



By: Dr. Werner Kraus, Head of the Research Division "Automation and Robotics"

Dr. Birgit Graf and Kevin Bregler,
Research Division "Automation and Robotics"

Dear Reader,

Service robotics is an industry on the move. One trend are bipedal robots or humanoids with gigantic investments in the last months. Whether these robots will be a game changer is still open and so far, no sales could be observed. However, they will serve as a technology base and other robots will benefit from the fast progress in AI, perception, and manipulation developed also for humanoids. One important growing market are autonomous mobile robots with around 300 manufacturers worldwide. This year's trade fair "Logimat" in Stuttgart/Germany could therefore be seen as the biggest service robotics show in the world. Further interesting markets are delivery robots in restaurants, field robots (however, not at scale so far), mobile assistants in lab automation, and robots for search and rescue or inspection. Here, four-legged robots are on the rise.

Many details about the market and technologies are described in the book at hand. The 2024 edition of "World Robotics Service Robots" presents numbers and market data from the previous year. As was the case in prior years, large growth markets contrast small, highly specialized niche markets, with many startups joining the fray and other companies unable to establish themselves on the market. We continued integrating ten interviews with robot manufacturers from all over the world. This year, we focused on the applications automated truck loading and unloading (as part of AP 51), outdoor intralogistics without public traffic (AP 53), as well as interaction and telepresence (AP 69 and AP 82). The interviews give insights into company strategies, market opportunities, and hurdles that should be overcome to widen the usage of service robots in the mentioned applications. In addition, updates from the market for interaction robots for private use were integrated in that respective chapter (AC 21). Some interesting findings from our chapter updates were the following:

- As far as *truck loading and unloading* is concerned, the manufacturers of such robot applications are addressing a "white spot" in intralogistics. This results not only from the shortage of labor, but also from regulations such as the break times that truck drivers have to adhere to. It is crucial to create a robust application that can cope with the high demands in terms of flexibility and complexity.

- Developments for *outdoor intralogistics* are all about creating highly customized solutions for specific customer needs, e.g. transporting goods between different production halls. Some of the biggest challenges include adapting to different weather and environmental conditions and ensuring reliable performance on different surfaces (concrete, gravel, etc.). In addition, compliance with strict safety standards and the integration of advanced technologies to protect employees are essential for safe and efficient outdoor operations.

- For *telepresence robots*, the use of “large language models” will certainly be a game changer to further improve interaction via speech. However, full autonomy of these systems is still a distant goal for many use cases. At this year's "Ana Avatar xPrize" challenge, the high level at which semi-autonomous or even teleoperated robotic devices can already act today became clear. Another point is that these devices are primarily aimed at people who are not used to handling robots. Therefore, usability must be high. There are also regulatory requirements, which can be particularly extensive in the medical environment.

In close cooperation, Fraunhofer IPA and IFR are observing 921 companies worldwide offering service robotics solutions (amongst them are about 8% startups). Both, the professional and the consumer service robotics domain benefit from technical innovations like digitization, cloud technologies, 5G/6G and artificial intelligence, specifically in machine learning, that lead to a technology push in service robotics. For the mentioned AI technology, there is already a variety of generative AI tools on the market. Generative Pre-trained Transformers using large language models, e.g. ChatGPT, will turn service robotics inside out, for example in terms of intuitive operation or support for creating program code. After less than two years, it is already clear that generative AI has become an integral part of everyday working life – especially for software development, as software code is highly formalized and widely available on the web serving as training data.

“World Robotics Service Robots” has established itself as the widely acknowledged reference publication in statistics, forecasts, market analysis, and profitability of robot investments. Robot suppliers, media, government bodies, financial analysts, and technology scouts are among its readers. It specifically provides profiles of the numerous service robot manufacturers worldwide. The many hyperlinks pointing to online resources invite to further investigate topics of interest by looking into selected publications and company websites. We are indebted to our colleagues editing the yearbook: Winfried Baum, Simon Baumgarten, Nikhil Srinath Betgov, Dr. Florenz Graf, Dr. Theo Jacobs, Florian Jordan, Max Kirchhoff, Dominik Moss, Cagatay Odabasi, Tobias Rainer Schaefle, Ph.D., and Miriam Schmelzer for their valuable editorial work. Furthermore, we highly appreciate the support of Dr. Anne Jurkat from IFR and Dr. Karin Roehricht from Fraunhofer IPA in preparing the report.

In case you have any suggestions or further inquiries related to service robotics, please do not hesitate to contact us!

Best wishes,

Dr. Werner Kraus, Dr. Birgit Graf, Kevin Bregler

Editorial

By: Jan Louwen, Global Head of AGV Robotics & Member of Global Robotics Management, Stäubli

Quo vadis, mobile robotics? A look at current trends and developments

It is an exciting time for mobile robotics. Global events, technological advancements, and changing market conditions are increasingly influencing our industry. The growing labor shortage on the customer side further drives the topic of automation, and thus mobile robotics. Established market players in particular are facing new challenges and are confronted with strategic questions. How do they want to position themselves? Which partnerships make sense? Which market segments can be tapped into? Are there promising niches that can be penetrated? These are not new considerations, but they have rarely been as prevalent as they are now. There are reasons for this.

Market dynamics: a broad playing field

The market for mobile robots is extremely dynamic and growing rapidly. This attracts investors and leads to many new players entering the market. On one side, there are providers with mobile transport robots for new, innovative concepts. On the other side, more and more manufacturers are entering the field with cost-effective solutions, putting significant pressure on the industry. China stands out in particular. Numerous Chinese companies are investing in mobile robotics and are increasingly celebrating successes in Europe and the USA. The competition in the industry is invigorated. This can and must be seen as an opportunity.

New technologies, new opportunities

It's not just the new market players that influence the dynamics, but also the rapid technological developments. Advances like 5G connectivity and GPS for outdoor navigation open up new possibilities and further drive the efficiency of solutions. New navigation methods, more powerful computers, and above all, the integration of artificial intelligence (AI) are helping mobile robotics increase availability. The boundaries of what is possible are regularly being pushed. This also impacts customer desires.

Standardization and modularity: the path to mass production

Historically, customized solutions dominated the market. They met the diverse customer needs and special applications. To increase the reliability of mobile robot solutions in the future, the development and production of serial products will become more important. For broad market penetration, manufacturers of customized solutions must think more in terms of modular products. This can sometimes be a rocky road, especially if the company does not already have the competencies around serial business in-house. Nevertheless, this rethinking is important. Stäubli benefits here from its internal know-how in mass production and pursues this path with its 3-ton platform PF3 and, in the future, with the counterbalance forklift FL1500. Equally important is close collaboration with customers. Despite AI and other customization options, it is often worth asking what the mobile robot really needs to be capable of. The interaction between integrator and manufacturer can also be a crucial step towards market penetration with standard products.

Figure 1: Thanks to its ultra-compact design, the Stäubli counterbalanced 1,5-ton forklift, FL1500 can operate in the tightest of spaces. Image credit: Stäubli

The core as part of the system: the software

Software is playing an increasingly important role in mobile robotics, from navigation software to fleet management and analysis tools. This goes hand in hand with rapid technological advancements. Software is undoubtedly gaining in importance. What often unjustifiably takes a back seat is mechatronics. In mobile robotics, it is at least equally important. To reliably and efficiently operate a mobile transport robot, the interplay of both areas is crucial. One must always view the whole as an integrated system. This will not change in the future.

More flexibility for mobile robots: new business models as opportunities

There is a visible trend within the industry: traditional sales models are being supplemented by new flexible business models. In addition to the now almost established temporary rental of mobile transport robots, leasing is also coming to the fore. These payment models with monthly fees are well-known in industry and logistics from manual forklifts. This provides customers with a significantly easier financial entry into automation, as capital costs are converted into operational costs. This principle will continue to permeate the industry in the future.

Contents

Foreword **3**

Editorial **6**

Contents **9**

Executive Summary World Robotics 2024 - Service Robots **11**

1 Introduction: World Robotics 2024 - Service Robots **14**

1.1 Definitions: robotics, service robotics, industrial robotics, and medical robotics 16

1.2 Compliance and privacy 20

1.3 Classification of service and medical robots 21

1.4 Sample description 26

2 Professional service robots **30**

2.1 Introduction 30

2.2 AP1: Agricultural robots 39

2.3 AP2: Professional cleaning 75

2.4 AP3: Inspection and maintenance robots 117

2.5 AP4: Construction and demolition 141

2.6 AP5: Transportation and logistics 161

2.7 AP7: Search, Rescue and security applications 236

2.8 AP8: Hospitality 257

2.9 AP99: Other professional service robots 283

3 Medical robots **288**

3.1 AP6: Medical robots 288

4 Consumer robots **332**

4.1 Introduction 332

4.2 AC1: Robots for domestic tasks 336

4.3 AC2: Social interaction, education 353

4.4 AC3: Care at home 368

5 Service and medical robotics industry structure **384**

5.1 Service and medical robot suppliers by region of origin and age 385

5.2 Service and medical robot suppliers – top 10 countries 389

5.3 Service and medical robot suppliers by business size 393

5.4 Consumer Service robot suppliers by application 394

5.5 Professional service robot suppliers by application 396

5.6 Medical robot suppliers by application 401

5.7 List of Service robot suppliers worldwide ... 402

6 Case studies ... 454

6.1 Introduction ... 454

6.2 Case Study 1 - Robotic Parking Systems Relieve Congestion in Smart Cities ... 456

6.3 Case Study 2 - Implementing Intelligent Robotics in Geriatric Rehabilitation at Singapore United Medicare Centre ... 461

6.4 Case Study 3 - Innok Robotics and Rigdon: A success story thanks to autonomous mobile robots and their off-road and outdoor capabilities. 466

6.5 Case Study 4 - Application of Autonomous Mobile Robots (AMRs) in the Front Section of Lithium Battery Factories ... 469

6.6 Case Study 5 - SolarEdge e-Mobility transforms production processes with FasThink ... 472

6.7 Case Study 6 - How cobots and AI are being used to revive coral reefs ... 476

References ... 479

Executive Summary World Robotics 2024 - Service Robots

The service robot industry is more diverse and less tangible than the industrial robot industry. IFR Statistical Department is currently aware of 921 service robot producers worldwide. This excludes prototyping services and system integrators. Many companies are still in the funding or prototyping stage and intend to offer a marketable product in the future.

In 2023, worldwide sales of professional service robot grew by 30%, medical robots by 36%. More than 205,000 of units professional service robots and more than 6,100 units of medical robots sold were registered by the IFR Statistical Department. The size of the RaaS fleet grew by 24% to more than 7,700 units.

Mobile robot solutions are already established in **transportation and logistics** (AP5) with 35% more units sold in 2023. More than every other professional service robot sold in 2023 was built for the transportation of goods or cargo. The RaaS fleet grew by 20% to more than 5,000 units in 2023. **Hospitality** robots (AP8) enjoy growing popularity: More than 54,000 units (+31%) were sold in 2023. Robotics is an important part of digitalization in **agriculture** (AP1) with almost 20,000 units (+21%) being sold in 2023. Demand for **professional cleaning** robots (AP2) grew by 4%. Sales of almost 12,000 units were reported to the IFR Statistical Department. There is also a considerable RaaS fleet of 2,369 units (+29%). Another growing market is the application group of **search and rescue and security** robots (AP7). 3,475 sold robots (+12%) were reported for 2023. There are several robotic devices for **inspection and maintenance** (AP3) available, but the portfolio of robots that conduct inspection and maintenance tasks autonomously (see chapter 1.4 for the difference between robots and robotic devices) is still limited. In 2023, almost 400 units (+67%) were sold. Service robots for **construction or demolition** (AP4) tasks constitute a niche market. The application group has nevertheless enjoyed a considerable growth rate of 58% in 2023. In 2023, sales of **medical** robots (AP6) were increasing by 36% to almost 6,200 units. RaaS business models are uncommon in this segment. Medical robots will be discussed in chapter 3.

There is still an abundance of specific product opportunities to be taken up by companies, therefore creating an attractive commercial market worldwide. Today’s service robotics market is composed of many niche products for professional services and a few high-volume applications both for professional and domestic use. Pioneers in the field of service robotics stress the significant opportunities for new companies entering this growth market with innovative products beyond the occasional robotics hype. Service robots for professional use are extremely diverse since they are usually designed to perform a specific task. Cost-benefit considerations from an end-user’s viewpoint are the main factor with respect to investment in such systems in addition to contributing to qualified and safe jobs. Although service robots are as diverse as their applications, three design categories can be distinguished: Modification of industrial robot components (e.g. automated warehousing and medical robots), use of advanced robot technology for the upgrading of high-end systems of existing product lines with automation functions. (e.g. cleaning, inspection), and new robotic designs “from scratch” (e.g. window cleaners, security robots).

The service robot industry is developing at a high pace with a lot of merger and acquisition activity. Many companies identify themselves as “deep tech”, meaning that they are willing to accept technological challenges during their product development phase to create technological advancement. Chapter 5 of World Robotics 2024 Service Robots offers an industry structure analysis of more than 900 service robot suppliers currently known to the IFR. This includes a full list of all companies and the applications they provide. **Customers of World Robotics Premium are able to download this list in Excel format**.

Although the service robotics industry is a young and growing industry, 92% of the suppliers are considered incumbents. This includes mature service robot suppliers as well as companies from other industries that added service robots to their portfolio. The 2010s saw a wave of new service robot manufacturers. Since then, the number of newly established companies steeply declined. IFR’s market observation suggests two reasons for the decreasing share: Some market segments have already achieved a level of maturity that sees companies growing, for instance AMRs for warehouse logistics. Sales of AMRs have been growing strongly for many years now and companies grew and became incumbents. Further, founding activities shifted away from the development of robot hardware. Many service applications are based on collaborative industrial robots, purchased from an industrial robot producer. The service robot supplier is therefore not considered a robot producer as the robot is purchased from a third party. These companies act like a system integrator, combining different components and developing software to create a solution.

Europe is the home of most service and medical robot producers,[1] hosting 405 companies (44%). Asia (268 companies) holds a share of 29% and 233 companies (25%) are from the Americas (almost exclusively North America). There are 15 companies from Australia and 2 from Africa. The top 5 home countries of service and medical robot manufacturers are the US with 199 suppliers, followed by China with 107 suppliers, Germany with 83 producers, Japan with 67, and France with 50 companies.

[1] Attribution of the company to a country and continent is done according to the location of the headquarter.

1 Introduction

Chapter 1 reviews definitions and classifications of service robots.

1 Introduction: World Robotics 2024 - Service Robots

This annual market report addresses the rapidly growing areas of service robotics and medical robotics in its entirety. It is the companion publication to World Robotics 2024 – Industrial Robots that covers the industrial robotics segment. World Robotics – Service Robots combines the insights of leading experts at the Fraunhofer Institute for Manufacturing Engineering and Automation (Fraunhofer IPA) and the statistics of the International Federation of Robotics (IFR).

In 2024, the IFR Statistical Department carried out a market survey of service robots for the 24th time. The statistical population of more than 900 companies worldwide was invited to participate and report data on their sales in 2022 and 2023. Participants were later invited to share their expectations for the timespan from 2024 to 2026. Additional data was gained from desktop research conducted from July to August 2024. **The results for each application group are presented at the beginning of the respective chapter**.

Chapter 2 provides detailed information on application areas of professional service robots, including a collection of typical products, prototypes, and suppliers. The brief examples of real-world applications provided in that chapter are complemented by more detailed case studies on the use of service robots that can be found on the IFR website at https://ifr.org/case-studies/service-robots.

Chapter 3 puts the focus on medical robots. This robot category used to be an application group in the professional service robot segment. From this edition on, the structure of this book follows the revisions made in ISO 8373, treating medical robots as a separate category.

Chapter 4 covers consumer service robots, which presumably represent the area with the most points of contact for the general public.

Chapter 5 provides an overview of the service and medical robot industry structure. This includes a list of all service and medical robot producers that are known to the IFR. If you represent a service robot producer that is missing in our list, please contact IFR Statistical Department (statistics@ifr.org) so that we can add your company.

About the IFR Service Robots Group: Founded on October 9, 2002, the IFR Service Robots Group is open to all companies producing service robots, components, or related services. Next to the excellent networking opportunity, it is the right place to discuss all antitrust-compliant, industry-relevant issues and topics. For further information, please contact the IFR Secretariat (secretariat@ifr.org).

How to get access

The present issue of World Robotics can be ordered at www.worldrobotics.org.

Contact

VDMA Services GmbH
-World Robotics-
Lyoner Str. 18
D-60528 Frankfurt am Main
Germany

Conceptual partner:
IFR Statistical Department
Telephone: +49 69 6603 1518
e-mail: statistics@ifr.org
Web: www.ifr.org

For questions concerning the purchase or delivery of World Robotics, please contact the distributor:

VDMA Verlag, verlag@vdma.org, www.vdma-verlag.com

For questions concerning the content of this publication, please contact:

IFR Statistical Department, email: statistics@ifr.org

1.1 DEFINITIONS: ROBOTICS, SERVICE ROBOTICS, INDUSTRIAL ROBOTICS, AND MEDICAL ROBOTICS

1.1.1 ISO 8373:2021 VOCABULARY DEFINITIONS

ISO 8373:2021 "*defines terms used in relation to robotics*" (§ 1). These vocabulary definitions relate to industrial robotics, service robotics, and medical robotics. This section describes the ISO definitions needed to understand IFR classification schemes and to distinguish IFR industrial robot statistics and IFR service robot statistics.

According to ISO 8373:2021, a **robot** is a "programmed *actuated mechanism with a degree of autonomy, to perform locomotion, manipulation or positioning*" (§ 3.1). Mechanisms that are using robot technology but do not satisfy the definition of robot, for instance teleoperated manipulators, are called **robotic device.** (§ 3.5). Robot technology includes perception, reasoning and planning algorithms (§ 3.3).

A **service robot** is a robot "*that performs useful tasks for humans or equipment*" (§ 3.7).

A **medical robot** is a "*robot intended to be used as medical electrical equipment*" (§ 3.8).

An **industrial robot** is an "*automatically controlled, reprogrammable multipurpose manipulator, programmable in three or more axes, which can be either fixed in place or fixed to a mobile platform for use in automation applications in an industrial environment*" (§ 3.6). Chapter 1.7 of World Robotics Industrial Robots provides an in-depth elaboration of IFR's definition of industrial robots and industrial robot classification schemes.

A **mobile robot** is by § 4.15 a robot that can "*travel under its own control.*" By § 4.16, automated guided vehicles (AGV) are mobile platforms *"following a predetermined path indicated by markers or external guidance commands…"* An AGV is therefore not a robot but a robotic device as it lacks the autonomy to determine its own path or navigate without external guidance. Mobile robots can travel on wheels (§ 4.15.1), legs (§ 4.15.2 and § 4.15.3) or by crawling on caterpillar tracks (§ 4.15.4). Note that mobility per se does not assign a robot to a specific category (industrial, service, medical). Note further that § 4.15 does not mention swimming, diving, or flying as types of locomotion. But from the example of underwater inspection provided in § 6.17 (teleoperation), it follows that at least diving is a type of mobility that is not ruled out generally.

A wearable robot (§ 4.17) is a robot "*attached to and carried by a human during use*", providing "*assistive force*". In practice, this describes powered exoskeletons and powered protheses.

ISO 8373:2021 further distinguishes personal from professional service robots (§ 3.7) but does not provide any definition of these terms. There are just a few examples of tasks considered as personal use (note 1 to § 3.7) and tasks considered as professional use (note 2 to § 3.7). The examples in both notes intersect to a large extend. Tasks like "*handling of items*", "*providing guidance or information*", "*cooking and food handling*", and "*cleaning*" are named as examples for personal as well as for professional use.

1.1.2 DEVIATIONS OF IFR DEFINITIONS FROM ISO DEFINITIONS AND IFR REFINEMENTS OF ISO DEFINITIONS – SERVICE ROBOTS AND MEDICAL ROBOTS

IFR generally defines robots according to ISO 8373:2021. There are, however, some details that are by IFR's experience not helpful to unambiguously distinguish the different robot categories, or that might be in contrast to the primary goal of IFR statistics – which is to provide information on the robotics industry to inform the robotics industry. IFR service and medical robot statistics will therefore deviate from ISO definitions in specific details described in this section.

Delimitation of industrial robots, service robots and medical robots

The ISO definition of "industrial robot" creates some room for interpretation. First of all, it is not clearly defined what constitutes an industrial environment and what separates it from other types of environments, e.g. workshops or laboratories. Second, as the previous definition by application (see ISO 8373:2012) was abandoned only for industrial robots, but not for service robots and the newly created category of medical robots, there is some inconsistency in the definition. Previously, the definition of the term service robot included that it is not used in "*industrial automation applications*" (§ 2.10, ISO 8373:2012). Now, this part of the service robot definition is deleted. This means that service robots can be used in industrial automation, but they still do not qualify as industrial robot if they do not satisfy the additional requirements listed in § 3.6.

The definition of **service robots by application** had proven successful in the history of IFR statistics. It also does not require a definition of the environment the robot is used in. The IFR application classification schemes for service and medical robots (see chapter 1.4), developed by the IFR Robot Supplier Committee and IFR Service Robot Group, define various service and medical robot applications. Note: The Robot Supplier Committee decided to include all robots of typically industrial kinematics in the industrial robot statistics. Robots with an industrial robot kinematic used in service applications are, therefore, counted in both statistics: In IFR industrial robot statistics such cases are counted in application class 905 ("other applications") as well as in their actual application class in IFR service robot statistics.

Medical robots used to be an application group in the professional service robot application scheme. Starting in World Robotics 2024, IFR statistics follow the new ISO definition and upgrade medical robots from an application group to a robot category. The classification in statistics, however, does not change and the old application group label AP6 is kept for medical robots in this edition of World Robotics.

The term **autonomous mobile robots** (AMR)[2] is marketing terminology and not defined in ISO 8373:2021. There seems to be a wide range of products running under this label. Usually, AMR is used as a synonym for "wheeled mobile robots" as defined by § 4.15.1

[2] Note that the words "autonomous" and "robot" are redundant, because a robot is autonomous by definition.

used in professional applications. Sometimes, these AMR are used in industrial environments but usually they neither have three axes nor do they have manipulation capabilities. Therefore, they do not satisfy the definition of an industrial robot. **IFR classifies AMR as service robots**. If the AMR is equipped with a robot arm (i.e. an articulated robot), **IFR statistics count the manipulator as an industrial robot and the platform as a service robot** (compliant with ISO 8373:2021, § 3.6, note 3).

Personal versus consumer versus professional service robots

As ISO 8373:2021 does not offer a definition of the terms personal service robot and professional service robot, IFR keeps its previously used terminology **consumer robots** (or consumer service robots) in contrast to **professional service robots**. Consumer robots are service robots for everyone. They do not require professional training -neither for setup nor for safe operation. They are intended for the layperson. Examples are domestic cleaning robots, automated wheelchairs, and social interaction robots. In contrast, professional service robots require a trained professional operator, where training can also refer to occupational safety training. Examples are cleaning robots for public places, delivery robots and fire-fighting robots.

1.1.3 SCOPE OF IFR SERVICE AND MEDICAL ROBOT STATISTICS

In contrast to IFR industrial robot statistics, which counts robots only, **IFR service and medical robot statistics include robotic devices in some application classes.** This is particularly the case if legal requirements prohibit autonomy or if the purpose of the application requires only limited autonomy.

In professional service robot statistics, this applies to AP7 (search and rescue, security).

In consumer robot statistics, the application group AC3 (care at home) includes robotic devices.

In medical robotics it applies to AP61 (diagnostics), AP62 (surgery), and AP63 (rehabilitation and non-invasive therapy).

Application classes that include robotic devices mention this in the description (see tables 1.2, 1.3, 1.4).

Excluded service robot applications

The IFR is the voice of robotics and represents the robotics industry. There are applications that use robot technology or technology that is often related to robotics but that is not represented by the IFR. The following applications are excluded and not represented by the IFR:

Military: The IFR promotes the peaceful use of robots. The use of robot technology for military purposes is neither covered in World Robotics and IFR statistics nor does the IFR represent this industry. **Dual use technologies are respected in their civil applications, only**.

Passenger transportation: The transportation of passengers in self-driving vehicles is an important future topic. Autonomous navigation technologies are used in robotics as well. Particularly in the segment of *outdoor delivery robots in environments with public traffic,* the challenges are like the ones faced in self-driving cars and buses. However, IFR considers passenger transportation as a part of the automotive industry. IFR does not represent the automotive industry and therefore World Robotics and **IFR statistics do not cover autonomous passenger transportation vehicles**.

Swimming, diving, or flying robots

§ 4.15 of ISO 8373:2021 provides several types of mobility that a robot can have. All these types are ground-based. Diving is mentioned indirectly in § 6.17, where the example of underwater inspection is provided. Swimming and aerial types of movement (e.g. flying) are not mentioned.

IFR service robot statistics include swimming and diving robots, but generally avoid aerial types of movement, i.e. drones. In special cases, especially if full autonomy is given, aerial robots are considered.

1.1.4 SUMMARY: IFR SERVICE AND MEDICAL ROBOT DEFINITION

- **A service robot** is a programmed actuated mechanism with a degree of autonomy to perform locomotion, manipulation or positioning to perform useful tasks for humans or equipment.
- In some applications, manually operated **robotic devices** with limited or even without autonomy are included.
- A **consumer service robot** is a service robot built for use by everyone. Neither safe operation nor setup require a professionally trained operator.
- A **professional service robot** is a service robot built for use by trained professional operators.
- **Autonomous mobile robot** (AMR) is a marketing term that is usually used as a synonym for wheeled mobile robots used in professional applications.
- **A medical robot** is intended to be used as medical electrical equipment.

1.2 COMPLIANCE AND PRIVACY

IFR Statistical Department ensures the confidentiality of individual company data and compliance with antitrust regulations. Access to raw data is strictly limited to the IFR Statistical Department staff. The IFR Statistical Department will never provide company-level data to third parties neither outside nor inside the IFR. The IFR Statistical Department publishes only aggregated data. The IFR Statistical Department will not reveal data if a data point consists of less than four observations. This is to prevent mathematical retrieval of company-level data.

1.3 CLASSIFICATION OF SERVICE AND MEDICAL ROBOTS

The IFR is using two schemes to classify service and medical robots: the application and the type of movement. Both classification schemes consist of classes at the lowest level, which are aggregated to groups.

There are four major types of movement that serve as the groups of this scheme: Ground-based (A), water-based (B), aerial (C), and wearable (D). The fifth group, type E is a residual group that covers everything not covered by A to D. On the class-level, ground-based robots can either be rolling (A1), walking (A2), be fixed in place (A3), or have any other ground-based type of movement (A4). Water-based robots can either be swimming (B1) or diving (B2). Aerial robots are usually flying (C1) but there might also be hovering robots in the future (C2). Similarly, wearable robots are powered exoskeletons (D1) today, but there might be other types of wearable robots (D2) in the future. Robots that do not fit into any of these classes, e.g. robots for orbital space or hybrid robots that fit into more than one of the above classes, can be classified as type E1. The full classification scheme including descriptions of each class is presented in Table 1.1.

Table 1.1

Classification of service robots by type of movement

Type		Description
A	Ground-based	Robots that move or stand on the ground
A1	Rolling	Rolling on wheels or caterpillar tracks
A2	Walking	Walking on legs
A3	Fixed in place	Immobile, cannot change physical location by itself, standing on the gound, desk or other fixed place, also hanging
A4	Other ground-based	Gound-based but none of the above (A1-A3), e.g. crawling, snakeing, climbing
B	Water-based	Robots that swim or dive (autonomous
B1	Swimming	Swim on the surface of the water, Note: If the robot can both swim and dive, it is counted as diving (B2)
B2	Diving	Dive under the surface of the water
C	Aerial	Robots that move through the air
C1	Fly	Flying in the air
C2	Hover	Hover above ground
D	Wearables	Robots that are worn by people
D1	Exoskeletons	Powered human exoskeletons
D2	Other wearables	Wearable robots other than D1
E	Others	Robots that are not A-D
E1	Other robots	Robots that do not fit into classes A-D, e.g. robots for orbital space Robots that fit into multiple classes, e.g. hybrid robots for water and ground or air

Source: IFR

The classification of service robots by application follows the concept outlined in chapter 1.2.4. This means, there are two distinct categories: consumer robots (AC – "applications, consumer") and professional service robots (AP – "applications, professional"). Chapters 3 and 4 of this book provides comprehensive explanations and examples of robots for each application class. Therefore, this section keeps explanations and descriptions rather brief and simple.

In the segment of consumer robots, there are three major application groups: domestic tasks (AC1), social interaction and education (AC2), and care at home (AC3). Robots that are intended for consumer use but do not fit into AC1-AC3 can be classified in class AC99 in group AC9 (other consumer robots). Domestic tasks are floor cleaning (AC11), window cleaning (AC12), gardening (AC13), outdoor cleaning (AC14), and other domestic tasks (AC19). Robots intended to be companions or to provide social interaction are classified in AC21, whereas robots specifically designed for education purposes are in AC22. Application class AC22 includes education robots used at school or in similar environments as well as robots for learning at home. Care at home applications refer mainly to mobility (AC31) and manipulation assistance (AC32). Robots that offer other care functions are classified as AC39. Note that care robots grouped in AC3 can also be used in professional care centers. The decisive criterion for consideration as a consumer robot in AC3 is the suitability for use by laypersons. Laypersons can also be professional caregivers that are not specifically trained to use robots. Also note that all classes in group AC3 include robotic devices because limited autonomy might be required or desired in care applications. If the use of a care robot requires professional training or education, it should be classified as "other medical robot" (AP69). Table 1.2 offers a full overview of all consumer application groups and classes.

Table 1.2

Classification of service robots by application

-consumer applications-

Application		Description
AC	**Consumer robots**	**Robots intended for use by everyone. No professional training required.**
AC1	Robots for domestic tasks	Robots for housekeeping and similar tasks around the house
AC11	Domestic floor cleaning (indoor)	Wet and dry cleaning of floors, e.g. vacuuming and wiping of floors
AC12	Domestic window cleaning	Cleaning of windows
AC13	Gardening	Gardening tasks, e.g. lawn mowing
AC14	Domestic cleaning (outdoor)	Outdoor cleaning tasks around the home, e.g. pool cleaning, yard cleaning
AC19	Other domestic tasks	Domestic tasks other than AC11 to AC14
AC2	Social interaction, education	Robots with social interaction functions, robots for children and student education
AC21	Social interaction, companions	Main purpose of the robot is to interact with and entertain users at home
AC22	Education	Robots desigend specifically to educate children or students
AC3	Care at home	Robots that support people in need of care (e.g. seniors or handicapped people) in their homes or home-like environments (e.g. retirement homes)
AC31	Mobility assistants	Robotic wheelchairs, robotic rollators/walkers, exoskeletons for walking disabilities. Includes robotic devices.
AC32	Manipulation aids	Robots that support seniors or disabled people in the manipulation of their environment (e.g. meal assistance robot, manipulators mounted to wheelchairs). Includes robotic devices.
AC39	Other care robots	Robots for care at home that do not fit into AC31 or AC32. Includes robotics devices.
AC9	Other consumer robots	Consumer robots that do not fit into any of above classes
AC99	Other consumer robots	Consumer robots that do not fit into any of above classes

Source: IFR

The category of professional service robot applications uses seven different application groups plus the residual group AP9 with class AP99 "other professional service robots" which is the appropriate class for all service robots that do not fit into any of the following groups and classes.

Agricultural applications of all kinds are grouped in AP1, which consists of four classes. AP11 includes all activities related to the cultivation of plants, from plowing the field to harvesting in greenhouses or outdoors. Robots for milking are in AP12, whereas other robots for livestock farming are in AP13. Agricultural robots that do not fit into any of the above can be classified as AP19.

Professional cleaning robots are – in analogy to domestic cleaning robots – divided into floor cleaning (AP21), and window and wall cleaning (AP22). Professional cleaning robots are also used for tank, tube, and pipe cleaning (AP23), hull cleaning (AP24). Because of the Covid 19 pandemic, many companies offer disinfection robots, so that the new classification scheme offers class AP25 for such machines. Professional cleaning applications that do not fit into any of the above can be classified as AP29.

Robots for professional inspection and maintenance are classified by the object that they are designed for. Robots designed for inspection of damage in building and civil construction of all kinds are classified as AP31. Inspection of tanks, tubes, pipes, and sewers is application class AP32. Note that robotic devices are not included in this group. There are numerous robotic devices available that provide inspection and maintenance services with manual remote control. It is beyond the scope of this publication and the representation of the IFR to cover all these machines. At least some basic autonomous functions like navigation are required to qualify a machine as a robot (see chapter 1.2.3).

Application group AP4 covers construction (AP41) and demolition (AP42) robots.

Group AP5 includes various logistics and transportation robots. Note that logistics is a very generic term that covers a wide range of different robot applications. Some logistics applications like packaging, pick and place, and palletizing are considered as industrial robotics and thus covered by the companion publication World Robotics Industrial Robots. Service robotics for logistics and transportation in the classes AP51-AP54 are classified along a two-dimensional matrix. The first dimension refers to the intended use indoors (AP51, AP52) or outdoors (AP53, AP54). The second dimension is the robot's ability to safely cope with public traffic. In a non-public environment, only people that are trained for the safe use and coexistence with the service robot may cross its path (AP51, AP53). Of course, the robot must still have safety features, but the supplier can expect that every person in the robot's working area knows about the dos and don'ts. This is different for robots that are applied in public traffic (AP52, AP54). In indoor environments, public traffic refers to visitors or any other general public that is not trained for the safe cooperation or coexistence with the robot. The robot must be able to react safely and anticipate unsafe behavior of people in its proximity, e.g. by stopping or slowing down its motion. In outdoor environments, public traffic may even require the robot to be able to autonomously participate in street traffic. Logistics also includes inventory management, e.g. counting and refilling of stock (AP55). Any other type of service robot for logistics or transportation that is not covered by AP51-AP55 can be classified as AP59. Note that passenger transportation is generally excluded by this scheme. In earlier ages of robotics, some companies suggested mobile platforms that could be used to transport people. The IFR concluded that such vehicles should generally be considered as cars or buses and are therefore beyond the scope of World Robotics or the representation by the IFR.

Table 1.3

Classification of service robots by applications

-professional applications-

Application		Description
AP	Professional service robots	Robots intended for use by trained professionals.
AP1	Agriculture	Robots for agricultural and farming applications
AP11	Cultivation	Plowing, seeding, harvesting, weeding, fertilizing, pesticide spraying of/for crop plants and fuit indoors (greenhouse) and outdoors (field, vineyard)
AP12	Milking	Milking
AP13	Other livestock farming	Livestock farming, except milking, e.g. feeding, barn cleaning
AP19	Other agriculture	Agriculture, but none of the above
AP2	Professional cleaning	Robots for professional cleaning applications
AP21	Floor cleaning	Cleaning of horizontal areas, e.g. floors in offices, hotels, public buildings, streets and sidewalks. Note: Robots for barn cleaning are included in class AP13
AP22	Window and wall cleaning	Cleaning of windows, walls and other vertical areas
AP23	Tank, tube and pipe cleaning	Inside cleaning of tanks, tubes or pipes
AP24	Hull cleaning	Outside cleaning of hulls (aircraft, train, other vehicles, tank, container)
AP25	Disinfection	UV, spray, wiping or other disinfection methods
AP29	Other professional cleaning	Professional cleaning other than above
AP3	Inspection and maintenance	Robots for inspection and maintenance
AP31	Buildings and other construction	Outside detection of damage in buildings, plants, bridges, tunnels and other civil construction
AP32	Tank, tubes, pipes, sewers	Inside detection of leakage in tanks, pipes, or sewers
AP39	Other inspection and maintenance	Inspection and maintenance, but none of the above
AP4	Construction and demolition	Robots for construction and demolition
AP41	Construction	Installation of buildings and other constructions, earthwork
AP42	Demolition	Tear-off of buildings and other constructions
AP5	Transportation and logistics	Mobile robots for transportation of goods or cargo and other logistics functions
AP51	Indoor environments without public traffic	Cargo/goods transportation in indoor environments without public traffic only, e.g. warehouses, factories, non-public areas of hospitals, airports, etc.
AP52	Indoor environments with public traffic	Cargo/goods transportation in indoor environments with public traffic, e.g. hospitals, hotels, restaurants
AP53	Outdoor environments without public traffic	Cargo/goods transport in outdoor environments without public traffic only, e.g. harbors, airports
AP54	Outdoor environments with public traffic	Cargo/goods transport in outdoor environments with public traffic, e.g. home delivery, parcel delivery in the streets
AP55	Inventory	Counting and refilling of stock and inventory
AP59	Other transportation and logistics	Mobile robots for transportation and logistics applications not mentioned above. No passenger transportation.
AP7	Search and rescue, security	Robots for emergency situations
AP71	Firefighting	Robots for Firefighting. Includes robotic devices.
AP72	Disaster relief	Robots for detection or rescue of survivors. Includes robotic devices.
AP73	Security services	Robots for security functions, e.g. surveillance, bomb squad support. Includes robotic devices.
AP8	Hospitality	Robots for interaction with guests or visitors
AP81	Food and drink preparation	Robots for food or drink preparation
AP82	Mobile guidance, information, telepresence	Robotic information desks or guides, e.g. in museums, shops, hotel receptions. Robots for virtual participation in real-world events. Note: Telepresence robots specifically designed for the medical field are covered in AP69
AP9	Other professional service robots	Robots that do not fit into any of the above classes
AP99	Other professional service robots	Robots that do not fit into any of the above classes

Source: IFR

The group of search and rescue and security robots includes robotic devices. These are used for firefighting (AP71), disaster relief (AP72), or security (AP73). Note that this includes only non-military applications (see chapter 1.2.3).

Hospitality robots are used for food or drink preparation (AP81) and for mobile guidance, information, or telepresence (AP82). Note that robots designed for various kinds of food delivery are grouped in AP5, and those for telepresence in the medical field (i.e. robots that feature sensors for tele-medicine) are classified as AP69.

The category of medical robotics has only one application group of the same name. The currently used code AP6 is a legacy of previous editions of World Robotics, when medical robotics was an application group of professional service robotics. Medical robotics has several classes that also include robotic devices, i.e. robotic technology that lacks sufficient autonomy to qualify as a robot. These classes are AP61 (robotic diagnostics), AP62 (robot-assisted surgery), and AP63 (robotics for non-invasive therapy and rehabilitation). In contrast, robots that handle and process samples in medical laboratories (AP64) and other medical robots (AP69) must be sufficiently autonomous.

Table 1.4

Classification of medical robots by applications

Application		Description
Medical robots		Robots intended to be used as medical electrical equipment
AP6	Medical robotics	Robots in medical applications
AP61	Diagnostics	Robotic diagnostic systems. Includes robotic devices.
AP62	Surgery	Robots for invasive therapy (surgery). Includes robotic devices.
AP63	Rehabilitation and non-invasive therapy	Robots for therapy (except surgery) and rehabilitation of patients after surgery or accidents. Includes robotic devices.
AP64	Medical laboratory analysis	Handling or processing of samples in medical laboratories
AP69	Other medical robots	Other robots for medical applications. Note: Robots for transportation in hospitals are included in class AP52

Source: IFR

1.4 SAMPLE DESCRIPTION

The International Federation of Robotics Statistical Department (IFR SD) conducts an annual survey among service robot suppliers worldwide. Data was either sent to IFR SD directly or through national robotics associations.[3] Additional data was acquired by comprehensive desktop research using sources such as annual reports and other publicly available information.

The service robot industry is more diverse and less tangible than the industrial robot industry. The IFR SD is currently aware of 921 service robot producers worldwide. This excludes prototyping services (i.e. companies that develop service robot prototypes upon request but do not intend to go into serial or mass production) and system integrators (i.e. companies that buy a third-party robot to create a service robot application). Many companies are still in the product development stage and do not have marketable products yet. The fact that 48 companies in our sample do not have any sales yet emphasizes this. These companies are still at the funding or prototyping stage and intend to offer a marketable product in the future. IFR Statistical Department is continuously seeking new service robot producers, so please contact statistics@ifr.org if you represent such a company and would like to participate in the annual survey.

The data reported here is sample data. It is not projected to the whole industry. It thus underestimates the actual sales figures and should rather be interpreted as a **minimum level of sales**. As the survey participation and the desktop research generate different sample compositions in each survey wave, the **statistics should be interpreted as cross-sectional. The IFR SD strongly discourages the creation of time-series data, compiling data from different issues of this publication**.

Table 1.5 presents more details on the sample and the relation to the statistical population. The statistical population consists of 921 companies. Thereof 409 companies are from Europe or from the MENA[4] region (44% of the total population), 279 companies are from the Asia-Pacific region (30% of the total population), 233 companies are American (25% of the total population). The IFR SD is currently not aware of any service robot producer in other regions of the world. Most companies (677; 74% of the population) offer professional service robots and 218 companies (24% of the population) offer consumer service robots. Medical robots are in the portfolio of 109 companies, thereof 45% (49 companies) from Europe + MENA, 29% (23 companies) from Asia, and 26% (28 companies) from the Americas (in fact: from the United States or Canada). There are six companies active in all three categories (consumer, professional, medical) and 50 more companies are active in consumer and professional service robotics.

The sample includes data from 298 service robot suppliers. Thereof 48 companies reported (or desktop research suggested) that there are no sales yet. These zero reports do not contribute to the minimum number of observations required to satisfy the IFR's

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[3] IFR SD gratefully appreciates the support of AER, CRIA, DIRA, JARA, and KAR.

[4] Middle East and Northern Africa. Note that there is an intersection between MENA and Asia. To our knowledge, this affects two companies. It was decided to assign them to MENA.

antitrust compliance rules (see chapter 1.3). The sample includes 126 suppliers from Europe and the MENA region, thereof 27 zero reports, and 107 suppliers from the Asia-Pacific region, thereof 4 zero reports. American companies are underrepresented with only 64 companies, thereof 17 zero reports.

Table 1.5

Service robot suppliers by region of origin: population versus sample

		Total	Consumer (AC)	Professional (AP1-5,7-9)	Medical (AP6)
		companies	companies	companies	companies
Europe + MENA	population	409	72	316	49
	sample	126 (27)	20 (2)	101 (24)	12 (3)
The Americas	population	233	62	155	28
	sample	64 (17)	13 (6)	41 (7)	10 (4)
Asia + Pacific	population	279	84	206	32
	sample	107 (4)	16	88 (6)	13
Others	population	0	0	0	0
	sample	0	0	0	0
Total	population	921	218	677	109
	sample	298(48)	49 (8)	230 (36)	35 (9)

Source: World Robotics 2024
The sum of categories AC, AP, and AP6 exceeds the total because a company can be assigned to more than one category.
Population of service robot manufacturers, excluding companies that only do prototyping. Note: In chapter 5, North Africa is included in Africa, Middle-East is included in Asia, and Pacific is included in Australia.
Sample including 48 companies that do not have sales yet (in parentheses).

Statistics use the number of robots (“units”) as a measure (see chapter 1.4).

“Robots-as-a-Service” (RaaS) business models are accounted for by the number of robots constituting the “RaaS fleet”, i.e. robots that are available for service. IFR SD defines all business models as RaaS that have the property of the robot hardware remaining with the robot supplier. This includes leasing, hiring, and others and should be seen in contrast to traditional sales, which transfer the property of the robot hardware to the customer.

In June 2024, the IFR conducted a separate survey for the forecast. The current forecast is based on these results and on the IFR’s assessment of the service robotics market.

one market

2 Professional service robots

Chapter 2 analyses the distribution for professional service robots and provides detailed information about the application areas, including a selection of typical products and suppliers.

2 Professional service robots

2.1 INTRODUCTION

Service robots for professional use are heterogeneous products since they are usually designed to perform a specific task. These machines can be found in hospitals or public buildings for delivering goods, executing tasks in dangerous or hazardous environments, or even helping in cowsheds and automatically milking cows. Cost-benefit considerations from an end-user's viewpoint are the main factors with respect to investment in such systems. There is a significant potential for improving cost, availability, and quality of service in tasks performed by robots, in addition to contributing to qualified and safe jobs. Although service robots are as diverse as their applications, three design categories can be distinguished:

- Modification of industrial robot components for application outside of the manufacturing environment, which is increasingly being pursued by industrial robot system integrators in search of new markets. Examples include automated warehousing and medical robots.
- Use of advanced robot technology for the upgrading of high-end systems of existing product lines with automation functions. This product philosophy can often be found in service robots for professional use such as cleaning and inspection.
- New robotic designs "from scratch", without past examples, by using robot technologies and components (navigation, environmental perception, etc.). Examples are window cleaners and security robots.

This chapter analyses the market for professional service robots. It contains descriptions of typical robot applications and provides further information about their use, technological maturity level, and manufacturers. It also showcases interviews from leading manufacturers in their respective application classes. The sections follow this structure:

- IFR statistics
- Types of operations carried out by the robot
- Level of distribution
- Cost-benefit considerations and marketing challenges
- Expert view (if available)
- Producers

Disclaimer: This chapter 2 is based on publicly available information and reflects only a part of worldwide activities in service robotics (which is continuously being collected by Fraunhofer IPA and IFR). Examples of service robot types and applications, including pictures in this edition, were selected without any bias and to the best knowledge of the authors. Trademark or copyright symbols are usually omitted in the text as well as business entities. All given URLs in this annual report could be retrieved as of April 30, 2024. We would like to thank our colleagues and students at Fraunhofer IPA who helped us prepare this report.

2.1.1 IFR STATISTICS

In 2023, worldwide sales of professional service robot grew by 30%. Close to 205,000 sold units were registered by the IFR Statistical Department. The size of the RaaS fleet grew by 24% to more than 7,700 units.

Mobile robot solutions are already established in **transportation and logistics** (AP5) with almost 113,000 units (+35%) sold in 2023. More than every other professional service robot sold in 2023 was built for the transportation of goods or cargo. Traditional sales remain the main channel of monetarization, but RaaS business models enjoy growing popularity: The RaaS fleet grew by 20% to more than 5,000 units in 2023.

Hospitality robots (AP8) enjoy growing popularity: More than 54,000 units (+31%) were sold in 2023. RaaS options are available in this application group, too, but cannot be revealed due to compliance reasons (minimum number of non-zero observations no reached).

Robotics is an important part of digitalization in **agriculture** (AP1) with almost 20,000 units (+21%) being sold in 2023. The agricultural robot sector is thus enjoying a solid growth rate. RaaS is picking up momentum with an exceptional high growth rate of 113%, albeit the absolute numbers in RaaS are rather small as compared to other application groups (e.g. transportation and logistics).

Demand for **professional cleaning** robots (AP2) grew by 4%. Sales of almost 12,000 units were reported to the IFR Statistical Department. There is also a considerable RaaS fleet of 2,369 units (+29%).

Another growing market is the application group of **search and rescue and security** robots (AP7). 3,475 sold robots (+12%) were reported for 2023.

There are several robotic devices for **inspection and maintenance** (AP3) available, but the portfolio of robots that conduct inspection and maintenance tasks autonomously (see chapter 1.4 for the difference between robots and robotic devices) is still limited. In 2023, almost 400 units (+67%) were sold. The RaaS fleet in that application group has decreased by 43%, however, due to the low number reported, this should not be regarded as a robust trend.

Service robots for **construction or demolition** (AP4) tasks constitute a niche market. The application group has nevertheless enjoyed a considerable growth rate of 58% in 2023. The numbers are very low and even a small increase in units sold in absolute terms will translate into a high growth rate.

In 2023, sales of **medical** robots (AP6) were increasing by 36% to almost 6,200 units. RaaS business models are uncommon in this segment. Medical robots will be discussed in chapter 3.

Application class A9 contains robots for **other professional applications** that do not fit into any of the other classes. Many of the units are powered exoskeletons intended to provide active support for workers, but there are also robots used in joyrides or simulators, professional lawn mowing robots used in sports and recreational facilities, robotic line painting solutions for sport fields, and robots in mining that are counted in this class.

Table 2.1

Service robots for professional use and medical robots in 2022 and 2023 by application group

	Application	2022	2023	2023/2022	2022	2023	2023/2022
		units sold		growth rate	RaaS fleet (in units)		growth rate
AP	**Professional service robots**	**158,130**	**205,129**	**+30%**	**6,261**	**7,784**	**+24%**
AP1	Agriculture	16,209	19,617	+21%	39	83	+113%
AP2	Professional cleaning	11,489	11,998	+4%	1,843	2,369	+29%
AP3	Inspection and maintenance	237	395	+67%	21	12	-43%
AP4	Construction and demolition	26	41	+58%	**	**	-
AP5	Transportation and logistics	83,592	112,986	+35%	4,180	5,007	+20%
AP7	Search and rescue, security	3,095	3,475	+12%	**	**	-
AP8	Hospitality	41,559	54,377	+31%	**	**	-
AP9	Other professional service robots	1,923	2,240	+16%	**	**	-
AP6	**Medical robots**	**4,540**	**6,179**	**+36%**	**0**	**0**	**-**

Source: World Robotics 2024
Results of IFR's annual survey and desktop research (230 professional service and 35 medical robot companies)
*Results cannot be revealed (minimum number of non-zero observations not reached). Data included in application group total AP.
**Results cannot be revealed (minimum number of non-zero observations not reached).

The top 5 application groups for professional service robots (excluding medical robots) by unit sales in 2023 are transportation and logistics (AP5) followed by hospitality (AP8), and with a considerable gap agriculture (AP1), professional cleaning (AP2), and search, rescue, and security (AP7).

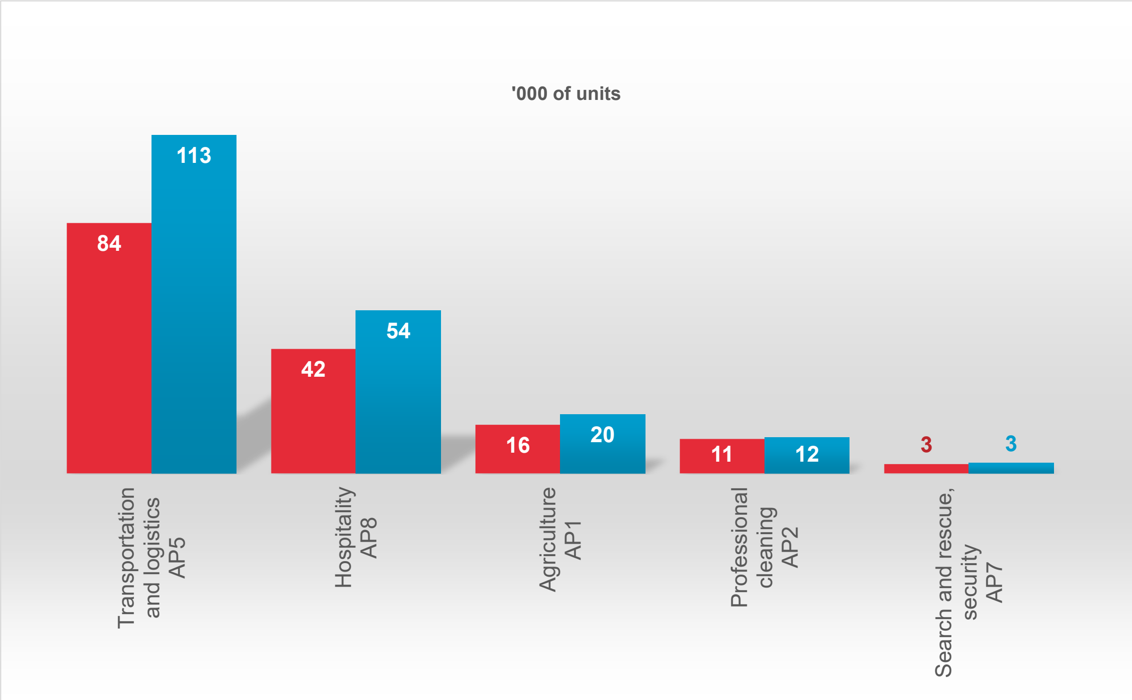

Figure 2.1: Service robots for professional use (excluding medical robots). Top 5 applications. Unit sales 2022 and 2023.

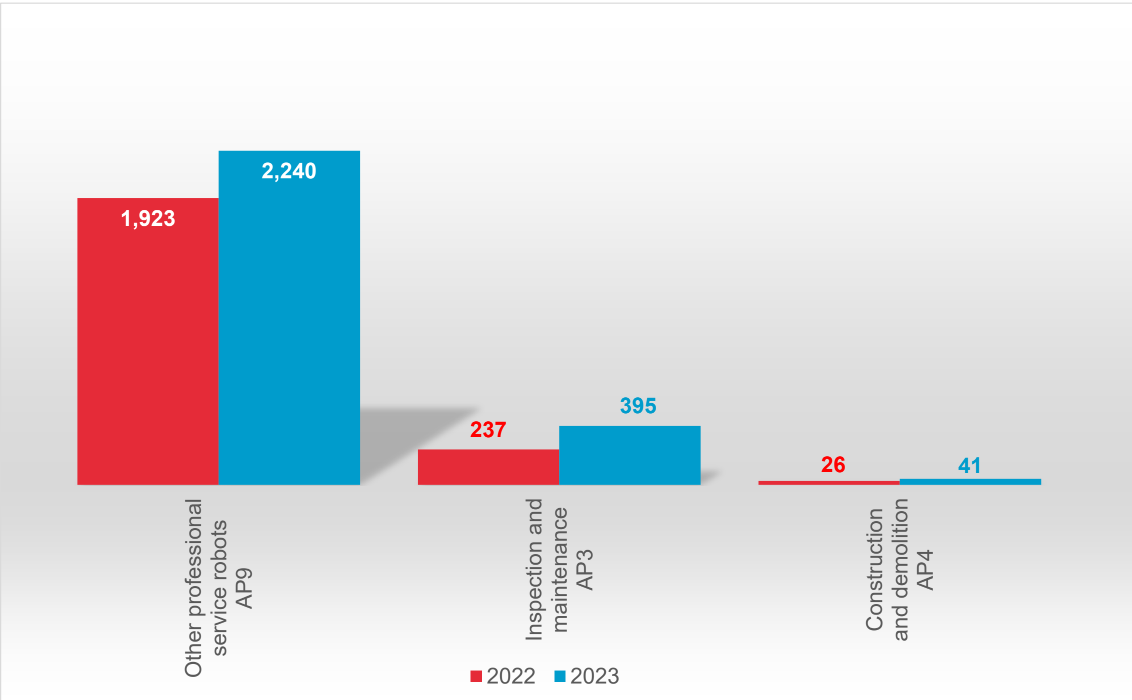

Figure 2.2: Service robots for professional use (excluding medical robots). Top 6-8 applications. Unit sales 2022 and 2023.

The evaluation of service robot sales by region of origin is based on the sample as described in chapter 1.4. The results are not weighted, or otherwise adjusted, to account for the regional proportions of the statistical population, i.e. the 921 service robot producers known to the IFR (see chapter 1.4 and chapter 5). The regional breakdown of professional service robots by country of origin reveals that almost 80% of the robots for professional use (excluding medical robots) originated from the Asia + Pacific region in 2023. The corresponding growth rate for this region is almost twice as high as the growth rate for the Europe + MENA region. Only the Americas have a higher growth rate, albeit at much lower absolute numbers. This most likely reflects the underrepresentation of manufacturers from the Americas in our sample due to low participation rates in the IFR's annual survey.

RaaS is a popular business model especially in the Americas where numbers in the RaaS fleet are comparable to units sold in 2022. The Asia + Pacific region has similar absolute values with almost 3,900 units offered as a service in 2023, but a much smaller growth rate (+5%). Europe + MENA is at lower absolute numbers but seems to be catching up rapidly (+110%).

Table 2.2

Service robots for professional use by region of origin (2022 and 2023)

	Application	Region	2022	2023	2023/2022	2022	2023	2023/2022
			units sold		growth rate	RaaS fleet (in units)		growth rate
AP	Professional service robots	Total	158,130	205,129	+30%	6,261	7,775	+24%
		Europe+MENA	29,227	33,918	+16%	262	550	+110%
		The Americas	3,871	8,927	+131%	2,762	3,839	+39%
		Asia+Pacific	125,032	162,284	+30%	3,237	3,386	+5%

Source: World Robotics 2024
Results of IFR's annual survey and desktop research (230 companies for professional use)
*Regional breakdown cannot be revealed (minimum number of non-zero observations not reached).
**Results cannot be revealed (minimum number of non-zero observations not reached). Data included in application group total (AP1, AP2, etc.).

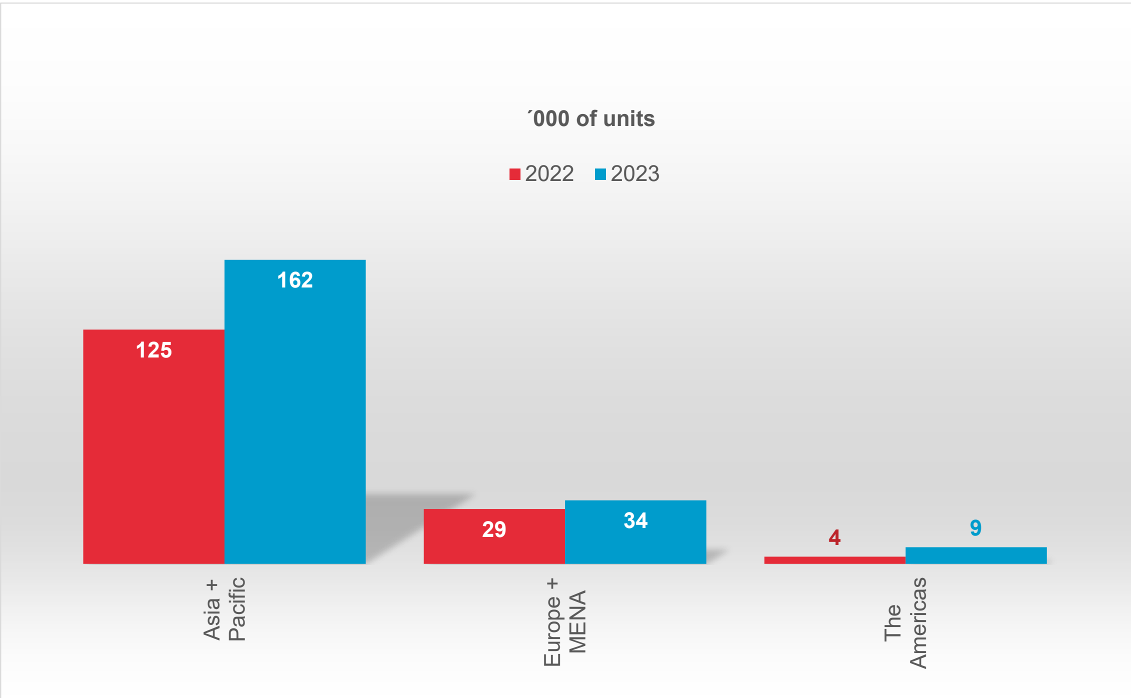

Figure 2.3: Service robots for professional use. Unit sales by region of origin 2022 and 2023.

The IFR SD has included the type of movement of service robots in its 2024 annual survey. The data was collected and is thus evaluated for professional service and medical robots together. Almost 98.2% of all professional and medical robots were ground-based of which nearly 68% were rolling and 32% fixed in place. Robots reported walking are less frequent owing to the still small number of legged robots or humanoids, but unit counts are growing (+35%). Compared to ground-based movements, water-based and aerial solutions are less popular, even though robots which can swim have experienced an impressive growth rate of +585%. None of the robots in the IFR's annual survey were reported to be diving. Wearables such as exoskeletons are a popular type of movement as well with 1276 units (+86%) reported. The available data does not allow to separately display professional and medical robots by type of movement, but we can reasonably assume most medical robots to be wearables or fixed in place.

Table 2.3

Service robots for professional use and medical robots in 2022 and 2023 by type of movement

	Application	2022	2023	2023/2022	2022	2023	2023/2022
		units sold		growth rate	RaaS fleet (in units)		growth rate
A	Ground-based	150,767	206,517	+37%	6,112	7,521	+23%
A1	Rolling	109,656	140,199	+28%	6,112	7,521	+23%
A2	Walking	34	46	+35%	**	**	-
A3	Fixed in place	40,603	65,399	+61%	**	**	-
A4	Other ground-based	474	873	+84%	**	**	-
B	Water-based	20	137	+585%	64	139	+117%
B1	Swimming	20	137	+585%	**	**	-
B2	Diving	0	0	-	**	**	-
C	Aerial	164	289	+76%	**	**	-
C1	Fly	164	289	+76%	**	**	-
C2	Hover	0	0	-	**	**	-
D	Wearables	1,092	1,939	+78%	**	**	-
D1	Exoskeletons	**	**	-	**	**	-
D2	Other wearables	**	**	-	**	**	-
E	Others	686	1,276	+86%	**	**	-
E1	Other robots	686	1,276	+86%	**	**	-

Source: World Robotics 2024
Results of IFR's annual survey and desktop research (230 professional service and 35 medical robot companies)
*Results cannot be revealed (minimum number of non-zero observations not reached).
**Results cannot be revealed (minimum number of non-zero observations not reached). Data included in application group total (A, B, etc.).

2.1.2 OUTLOOK

There is a lot of potential for service robot applications in many industries. One of the main drivers will be **demographic change**, which is already burdening labor markets in many economies. Developed countries like Japan, the United States, the Republic of Korea, or Germany -to name just a few examples- are already facing labor shortage. Using robots to automate 4d tasks (*d*irty, *d*ull, *d*angerous, *d*elicate) will be a crucial factor to attract labor of all kinds of qualification levels in agriculture, services, and manufacturing. With labor being scarce and technological progress taking place rapidly, the economic viability will improve in the next decade. The effort to increase **resilience** of production against pandemics and international political conflicts by reshoring capacity will create additional demand for service robots. The growing availability of **RaaS**

options allows customers with limited access to capital to shift from Capital Expenditure (CapEx) to Operational Expenditure (OpEx).

Technological progress is not only being made in the core robotics domain but also in **adjacent technologies** like artificial intelligence or machine vision. The latest advances in **generative AI** can be disruptive. This will improve robot performance and applicability. Mobile robots are the base for many service robot applications. Transportation, inspection, cleaning, security, and many agricultural tasks require mobility. The range of applications will widen as the supply of mobile robots with manipulation capabilities (**mobile manipulators**) grows. The successful deployment of mobile robots requires the development of appropriate environmental conditions. These conditions are manifold and require actions by many different actors. For instance, growing fleet sizes and the joint operation of AMRs and AGVs of different vendors is easier with a standardized interface that can be addressed by a single fleet control software. VDA 5050 is such a standard that is gaining popularity, especially in Europe. Mobile robots that move inside of buildings like offices or hospitals need an interface to building automation (e.g. doors, elevators) and security systems. The lack of such **standards** requires individual solutions for each implementation, making the deployment of transportation or cleaning robots expensive and often not economically viable. The **legal environment** is often a burden for robotics in public space. Last-mile delivery by transportation robots is technically feasible and solutions are available but the deployment of unmanned vehicles in public space is often not covered by existing laws. Politicians need to create the appropriate legal environment, including a link to applicable **safety standards**. The lack of mandatory standards and legislation is currently perceived as a major headwind for the commercial success of service robotics. Future regulations, standards and requirements should be developed on a supranational level to avoid market entry barriers.

The **overall global economic conditions remain tight**. Inflation rates are still above the economically desired level, while interest rates are high and expectations for global GDP growth are rather low. Additional regional headwinds are also dampening the propensity to invest. But the growing popularity of RaaS models decouples service robot demand from investment climate, especially in the service sector, e.g. in hotels and restaurants. Labor shortage due to demographic change is a predominant problem in the service sector, in agriculture, and in the manufacturing sector and employers are seeking new ways to improve working conditions by taking physical stress of the workers.

Service robotics is still in a very early stage of market penetration. The long-term prospects are therefore excellent. As outlined above, there are some short-term challenges but even under these conditions, demand for service robots is growing.

Transportation and logistics will remain an application group with strong double-digit growth rates of 50% on average each year from 2024 to 2027. Indoor transportation in non-public environments (e.g. warehouses, factories) will remain a growing segment that will also see higher payloads. Demand for such robots is for instance in battery production. This will also include outdoor transportation between different buildings on the factory premises (i.e. in non-public environments). The IFR observes more mobile robot solutions which are built for both indoor and outdoor use. The growing portfolio of transportation robots for indoor public environments will certainly create high growth rates in this segment. There is a wide range of indoor public environments, from restaurants to hotels, offices, hospitals, train stations, and airports that could make use of robotic solutions. The development of dynamic navigation systems, and flexible fleet management systems will further drive market growth. Key customers of mobile robots will include manufacturing, warehousing, and maintenance sectors, all seeking to reduce labor costs and enhance operational safety. There is a tremendous market potential for transportation robots in outdoor environments with public traffic, e.g. last-mile delivery. Marketing and monetarization options will depend on the availability of regulatory frameworks which currently still prevent the large-scale deployment of such robots in most countries.

There is also a huge potential for **hospitality** robots. Robot guides could support travelers and tourists at airports or tourist venues (e.g. museums). Telepresence robots could support efforts to reduce carbon emissions as business travel could be substituted by virtual presence, even if mobility is required (e.g. at trade shows). Labor shortage in the service sector will support demand for hospitality robots. Strong double-digit growth rates (+30%) are expected on average each year from 2024 to 2027.

The market for **agricultural** robots will see many new products within the next decade, especially for various cultivation tasks from plowing over seeding and weeding to harvesting. The shortage of labor supply for such tasks is creating high demand that cannot yet be satisfied because the portfolio of market-ready robots is still small. But starting from a small base, consistent double-digit growth rates (+20%) are expected as more and more products become available. Robotic innovations will enable a more sustainable production of agricultural produce and improve animal welfare.

Demand for **professional cleaning** robots is expected to accelerate over the next few years. Rising minimum wages in many European countries and labor shortage will make robotic cleaning economically viable, particularly in the floor cleaning segment. There is a trend towards smaller floor cleaning robots, resembling more those for consumer use. Smaller devices will certainly contribute to easier deployment. There is also a tremendous potential for disinfection robots in hospitals, but existing hygiene standards often limit the economic viability as manual cleaning remains mandatory. The expansion of solar power generation in solar parks will create demand for panel cleaning robots. Overall, the application group is expected to grow steadily by +20%.

Robotic devices for **firefighting and disaster relief** are a niche market that nevertheless has potential for growth. Demand for **security** robots, patrolling autonomously on business premises and in some countries also in public, will be growing at a projected +10%.

Service robots for **inspection and maintenance** will enjoy growth rates of +60%. Given the low base that this segment is starting from, high double-digit annual growth rates are possible over the next few years. The range of tasks that robots can inspect autonomously will be growing as machine vision technology and artificial intelligence make rapid progress and mobile manipulators can be used to do maintenance operations especially in more complex outdoor scenarios.

There are some innovative ideas how to automate **construction and demolition** tasks, but the portfolio of marketable products is still limited. Many solutions remain robotic devices with limited autonomy. Robots will also increasingly be applied to prefabricate customized components like roof trusses or walls that just need to be assembled on-site – but these robots are in the sphere of industrial robotics. However, we see existing solutions slowly reaching scalability. Lack of skilled workers and high costs of construction will be a major driver of innovations in that segment. Considering that the base of units deployed is very small, high growth rates are possible.

In **medical** robotics, robotic devices for surgery are currently becoming the new standard for invasive and non-invasive therapy of certain medical conditions and rehabilitation. A major driver of growth in the medical robot segment are surgical applications which offer a high return on investment. A major obstacle for innovations in the medical robot field are regulatory frameworks and reimbursement policies for hospitals and care facilities. Robots supporting medical laboratories could be a solution to the shortage of skilled professionals, but robotic automation is not yet established in this segment. It will probably take a few more years to change this.

Table 2.4

Forecast: service robots for professional use 2024-2027* by application group

	Application	2023	2024-2027*	2027*
		units sold	CAGR	units sold
AP	**Professional service robots**	**205,114**	**+41%**	**804,530**
AP1	Agriculture	19,617	+20%	40,678
AP2	Professional cleaning	11,998	+20%	24,879
AP3	Inspection and maintenance	395	+60%	2,589
AP4	Construction and demolition	41	+40%	158
AP5	Transportation and logistics	112,971	+50%	571,916
AP7	Search and rescue, security	3,475	+10%	5,088
AP8	Hospitality	54,377	+30%	155,306
AP9	Other professional service robots	2,240	+15%	3,918
AP6	**Medical robots**	**6,179**	**+15%**	**10,807**

Source: World Robotics 2024
Results based on annual survey and IFR's market assessment
CAGR: Compund Annual Growth Rate
*projection using CAGR

2.2 AP1: AGRICULTURAL ROBOTS

Author: Kevin Bregler, M.Sc.

An agricultural robot is a robot used for agricultural purposes. Agricultural areas are essentially characterized by providing a semi-structured or completely unstructured, often dynamic environment. Agricultural robots are intended to serve several purposes at once when used in specific applications. On the one hand, they should assist human workers and increase productivity in times of severe demographic changes in the EU[5] and other high-income countries / areas such as Japan, Australia, and North America[6] and, on the other hand, they are meant to be an enabler of more sustainable precision agriculture[7]. Therefore, agricultural robots are used in the following areas:

- Arable farming, horticulture (specifically vegetable/fruit cultivation), with all the associated tasks, i.e. field management, crop protection, harvesting, and logistics in the field (see chapter 2.2.1 Cultivation)
- Livestock management to reduce the workload of livestock farmers, especially for
  milking cows, herding, and barn management (see chapter 2.2.2 Milking)
- Permanent crops and forestry

The market for agricultural robots is experiencing a strong growth phase in the areas described. In the following chapters, the application areas are examined in more detail and the corresponding market developments are described precisely.

5 https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Farmers_and_the_agricultural_labour_force_-_statistics.

6 https://population.un.org/wpp/Graphs/DemographicProfiles/Pyramid/1829.

7 https://www.edf.org/ecosystems/resilient-agriculture/precision-agriculture.

IFR statistics

Agricultural robots enjoy a solid two-digit growth rate with almost 20.000 units sold in 2023. RaaS is picking up momentum with an exceptional high growth rate of 113%, however, absolute values are still small.

There is a lot of research and development to use robots for the **cultivation (AP11)** of plants and crops, which encompasses a variety of tasks. The number of marketable products is growing but it still requires some pioneering spirit (and funding) for farmers to use a robot in the field. In 2023, almost 2,000 units (+2%) were sold. Close to 17,600 robots (+24%) for **other agricultural tasks** like milking and barn cleaning were sold in 2023.

Table 2.5

Professional service robots for agriculture (2022 and 2023)

	Application	2022	2023	2023/2022	2022	2023	2023/2022
		units sold		growth rate	RaaS fleet (in units)		growth rate
AP1	Agriculture*	16,209	19,617	+21%	39	83	+113%
AP11	Cultivation*	2,007	2,038	+2%	**	**	-
AP12, AP13, AP19	Milking, other livestock farming and agriculture*	14,202	17,579	+24%	**	**	-

Source: World Robotics 2024
Results of IFR's annual survey and desktop research (38 robot companies for agriculture)
*Regional breakdown cannot be revealed (minimum number of non-zero observations not reached).
**Results cannot be revealed (minimum number of non-zero observations not reached). Data included in application group total (AP1, AP2, etc.).

2.2.1 AP11: CULTIVATION

Cultivation was an early adopter of robotics. French company Naio Technologies, as one of the first European and global players, has been on the market since 2011 with robots such as Oz or Dino. Over the subsequent years, many other companies with similar applications, especially weed control, were established and the market introduction phase is slowly coming to an end. As the increasing number of robot units sold shows, the transition to a growth phase has recently begun. The use of agricultural robots is also gaining support and acceptance among end users, and sales are, therefore, gradually picking up. The technologies around autonomous robotics have also matured and can now be used more robustly and increasingly without human supervision. In doing so, most companies are developing ground-based systems to support or take over specific tasks within cultivation. In addition, uncrewed aerial vehicles (UAVs) are being used for inspection, monitoring, mapping, and precision agriculture from the air. Due to the enormous variety of drone systems and the multi-use of such systems, i.e. virtually any drone can be equipped for specific purposes, this chapter does not provide a detailed overview of drone manufacturers. Only air-ground systems, i.e. a combination of UAVs and ground-based robots, such as Tevel's system for apple harvesting, are considered.

When looking at the application more closely, it can be observed that the challenges to agriculture are many: The lack of human workforce in agricultural regions, the need for food and fiber (increased demand of 35% to 56% between 2010 and 2050)[8] for a growing global population, societal demands for more sustainable agriculture[9], and stringent (political) regulations.[10]

Figure 2.4: Agrointelli's Robotti is an approach where the actual implement is autonomized. Many common agricultural implements can be clamped into the robotic device. Image credit: Agrointelli.

Robotics will play a key role in addressing these challenges in the coming years, particularly through the implementation of precision agriculture as an agricultural management concept that focuses on the individual treatment of each crop, ensuring more sustainable cultivation while maintaining or even increasing productivity. The associated technological challenges and thus driving factors in the establishment of these new systems are mainly found in the following areas:

- Interoperability of new robots and conventional agricultural machinery or farming systems. An interesting approach was shown by Agrointelli with its Robotti that combines conventional implements with an autonomous drive unit. In this way, farmers can seamlessly integrate this new technology into their existing farm implements.
- Low-cost sensors or sensor data analysis that enable the capture of high-quality data.

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8 Dijk, M.v. et al.: A meta-analysis of projected global food demand and population at risk of hunger for the period 2010–2050, nature food, 2021, no.2; https://www.nature.com/articles/s43016-021-00322-9.

9 https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en.

10 https://www.epa.gov/agriculture/laws-and-regulations-apply-your-agricultural-operation-farm-activity.

- Development of reliable, AI-based autonomy that works robustly in all application-specific environmental scenarios.
- Mobile manipulation that can achieve the skill and handling of human manipulation to perform harvesting operations for instance in existing cropping systems.
- A robust system consisting of hardware and software designed for uninterrupted and reliable autonomous operation in a highly dynamic and inhomogeneous environment. More specifically, skilled personnel or farmers do not have to be near the machines to maintain the work process and to ensure the machine can handle unforeseen events autonomously.

In the following chapter, the types of applications of agricultural robots are presented with specific examples of systems already available on the market. A subdivision of the robotic applications has been made according to the phases of the agricultural cultivation process.

2.2.1.1. TYPES OF OPERATIONS CARRIED OUT BY THE ROBOT

The cultivation process in agriculture depends, on the one hand, on the crop and, on the other hand, on the type of cultivation system used. A distinction should be made between conventional arable farming and cultivation in greenhouses or vertical farms. Cultivation in the latter is comparable to factory automation and makes it possible to create controlled environmental conditions and to permanently install infrastructure for automation, such as rail-based guidance. Greenhouse automation is, therefore, already very advanced compared to conventional farming. In conventional farming, the complexity of the environmental conditions is much higher. The most important cultivation steps in conventional agriculture can be described as follows:

- Tillage
- Sowing and planting
- Crop protection
  - Weed control
  - Pest control
  - Disease control
- Fertilization
- Harvesting
- Irrigation

All these processes have to be carried out by farmers with machines. In principle, it is possible to automate all these processes, although the challenge of automation varies depending on the particular step. Factors that can have a significant impact on the automation challenge are as follows:

- Complexity of the dexterity task (especially for soft fruit harvesting)
- Energy source for the operation (battery, combustion engine)

- Degree of autonomy (basic GPS guidance, up to complete context interpretation)
- Type of drive (continuous track, wheel drive with or without single-wheel steering)
- The dependency of a task on external conditions like weather or local characteristics

The environment in which agricultural robots usually work is mostly semi-structured. For example, as previously described, in greenhouses the parameters can be regulated very precisely, for example the climate, lighting and soil conditions, etc. This significantly reduces the complexity of automation technologies. Nevertheless, the environment is not completely arbitrary but at least structured in terms of layout and certain occurring features, such as crop rows or field borders. The layout and structure of the fields can be used, but they must be able to cope with varying weather, lighting and dynamic environments.

Orchards and unstructured cultivation (forage crops such as meadows) have the most complex context in terms of their layout, topology, and the expected features, for example as orientation possibilities.

Automation solutions are already being developed for all the applications described. Professional service robots, mostly autonomous mobile and ground-based robots, are introduced in agriculture primarily for outdoor operations, although some autonomous mobile robots are also used for special applications, such as moving plants in pots in greenhouses and nurseries. The main applications of autonomous robots in outdoor agriculture are crop protection and seeding. This area has seen a real boom of new startups in recent years with various concepts for implementing these tasks with robots.

Many other application areas described previously pose greater challenges for robotics developers. Such challenges can result from the high complexity of the task (e.g. harvesting fruit or early detection of diseases and pest infestations) or from safety requirements, such as for heavy autonomous machines with higher speeds (e.g. tillage). The growing interest in agricultural automation can also be seen in several international events, research initiatives, and competitions, for instance in Australia, the USA, Europe, and Japan.[11, 12]

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[11] EU projects on smart agri-food systems: http://www.europarl.europa.eu/RegData/etudes/STUD/2016/581892/EPRS_STU(2016)581892_EN.pdf.

[12] Field Robot Event 2024, 11.-13.06.2024, Erwitte/Lippstadt (GER); https://fieldrobot.nl/event/index.php/2023/11/27/field-robot-event-2024/.

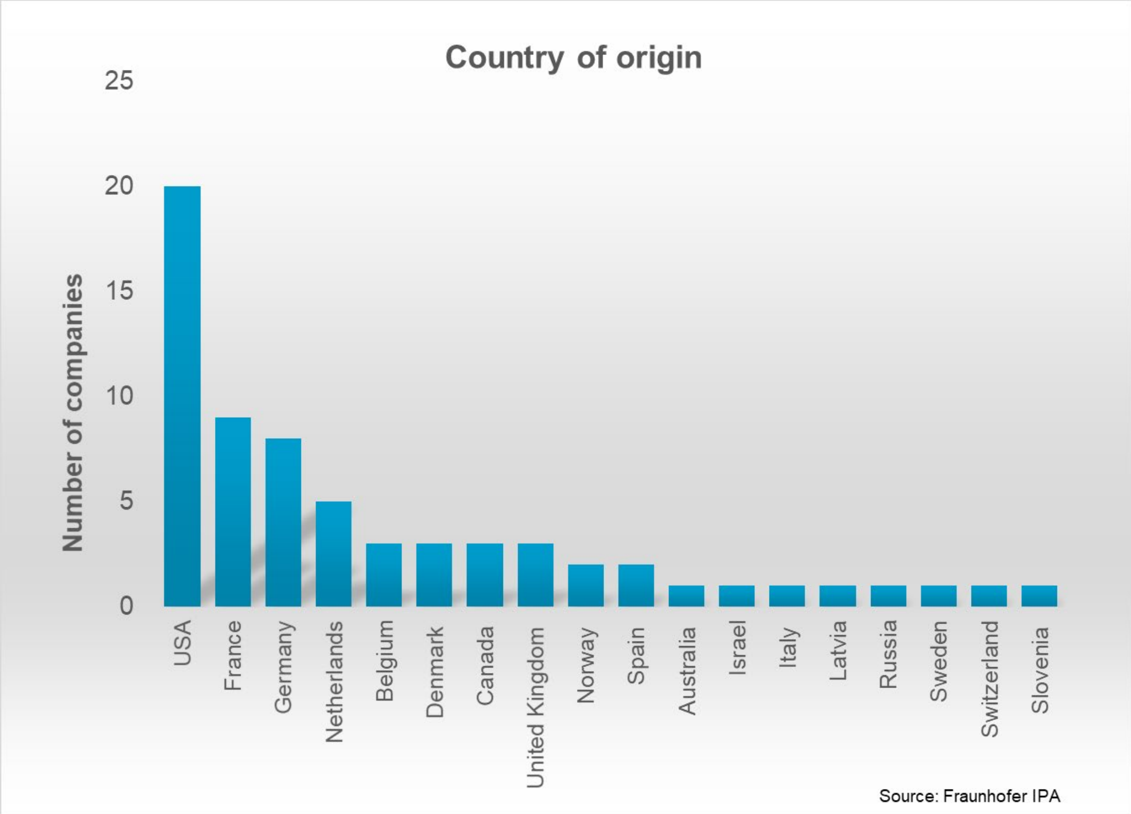

Figure 2.5: The distribution of robotics companies by country of origin. Only ground-based robots are considered. Software-only and drone manufacturers are not included.

Besides ground-based robots, drones will have a transformative effect on agricultural automation. Drones are used and evaluated in research projects in areas such as soil and field analysis, surveying, aerial seeding, crop spraying, irrigation, and plant health assessment.[13] In the future, drones might autonomously collaborate with each other in swarms to tackle tasks collectively and even support ground-based robots with data and information.

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13 Mazur, M.: Six Ways Drones Are Revolutionizing Agriculture MIT Technology Review, July 20, 2016; https://www.technologyreview.com/s/601935/six-ways-drones-are-revolutionizing-agriculture.

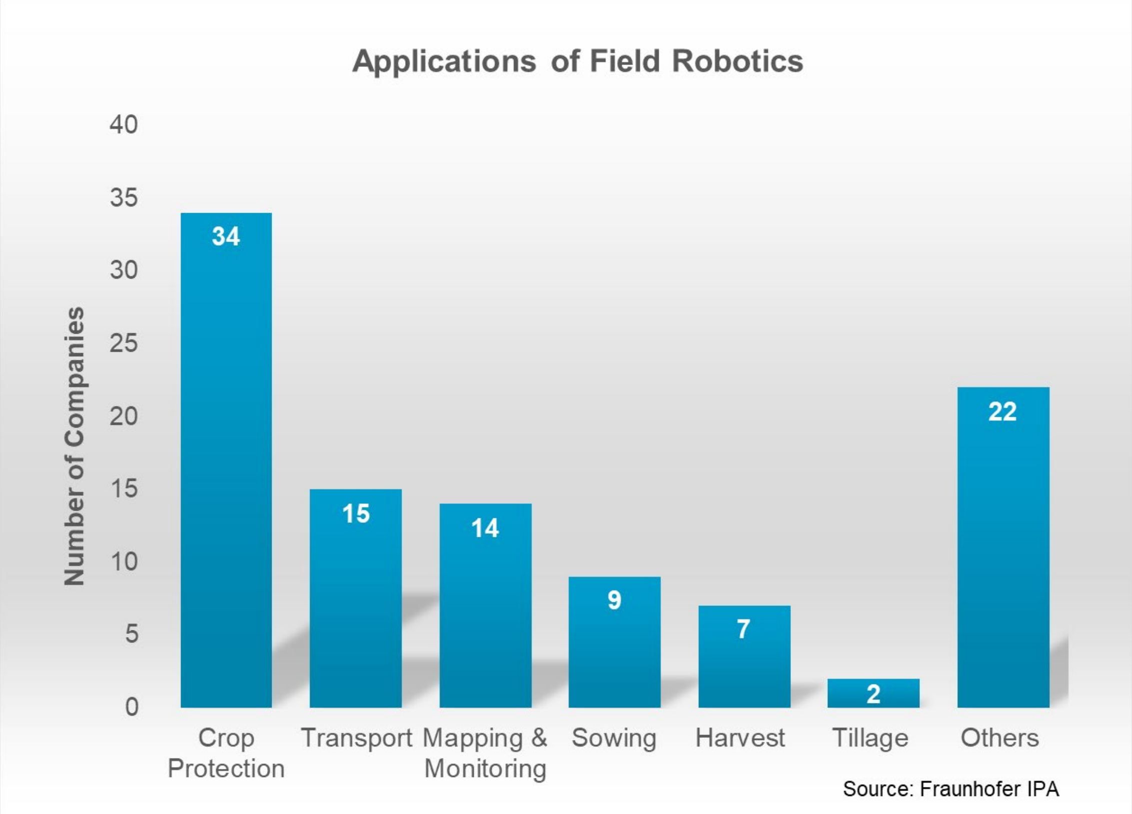

Figure 2.6: The distribution of robotics companies by application area. Multiple entries are possible, as many robots serve more than one application. The distribution therefore provides an overview of the focus of current trends.

2.2.1.2. LEVEL OF DISTRIBUTION

Systems for autonomous guidance of agricultural machinery, such as tractors or harvesters, are already established in Europe, Australia, Japan, and the USA and have been available for purchase as assistance systems from major equipment suppliers for years. Their use is made possible by global navigation satellite systems (GNSS) and in some cases supported by optical sensors, such as light detection and range (LiDAR) or (depth) cameras. For this, precise a priori information of the field to be traversed or cultivated must already be available, i.e. maps and, if applicable, the precise position of the crops.

Many small robot systems, for example for weed control and sowing, work according to the same principle and are, therefore, limited in their autonomy and especially in their situational reactivity. This can also lead to system failures if the environmental conditions deviate from the a priori information. Full autonomy is only achieved through active, real-time environmental interpretation that enables dynamic reaction to changes in the environment.

In the following, exemplary systems are presented for the application areas described above. A more detailed overview of companies offering autonomous robots can be found in the producer overview.

Robotic transformation of conventional agricultural machines

Robots can be classified according to many characteristics. For example, they can be classified according to the type of movement (wheel or track drive, ground-based or airborne), the degree of autonomy (e.g. autonomy level in the automotive industry), or weight, speed, and machine specifications. The latter classification is particularly interesting with regard to regulations or directives and the type of energy supply, as the following figure shows.

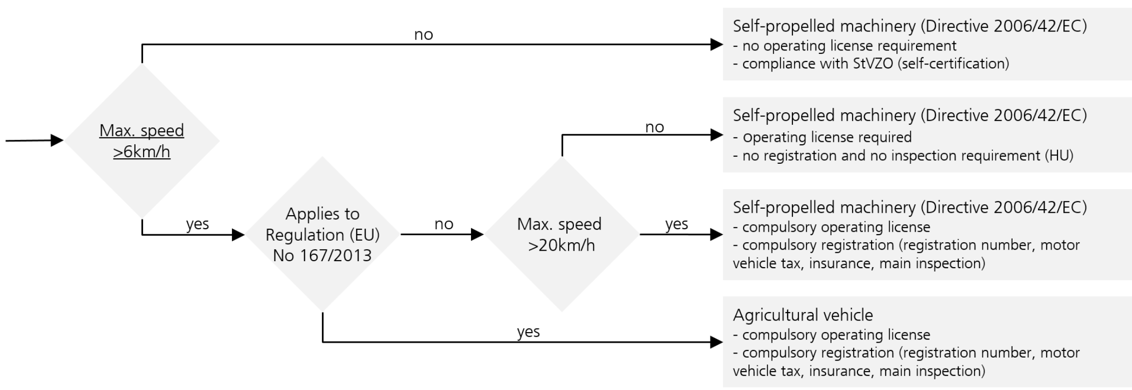

Figure 2.7: Exemplary procedure for classification according to EU directive or applicable regulations in Germany (source Fraunhofer IPA).

In terms of legal acts concerning the type of machinery and thus the safety measures to be followed, the "Machinery Directive, Directive 2006/42/EC of the European Parliament and of the Council"[14] and the "Regulation (EU) No 167/2013 of the European Parliament…of agricultural and forestry vehicles"[15] provide an overview of the common level of safety of machinery placed on the market or put into service that is required in all Member States of the EU. These acts affect the feasibility and cost-effectiveness of such systems compared to conventional machines. However, certain tasks in agriculture can be carried out primarily with heavy machinery, as a certain amount of traction is necessary to perform the work.

Among the newly emerging companies in the field of agricultural robotics, there is also a clear trend towards electrified small machines for applications that do not require high power density. In terms of weight and size, this represents a new category of machine and is therefore not in direct competition with the established tractor manufacturers. Compared to tractors, this new type of machine can also achieve higher energy efficiency in the corresponding application areas. The exemplary presentation of robots in the corresponding areas of application does not exclude other areas of application. Manufacturers often try to use their systems in a multi-application way to achieve higher

14 https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32006L0042.

15 https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=celex:32013R0167.

utilization of the machines. Machines with several application areas are, therefore, only listed once as an example.

Tillage

Tillage can be divided into primary tillage and secondary tillage:

- Primary tillage includes loosening and mixing the soil or surface turning. Plant material can be mixed in to prepare the structure of the soil and to increase its performance.
- Secondary tillage aims to make the topsoil finer, to prepare and, if necessary, shape the seedbed. Seedbed preparation can be done with harrows, such as power harrows, tillers, rollers, or cultivators.

In conventional agriculture, weed control is also partly done by tillage. This is achieved with heavy implements, such as hoes or cultivators, which loosen the top few centimeters of soil around the crops without affecting the crops themselves. However, weed control is considered separately in this report and is not part of the systems described here.

Primary and secondary tillage in conventional agriculture requires tractors and crop-dependent implements, such as the described power harrows. Agxeed from the Netherlands focuses on this area as a startup and offers an autonomous machine that can be regarded as a kind of cab-less tractor, as it uses a similar concept to conventional tractors with implements. As a tractor manufacturer, Claas has already secured cooperation with Agxeed through investments in 2021.

Figure 2.8: Agbot 5.115T2 with implements for soil preparation. Seedbed preparation can be performed with a speed of up to 11km/h. Image credit: Agxeed.

With the broad availability of precise real-time kinematic (RTK) GNSS systems, which offer centimeter-level accuracy, localization in the field combined with sensor-based crop detection opens up opportunities for automated tractors.[16] Prototype designs for autonomous tractors have been presented by almost all major agricultural machinery manufacturers: Driverless tractors from Case IH Magnum Series' Autonomous Concept Vehicle, John Deere's autonomous 8R-tractor, Yanmar's Robot Tractor, Fendt's ProbotIQ Xpert, New Holland's NH^{Drive} concept, or the Autonomous Tractor Corporation, to name only a few examples. Meanwhile, autonomy KITs are also available, i.e. software developments that can upgrade existing vehicles if they are properly prepared. Such systems, like Rowcroppilot from Robot Makers GmbH, are commercially available as technology add-ons for tractors. In addition, John Deere unveiled its first fully autonomous tractor at the Consumer Electronics Show (CES) in 2022 and announced new AI capabilities around the autonomy of processes at the CES 2024.[17][18] The use of these machines in their current technological maturity, however, is not possible in all areas. For example, depending on the classification of the agricultural machines, they can only be used under certain restrictions (very low speeds, permanent monitoring, or fencing of the terrain). Government regulations also vary from country to country, so it will take some time before autonomous robots are seen working in fields across the board.

Sowing and planting

As one of the first players, Farmdroid from Denmark has focused on a combination of seeder and weeder, named Farmdroid FD20. When combining the different operations with the same basic autonomous machine, attention must be paid to the conditions for carrying out the work process.

One reason for combining sowing and weeding is the additional information generated by the sowing process, which is a prerequisite for the downstream weeding process. Thus, the sowing process can be carried out with GNSS-based guidance, as only basic information, such as field boundaries, is required. Placing and tracking the plant seeds then provides the necessary additional information for the weeding process, which can be carried out as the crop grows. Precise, plant-specific, but purely GNSS-based weed control thus becomes possible. The FD20 is already being marketed as a product and has significantly shaped the design and structure of agricultural robots on the market.

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[16] McGlynn, S., Walters, D.: Agricultural Robots: Future Trends for Autonomous Farming. JETIR, vol. 6, Issue 4, April 2019; http://www.jetir.org/papers/JETIRBB06180.pdf.

[17] https://www.deere.com/en/news/all-news/autonomous-tractor-reveal.

[18] https://ces2024.deere.com/.

Figure 2.9 Several Farmdroid FD20s carry out sowing in the field. They can work autonomously through GNSS localization and a safety concept implemented via bumpers. Image credit: Farmdroid.

Several other companies also provide robots for sowing, often robots that, similar to tractors, can perform many agricultural tasks with the necessary implements. Robotti from Agrointelli in Denmark is one such example. Other manufacturers with robots for sowing are Naïo Technologies from France, Agxeed from the Netherlands, and Rowbot from the USA.

Crop protection

Crop protection is a constantly evolving area of application within the crop cultivation process. Organic and conventional crop protection differ considerably in some respects, but they all share the same goal: To keep crops as free from damage as possible and to provide them with the best possible growing conditions, which are a prerequisite for high productivity.

Crop protection can be divided into three sub-areas: Weed control, pest control, and disease control. In all three areas, large quantities of herbicides are used in conventional agriculture – 1,7 million tons worldwide in 2021.[19] A serious positive impact on the environment is to be achieved by reducing or even eliminating the use of pesticides.[20]

19 https://www.fao.org/faostat/en/#data/RP/visualize.

20 https://www.epa.gov/caddis-vol2/herbicides#:~:text=The%20most%20direct%20effects%20of,macrophytes%2C%20periphyton%20and%20phytoplankton.

Therefore, there are a number of regulations from policy makers to heavily limit the use of herbicides in particular, which account for nearly 50% of global pesticide use.[21]

Due to this and the enormous financial losses of not performing weed management in most crops, there is a great need for alternative weed management strategies. The associated methods can be categorized as follows:

- Mechanical
- Thermal
- Biological
- Chemical

Mechanical and thermal processes, in particular, can be carried out very well with small robots. Many of these small weeding robots have been developed and launched in recent years. Naïo Technologies, one of the most established companies in agricultural robotics, offers a whole range of robots for weed control in various applications. Oz, for example, is designed for weed control in lettuce crops and travels between rows to remove weeds close to the plant with finger hoes or similar tools. Agrointelli, Farmwise from the USA, or Saga Robotics from Norway have also introduced novel concepts for weed control and further crop protection tasks. All the aforementioned robots perform mechanical weed control. However, thermal methods also have advantages, especially in terms of speed. Flaming, superheated steam, electrocution, or laser irradiation are possible thermal treatments. With Carbon Robotics, a US company has introduced a robot that can irradiate and kill weeds in the cotyledon stage with a laser.

To optimize existing chemical crop protection measures as well, a robotic implement for tractors called ARA has been developed by Ecorobotix. The system can treat large row crops, vegetable crops, and pastures. The weeds are detected with camera systems and artificial intelligence and then precisely sprayed with small amounts of herbicide. This effectively reduces the amount of herbicide used. Besides new robots and robotics technologies, software tools are being developed for the automation of conventional agricultural machines. Octinion and Autonomous Solutions Inc. have introduced the first software products.

21 https://www.niehs.nih.gov/health/topics/agents/pesticides/index.cfm.

Figure 2.10: With Oz, Naïo Technologies has launched one of the smallest robots for professional weed control. Like conventional tractors, it can integrate various tools and work with them. Image credit: Naïo Technologies.

Fertilization

Applying the principle of fertilization according to plant requirements, the fertilization measure is determined by the nutrient requirement of the cultivated crop. It is not easy to ensure that fertilizer is applied in accordance with plant requirements by means of conventional, unmonitored fertilizer application.[22] In conventional cultivation, particular attention is paid to three groups of fertilizers: Nitrogen (N), phosphorus (P), and potassium (K), plus other supplements. The form of fertilizer to be applied can be as follows:

- Liquid manure, slurry
- Liquid organic fertilizers (sewage sludge, digestate)
- Organic-mineral fertilizers (lime sludge)
- Poultry droppings (dry chicken droppings and chicken manure)

There are now some implement systems that can monitor conventional fertilizer application and apply fertilizer more precisely on a field-specific basis. One such example is John Deere's Exavtshot, unveiled at CES 2023.[23] In combination with soil monitoring, leaching of nitrates into surrounding water bodies or groundwater can be avoided. Also,

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22 https://www.umweltbundesamt.de/en/data/environmental-indicators/indicator-nitrate-in-groundwater#at-a-glance.

23 https://www.agdaily.com/technology/john-deere-unveils-precision-seed-fertilizer-at-ces-2023/.

Rowbot was not developed for fertilization in corn crops as an implement but as an autonomous system. Corn requires a lot of nitrogen and is widely cultivated worldwide both as a fodder crop and as an energy crop.

Harvesting

When harvesting fruit and vegetables, it is not possible to carry out the process autonomously without the two basic technologies of perception and grasping. Developments in the field of grasping fruit and vegetables are mostly at the research stage. The grasping tools are particularly challenging here because the fruit to be grasped are very different in shape, size, and texture. Therefore, there are different approaches available, such as grasping with soft grippers, sucking fruits from trees, or even shooting out nuts. An important factor in the cost of automatic harvesting is the picking speed: The faster, the better. For all fruit, it must be possible to harvest them without damage. This is particularly challenging when harvesting soft fruit quickly. In addition to technological development, another approach is being driven to avoid the problems mentioned above. This relates to the actual cultivation system. For example, it can be helpful to pre-structure the crop trees or bushes, which increases fruit detection and picking speed by simplifying the grasping process. Examples of a manufacturer of an automated harvesting system with a co-design for an entire cultivation system for strawberries is Organifarms, a German start-up; but there are also other examples of fruit-picking robots, such as Harvest Croo and Octinion.

Figure 2.11: FFRobotics has introduced a robot that manages the harvesting of apples through a versatile gripper transport system. Image credit: FFRobotics.

One area where commercially ready harvesting systems are already available is apple growing. These systems work on the ground, as presented by FFRobotics from Israel, with multiple grasping tools and subsequent conveying.

Another way of tackling the challenge is a ground-air system such as the one from Tevel-Tech, also based in Israel, which can harvest apples, pears, peaches, plums, and apricots from the treetops with the help of drones.

More generally, in the field of object detection and environment perception, there has been rapid progress in the research and development of learning algorithms, partly also in self-supervised learning. New models such as SAM (Segment Anything Model) from Meta[24] give an idea of how fast development will continue to occur in the coming years. Recognition algorithms are becoming increasingly robust to variations in the appearance of objects and environmental conditions, even in very difficult lighting conditions. Problematic challenges are very practical ones that can only be solved by a combination of perception and manipulation, such as the occlusions of objects to be identified, as can occur in the case of strongly branching bushes or trees. For reliable recognition, such occlusions must first be resolved, for example by moving the occluding object.[25]

For vegetables, there are a few systems under development or on the market. For autonomous asparagus harvesting there are solutions by AVL in the Netherlands or by Autopickr from the UK.

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24 https://segment-anything.com/.

25 Kootstra, G. et al.: Selective harvesting robotics: current research, trends, and future directions. Current Robotics Reports, 2021, 2, No. 1, pp. 95-104; https://link.springer.com/article/10.1007/s43154-020-00034-1.

Figure 2.12: AVL's full harvesting robot for asparagus can support the scarce resource of labor in asparagus cultivation. Image credit: AVL Motion Groep B.V.

Other applications in farming

There are several other applications that cannot be categorized like the arable farming phases outlined above, but which nevertheless have high potential for automation in the context of agriculture. In arable farming itself, this applies to all logistics processes. Since harvesting in particular poses great challenges for robotics due to the high demands on agility and the integration of many complementary technologies; and since the harvesting process itself can be fundamentally different depending on the crop, many tasks will still have to be carried out by human labor for the foreseeable future. However, robotics can also offer support in these areas, for example through autonomous logistics processes in the field. A very successful example of this is the robot Burro from the company of the same name. Burro, i.e. the basic platform, can be enabled for further processes by building modules.

An example from horticulture is the Rainos irrigation robot from Innok Robotics. It also consists of a basic platform, its own Heros, and is expanded with modules for new applications, such as the irrigation of cemeteries.

New applications like these often make use of certain features of the environment. For example, robots like Rainos can work in cemeteries at night, after the cemeteries are closed, without having to provide specific safety precautions or human interaction. Such robots mainly use a priori information, such as existing grave maps in the cemeteries and GNSS guidance, to perform the tasks.

Harvest Automation also offers a robot, the Harvest HV-100, which can assist plant growers with a variety of tasks. As such, a swarm of Harvest HV-100s can relieve horticulturists of many tedious work processes, such as the (re)placement of plants in farm areas and the application of water, pesticides, herbicides, and fertilizers. In this way, robots can help reduce the use of resources and replace tedious manual human labor.

Figure 2.13: The HV-100 automates the most physically challenging task in ornamental horticulture production: The accurate placement of the plants in greenhouses or outdoors in any weather conditions. Image credit: Harvest Automation.

Figure 2.14: The Rainos irrigation robot from Innok Robotics autonomously waters the green areas and beds of cemeteries. By closing off the cemeteries at night, the robots can work largely undisturbed. Image credit: Innok Robotics.

2.2.1.3. COST-BENEFIT CONSIDERATIONS AND MARKETING CHALLENGES

Agriculture to date has experienced a high degree of mechanization. Accordingly, a lot of turnover is made in the agriculture machine industry every year. German manufacturers alone made over €5.6 billion revenue inland and nearly €13 billion revenue with exported agricultural machines in 2023.[26] Past growth in productivity in the agricultural sector was possible due to the increased use of technology in recent decades. This is reflected by the increasing degree of capital intensity in agriculture: With €284k of capital for each member of its workforce, agriculture is one of the most capital intensive sector of all industries; furthermore, the available funds per enterprise is €117.4k in Germany, of which, after deduction of withdrawals, an average of €32.9k/year is left over for capital expenditure. Due to constraint investment volumes, spending decisions in every large agricultural enterprise is made systematically and based on economic profitability. As far as investments in new technologies are concerned, it has

[26] In- und Auslandsumsatz der Landmaschinenindustrie¹ in Deutschland in den Jahren 2005 bis 2023 (in Millionen Euro) [Graph], Statistisches Bundesamt, March 18, 2024; https://de.statista.com/statistik/daten/studie/1237059/umfrage/in-und-auslandsumsatz-im-landmaschinenbau/.

been found that also in the agriculture industry such investments are dependent not only on the economic situation of the enterprise but also on other qualitative factors, particularly the educational level and sometimes also the age of the decision-makers. This set of socio-economic factors is comparable to most industrial countries, meaning there is a significant interest and potential in robot investment in virtually all types of farming (dairy farming, livestock, crop, fruit, etc.).

Future demand for automation in farming is expected to be very high as the following trends need to be met:

- The World Bank states that the world will have to produce 70% more food by 2050 if the global population continues to grow at its current pace. Crop yields – the amount of crops harvested per unit of land – will at least have to rise by as much as the crop demand to avoid further encroachment of cropland into natural habitats.[27]
- The U.S. Department of Agriculture reported a median age of producers of agricultural products of 58 in 2017, compared to 55 in 2012, with other countries showing similar data. The inability to provide agriculture with a well-paid, legal workforce (e.g. in the USA) has been one of the major driving forces of robotics and automation.[28]
- The necessity of reducing the ecological footprint of farming through precision farming, especially due to customer demand and food policies.[29]

Hence, the potential for automation in agriculture is very high from an economical and technical point of view. In recent years, conventional farming machines have been upgraded with automated features, e.g. driverless tractors. Moreover, new fully automated mobile farming robots have emerged, which can potentially take over the tasks of these machines and human labor in the future. The alternative to these automated tractors and machines at present is manual labor with or without operated machinery. In comparison to robotic solutions, this translates into tendencies towards lower investment costs and higher variable costs. In concrete terms, profitability studies are also being carried out in the various application areas, such as weeding or harvesting. They are presented below as examples.

A recent paper by Shang et al. (2023) investigates the Maximum Acquisition Value (MAV) for weeding robots in German sugar beet farming. Weeding, as part of the application area “crop protection”, is a promising business area, as can be seen in the

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27 Agriculture Finance & Agriculture Insurance. The World Bank Group, September 23, 2019; https://www.worldbank.org/en/topic/financialsector/brief/agriculture-finance.

28 2017 Census of Agriculture. US Department of Agriculture, 2017, issued 2019; https://www.nass.usda.gov/Publications/AgCensus/2017/Full_Report/Volume_1,_Chapter_1_US/usv1.pdf.

29 European Parliamentary Research Service (EPRS): Precision agriculture and the future of farming in Europe. Scientific Foresight Study, December 2016; http://www.europarl.europa.eu/RegData/etudes/STUD/2016/581892/EPRS_STU(2016)581892_EN.pdf.

high distribution of companies in this area (see Figure 2.6. The MAV is the break-even investment price that renders the same net profit level as when using the current weeding methods. The study finds that technology attributes are more influential than labor cost in determining the MAVs of weeding robots. For organic farming, the area capacity of a robot impacts its MAV the most, followed by weeding efficiency. For conventional farming, supervision intensity is the most influential factor, followed by weeding efficiency. The study shows that the MAVs of mechanical weeding robots in organic farming range from €62,564 to €694,073 with a mean value of €279,884. According to the research, organic farms can benefit more from mechanical weeding robots than conventional farms and can afford to pay considerably more for them to maintain their current net profit level. The study also finds that the wage rate of unskilled labor has a larger impact than the wage rate of skilled labor on the MAV of a weeding robot in organic farming. The implication is that the shortage in seasonal labor could be one important driver for adopting mechanical weeding robots in organic farming. However, high supervision costs in robotic weeding can cause economic infeasibility in conventional farming. The study finds that plot characteristics have limited importance in determining the MAVs of weeding robots, compared to technology attributes and labor cost. The study suggests that the adoption and diffusion of weeding robots might start among organic farms, and that the availability of weeding robots (and generally agricultural robots) might change the conversion decision of conventional farms.[30]

Another example are fruit-picking robots, which have been under development for many years. These robots aim to locate and detect ripe fruit on trees or vines (e.g. apples, grapes) or on the ground (e.g. strawberries). Crucial for economic success, besides classification and location of the fruit, is the picking time. The underlying concept of manipulation, gripping, and harvesting is challenging from a technical point of view. So far, many research projects have been performed, but little has filtered through into the commercial world. For example, the first products for strawberry harvesting have emerged over the last few years, like the Berry robot from Organifarms GmbH (Germany) and a similar system from Fieldworks Robotics (UK). Another successful project has emerged with a harvesting system for apples using suction instead of a complex gripping process (Washington State University, USA).[31]

Other research takes a holistic approach toward fruit picking through growing a special culture of plants, trying to have plants grow in a predictable fashion for easy automated harvesting and maintenance. Examples of this are cucumbers, peppers, and tomatoes.[32]

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30 Shang, L. et al.: How much can farmers pay for weeding robots? A Monte Carlo simulation study, Precision Agric 2023;
https://www.researchgate.net/publication/369823126_How_much_can_farmers_pay_for_weeding_robots_A_Monte_Carlo_simulation_study.

31 https://www.geekwire.com/2019/apple-picking-robots-gear-u-s-debut-washington-state.

32 Tijskens, L. M. M. et al.: From fruitlet to harvest: Modelling and predicting size and its distributions for tomato, apple and pepper fruit, Scientia Horticulturae, vol. 204, 2016, pp. 54-64; https://www.sciencedirect.com/science/article/pii/S0304423816301558.

As most vegetables are cultivated and harvested in greenhouses, deleafing the plant around the vegetables is considered a tedious task. The Kompano Deleaf-Line from Priva (the Netherlands) provides growers with an economically viable fully automated alternative to manual deleafing of tomato crops. The robot should find and remove as many leaves as possible with minimal residual work, cut the leaf with minimal risk of disease, such as Botrytis, and remove the leaves quickly enough and thereby cost effectively.

Also, mobile GPS-supported systems for specific tasks have become available. As an example of this category, a rice-planting robot has been presented by the National Agriculture and Food Research Organization (NARO, Japan). The award-winning robot is designed to assist farmers by working autonomously to plant rice within a set of programmed coordinates. It takes the robot about 50 minutes to seed 3,000 square meters (0.75 acre) of land.[33] The robot allows farmers to easily record how much fertilizer and pesticide have been used in which parts of the field as rice grows. It is, therefore, expected to contribute to food safety and security, help society cope with an aging and decreasing farming population, and facilitate the improvement of Japan’s self-sufficiency in food. However, where environments are more structured and protected against climatic conditions, such as in greenhouses, the use of robots may be more favorable. Greenhouse automation by robots could provide workforce stability, production efficiency, and boost profit margins, something sorely needed in the nursery and greenhouse industry.

As many robots are still unable to deliver added economic value, the acquisition of a robot often seems to be interesting only for early adopters. However, prospects for further automation in agriculture appear to be generally bright, as has been proven by economic feasibility. With rising labor costs and increasing food demands, agricultural robots are seen as a major source of innovation in the primary sector.

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33 https://www.youtube.com/watch?v=-ZxVm6QgLc8.

2.2.1.4. EXPERT VIEW

Three interviews with the companies Naïo Technologies from France, Innok Robotics from Germany, and Burro from the USA are presented below. The interviews were conducted in 2023 as part of the major focus chapter revision by IPA Fraunhofer.

2.2.1.4.1. INTERVIEW WITH NAÏO TECHNOLOGIES

Company:	Naïo Technologies, Escalquens, France
No. of employees:	80
Products:	Farming Robots (Oz, Orio, Jo, Ted)
Interview partner:	Gaëtan Severac (Co-Founder)

Why did you choose to develop robots for the agricultural sector?

I founded Naïo Technologies eleven years ago with my co-founder Aymeric Barthes. We both have a technical background, both came from robotics, and Aymeric actually grew up on a farm. The main trigger was that eleven years ago we kept hearing from farmers that they were running out of labor. Even then, there was a shortage of skilled workers, even if it was not as acute as it is today. Also, at Naïo Technologies, we are convinced that we need to make agriculture a sustainable production system with the help of robots.

When Naïo Technologies started, what was the key decision for your product development?

At Naïo, we strongly believe that robots will play an important role in future farming systems. We have to deal with numerous challenges, ranging from climate change, biodiversity, and insect decline to an ever-increasing shortage of skilled labor. In short, we need to start looking at advancing agricultural transformation now. With Oz, Orio, Ted, and Jo, we already have a product range for many applications, and have sold more than 350 units to date.

What are currently (2023) the biggest challenges and what will the biggest challenges be in the next five years?

The biggest challenge for us technologically is full autonomy. This means that we achieve very good results in the entire process, which in the case of weed control is ultimately the complete removal of the weeds without the crops suffering any negative impacts and at the same time requiring practically no human supervision. From a purely regulatory point of view, Oz, our smallest robot, is already allowed to drive autonomously. Ted and Oreo will follow this year after we officially certify them as machines according to the Machinery Directive. So, both from a regulatory and technological point of view, we are confident that our machines pose no danger to humans or animals when employed without human supervision. The challenge lies in the process itself or, to put it more pointedly, in the safety of the crop.

How do you plan to develop your products technologically to overcome these challenges?

The technological challenges, such as full autonomy, are met by Naïo, but we also work a lot with other teams in agricultural technology, especially focusing on the standardization of technologies.

What are the biggest hurdles for bringing your robots to market?

One of the big challenges in a relatively new market for robotics and automation, such as agriculture, is breaking old habits. Processes that used to work in a certain way are being changed by autonomous robots and we, as robotics providers, need to be able to show that changing habitual processes to automated systems has benefits and does not increase the risk in the farming process. We also need to explain the use of robotics. One example is preventive action instead of cure of the crops. With the possibility of using robots at a much higher frequency than conventional agricultural machinery, as they can theoretically work autonomously 24/7, certain crop protection processes can be rethought. For this to happen, however, there must be an intensive exchange between all the actors involved, and we are working on this.

2.2.1.4.2. INTERVIEW WITH INNOK ROBOTICS

Company:	Innok Robotics, Regenstrauf, Germany
No. of employees:	22
Products:	Rainos, Heros, Induros, Inspectos
Interview partner:	Helmut Schmid (Member of the Advisory Board)

Why did you choose to develop robots for the agricultural/outdoor logistics sector?

Innok Robotics has existed since 2012 and between 2012 and 2019 focused on project and contract business together with universities and research institutions to advance technologies for outdoor robots. In 2019, the decision was made to implement the expertise in a robotic platform with autonomous navigation, that is the Heros, and, based on this, to create variants of this platform for specific areas of application. This is how our Rainos, Induros, and Inspectos products, which we now offer in our product range, came about.

When Innok Robotics started, what was the key decision for your product development?

The products, Rainos, Induros, and Inspectos, all of which use Heros as the basic platform, have emerged from an investigation of various application areas, some of which are very complex, where the shortage of skilled workers was very present. Rainos can be used as an example to illustrate this point. Rainos was a development driven by one of our customers. Their problem was that they had an acute shortage of staff in cemetery areas for plant and grave watering. This was a perfect use case for Innok Robotics, where our years of expertise in the outdoor sector came into their own. In the concept phase of Rainos, we then looked at the challenges of the application together with our customer and jointly outlined the technologies we needed for successful implementation. That was then the starting signal for our Rainos cemetery watering robot. The exciting part is that we can now apply this to many other applications, for example in agriculture.

What are currently (2023) the biggest challenges and what will the biggest challenges be in the next five years?

With Heros, we already have a platform that has mastered many fundamental challenges. We have a navigation system that can switch from indoor to outdoor, i.e. can also localize independently of GPS, we have a vehicle that is robust in wind and weather, and we can also move over rough terrain.

However, we have to distinguish between public and non-public terrain in the application, because different safety requirements apply there. So far, we have been moving primarily in non-public areas. The development of public areas will involve special requirements for navigation and for the vehicle itself. But even in non-public areas, fail-safe locomotion, especially with very uneven surfaces, but also extreme weather conditions, is still a difficulty that we have to deal with.

How do you plan to develop your products technologically to overcome these challenges?

We now see ourselves primarily as a software company. Our hardware is already very mature and can cope very well with the conditions we have to face. We will also improve usability in order to be able to adapt more quickly to new environmental conditions, allowing us to open up new areas of application.

What are the biggest hurdles for bringing your robots to market?

There are certain difficulties, such as CE certification and risk analyses. These are not barriers, but they are definitely challenges in the regulations that can represent small pitfalls. From my point of view, however, it is much more important to inform the customers. Unlike in industry, for example in the automotive or electronics industry, our customers are not familiar with robotics. For this group of customers, robotics must not be a deterrent, i.e. not viewed as a complicated system, but must be operable by everyone. One way to reduce the entry barrier can be service models, such as robotics as a service.

2.2.1.4.3. INTERVIEW WITH BURRO

Company:	Burro, formerly Augean Robotics, Philadelphia, Pennsylvania, USA
No. of employees:	40
Products:	Burro, autonomous ground vehicle for permanent crops and solar panel operations
Interview partner:	Charles Andersen (CEO)

Why did you choose to develop robots for the agricultural sector?

I grew up on a farm and worked with conventional machinery on the family farm. During that time, I realized that there is a lot of work that takes place outside the tractor cab, for example, work that involves pruning, weeding, spraying, crop picking, and mowing. In other words, there was so much tedious work that could not be done by any mechanical systems and had to be done laboriously and by hand. Even then, it was clear to me that I wanted to use autonomy and technology to solve these challenges. After my education and after I finished my MBA, it was clear to me that I wanted to turn my ideas into a new product, and I was faced with the decision of how to use autonomy in the current agricultural market to improve the described challenges without having to compete with the big machinery manufacturers like John Deere, Kubota, or CNH.

When Burro started, what was the key decision for your product development?

The large machinery manufacturers have already mechanized the growing processes of the main crops such as corn, or other grains, extremely efficiently. Large tractors or harvesters can handle thousands of acres a day with just one person. Most of the manual labor used in agriculture is in the niches of high value crops. Workers in these fields have to do an incredible amount of work, some of it very complex. To me, the connecting component is carrying or towing goods in the field as an assistive system. Therefore, I started, along with my two co-founders, developing such a robot as the first prototype. That was in 2017/2018. This year, we plan to reach the more than 500 units sold mark, which are already deployed globally. The focus of our product today is as a carrying and towing vehicle in mostly permanent crops, which includes table grapes, blueberries, blackberries, raspberries, nursery crops, stone fruit, and citrus, and even outside of the cultivation, solar panel sites.

What are currently (2023) the biggest challenges and what will the biggest challenges be in the next five years?

Challenges with our product often reside in the nature of the application. Precisely because our products are used in so many applications and scenarios, our customers often use them for use cases other than those for which we originally intended them. Of course, this provides us with very interesting insights into new areas of application, but it also naturally poses particular challenges for further development and maintenance.

How do you plan to develop your products technologically to overcome these challenges?

To address these challenges, we track autonomous miles per user intervention, and that reliability rate increases continuously for us as the runtime increases. In concrete terms, this means that for several years now, we have been using the cameras on our robots to process around two terabytes of image material per hour of operating time for each individual system.

What are the biggest hurdles for bringing your robots to market?

For us, issues like safety are no longer market barriers. Our robot is equipped with many redundancies and some safety features that allow us to move among and between workers. One of the biggest challenges for us, as a company, is scaling and ROI. I see Burro on a very good path there. As I said before, we will reach the 500 units shipped mark this year, and in terms of market development, Europe could also be one of the next steps. So far, we have not sold any units there. An important step in entering a new market is to build up a sales and maintenance network. As soon as we address Europe, these will be the corresponding next steps.

2.2.1.5. PRODUCERS

Advanced Intelligent Systems, Advanced.farm, Afara Agricultural Technologies, Agrobot, Agrointelli, Agxeed, Amazonen-Werke, Art Robot, ArvaTec, ATC Autonomous Tractor Company, Autonomous Solutions, Autopickr, Biogriculture, Blue River Technologies, Brüggli, Burro, Carbon Robotics, Carré, Dahlia Robotics, DJI, Dogtooth Technologies, Earth Rover, Earth Sense, EcoRobotix, Ekobot, Elatec, F Poulsen Engineering, Farmdroid, Farming Revolution, FarmWise, Ferrari Costruzioni, FF Robotics, Garford Farm Machinery, Harvest Automation, Harvest Croo, Hyundai Rotem, Innok Robotics, Iseki, John Deere, Meropy, Metomotion, Naio Technologies, Nexus Robotics, Niqo Robotics, Octiva, Odd.Bot, Organifarms, Panasonic, Pek Automotive, Pixelfarming Robotics, Ripe Robotics, RoboticsPlus, Rowbot Systems, Schmiede.one, Sitia, SwarmFarm Robotics, Tensorfield Agriculture, Tevel Aerobotics Technologies, Trimble, Vision Robotics, Vitibot, Vitirover, Wado Sangyo, Wall-ye, XAG, Xihelm, Xmachines, Yamaha, Yanmar, Zauberzeug

2.2.2 AP12: MILKING

Cow-milking robots were among the first robotic systems to be used in agriculture. Numerous milking robot products have emerged in recent years with resounding success: Milking robots have found wide acceptance among dairy farmers worldwide.

2.2.2.1. TYPES OF OPERATIONS CARRIED OUT BY THE ROBOT

Cow-milking robots consist of a stationary unit into which the cows walk independently to be milked. A transponder around the cow's neck informs the robot about its details, enabling a range of herd management tasks, such as monitoring the control of the milk yield, the milk flow, and the milk quality. The milking robot executes the entire milking process, beginning with teat cleaning and ending with the removal of the last teat cup and spraying of the teats. The information gathered during the milking process is presented to the farmer through a computer-based herd management system.

Figure 2.15: The Lely Astronaut A5 Automatic milking system, teat cups attached to the udder, shown from behind the cow. Image credit: Lely.

2.2.2.2. LEVEL OF DISTRIBUTION

The following features characterize the dairy farming industry:

- High pressure on prices because of political decisions, such as the mandatory milk quota.

- Despite existing automation solutions, such as the rotary milking parlor, there is still a need for approximately one human worker per 30-50 cows.
- Labor costs per liter of milk make up around 22% of the total.
- The shortage of milking staff is likely to become worse in most industrialized countries.
- Strict hygiene rules.

The advantages for farmers are obvious: Less manual work and more time for computer-based herd management to monitor and control the health of the herd. The benefits for the cows are just as significant: They are free to choose when to be milked. The systems allow "free-flow cow traffic". Experience has shown that, left to themselves, cows will enter the unit to be milked two to four times a day, at almost any time of the day or night. However, current milking robots are mostly applied to smaller herds of between 80 and 500 cows due to their limited throughput. The application of the automatic milking systems to larger herds is possible but requires a complete restructuring of the barn and herd layout. Automatic rotary milking systems, such as the Delaval automated milking robot, aim at serving large herds of more than 300 cows. A study conducted among owners of automated milking systems in Spain proved that farms with the best results in terms of quality of life and leisure (improving mental health and more time for family and hobbies) seem to be those with one milking robot and an adequate number of animals adjusted to optimize the use of a milking robot.[34] It has been shown in further studies that cows seem healthier and happier with a milking robot.[35]

[34] Castro, A.; Pereira, J. M.; Amiama, C.; Bueno, J.: Typologies of dairy farms with automatic milking system in northwest Spain and farmers' satisfaction, Italian Journal of Animal Science, vol. 14, no. 2, 2015, pp. 207-219; https://doi.org/10.4081/ijas.2015.3559.

[35] Holloway, L.; Wilkinson, K.; Bear, C.: Re-capturing bovine life: robot-cow relationships, freedom and control in dairy farming; http://orca.cf.ac.uk/39368/1/geogroboticsIBG%202011%20presentation.pdf.

Figure 2.16: The Dairyrobot R9500 is engineered to enhance the milking process for the cow. GEA's proven In-Liner Everything technology performs every step of the milking process – stimulating, teat cleaning, fore-stripping, milk harvesting, and post-dipping – in a single attachment. This process, which occurs within the teat cup, is key to harvesting quality milk while maximizing the efficiency of a robotic milking facility. Image credit: GEA.

A milking robot system incorporates a milking management system, which relies on the identification of each cow by ear tags, transponders, or pedometers. Each robot is cost-effectively handling 60 or more cows.[36] Cost analysis has shown that milking robots are profitable, resulting in €0.02 to €0.04 earnings per liter (in Europe) given current farm production prices of €0.25 to €0.40 per liter. Products of various capacities and scalable systems that can be stepwise adapted to increasing cow herds are available on the market.

In the milking system, every cow is identified to ensure the system can decide whether the cow is going to be milked or not. As a rule, a cow should be ready to produce about seven liters of milk before being milked. If a cow returns to the milking system too early, it is not milked. Other features of automated milking systems:

[36] Castro, A.; Pereira, J. M.: Estimating efficiency in automatic milking system, Journal of Dairy Science, vol. 95, no. 2, 2012, pp. 929-936; https://www.researchgate.net/publication/317174754_Estimating_efficiency_in_automatic_milking_systems. And a newer source from Farmers Weekly 2019: https://www.fwi.co.uk/livestock/dairy/a-dairy-farmers-guide-to-switching-to-robotic-milking.

- Lasers and vision systems that make it possible to detect and localize the teats.
- Multi-purpose manipulators that can accommodate udder and teat irregularities, handle teat cleaning, cup attachments, and disinfection.
- The robot arms are either customized kinematics (actuated by water hydraulics or pneumatics) or modified industrial robot arms.
- Automatic disposal of manure and cleaning.
- Indicators for measuring flow, quantity, milking time, and quality from individual teats as well as yield.

Once the cow has been identified, the manger frame is adjusted to the individual cow's length and the feed is dispensed to the manger according to the requirements of the particular cow. The dairy industry of the future will be far more automated than today's, using automated milking systems which, besides high productivity and cost efficiency, will satisfy the demand for higher milk quality and more species-appropriate conditions for dairy herds.

A general assessment, including all factors of dairy cow management, concluded the overall positive effects as early as 2012 (for the US market)[37]:

- Increase in milk production by up to 12%.
- Decrease in labor by as much as 18%.
- Dairy cow welfare by allowing cows to choose when to be milked.
- Robots in livestock farming improve or at least objectively document animal welfare on farms, facilitate product segmentation and better marketing of livestock products, and improve the economic stability of rural areas.
- A thorough, scenario-based cost-benefit calculation for a milking robot, including a calculator, can be accessed at the University of Minnesota, proving the robust effects and laying out the importance of increasing milk yield per robot.[38]

In a 2016 study, labor audits conducted on both automatic milking (AM) and conventional milking (CM) farms showed a 36% reduction in labor demand associated with AM. However, medium-specification conventional milking technologies consistently achieved greater profitability, irrespective of the farm size. The AM system achieved intermediate profitability at a medium farm size; it was 0.5% less profitable than high-specification

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[37] Jacobs, J. A.; Siegfort, J. M.: The impact of automatic milking systems on dairy cow management, behavior, health, and welfare, Journal of Dairy Science, vol. 95, no. 5, 2012, pp. 2227-2247.

[38] Salfer, J. A. et al.: Finances and returns for robotics diaries; including an online cost-benefit tool, 2017; http://dairy.unl.edu/documents/Salfer_EconomicsinRobots.pdf.

technology at large farm size. The difference in profitability was significant in the years after the initial investment.[39]

In the EFFIROB study, a full scenario of a robot system for dairy farming is analyzed with respect to cost-effectiveness, qualitative decisional factors, and market size assessment as a template for similar product planning processes.[40] There, the outstanding cost-effectiveness for different cattle herd sizes based on different milking robot designs has been detailed.

2.2.2.3. COST-BENEFIT CONSIDERATIONS AND MARKETING CHALLENGES

Besides dairy farming, livestock management is one of the current challenges within agriculture. In automated farm animal management, various tools and methods are used to measure the well-being of each animal with high precision and to help farmers make better decisions regarding animal husbandry systems. Animal husbandry systems and the use of new technologies in them must be distinguished into indoor and outdoor husbandry. To quickly and efficiently detect deviations in certain parameters in indoor husbandry like barns, a large amount of data must be collected and analyzed. For this purpose, animal-specific parameters are determined, but also those from their environment, such as temperature, smoke level, or humidity. Accordingly, various types of cameras, microphones, as well as more complex sensor combinations can be used as sensors.

In free-range farming, sensory monitoring becomes much more difficult as the environmental conditions can only be controlled to a limited extent and are highly dynamic in some cases. Examples of this are large livestock pastures.[41]

2.2.2.4. PRODUCERS

DeLaval International, GEA Farm Technologies, Joz, Lely, Lemmer Fullwood, SAC (BouMatic)

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[39] Shortall, J. et al.: Investment appraisal of automatic milking and conventional milking technologies in a pasture-based dairy system, Journal of Dairy Science, vol. 99 no. 9, 2016, pp. 7700-7713.

[40] EFFIROB study: https://www.ipa.fraunhofer.de/en/reference_projects/EFFIROB.html.

[41] Monteiro, A.; Santos, S.; Gonçalves, P. Precision Agriculture for Crop and Livestock Farming—Brief Review. Animals 2021, 11, 2345; https://doi.org/10.3390/ani11082345.

2.2.3 AP13: OTHER LIVESTOCK FARMING

Besides dairy farming, livestock management is one of the current challenges within agriculture. In automated farm animal management, various tools and methods are used to measure the well-being of each animal with high precision and to help farmers make better decisions regarding animal husbandry systems. Animal husbandry systems and the use of new technologies in them must be distinguished into indoor and outdoor husbandry. To quickly and efficiently detect deviations in certain parameters in indoor husbandry like barns, a large amount of data must be collected and analyzed. For this purpose, animal-specific parameters are determined, but also those from their environment, such as temperature, smoke level, or humidity. Accordingly, various types of cameras, microphones, as well as more complex sensor combinations can be used as sensors.

In free-range farming, sensory monitoring becomes much more difficult as the environmental conditions can only be controlled to a limited extent and are highly dynamic in some cases. Examples of this are large livestock pastures.[42]

2.2.3.1. TYPES OF OPERATIONS CARRIED OUT BY THE ROBOT

Barn automation is also on the rise with robotic barn cleaners, feeders, and transportation systems. Various mobile barn cleaners have been introduced by Lely, Schauer Agrotronic GmbH, and Peter Prinzing GmbH, which help to keep barns with slatted floors clean by automatically moving across the barn without disturbing the cows. The battery-driven and auto-rechargeable cleaner is programmed for optimal coverage of the floor. A slide fitted underneath pushes the dung through the openings of the slatted floor.

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[42] Monteiro, A.; Santos, S.; Gonçalves, P. Precision Agriculture for Crop and Livestock Farming—Brief Review. Animals 2021, 11, 2345; https://doi.org/10.3390/ani11082345.

Figure 2.17: Several Lely barn robots: The Lely Astronaut Vector automatic feeding system, the Lely Collector barn cleaning robots, and the Lely Astronaut milking robot. Image credit: Lely International.

The Lely Juno robotic feeder drives automatically over the feeding alley by following the feeding fence. It pushes the feed towards the fence as often as required without disturbing the cows. A similar application has been presented by Delaval and Hetwin.

One of the latest developments on the market is the new cow-feeding robot Dairyfeed F4500 from GEA. The fully autonomous driving robot can be adapted to various terrains, farm layouts, and farm sizes. It weighs, cuts, mixes, and distributes fresh feed every hour for up to 300 cows in different nutritional groups. Its sensors analyze various ingredients and mix quality, supporting the farmers in obtaining the best possible ration. Also recognizing leftover feed, the new robot adjusts the next mix accordingly, thus minimizing feed waste.

Figure 2.18: The new cow-feeding robot from GEA. Image credit: GEA.

Other initiatives are starting to look into robotic assistance for animal care and herding.[43] Faromatics, acquired by AGCO in 2021, presents another approach in the market of livestock robots. Their robot Chickenboy enables continuous monitoring of the animals to ensure their needs can be detected quickly and reliably. Meeting those needs helps farmers to improve the health and welfare of their animals and to become more competitive. Other tasks in poultry farming are collecting eggs, encouraging the animals to move, and cleaning the floors. The robot family XO developed by the French company Octopus Biosafety performs several of these tasks at once with a focus on barn hygiene. Spoutnic NAV, a robot from Tibot, also a French company, is intended for use in broilers. The tasks of this small ground-based robot are to stimulate the movement of the poultry while aerating the litter.

2.2.3.2. LEVEL OF DISTRIBUTION

While milking robots are already widely established and produced in large numbers, robots for use in livestock farming are still in the establishment phase. However, solutions for herding animals and automating barns appear to be catching on quickly, especially in highly productive, agricultural regions. However, there is a much smaller and less lively startup scene in this area than, for example, in the field of arable farming. The relevance

[43] StaldTek – The Pigpens of the Future: http://www.dti.dk/inspiration/26383.

of this area can, however, be clearly derived from the acquisition of Faromatics by AGCO.

2.2.3.3. COST-BENEFIT CONSIDERATIONS AND MARKETING CHALLENGES

The following characteristics are relevant to livestock farming:

- High price pressure from highly efficient livestock farms.
- Pressure on producers has increased due to various scandals, mainly concerning the problem between industrialized animal farming and animal welfare.
- Skilled workers in the field of animal fattening are increasingly difficult to obtain.
- Due to recurring outbreaks of diseases, such as African swine fever, hygiene regulations have to be followed very strictly.

The use of robots in livestock farming provides many advantages to the farmer. Especially the robots in a barn can offer significantly better 24/7 protection for the animals. This starts with the monitoring tasks that the robots can carry out. The important parameters can be monitored permanently and broken down by animal. In addition, animal welfare is increased through, for example, more regular cleaning of the barn and the avoidance of bad conditions, such as excessively high air or litter humidity.

Stress can also be identified as an additional factor. All this leads to fewer problems in animal production and higher product quality.

2.2.3.4. PRODUCERS

DeLaval International, GEA Farm Technologies, Hetwin Automation Systems, Joz, Lely, Lemmer Fullwood, Octopus Biosafety, Prinzing Maschinenbau, Schauer Agrotronic, Sveaverken

2.3 AP2: PROFESSIONAL CLEANING

Authors: Dipl.-Ing. Theo Jacobs; Miriam Schmelzer M.Sc.; Dipl.-Inf. Winfried Baum

A clear distinction needs to be made between professional cleaning robots and those used domestically in private homes, which are dealt with in chapter 4.2.1. Differences in these domains can be found in unit costs, reliability, dependability, and life-cycle requirements. In addition, legal requirements regarding data security and hardware construction according to industrial norms play a role. Some newer professional cleaning robots by e.g. Gausium or Nexaro resemble those for consumer use in the sense that they are as small and compact. They must, however, fulfill different industrial norms than consumer products.

The cleaning of offices, facades, vehicles, and other objects is usually outsourced to service providers. Despite a period of uncertainty during the COVID-19 pandemic, the market for professional cleaning has experienced constant growth for several decades. With a global market size for contract cleaning services of USD 268.9bn in 2022, an increase to USD 409.6bn is expected by 2030, with a Compound Annual Growth Rate (CAGR) of 5.4%.[44] Professional cleaning is, however, a labor-intensive domain with a constant lack of workers due to demographic change. In addition, many cleaning tasks, like facade cleaning or tank cleaning, include a high risk for workers. Cleaning robots therefore have the potential to not only increase efficiency and overcome the shortage of skilled workers but also ensure risk-free working conditions.

While autonomous robots in floor cleaning are already well established, other market segments are slowly following suit, for example in disinfection or solar panel cleaning. In 2022, professional cleaning was among the top 5 professional service robot applications with 6,900 units sold. In addition, cleaning robots have become a constant highlight at exhibitions, like 2024 Interclean in Amsterdam.[45] The following chapters provide an overview of existing solutions.

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[44] https://www.researchandmarkets.com/reports/338539/contract_cleaning_services_global_strategic.

[45] https://www.intercleanshow.com/amsterdam/programme/activities#robotarena.

IFR statistics

Demand for **professional cleaning** robots (AP2) grew by 4%. Sales of almost 12,000 units were reported to the IFR Statistical Department. There is also a considerable RaaS fleet of 2,369 units (+29%).

The main application in this group is **floor cleaning** (AP21). Around 70% of the sales in this application group belong to this class (8,501 units). When the COVID-19 pandemic began, many service robot providers quickly developed **disinfection robots** (AP25), spraying disinfectant fluids, or using ultraviolet light. The IFR now sees sales picking up in that segment with 224 units sold and a remarkable growth rate of +102%. In the class of **window, wall, tank, tube, pipe, hull cleaning, and other professional cleaning** (AP22-24, AP29), many solutions on the market are robotic devices that lack autonomy because they are remote controlled, and thus excluded from the statistics. **Other professional cleaning** (AP29) includes, for instance, professional pool cleaning robots and solar panel cleaning robots. Across the application classes AP22-AP24, and AP29, almost 3,300 units (+14%) were sold.

Table 2.6

Professional service robots for professional cleaning (2022 and 2023)

Application		2022	2023	2023/2022	2022	2023	2023/2022
		units sold		growth rate	RaaS fleet (in units)		growth rate
AP2	Professional cleaning*	11,482	11,987	+4%	1,843	2,369	+29%
AP21	Floor Cleaning*	8,498	8,501	+0%	**	**	-
AP25	Disinfection*	111	224	+102%	**	**	-
AP22-24, AP29	Window, wall, tank, tube, pipe, hull, and other professional cleaning*	2,873	3,262	+14%	**	**	-

Source: World Robotics 2024
Results of IFR's annual survey and desktop research (31 professional cleaning robot companies)
*Regional breakdown cannot be revealed (minimum number of non-zero observations not reached).
**Results cannot be revealed (minimum number of non-zero observations not reached). Data included in application group total (AP1, AP2, etc.).

2.3.1 AP21: FLOOR CLEANING

2.3.1.1. TYPES OF OPERATIONS CARRIED OUT BY THE ROBOT

Conventional professional floor cleaning robots have a similar size and shape as standard cleaning machines, like walk-behind or ride-on floor cleaning machines. However, more and more smaller robots are also entering the market. These smaller robots are designed to clean in narrow areas, some are even small enough to clean under tables or other obstacles. All floor cleaning robots are able to drive autonomously around the cleaning area, i.e. they feature navigation control systems and sensors (ultrasonic, laser scanner, etc.) for detecting environments and preventing collisions with obstacles. The majority of floor cleaning robots can perform scrubbing tasks. Additional tasks are sweeping, vacuuming, mopping, and high-pressure cleaning. This can be enriched by adding means for disinfection.

Recently, robots offering multiple cleaning solutions have been introduced to the market, such as the Phantas from Gausium or the Pudu CC1 from Pudu Robotics. In these models, the cleaning module can be switched, for example, between scrubbing, mopping, vacuuming, and sweeping. This offers the possibility of cleaning different types of floors, such as hard floors and soft carpets, with just one robot. In addition, Gausium states that the Phantas is able to recognize and distinguish between different types of floors. For example, if carpet is detected during wet cleaning, the robot lifts the wet cleaning module and pauses cleaning until it is back on a hard floor.

Figure 2.19: Gausium Scrubber in a health care facility. Image credit: Gausium Robotics.

Several designs have been proposed that offer dual-mode operation, which means that they can be used as manual machines during the day or in difficult environments and operate autonomously for the rest of the time. Navigation systems have evolved from an initial programming cycle ("teach-in") to memorize the path around the area to flexible online path planning in a predetermined area that also allows the robot to react to obstacles and to clean in areas frequented by humans, such as train stations.

For autonomous operation, the robots use sensor data to generate a map of their operating environment during a single teach-in run. Usually, the robots can either be pushed through the environment manually or tele-operated. If necessary, the map can be edited, e.g., to add no-go areas. The robots can then use this map for orientation and adapt their routes accordingly. Some manufacturers also offer software for fleet management, which makes it possible to control and coordinate several cleaning robots.[46]

A growing number of manufacturers are offering service stations which the robots can approach autonomously to recharge their batteries and, for example, to exchange dirty and fresh water. The cleaning robots drive to their working area, carry out the cleaning process (sweeping, scrubbing, drying, etc.) and return to the charging station when they run short on power or cleaning media. Pudu robotics also offers breakpoint resume cleaning. This feature allows the robot to remember the position where it interrupted its

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46 https://www.therobotreport.com/neo-2-cleaning-robot-includes-avidbots-updates-ai-fleet-management/.

cleaning task to recharge and to continue cleaning at that position after it has been fully charged.

For some robots, it is possible to use personnel elevators by radio command and thus operate on different building levels. Similar to manually guided machinery, the robots are most efficient on large surface areas, i.e. halls, corridors, train stations, hospitals, large industrial or research centers, and supermarkets. Since around 2015, designs provide 3D sensor systems for navigation in complex environments. Another advantage besides autonomous cleaning is the automatic documentation of the performed work, which can be recalled on site or online. Some robots are equipped with cameras to improve the perception of the environment, e.g. for better obstacle avoidance. In addition, Gausium offers Auto Spot Cleaning, a feature where the robot scans the floor to detect dirty spots and cleans them. If the dirt is too coarse to be cleaned by the robot, it informs the operator. In contrast, some manufacturers avoid cameras on purpose in order to be able to operate in a privacy-compliant manner between people in public areas.

Figure 2.20: Cleaning robot RA660 Navi XL from Cleanfix – cleaning a tech center in Dubai. Image credit: Cleanfix Reinigungssysteme AG.

2.3.1.2. LEVEL OF DISTRIBUTION

Cleaning robots have been developed for indoor use in supermarkets, shopping malls, or in schools where large surfaces have to be cleaned at regular intervals.

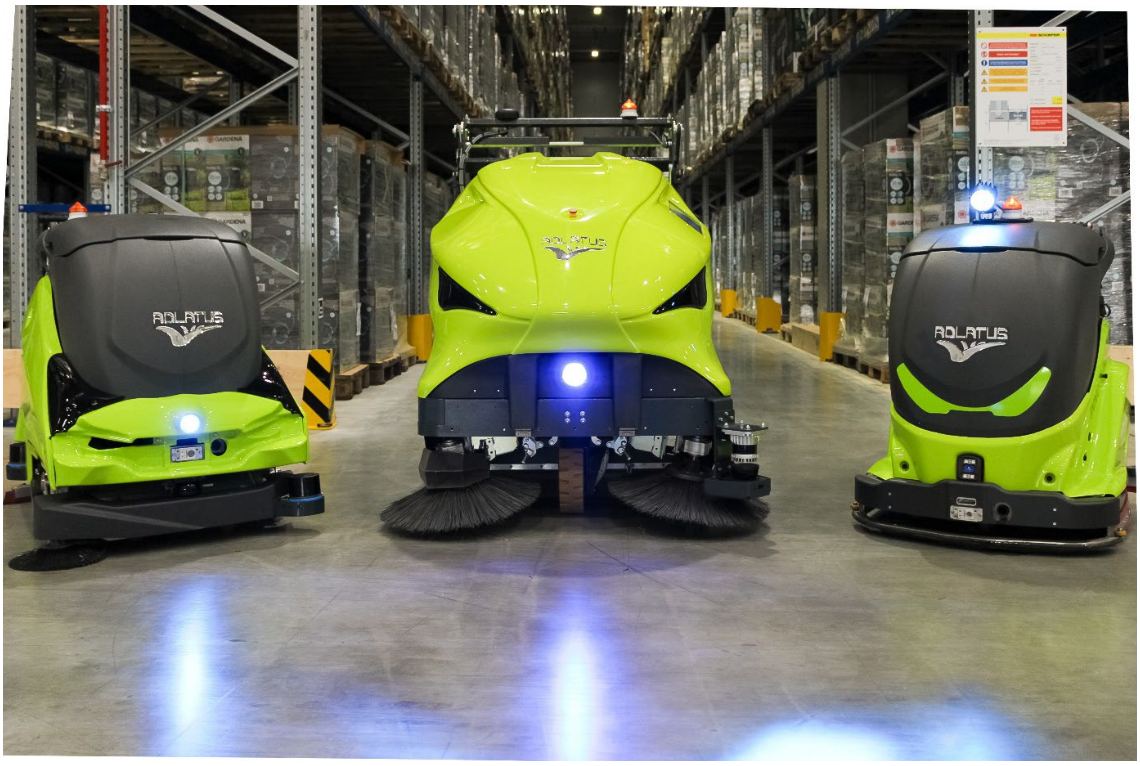

Figure 2.21: Depending on the application and the amount of dirt, Adlatus Robotics offers fully autonomous robot sweepers or scrubber-driers, all of which are equipped with a service station. Image credit: Adlatus Robotics GmbH.

The first professional floor cleaning robots date back to the 1990s but never achieved wider distribution due to poor cost efficiency and acceptance. The level of distribution of floor cleaning robots fell short of earlier projections until about 2015, when a tipping point was reached. Due to cheaper equipment and increased robot skills, the market appeared more attractive for manufacturers and end users.[47] In 2016, the French railroad company SNCF tested automated floor scrubbing robots at four train stations in Paris and then contracted cleaning robots for several years. Deutsche Bahn in Germany held a floor cleaning competition for robots at Berlin's main station in 2018 and continued to cooperate with the German manufacturer Adlatus.

In 2018, Walmart started to deploy cleaning robots in their stores as "janitors" in cooperation with Brain Corp, a company specializing in the development of the control software for cleaning robots. By mid-2019, 360 robots were deployed with 1,500 more ordered. Avidbots has successfully deployed floor cleaning robots at airports, for

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47 Ward, C. W.: Robots in Commercial Cleaning: The Coming Robot Tsunami, July 20, 2018; https://cybercleansystems.com/robottsunami.html.

example in Cincinnati, Paris, Tokyo, and Singapore. In 2019, they launched a cooperation with DHL North America with the goal of placing their robots in logistic centers worldwide. As of 2022, 25 robots have also been deployed in one of Australia's largest shopping mall chains.

Figure 2.22: Neo 2 is a fully autonomous floor scrubbing robot chosen by organizations around the world and deployed in a variety of commercial environments, including warehouses, shopping malls, box stores, airports, train stations, schools, universities, and hospitals. Image credit: Avidbots.

Furthermore, vacuum cleaning and sweeping robots for large floor areas in commercial applications have entered the market as well, such as the Fybots sweep. Typical customers are facility management operators for warehouses, offices, stores, and factories. Tailos develops vacuum cleaning robots which are considerably smaller than usual models for professional cleaning and are designed for cleaning in hotel rooms.

Figure 2.23: The sweeping robot Kemaro 900 can hold up to 35 liters of dust in its tank. Image credit: Kemaro.

Outdoor versions of cleaning robots are far more uncommon, partly because of the more challenging environment, including pedestrians, road traffic, and changing weather conditions. The first manufacturers of road sweeping robots are Westfield, Enway, and Trombia. In 2020, Lionsbot signed a contract with the Government of Singapore to deliver street cleaning robots. Since 2019, the Infore Environment Technology Group has been servicing parks and public roads in Shenzhen's Futian district with sanitation and road sweeping robots as part of a 10-year contract.

2.3.1.3. COST-BENEFIT CONSIDERATIONS AND MARKETING CHALLENGES

For the investor, the principal aim in using a cleaning robot is to reduce labor costs, usually expressed as a cost benefit per square meter of maintained floor. The economic viability of cleaning robots depends very much on their degree of labor savings, which in turn depends, above all, on their degree of utilization but also on the degree of autonomy and simplicity of installation and the teaching process. However, today's robots are mostly viable in large, unobstructed areas.

For a long time, autonomous navigation – and the respective controller hardware – has been considered a major cost driver for cleaning robots. Between 2010 and 2015, however, off-the-shelf navigation systems became available from technology suppliers, such as the Ant system from Bluebotics, Synapticon, Navitec Systems, Brain Corp, Inmach, or Tamella. Furthermore, open-source packages for general mobile robot navigation have been successfully implemented in various types of mobile robots, as seen with the major success of the free Robot Operating System (ROS).[48] With over 34,000 deployed robots for floor cleaning but also for inventory in 2024 using Brain OS, Brain Corp claims to have facilitated over 17 million total autonomous hours of operation.[49]

Figure 2.24: Autonomous scrubber in a shopping mall. Image credit: Lionsbot.

Floor cleaning robots can be used most effectively when the robot takes over the monotone cleaning of large, open areas, while cleaning personnel can focus on more challenging tasks, such as cleaning offices or bathrooms in the same building. Operating the robot therefore enriches the job of cleaning personnel. Another motivation for using a cleaning robot is that the cleaning results can be documented. Today, many cleaning contracts include result-oriented cleaning, which means that instead of a fixed cleaning schedule, a service provider only cleans when a room lacks cleanliness. For validation of the results, a robot can provide objective verification of cleaning, quality control, and documentation. In addition, Lionsbot and Gausium claim to consume significantly less water than standard manual cleaning machines, for example, by filtering the water.

48 ROS navigation: http://wiki.ros.org/navigation.
49 https://braincorp.com/.

2.3.1.4. EXPERT VIEW

Five interviews with the companies Gausium from China, Cleanfix Reinigungssysteme from Switzerland, Adlatus Robotics from Germany, Avidbots from Canada, and Lionsbot, Singapore are presented below. The interviews were conducted in 2023 as part of the major focus chapter revision by Fraunhofer IPA.

2.3.1.4.1. INTERVIEW WITH GAUSIUM

Company:	Gausium, Shanghai, China
No. of employees:	1,001-5,000
Products:	Floor Cleaning and Delivery Robots (Phantas, Vacuum 40, Scrubber 50, Scrubber 75, Sweeper 111, Delivery X1)
Interview partners: and	Peter Kwestro (Global Business Development Director), Katja Wang (Global Branding MarCom Manager)

Why did you choose to develop robots for floor cleaning?

We started in 2013, when we provided SLAM technology solutions to other robotics companies. In 2015, Singapore Changi International airport wanted us to design a floor cleaning robot to empower their cleaning efficiency and build an innovative impression for the city. Inspired by this request, we developed our first cleaning robot for hard floors. We realized that there was a high demand for more efficient cleaning solutions due to the lack of cleaning staff around the globe, caused by the aging global population in many parts of the world. This is how we started to design a full range of floor-cleaning robots to provide the market and cleaners with a tool that makes them more productive, allowing them to perform their jobs or spend time on other tasks. Cleaners are becoming more like operators who can use these robots almost like real “co-assistants”, helping them on demand or remotely controlled, including real-time corrections, constant supervision, and transparent automated reports during and after cleaning. We are very happy to contribute in this way, which has a great social impact of improving the industry’s productivity without adding more pressure, while being an economic and appealing solution at the same time. We believe in working smarter, not harder.

What was the most impactful decision for your product development?

We chose to design the full solution “in-house”, including both hardware and software, without looking at existing algorithms and technology, so that we could develop them in the most efficient way possible. We did not take shortcuts but took the hard way by finding challenging solutions to make them a truly valuable asset for the industry. We did not want to create just another gadget or “early adopter” innovation that would be nice to have, but instead wanted to create a comprehensive series of everyday, meaningful, and valuable solutions that were easy to install and use. This approach had the most impact, which makes us the acknowledged industry leader in professional cleaning robots today.

What are the biggest hurdles in terms of bringing your robots to the market?

Every innovation and change in a specific market, especially in the rather conservative cleaning market, needs some time before end users and the thousands of cleaning companies that outsource floor cleaning in most parts of the world can be convinced that our technology really provides a serious and mature solution. Besides participating in global trade shows and winning many innovation and even design awards, it was only last year, after COVID-19 hit, that our market realized we already had a "ready-to-use" solution for them. Today, the challenge is not whether floor cleaning robots are needed and will help cleaners globally - they have already proven to be a solution for the needs of the cleaning industry, outsourced or not. Now, the question is more about when every cleaner will operate a floor cleaning robot, if this is actually possible, so we can continue to clean our buildings, regardless of the sector we are in.

Looking into the future, what are the biggest challenges ahead for your customers?

Like with all new technology, some customers in the industry are still very reactive, thinking that the aging population, lack of staff, and declining productivity will not affect them. It is our challenge to convince those who still believe that floor cleaning robots are something for the future, making them realize that thousands of them are already used on a daily basis. We must provide a professional solution for all the stakeholders involved, managing the right implementation and acceptance and convincing them that our robotics help cleaners to keep their jobs instead of losing them, partly with a different job content. The triangle between building service contractors (BSCs), building owners, and robots is another challenge, where the traditional business model of BSCs is changing from selling "cleaning hours" to selling cleaning results with the best productivity against the backdrop of reasonable "costs of cleaning" and avoiding the problem of a lack of staff. We all once accepted that laundry machines took over laundry cleaning, and cars and trains took over most of the "horseback" transportation. Some business owners still have to overcome our natural human instinct to "resist change" and accept that floor cleaning robots are there to help us and are desperately needed in many situations.

How are you planning to further develop your products to tackle these challenges?

This question is also on our top priority list. We have tried to make the robots more intuitive by adding AI elements to the technology, making them even more user friendly and completely autonomous compared to the first-generation floor cleaning robots. This way, users who are still hesitating can quickly be convinced of the added value of our robotic solutions. They are not a threat but a welcome asset to their situation and can really help them become more productive and solve a big part of the HR problems in the cleaning industry. The robots work together with cleaners, site by site, as a co-assistant, completely under the control of the humans who work with them. Once they have worked with them, they do not want to miss their autonomous buddies anymore! Besides this, we are also developing non-robotic solutions that make cleaners more productive without adding more pressure to the job. This development will also help to understand the value and benefits of the robots, allowing us to strengthen both solutions at the same time. I would suggest you keep following us closely.

2.3.1.4.2. INTERVIEW WITH CLEANFIX REINIGUNGSSYSTEME AG

Company:	Cleanfix Reinigungssysteme AG, Henau-Uzwil, Switzerland
No. of employees:	180
Products:	Floor Cleaning Robots (RA660 Navi M, RA660 Navi XL, S170 Navi, Kemaro 900)
Interview partner:	Felix Rüesch (CEO)

Why did you choose to develop robots for floor cleaning?

The owner of the company had this idea about 15 years ago. At that time, Cleanfix already produced a range of normal manually operated cleaning machines, which are still our main business. So, we are not a startup. The company owner was convinced that automated cleaning machines are the future. He therefore commissioned the Cleanfix R&D team to develop a scrubber-dryer robot, which can do the cleaning without human interaction. The goal was to be the first company in the world to offer this solution to the market. The first robot launched by Cleanfix was the Robo 40. There was absolutely no acceptance in the market and great doubts about its future due to its limited performance.

What was the most impactful decision for your product development?

We can clearly say that is the navigation. It was the biggest challenge and also involved the most difficult search for the right basic software and algorithm ten years ago. Cleanfix tried to work together with several partners. About nine years ago, we decided to go with Bluebotics.

What are the biggest hurdles in terms of bringing your robots to the market?

It is still the cleaning industry and the people who are ultimately responsible for doing the cleaning. They are not used to working with new technology, unlike factory and office workers. Furthermore, sales staff were focused on manually operated machines and not trained in selling a totally new high-tech product. The same applies to the dealer network. For many other products, development and market launch are proceeding more gradually, making life easier for everyone involved in the process.

Another challenge was the price. Unlike in factories, where the well-known industrial robots or CNC machines operate 24/7, it is more difficult to find a return on investment when the process is done only once a day or once every two days and not the whole day long. Furthermore, the person who would otherwise do the cleaning is a low-income worker, which makes the calculation even more difficult.

Looking into the future, what are the biggest challenges ahead for your customers?

Our customers will have more and more problems finding staff willing to do the cleaning work, in particular during night shifts. I have also heard about limited trust in cleaning staff, especially concerning industrial espionage. Therefore, the customers will become more and more open to robotic cleaning, and there will no longer be a discussion about the benefits of robots.

Now, it is about finding the right people who are willing to gradually integrate them, as cleaning robots are still not able do the whole job.

How are you planning to further develop your products to tackle these challenges?

We try to make improvements step by step. Many companies, like startups, enter this market laterally. This is a challenge for traditional manufacturers of cleaning machines, not only for Cleanfix, but I still think we are in a good position. For many of our traditional competitors that have been producing manually operated cleaning machines for 40 to 50 years, their R&D teams, sales teams, and IT teams need to take a completely different approach.

But there are startups with a huge amount of venture capital that makes them extremely powerful. They can tackle this process in a more relaxed manner and without any risk to their reputation. And if the worst comes to the worst, they can simply close the door and shut up shop. For companies with a long history in producing cleaning machines, the customers interested in robots are often long-term customers. If they are not satisfied with the new products, there is a risk of losing them for the main business sector, too. This means, there is the ultimate risk of losing our reputation and trust in the full brand name.

So, these are the challenges we are facing, and we are planning to tackle them by doing our R&D work slowly and methodically, and we will see whether we are able to manage everything in the future or not. It is a challenge many other industries face, too.

2.3.1.4.3. INTERVIEW WITH ADLATUS ROBOTICS GMBH

Company:	ADLATUS Robotics GmbH, Ulm, Germany
No. of employees:	39
Products:	Floor Cleaning Robots (CR700, SR1300)
Interview partner:	Matthias Strobel (Founder and CEO)

Why did you choose to develop robots for floor cleaning?

We have a long history in service robotics, even before founding Adlatus Robotics in 2015. During this time, since around 2000, we began recognizing the importance of cleaning robots.

The reason for starting the new brand Adlatus in 2015 was the high demand from customers. Our technology base was ready; and there is a clear business case for professional floor cleaning robot systems. Typically, the return on investment is between one and 1.5 years compared with manual cleaning, and there is the possibility to raise the cleaning quality and frequency without increasing the costs, since the robot operating times are basically decoupled from costs in the case of fully autonomous robots.

Moreover, there is a high potential for the future to rethink cleaning processes and additional possibilities for turning data into business.

What was the most impactful decision for your product development?

To focus on fully autonomous robot solutions instead of just cobot approaches. This was the key to flexibility and economy since it enables operation without humans and thus the decoupling of the operating times and costs mentioned above.

However, we had to ensure highly reliable operations, since there is nobody around who can intervene should an unexpected situation arise, as well as a high integration level into the building and factory automation systems.

There are also cleaning tasks that will continue to be done by people. However, we believe that everyone should do their job in a self-contained manner. This is the only way to fully exploit the advantages of an automated solution as an economic solution. Our robot does not have to stick to fixed working hours and is therefore available 24/7. We want to make full advantage of this feature.

What are the biggest hurdles in terms of bringing your robots to the market?

Autonomous robot technology is our strength. Setting up an international sales network for service robots was and is still an ongoing concern for us and even for competitors from the cleaning sector, as their sales and service staff are often not dedicated to robotic solutions. So, there is the need for us to establish and train a sales and service partner structure.

In addition, a cleaning robot can be used in a wide range of environments, but each one brings new challenges to the system that need to be solved.

Looking into the future, what are the biggest challenges ahead for your customers?

The lack of qualified workers or even workers. Therefore, our customers are focusing on their core business processes with the existing workforce. More and more automation solutions are available, for example in automated transport systems. Cleaning is essential to enable their operations. Therefore, there is a high demand for automated cleaning robots to overcome these increased hurdles while still dealing with the challenges of a lack of workers.

Moreover, our customers need professional and industrial grade cleaning robots which they can trust in terms of safety and data security, especially to avoid industrial espionage.

How are you planning to further develop your products to tackle these challenges?

The ADLATUS cleaning robots have a high degree of automation due to their fully autonomous operation and, therefore, guarantee uncrewed operation. This is also because of the fully autonomous service stations. The current developments regarding high-level integration into the building management systems also enable them to access every area, for instance during their nightly operations, since they are able to open doors and use elevators while being aligned with fire alarm systems, for example. With our trusted robotics platform, we guarantee safety and security by design. In addition, we have a lot of R&D going on to extend robot operations in public indoor and outdoor areas, where, beyond safety, the human machine interaction design is essential for the robot’s acceptance.

2.3.1.4.4. INTERVIEW WITH AVIDBOTS

Company:	Avidbots Corp, Kitchener, Canada
No. of employees:	51-200
Products:	Floor Cleaning Robot (Neo 2, Neo 2W)
Interview partners:	Dave Veroba (Senior Manager), Brent Hanniman (Director Product Management)

Why did you choose to develop robots for floor cleaning?

Floor cleaning is a necessary activity for most organizations. Without a clean facility, business goals are hard to achieve. Clean floors help ensure a company's image, productivity, and health and safety.

Time spent cleaning floors does not directly add the same value to an organization the way producing products and delivering services do. In many organizations, the role is filled by line staff and productivity is lost while they clean, while others have to spend more time managing outsourced suppliers. In addition, floor cleaning requires manual tools or tools that demand an operator and significant employee time and is not easy. The activity is routine in nature. It also involves hard work, dust, and dirt, which are all potential health hazards.

In a world where it is hard to find manual labor and employees are looking for more responsibility, filling cleaner roles can be challenging.

Floor cleaning activities also lend well to automation, offering a 'ground floor' entry point to industrial automation. With respect to automation, floor cleaning is a 'low hanging fruit'.

What was the most impactful decision for your product development?

Our focus on quality first has likely had one of the largest impacts on our product development. This focus on quality has allowed us to create the most advanced autonomy solution in our space and to expand and adapt it effectively across the wide range of customers and environments we serve. Those investments mean that our robots are successfully completing more missions with less operator support than any of our competitors, leaving us with many happy customers and giving us a true edge. That same attention to quality to ensure that our robots clean as well as the manual machines they are replacing has also been key. It has allowed us to compete against and disrupt decades old incumbents while at the same time sets us apart from a wide range of robotics newcomers, who automate the process but leave the customer unsatisfied with the result.

Great attention has been given to how our customers use our robots. We have invested heavily in creating a top-of-the-line autonomy system as well as a remote assistance function that allows our operators to free up the robot in extreme cases. This results in a seamless experience to our customers - press the button and let the robot do the cleaning.

What are the biggest hurdles in terms of bringing your robots to the market?

One of the largest hurdles when bringing our solution to market is awareness and acceptance.

On the awareness side, many of our customers might have thought about automation, but it is typically in their core business areas, not necessarily in cleaning. When they see the application, it feels like a no-brainer for them, but we focus a lot on driving awareness for the application across multiple verticals.

In terms of acceptance, we are also seeing that there is some hesitation with cleaning staff to trade up their old scrubber and work with a robot. This hesitation has a lot to do with the solution being new to them and them being timid working around an automation solution. We are tackling that by keeping our user experience simple and providing training and materials that easily explain robot operation.

Looking into the future, what are the biggest challenges ahead for your customers?

The number one challenge for our customers moving forward will continue to be labor shortages. In the retail space, we already see 600% turnover of cleaning staff, while in warehouses and factories cleaning is often being done by line staff because cleaning staff just cannot be found. With aging populations around the globe and the movement of labor away from these tasks, we only see this challenge becoming more acute and widespread.

Besides a shortage of labor, the acceleration of the digital transformation is another major challenge for our customers. Across all verticals, our customers are eager to stay competitive and digitalization and new technologies are offering new opportunities to improve processes that were previously unthinkable. This means that they need to act quickly to ensure their competitors do not see significant gains faster, but at the same time, they find themselves often overwhelmed on how to start.

How are you planning to further develop your products to tackle these challenges?

To support our customers in their labor issues, Avidbots is looking to bring additional robots to market that will allow our customers to automate even more of their cleaning tasks, reducing the need for labor out of the gate. At the same time, we will continue to make improvements to our existing user interface and usability of our robots, as well as deliver several new products to ensure that onboarding of new operators is as easy as possible.

When it comes to digitalization, most of what we do to help our customers is to continue to educate them on how automating their cleaning can support their business as a whole. In order to support decision-makers in delivering returns on their investment, we will be continuing to innovate and expand our web-based reporting capabilities. In addition, we will be looking to support them further in making that information available to their own digitalization dashboards to enable reporting on their overall digitalization initiatives.

2.3.1.4.5. INTERVIEW WITH LIONSBOT INTERNATIONAL

Company:	Lionsbot International, Singapore
No. of employees:	201-500
Products:	Floor Cleaning Robots (R3 Vac, R3 Scrub (Pro), Leobots, R12 Rex Scrub, R12 Rex CS)
Interview partner:	Dylan Terntzer (CEO)

Why did you choose to develop robots for floor cleaning?

My wife and I have been in the cleaning industry for 21 years, distributing cleaning equipment since 2002. So, by 2017, we were very interested in cleaning robots, but unable to find the right cleaning robot at that time. They were either too big, too expensive, or too difficult to use. That is why we decided: Let's make our own robots. And we were very lucky that we found our co-founder, Professor Mohan from a university in Singapore, and together we started Lionsbot.

What was the most impactful decision for your product development?

I think the most impactful decision for our product development came from the user experience and how the users approached the robots. So, our initial robots were designed from our point of view. But then our whole robotic development began to evolve when we started to work with the customers and saw things from their point of view: How do they use it, what difficulties do they face. And that really guided our product development. So, literally it is about listening to the customers. I know it sounds very normal, but that was the biggest impact.

What are the biggest hurdles in terms of bringing your robots to the market?

I think there were quite a few hurdles. One hurdle was to understand what each region requires. For example in Singapore, we do not have to cope with snow, which entails salt, grit, and water. So, we have never faced issues related to these conditions. However, when we went further north during the winter, we were surprised to see how much snow there was, and that was yet another hurdle, because we had never designed our products for such conditions.

Another challenge was certification, as different regions require different kinds of certification, and they cannot always be aligned. Meaning, just because we are CE certified, for instance, it does not mean we will automatically be UL certified. You need to have the right certification for the specific regions. Another hurdle was to design robots that are robust, cost effective, and yet easy to use. So, you have to combine all three factors. You can just make a very strong robot that is hard to use or you can just make a very easy-to-use robot that is fragile. You have to achieve all three things together and yet offer excellent value for money.

Looking into the future, what are the biggest challenges ahead for your customers?

In my opinion, the challenges for our customers used to be just a mindset: Why should I use robots instead of a cleaner? Is this robot going to take my job? But this mindset has totally changed. I would say it has changed because there are simply not enough cleaners in the world and every cleaning contractor is being impacted. Every large area that needs to be cleaned is being impacted.

There are simply not enough people to cope with the amount of cleaning work. Hence, cleaning contractors need cleaning robots. So, the biggest challenge right now is how to integrate cleaning robots into cleaning schedules. What I mean by this is (because our products are floor cleaning robots): How can you manage to have the robots clean the floors, while assigning a certain number of cleaners to clean the windows and tables, and how to train everybody properly? Integration is now moving towards mass adoption; it is about how to integrate everything in order to use it effectively. It is no longer about just having user trials or short-term trials. Today, it is about mass deployments.

How are you planning to further develop your products to tackle these challenges?

We are, of course, always planning and developing, ensuring our robot is even easier to use. On top of that, our goal is to automate it more so that we can link and integrate it into a customer's operating system or cleaning schedule. So, if the robots become more automated, they will require less user involvement and be able to clean more areas of a building. Another plan is to also achieve a better return on investment with the robots for the customers. The robots, whether they have to clean a larger area or a smaller area, need to become less costly. This is all part of our overall plan.

2.3.1.5. PRODUCERS

Adlatus Robotics, Agora Robotics, Amano, Avidbots, Beijing Yunji Technology, Bharati Robotic Systems, Candroid Robotics Corporation, Chuangze Intelligent Robot, Cleanfix, CloudMinds Technology, Cyberdyne, Cyberworks Robotics, Discovery Robotics, Enway, Fybots, Gausium, Guandong Unipin Medical Technology, Hako, Hefter Cleantech (Vermop Gruppe), ICE Cobotics, Janyu Technologies, Kärcher, LionsBot, Makita, Minuteman International, Nilfisk-Advance, Nippon Signal, Otsaw Digital, PalNPaul, Panasonic, Peppermint Robotics, Shanghai Keenon Intelligent Technology, SoftBank Robotics, Solenis, Sparkoz, Sveaverken, Syrius, Tailos, Tennant, Triooo, UBT Robot, UniRing, United Robots, Vorwerk, WayBot Robotics, Wolf-e Robotics, Zaco/I Life, Zauberzeug, ZhenRobotics

2.3.2 AP22: WINDOW AND WALL CLEANING

2.3.2.1. TYPES OF OPERATIONS CARRIED OUT BY THE ROBOT

For both visual and maintenance reasons, glass facades have to be cleaned every few months. Window cleaning robots either follow a track or, when suspended from the roof, move freely over the facade. Some modules use suction cups or fans pushing the robot towards the facade for stabilization. While specific solutions may be worthwhile for large buildings, smaller buildings rely on standardized systems. Current developments are aimed at mechanical platforms being suspended by two ropes, thus allowing them to move relatively freely vertically and horizontally across the facade. The increasing number of high-rises (with 50% worldwide currently being constructed in China) make the automation of facade cleaning more and more interesting.

The current standard for automatic cleaning is the use of robotic devices, which are tele-operated by cleaning personnel from the ground or the roof. However, a few robots are also able to operate entirely autonomously by detecting the edges of the window and adjust the cleaning path accordingly.

2.3.2.2. LEVEL OF DISTRIBUTION

The first custom robot devices designed for a particular building were introduced around 2010; for example, a robot produced by Robosoft for the Louvre pyramid and a Fraunhofer robot for the exhibition grounds in Leipzig and a train station in Berlin (Lehrter Bahnhof).[50] For a long time, none of these robots found wider industrial acceptance. Many other companies have in the meantime developed relatively simple, tele-operated systems consisting of a winch and a mobile cleaning element that can be used on every vertical facade offering roof access. Such concepts also exist on a larger scale with industrial manipulators installed in a conventional cleaning lift, as introduced by Auconic in 2019.

Fully autonomous window cleaning robots that can move on glass facades without a human operator have, for example, been developed by Serbot. They use a mobile system with suction cups that is additionally secured by a single cable. A cleaning robot that is positioned with four cables, two from the roof and two from the ground, has been developed by Kite Robotics and was installed at Utrecht central station in 2019. Skyline Robotics is using two Kuka manipulators placed in a cleaning lift.

A challenge for facade cleaning robots is the increasing complexity of modern facades with rounded edges and design elements. Robot manufacturer Nihon Bisoh is addressing this problem with a robot moving on horizontal rails around the building. A vertical moving lift can transfer the robot to a different rail or help it to overcome gaps in the facade.

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[50] Elkmann, N., Hortig, J.; Fritzsche, M.: Cleaning automation. In: Nof, S. Y. (ed.): Springer Handbook of Automation. Berlin, Heidelberg: Springer, 2009, pp. 1253-1264.

2.3.2.3. COST-BENEFIT CONSIDERATIONS AND MARKETING CHALLENGES

Window cleaning robots bring about cost reductions, mainly through improved safety and higher productivity. Concerns about workers' safety have become increasingly pronounced due to the regular occurrence of accidents and the construction of ever-taller buildings. Therefore, the use of tele-operated devices is already a gain, as cleaning becomes less physically demanding. Additional advantages of autonomous window cleaning robots are:

- Continuous cleaning processes, also in the case of output-oriented service levels, through permanently installed equipment on buildings
- Predictability of costs thanks to the deterministic "plannability" of work
- Objective verification of service provision
- Reduced dependence on weather and time of day

Window cleaning with robots needs to achieve a return of investment within a few years. Similar to the market for robotic floor cleaning, companies such as Kite Robotics or Skyline Robotics provide a Robot-as-a-Service model that reduces the financial risk for customers. Apart from the cost aspect, the quality of cleaning is still considered an issue. Especially for luxury apartments, where a view over the city is expensive, dirt that remains in the corners of windows would be considered a no-go.

To optimally employ window-cleaning robots, certain criteria in the design of a building have to be met. Architects, however, are often reluctant to adapt their construction plans to the needs of robots. Consequently, construction peculiarities (such as arcades, balconies, or inlets) frequently prevent the use of robots.

2.3.2.4. PRODUCERS

Autonopia, HyCleaner, Janyu Technologies, Kite Robotics, PalNPaul, Serbot

2.3.3 AP23: TANK, TUBE, AND PIPE CLEANING

2.3.3.1. TYPES OF OPERATIONS CARRIED OUT BY THE ROBOT

The cleaning of tanks, tubes, and pipes is closely related to the inspection of these facilities, which is discussed in chapter 2.4.2. While cleaning and inspection robots rely mostly on the same mobile platforms, cleaning robots are equipped with additional tools. The majority of equipment used for these tasks is tele-operated robotic devices, despite frequently being referred to as “robots”. However, some autonomous devices are entering the market, depending on the task carried out.

Fuel and oil tank cleaning

Above-ground fuel storage tanks require regular cleaning. The sludge is removed to eliminate fuel contamination and to recover lost storage capacity. Removing the sludge by conventional methods requires an empty tank, which results in extended downtime. Cleaning oil storage tanks manually results – apart from working in flammable, explosive, and toxic environments – in low efficiency and environmental pollution problems. Robots and robotic devices for tank cleaning can be inserted into a full tank and pump out the sludge. To work in these explosive atmospheres, the devices must be certified according to “Atmosphères Explosibles” (ATEX). Tank cleaning robotic devices use a method of dilution that does not require the tank to be emptied. By diluting the sludge and heating it (to approx. 60°C), they constantly control the sludge’s viscosity to ensure it reaches and maintains a consistency at which it can be pumped out of the tank. This method permits the recovery of fuel that is trapped in the sludge. Subsequent centrifugation separates small particles and frees them from the oil, thus further reducing toxic waste.

Rust removal

Removing rust from a gas tank can be accomplished using abrasives, such as gravel or washers, or using acids (muriatic acid or vinegar), washing soda, or tank coating kits. To achieve this task, mobile robots and robotic devices can be equipped with tools for water jetting, power tools for rust and paint removal, or vacuum suction systems.

Water tank cleaning

Water tanks need to be cleaned at intervals of between one and five years to comply with specific national laws. Conventional cleaning requires professional personnel certified for working in confined spaces to execute this task. Tanks are often emptied for a period of up to two weeks to perform the work. Due to poor working conditions and high wages, more and more cleaning devices that are either tele-operated or autonomous devices are being used instead. The basic principle is to deploy a vehicle that automatically traverses the water tank and can also work as an underwater vacuum cleaner. Autonomous cleaning robots perform path planning, such as covering the floor in meanders, with ultrasonic sensors.

Pipe and duct cleaning

Cleaning air conditioning ducts is important to maintain a free flow of air and to prevent health risks. Pipe and duct cleaning with robotic devices has become quite common due to a lack of alternatives with respect to accessibility of pipes and ducts. Several designs have been suggested which typically share a wheeled or tracked mobile platform carrying a brush. Generally, tele-operated robotic devices, which are typically controlled via a cable connection that also transmits a camera image, dominate the market in this area.

2.3.3.2. LEVEL OF DISTRIBUTION

While remotely controlled vehicles for the inspection of confined environments have existed since the 1990s, robots with a certain degree of autonomy are still uncommon and, in many cases, research prototypes. In 2021, the Sprint Robotics Collaborative ("industry driven initiative that promotes robotics techniques in technical inspections and maintenance of capital-intensive infrastructure"[51]) identified numerous application scenarios of robotics in the areas of field inspection, cleaning, and maintenance. Current and particularly future product developments and scenarios are described in their roadmap.

Fuel tank cleaning

Numerous cleaning and maintenance providers use robotic devices as part of their services to clean oil storage tanks, refineries, bulk fuel terminals, chemical plants, and fuel tanks for oil-fired power plants. Typically, mobile platforms are tele-operated using a television monitor to perform cleaning from outside a tank.

The possibility to clean fuel tanks autonomously was explored by the Dutch research project Smart Tooling, which was discontinued in 2020.[52] Apart from Nobleo Technology, a supplier of motion control and artificial intelligence solutions, companies from the petrol industry, such as BASF, were involved.

Water tank cleaning

For water tanks, tele-operated equipment eliminates the need for professional personnel and taking a water tank offline. Manufacturers are, for example, Weda or Mechanics

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51 https://sprintrobotics.org/about/.

52 https://smarttooling.eu/project-smart-tooling.

Design. The tracked vehicles allow the cleaner to reliably move in sandy conditions without getting stuck. Additional functions include measuring and documenting water quality.

Figure 2.25: Water tank and fountain cleaning robot. Image credit: Palnpaul Inc.

Fully autonomous water tank cleaning robots have been designed by Palnpaul. Weda also sells autonomous robots with a similar design as swimming pool cleaning robots.

2.3.3.3. COST-BENEFIT CONSIDERATIONS AND MARKETING CHALLENGES

In 2023, the market size of the petrol tank cleaning business was estimated to be USD 1.04bn and expected to reach USD 1.35bn by the end of 2029.[53] If such work is carried out manually, hazards include not only suffocation, contact with chemicals, and explosions but also slipping and falling inside the tanks. In the UK alone, around 25 employees die every year while working in confined spaces.[54] These risks seem to favor a wider usage of automated systems in the future. In "high risk" tanks, such as those where emissions from the tank venting or pyrophoric materials preclude gas freeing, a robotic device can work under a nitrogen blanket or another inert atmosphere. In

53 https://www.marketdataforecast.com/market-reports/petroleum-tank-cleaning-market.

54 -https://www.engineerlive.com/content/robotic-tank-cleaning-technology.

addition, the manhole cover can be closed after the robot has been inserted, which reduces the release of gases and increases safety. The cleaning method with robotic devices significantly reduces cleaning time (three to five times quicker than manual work) because the device can stay longer inside the tank and does not need recovery breaks.

Fuel tank cleaning consists not only of the actual tank cleaning device but also requires filtration and waste disposal units outside the tank as well as personnel supervising the process and ensuring safe operation. Therefore, the benefit of an autonomously moving cleaning unit seems limited compared to cheaper, tele-operated devices.

Water tank cleaning

An innovation challenge published by Singapore's National Water Agency in 2020 indicates the expected benefits of using robots for cleaning water tanks:[55] Firstly, there is no need for qualified personnel to work in confined spaces. Furthermore, personnel currently need to be tested regularly for water-borne diseases, such as typhus and cholera, while a robot can easily be cleaned and disinfected before being inserted into a new tank. At present, manual work has to be carried out in unlit caverns, where surfaces are often slippery. Using robots or robotic devices thus also reduces the risk of tripping and falling.

Compared to fuel tank cleaning, water tank cleaning needs less logistics for the cleaning process and, therefore, seems more attractive for employing autonomous robots. Especially robots that remain inside tanks and perform cleaning regularly, e.g. on a weekly basis, could be a way to reduce costs and ensure high water quality.

Duct and pipe cleaning

Most manufacturers of robotic devices for duct cleaning report a very good return on investment for many types of ducts. Autonomous navigation and navigating the robots through vertical ducts or ducts with complex junctions remain major problems.

2.3.3.4. PRODUCERS

Koks Robotics, PalNPaul, Robot++, Robotics Design

[55] https://tinyurl.com/Water-Tank-Cleaning2020.

2.3.4 AP24: HULL CLEANING

2.3.4.1. TYPES OF OPERATIONS CARRIED OUT BY THE ROBOT

Ships, boats, and aircraft require regular cleaning. As the surfaces to be cleaned are usually large and hard to access due to their height, shape, or submersion in water, numerous devices for automatic cleaning have been designed and are now commercially available. In many cases, however, such devices are tele-operated. Only a few devices are autonomous robots.

When it comes to ships, cleaning includes the hull above and below the waterline but also the freight holds. Typical hull cleaning robots use high-pressure water (above the waterline) or brushes (above and below the waterline). As the hulls are made of steel, magnets are frequently used to ensure contact between the cleaning device and the surface as well as to allow the climbing of walls and even overhead cleaning.

While the use of antifoul paint was very common on ships in the past, international regulations have now banned the most poisonous and thus most effective paints, which makes the removal of marine organisms growing on hulls (also known as biofouling) a new problem for all shipping companies. In addition, regulations for the prevention of transferring marine species from one region of the world to another also requires the cleaning of vessels before they are allowed to enter ports. These factors and the emerging technology make ship cleaning with robots and robotic devices a promising market.[56]

Similar to ships, yachts have to be cleaned regularly to remove biofouling. For this task, smaller robots are used which rely, e.g., on suction cups to ensure contact with the hull.

Aircrafts have to be cleaned at regular intervals to ensure their general appearance and to prevent surface corrosion. In addition, a clean surface is necessary to easily detect surface cracks. An alternative to manual cleaning has been introduced in the form of robotic devices consisting of a mobile platform equipped with a manipulator and a brush tool.

2.3.4.2. LEVEL OF DISTRIBUTION

Fleet Cleaner operates semi-autonomous cleaning robots at all Dutch seaports. The devices are tele-operated but position themselves on the hull to assist the operator and for documentation purposes. The robots, which use magnets for attachment, capture all the removed fouling and pump it to the mothership, thus ensuring operation in ports without contaminating the water. The Hullbug from Searobotics relies on soft brushes to remove biofouling at an early stage. The system can be tele-operated or work autonomously and incorporates the use of a biofilm detector that can differentiate

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[56] Curran, A., O'Connor, B., Lowe, C., King, E.: Analyzing the Current Market of Hull Cleaning Robots, Washington DC, 2016; https://digital.wpi.edu/concern/student_works/ws859f89n?locale=zh.

between unclean and clean surfaces. Other designs use hot seawater to kill organisms on the hull, which are later washed away by the waves when the ship sails.

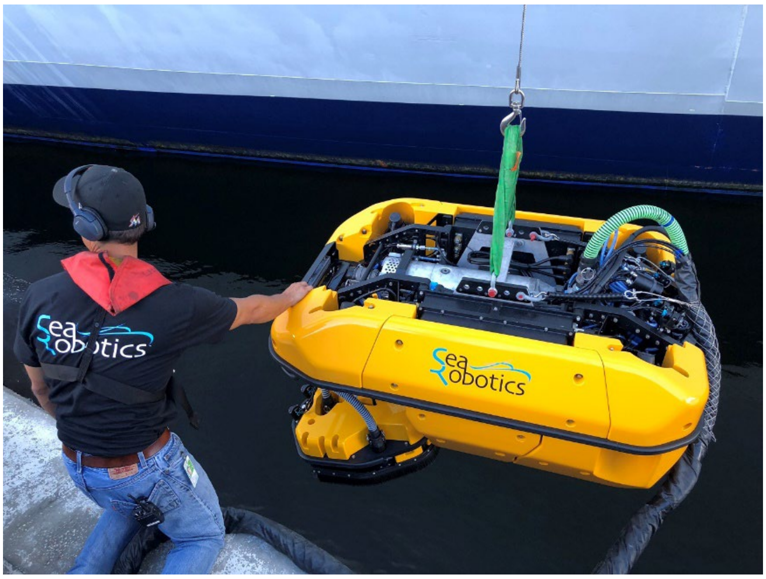

Figure 2.26: The Hullbug, Hull Bio-inspired Underwater Grooming system, is a modular system that can be operated remotely or work autonomously. The interchangeable grooming/cleaning tools form the front of the system and range from light brushing tools for biofilm removal to dual cavitating water jet tools. Image credit: Searobotics.

For smaller boats, the Keelcrab mobile robot or, similarly, the Hullbot offers a substitute to antifouling by keeping the hull clean and reducing the use of water polluting antifouling paints. These devices are attached to the surface being cleaned with the help of vacuum.

Robots for cleaning aircraft date back to the 1990s, when the Skywash aircraft cleaning robot was used to clean large airplanes at Frankfurt/Main airport. A few years ago, simplified semi-automated versions of such a robot system for aircraft cleaning were introduced by Aerowash and Aviator Robotics.

Another system is a laser coating removal platform to remove paint and other coatings from aircraft structures. This system, developed by Besnovo, is part of an environmental initiative to reduce toxic paints or coatings from aircraft structures. It is, however, tele-operated.

2.3.4.3. COST-BENEFIT CONSIDERATIONS AND MARKETING CHALLENGES

For complex cleaning tasks, such as ship hulls, there is often hardly any alternative to automated task execution. However, as most of the robots are special machines produced in small quantities, unit costs tend to be high, thus hampering a short-term return on investment.

In the case of ship hull cleaning, it is well known that the build-up of marine organisms on a ship's hull can reduce its speed by up to 10%.[57] To compensate for the drag, the ship may have to use as much as 40% more fuel. Increasing pressure to reduce carbon dioxide and other emissions and increased costs for fuel make the use of cleaning robots more profitable for shipping companies.

It takes a crew of 18 people to manually clean a mid-size aircraft. Cleaning aircraft with a robotic device has not only the potential to complete the cleaning task twice as fast, but also achieves a better quality finish and uses less water.[58]

2.3.4.4. PRODUCERS

Aviator Robotics, Besnovo, BlastOne, Fleet Cleaner, Hullbot, KeelCrab, Robot++, SeaRobotics, TAS Global

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[57] Hornemann, M.: Antifouling Symposium 2003. Symposium at INTERBOOT, September 22, 2003, Friedrichshafen (Germany).

[58] https://www.groundhandlinginternational.com/content/news/air-india-sats-invests-rs-55m-in-india-s-first-automated-aircraft-cleaning-robot/.

2.3.5 AP25: DISINFECTION ROBOTS

2.3.5.1. TYPES OF OPERATION CARRIED OUT BY THE ROBOT

Preventing the spread of germs is a constant challenge in hospitals and care homes. To stop hospital-acquired infections, considerable effort is necessary to clean and disinfect rooms as well as frequently touched objects, like handrails, desks, or elevator buttons. In addition, the growing problem of multi-resistant germs has also raised the question of which disinfection methods are best suited to kill germs efficiently without causing resistance. During an ongoing pandemic, the need for disinfection is expanded to all places that are frequented by many people, such as public transport, office buildings, or shopping malls. Thus, the COVID-19 pandemic has been a main driver for the market growth of disinfection robots. Usual means for disinfection are:

- High frequency ultraviolet light (UV-C)
- Spraying disinfection chemicals, such as hydrogen peroxide or hypochlorous acid
- Air filtering
- Mechanical wiping

These means can also be combined for better effect.

Disinfection with UV light has the advantage that the light instantly reaches all surfaces exposed to the robot. By moving around a room, furniture can be treated from all sides, e.g. in operating rooms. However, some shaded areas that cannot be reached will always remain; leaving the requirement for additional manual cleaning of critical spots once the robot has finished its job. Sprayed chemicals have a better chance of reaching obstructed areas, especially when they are sprayed from various positions as the robot moves around a room. Both UV-C and spraying disinfection cannot be applied in the presence of humans for safety reasons. Furthermore, another drawback of spraying is the time required to air the room before a person can use it again. Robots performing mechanical wiping address the problem that germs covered in dirt or grease cannot be reached by UV light or chemicals. This is especially a problem on surfaces often touched by hands, such as door handles and handrails.

Figure 2.27: Alvo Ultra V-bot – disinfection in an operating room. Image credit: Wobit.

2.3.5.2. LEVEL OF DISTRIBUTION

While robots used for disinfection played a minor role until the end of 2019, the COVID-19 pandemic has created a massive interest in robots for autonomous disinfection.

The Danish company UVD is one of the few manufacturers who already offered a disinfection robot as a product before the COVID-19 crisis. The company was founded in 2016 and won the IERA Award in 2019. Since then, the manufacturer has introduced the third generation of its robot and acquired a contract with the EU to deliver 200 robots to various hospitals in Europe.

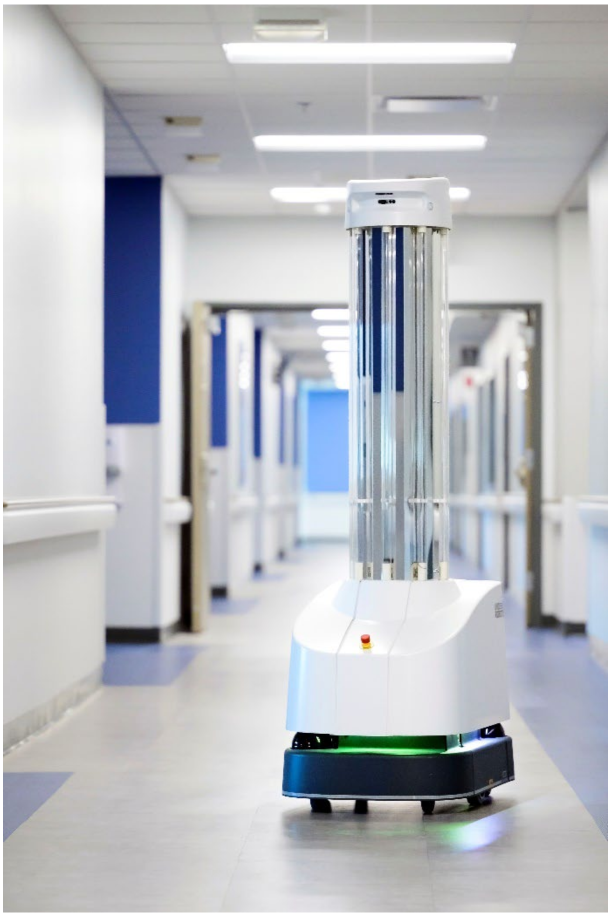

Figure 2.28: The UV-Disinfection Robot is a disinfection robot for hospitals and manufacturing. It is used with the aim of reducing the infection rates of hospital-acquired infections and microorganisms in production. The UV-DR has a kill rate of 99.9% and moves autonomously and safely around facilities. Image credit: Blue Ocean Robotics.

Similar robot designs with UV-C light have appeared on the market since the beginning of 2020. Such robots are available from Metralabs, Otsaw, Amyrobotics, and Kompaï. Various developments of new UV disinfection robots were financed in the EU project DIH-HERO.[59]

An important aspect of the use of such robots is the fact that some of them are approved only for local markets, e.g. for some Asian countries.

New designs, e.g. from UVD and Advanced Intelligent Systems, also address human safety by using infrared sensors to detect people in the environment and to switch off the UV light. To treat hotspots with UV light when people are present, F&P Robotics has developed an attachment for the manipulator of its mobile robot Lio, which positions UV lights around a door handle while shielding them to the outside. Otsaw offers a mobile

[59] Jovanovic, K. et al.: Digital Innovation Hubs in Health-Care Robotics Fighting COVID-19: Novel Support for Patients and Health-Care Workers Across Europe. In: IEEE Robotics & Automation Magazine. - Piscataway, NJ, USA: IEEE. ISSN: 1070-9932 - 28 (2021), no. 1, S. 40-47; https://ieeexplore.ieee.org/abstract/document/9330556.

robot with two horizontal beams containing UV lights that can move through the aisle of an aircraft while disinfecting the seats to its left and right.

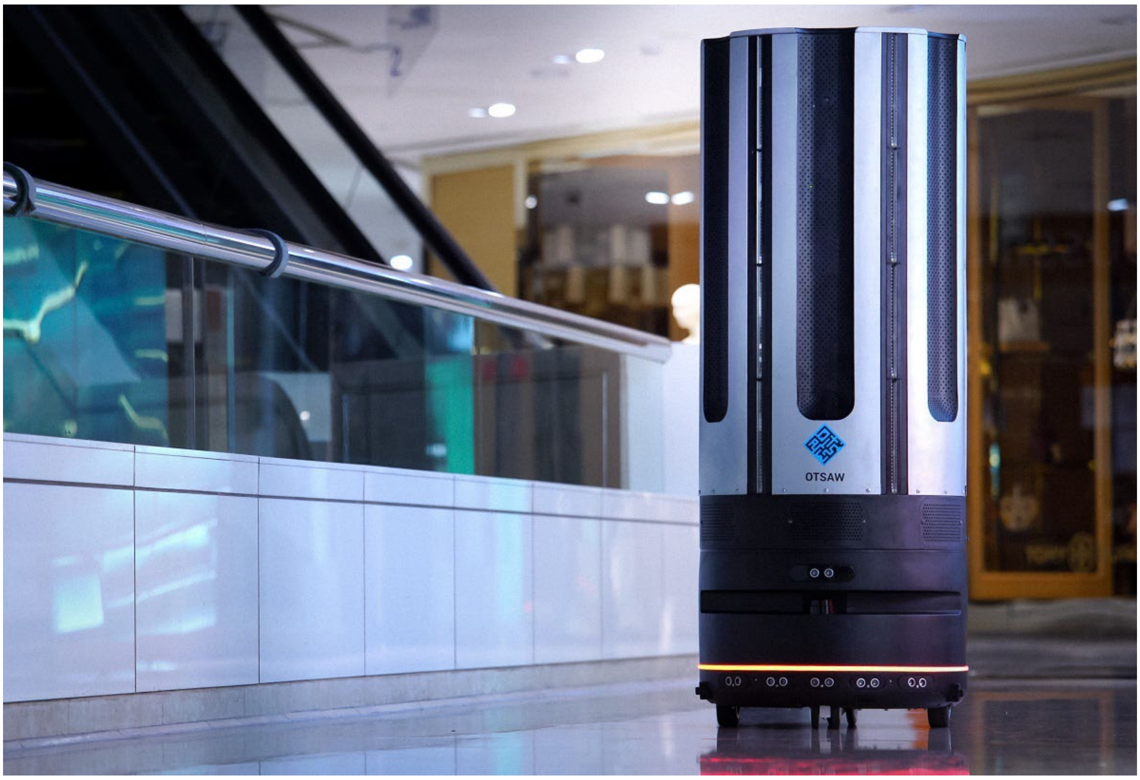

Figure 2.29: O-RX is a UV-C LED autonomous disinfecting robot with a disinfection rate of 99.999% at 2.5 meters. Image credit: Otsaw Digital.

Robots for spraying disinfection chemicals have been introduced, e.g., by Cyberdyne, Fybots, iClean, and SMP Robotics. Some robots also offer a combination of disinfection methods, such as the combination of UV-C light and spraying (e.g. Keenon). In addition to UV-C disinfection, a robot from Amyrobotics sucks air in through its structure and leads it through a filter. Some manufacturers of floor scrubbing robots have added an UV-C light source (Nilfisk, Aziobot) or an additional tank with a chlorine dioxide solution (Adlatus) to their machines to improve the cleaning result. Together with the mechanical removal of dirt, a good disinfection result can be expected in these cases.

Recent research projects have investigated the precise disinfection of frequently touched objects, based on detecting, e.g., door handles and switches using computer vision.[60] This also includes the use of a building information model (BIM) to determine object positions.[61] Furthermore, a combination of different disinfection means with mechanical wiping was investigated.

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60 Research Project MobDi: https://www.mobdi-projekt.de/en.html.

61 Research Project Balto: https://nachrichten.idw-online.de/2021/05/03/disinfection-robot-value-created-by-linking-up-to-building-data/.

In the DeKonBot project, Fraunhofer IPA has developed the prototype of a disinfection robot that automatically recognizes surfaces to be cleaned, specifically door handles, door knobs, light switches, and elevator buttons, and then cleans them with its cleaning pads attached to the robot arm, which are wetted with disinfectant.[62] By following and automating the legally prescribed procedure for surface disinfection, the robot has the potential to relieve the burden on nursing or cleaning staff. The DeKonBot 2 robot is more compact, more flexible, and closer to the product than its predecessor. With its cleaning brushes, the robot removes dirt from the surfaces to be cleaned and simultaneously applies disinfectant to the entire area. Currently, another new cleaning tool is being integrated into the robot that performs cleaning and disinfection - as is customary in hospitals - with the help of microfiber cloths and can also change them autonomously after use. The robot will also be able to disinfect other surfaces in the hospital, such as handrails, tables, and chairs. The project is also looking at the independent opening of doors, so that in the long term the robot will also be active in treatment rooms when they are not being used at night.

Figure 2.30: Using its cleaning brushes, DeKonBot 2 removes coarse dirt from door handles and comprehensively applies the disinfection fluid. Image credit: Fraunhofer IPA.

62 https://www.ipa.fraunhofer.de/en/press-media/press_releases/fraunhofer-ipa-presents-disinfection-robot-dekonbot.html.

Some research institutions and companies are also already working on 3D cleaning, i.e. cleaning surfaces above the floor. For example, Fraunhofer IPA developed hardware and software in the “Rorebo” project to enable robots the cleaning of handrails, tables and the door leaf above the handle. In addition, the prototype is able to open doors. As far as companies are concerned, the robot from Jingwu uses a robot arm to pick up various cleaning devices such as a brush, a mop, or a squeegee and use them to clean mirrors, sinks, toilets, and floors in bathrooms. Somatic also addresses the task of cleaning bathrooms, using a combination of spraying and squeegeeing the surfaces.

At the start of the COVID-19 pandemic, many companies quickly adapted existing robot platforms to other tasks (e.g. autonomous mobile robots (AMR) for transport) and equipped them with a means for disinfection. Quite often, this was done to meet the desperate demands of the healthcare sector and governments for tools to fight the pandemic. Today, many of these “quick and dirty” solutions have vanished again. On the other hand, disinfection robots particularly designed for that purpose have become a permanent addition to the portfolios of many robot companies. This indicates that the robots seem to have proven themselves, and further need for such robots in the “new normal” is expected.

2.3.5.3. COST-BENEFIT CONSIDERATIONS AND MARKETING CHALLENGES

Disinfection robots have the advantage that human cleaners do not have to enter contaminated areas. In addition, robots can easily withstand strong cleaning agents and are immune to the effects of ultraviolet light, thus allowing continuous operation also in confined spaces. Furthermore, robots allow more frequent disinfection than would be possible with cleaning personnel, while at the same time providing reliable documentation and avoidance of human error.

Disinfection robots have a high potential for cost reduction if they are used in settings that maximize their productivity, for example when large, open areas can be disinfected without frequent human intervention. Similar to other cleaning tasks, the robots provide a possibility to overcome the shortage of personnel.

2.3.5.4. EXPERT VIEW

The interview presented below was conducted in 2023 as part of the major focus chapter revision by Fraunhofer IPA.

2.3.5.4.1. INTERVIEW WITH UVD ROBOTS

Company:	UVD Robots (part of Blue Ocean Robotics), Odense, Denmark
No. of employees:	11-50
Products:	Disinfection Robot
Interview partner:	Claus Risager (founder and CSO)

Why did you choose to develop disinfection robots?

Our story goes back to 2014, nine years ago, when Professor Kolmos of the local University Hospital in Denmark was in the media talking about patients dying from microorganisms, which were resistant to antibiotics, and that this problem was growing. I knew that some companies were working with UV light to kill or to deactivate microorganisms. But the problem was that if microorganisms are not hit directly by the light or are too far away, they are not deactivated. So logically, if you could move around with the light and expose the surfaces to the right amount of light, it would be very effective.

So, I had the idea of using a robot to do this task. When combining this light system with an autonomous robot, we adapted everything to make sure it can sense the environment, understand the multitude of objects and surfaces, and be effortlessly programmed by members of staff, who simply need to inform it about the presence of pathogens in the room. This allows the robot to adjust its path and the duration of light exposure accordingly.

What was the most impactful decision for your product development?

There are a lot of different things that turned out to be really important. The most important part of it all lies in our collaboration with Professor Kolmos. Through our partnership with him and his team, we received invaluable feedback that not only validated many of our ideas but also guided us toward the further development of others. It was very, very important to end up with a robot that was easy to use and really did the job properly. Putting the users and the experts from the hospital at the heart of the overall development was the best and most important decision we made.

What are the biggest hurdles in terms of bringing your robots to the market?

During the initial stages, one surprising challenge we encountered was the integration of our high performance robot into daily workflows and ensuring its ease of use on a daily basis. As such, we needed to change the user interface several times and perform continuous upgrades. Ensuring seamless interaction between users, their instructions, the robot and its feedback to the users, was a major challenge.

Another notable aspect is that members of the cleaning staff often lack sufficient technical knowledge about microorganisms and disinfection. Therefore, it must be possible to operate the robot without any real understanding of these topics.

From an internal perspective, our origins may lie in robotics, but we have evolved beyond being merely a robot company. Today, we are just as much an infection prevention company with many experts in microbiology, who know how hospitals work and how services are provided. Due to the lack of relevant distributors for this market segment, we actually dealt directly with the hospitals in the beginning. So, you start out as a roboticist and end up as a specialist in a very small part of the world.

Looking into the future, what are the biggest challenges ahead for your customers?

I think one of the challenges they face is that the number of multi-resistant microorganisms, some of which pose significant difficulties in their elimination from the environment. For example, this problem is especially prominent when dealing with microorganisms that produce a biofilm. This means they cannot be deactivated with UVC light or chemicals alone. Thus, we spent a lot of time developing solutions that combine chemicals and UVC light, where we first change the structure of the biofilm so that the UVC light can penetrate it. While it is possible to deactivate these kinds of microorganisms, reaching that point can be relatively complicated.

How are you planning to further develop your products to tackle these challenges?

The key thing for our progress lies in enhancing the intelligence of the robots, enabling us to tailor their disinfection capabilities to target, for example, specific pathogens, regardless of whether they are in a spore or live microorganism state. We already have customers where our robots are connected to the hospital system. For instance, after an infected patient leaves the hospital, we are informed about the patient's infection and the robot then uses this information to adjust its process correspondingly.

If you can prevent a patient from being infected, it frees up a bed for 20.6 days. In 20.6 days, you can admit 4.6 new patients.

2.3.5.5. PRODUCERS

Addverb Technologies, Advanced Intelligent Systems, Aeolus Robotics, Agora Robotics, Aitheon, Akara Robotics, Amyrobotics, Asimov, Ava Robotics, Beijing Yunji Technology, Blue Ocean Robotics, Build with Robots, Candroid Robotics Corporation, Casun, Chuangze Intelligent Robot, CloudMinds Technology, Co-Robotics, Dalu Robotech, DF Automation & Robotics, Done Robotics, Fubao Intelligent Technology, Fybots, Guandong Unipin Medical Technology, Guangdong Jaten Robot & Automation, HD Hyundai Robotics, ICA, Inbot Technology, Infocom, Inovasyon Mühendislik, Janyu Technologies, Kelo Robotics, Kompaï Robotics, Loop Robots, Luvozo PBC, Marses, MetraLabs, Milvus Robotics, Nevoa, Ohmnilabs, Otsaw Digital, PalNPaul, Rice Robotics, Robotise, Sesto, Shark Robotics, Shenzhen Guoli Intelligent Technology Co. LTD, Smart Robotics, Solaris Robots, Techmetics Robotics, Tru-D, United Robots, Wolf-e Robotics, Zhejiang Blue Point Robotics

2.3.6 AP29: OTHER PROFESSIONAL CLEANING

Solar panel cleaning

With the increasing number of solar parks worldwide, their regular cleaning receives increased attention for maintaining their efficiency in electric power conversion. Depending on the availability of water, dust can either be washed off or just be removed with brushes. Numerous robotic products have entered the market as an alternative to manually dusting off the panels. While the first devices were often tele-operated, more and more autonomous cleaning robots have now entered the market.

For inclined solar panels, many cleaning robots run on horizontal rails attached to the upper and lower edge of the modules or use the edges of the modules themselves as rails, meaning one robot can clean one row of solar panels. Such devices are, for example, available from Aka Intelligence, Nomadd, or SolarACM. For horizontal panels, robots exist that move freely on the surface, featuring navigation for full area coverage. Bladeranger, Ecoppia, Serbot, or Miraikikai, e.g., offer such devices.

Figure 2.31: Ecoppia's fully autonomous, water-free solar panel cleaning robotic solution. Image credit: Ecoppia.

Figure 3.32: Serbot pvClean is an efficient and attractively priced solar panel/glass surface-cleaning device for inclination angles of between 15° and 20°. Image credit: Serbot.

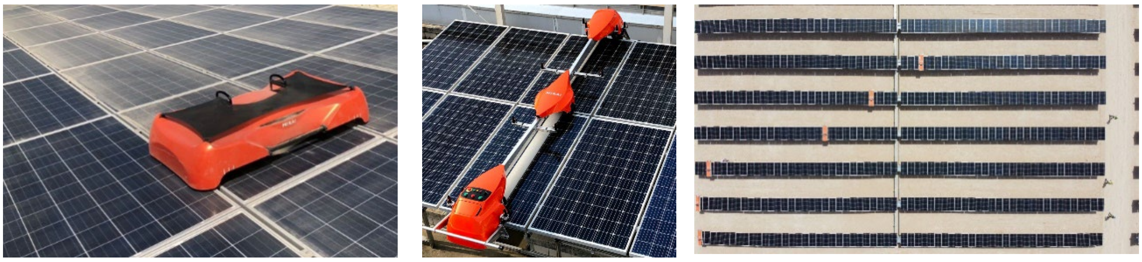

Figure 2.33: These solar panel cleaning robots from Miraikikai use sensors and an autonomous control system to automatically sweep all over the photovoltaics array. The system does not need any water and reduces costs by up to 80% compared to manual cleaning processes. With the help of a specialized mechanism, it can cross the gaps between the modules. The new model 4 (right) is designed for large utility-scale solar power plants with single axis tracker arrays located on the ground in arid regions and deserts. Image credit: Miraikikai, Inc.

Swimming pool cleaning

Professional pool-cleaning robots exist for public swimming pools, including Olympic-sized ones. The devices work like an underwater vacuum cleaning robot, sucking water through a filter to remove dirt particles and other objects. Using ultrasonic sensors or vision for localization and navigation, various cleaning patterns can be realized, from random patterns up to selective cleaning of certain areas. Many robots are also able to clean the walls of pools. Contact with the wall surface is maintained by the vacuum of the cleaning gear.

Autonomous pool-cleaning robots are, for example, offered by Hexagone, Keelcrab, Mariner 3s, or Palnpaul. Weda also offers pool cleaning robots for large fish tanks.

Litter removal from natural waters

The pollution of natural water bodies with litter, especially with plastics, has become a global problem. In many countries, a new awareness for the problem of pollution has formed within the last years. Some manufacturers address this issue with robots or robotic devices that are able to clean water surfaces or beaches.

Clearbot is a non-profit company, which has developed autonomous boats that use computer vision that detect and collect litter floating on the water surface. A similar prototype with an integrated conveyor belt to pick up floating objects has been designed by Clean Sea Solutions. A device from Ranmarine Technology can be tele-operated as well as used in autonomous operation.

Figure 2.34: Ranmarine Technology specializes in the design and development of industrial autonomous surface vessels (ASVs) for ports, harbors, and other marine and water environments. Ranmarine's current products include the Wasteshark™ range, designed and used to to clear plastics, bio-waste, and other debris from waterways. The data enablement of the products allows customers to closely monitor the environment and makeup of their water. This creates an accurate picture of the water's DNA to pinpoint any unquantified concerns. Ranmarine products are designed to be used manually or autonomously with online control and access. Image credit: Ranmarine Technology.

In the German research project Seaclear[63], a more complex system consisting of a boat and several autonomous underwater and aerial drones is being tested with the goal of identifying and collecting litter on the sea floor.

Robotic devices also exist for cleaning beaches, such as systems from Dronyx and PTTEP. While these systems are tele-operated, recent research projects aim to provide autonomous navigation on the beach using natural landmarks.[64]

Other robotic cleaning applications

A versatile robot for cleaning an entire bathroom, including sinks and bathtub, is currently being developed by Peanut Robotics. The system can autonomously change between tools, such as mops and spray bottles, and is intended to be used, for example, in hotels. A similar product has been announced by Somatic.

2.3.6.1. PRODUCERS

Angsa Robotics, Aquagenesis Intl, ART Robotics, Beijing Multifit Electrical Technology, BladeRanger, Clean Sea Solutions, Ecoppia, Guandong Unipin Medical Technology, Hexagone Manufacture, HIT Robot Group, HyCleaner, KeelCrab, Mammotion Tech, Mariner 3S, Maytronics, Miraikikai, Nomadd, Peanut Robotics, RanMarine Technology, Robosea, SolarACM, Somatic, Trombia Technologies, Weda

63 https://seaclear-project.eu.

64 Ichimura, T.; Nakajima, S.: Performance Evaluation of a Beach Cleaning Robot "Hirottaro 3" in an Actual Working Environment; 2018 18th International Conference on Control, Automation and Systems (ICCAS 2018); https://ieeexplore.ieee.org/abstract/document/8571634.

2.4 AP3: INSPECTION AND MAINTENANCE ROBOTS

Author: Dominik Moss, M.Sc.

Inspection by robots is one of the most prominent robotic tasks.[65] Besides considerations of cost-effectiveness, there may often be no other alternative than to send a robot to the area of interest. This might be due to safety considerations or – which is more common – because an area is difficult to access for humans. The statistics differentiate between the different application areas of robots which require distinctive designs regarding their size, mobility, dexterity, use of sensor equipment, and operational mode (from semi to fully autonomous). Overlaps with cleaning systems, rescue robots, and defense applications exist in terms of employing robotic platforms.

IFR statistics

There are many robotic devices for inspection and maintenance but just a few robots. In 2023, almost 400 robots (+67%) were sold. The RaaS fleet in that application group has decreased by 43%, however, due to the low number reported, this should not be regarded as a viable trend. The main application area of inspection and maintenance robots with close to 77% of all sales were for **buildings and other construction** (AP31). In 2023 306 units were sold (+104%). **Tank, tubes, pipes, sewers, and other inspection and maintenance** robots (AP32-39) experienced a sideways movement with 89 units sold and +2% growth rate.

Table 2.7

Professional service robots for inspection and maintenance (2022 and 2023)

	Application	2022	2023	2023/2022	2022	2023	2023/2022
		units sold		growth rate	RaaS fleet (in units)		growth rate
AP3	Inspection and maintenance*	237	395	+67%	21	12	-43%
AP31	Buildings and other construction*	150	306	+104%	**	**	-
AP32-39	Tank, tubes, pipes, sewers, other inspection and maintenance*	87	89	+2%	**	**	-

Source: World Robotics 2024
Results of IFR's annual survey and desktop research (10 professional inspection and maintenance robot companies)
*Regional breakdown cannot be revealed (minimum number of non-zero observations not reached).
**Results cannot be revealed (minimum number of non-zero observations not reached). Data included in application group total (AP1, AP2, etc.).

2.4.1 AP31: BUILDINGS AND OTHER CONSTRUCTION

2.4.1.1. TYPES OF OPERATIONS CARRIED OUT BY THE ROBOT

The operation and productivity of expensive equipment and infrastructure, such as buildings, bridges, plants, and offshore installations, must be secured. Robots for this area of application typically carry out the regular acquisition of data of any kind or the execution of simple physical operations, such as operating switches, valves, or handles.

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65 See, for example, the investment in Gecko Robotics: Shieber, J.: Building robotic safety inspectors nabs Gecko Robotics USD 40 million, December 16, 2019; https://techcrunch.com/2019/12/16/robotic-safety-inspectors-net-gecko-robotics-40-million/.

The following characteristics of robots can be observed in this area:

- *Mobile platform:* Typically wheeled or tracked in different sizes for difficult environments. With regard to small-scale engineered robotic mobility, mechanisms based on multiple legs, magnets, suction, rotors (for creating lift), etc. add to the wealth of very different designs of inspection and maintenance systems.
- *Sensors*: Application-specific sensors are put on the mobile platform or on a robotic arm with various degrees of freedom (from simple rotational units to full robotic arms) for increased kinematic dexterity.
- *Communication units* for sensor signal transmission and task transmission.
- *Operating centers* for specifying, monitoring, and documenting the robot's tasks.

Depending on the environment, the robots have to fulfill additional requirements. In electric power infrastructures, they have to overcome high electro-magnetic fields, and in chemical plants, they often have to own explosion-proof certificates. At nuclear sites, where they are used to relieve humans from having to work in dangerous conditions, the robots require radiation-proof designs.

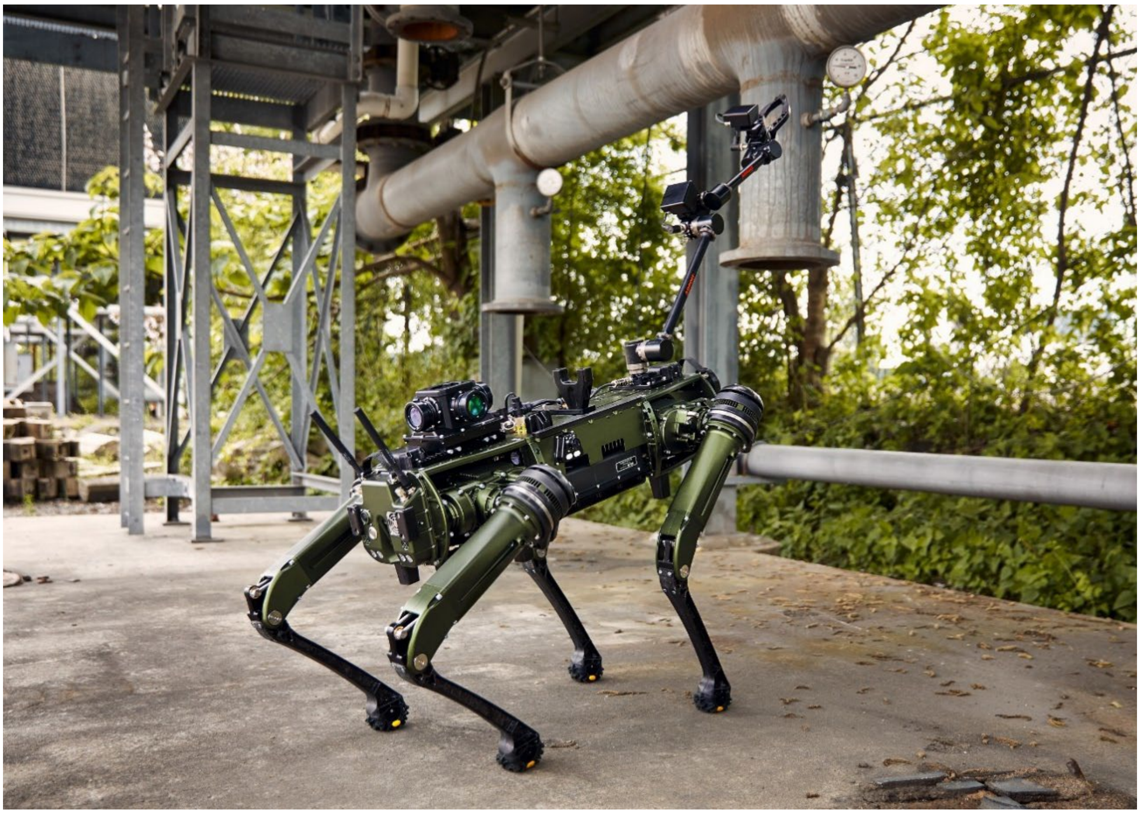

Figure 3.35: Vision 60 Quadrupedal Uncrewed Ground Vehicle is used for various industrial inspection applications. Image credit: Ghost Robotics.

2.4.1.2. LEVEL OF DISTRIBUTION

Industrial plants and buildings

Since the early 1990s, large-scale industrial facility suppliers, such as Hitachi, Mitsubishi, and Toshiba have been interested in mobile robots for the automatic inspection and monitoring of plants and industrial equipment. Typically, these were mobile autonomous systems (often running along prepared tracks/lines) equipped with sensors and offering radio transmission to collect relevant data. Numerous mobile, mostly wheeled or tracked platforms are equipped with on-board sensors or partly guided by manipulators for use in industrial environments. The overlap with surveillance robots is obvious. An example for a wheeled inspection robot is Rover from Energy Robotics, which is based on the robot hardware from Rover Robotics. Alternatively, Energy Robotics also provides their fully autonomous inspection framework on the tracked platform EXR-2 from Exrobotics, which is certified for Zone 1 environments according to International Electrotechnical Commission System for Certification to Standards Relating to Equipment for Use in Explosive Atmospheres (IECEx) and “Atmosphères Explosibles” (ATEX). A similar robot from Taurob Robotic Inspection additionally uses a five degree-of-freedom (DOF) robotic arm on top of the mobile platform to improve the inspection area.

Figure 2.36: The ExR-2 is designed to support operations fully autonomously when investigating potential hazardous situations, with a light detection and range (LiDAR) and AI/ML computer on board that enable the robot to autonomously navigate in a complex environment. Image credit: Exrobotics.

An autonomous mobile robot for cleanroom condition monitoring (e.g. for semiconductor plants) has been introduced by Metralabs. These robot types typically watch out for hazards and monitor environmental conditions, such as air quality, radiation, and smoke. They additionally check buildings and inspect remote trouble sites to reduce on premise visits by humans. Their counterpart in clinical or other public environments is the UV disinfection robot (see chapter 2.3.5 for more information).

Figure 2.37: A Taurob inspector exiting its docking station to start an autonomous inspection mission on an offshore oil platform in ATEX mode. Image credit: Clemens Fröschl, Taurob.

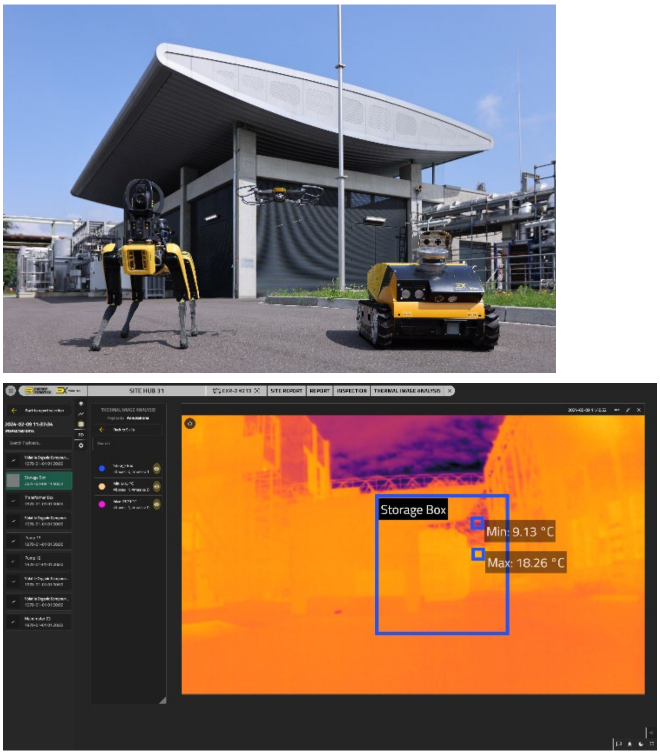

Figure 2.38: Left: Mixed fleet of robots and drone deployed by Energy Robotics for automated inspection at Shell's largest facility in Germany. Right: Thermal anomaly detection: Asset owners can access AI-powered insights and plan autonomous inspection missions through the Energy Robotics user interface. Image credit: Energy Robotics.

Over the last years, the use of multi-legged mobile robots has increased with the Spot[66] robot from Boston Dynamics, which is used, for example, by Ford for scanning the plant ahead of a redesign[67], for offshore energy inspections, and for chemical production facilities, realized by Energy Robotics.

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66 Holland, M.: Boston Dynamics: Roboter Spot für 74.500 US-Dollar zu kaufen, June 17, 2020; https://www.heise.de/news/Boston-Dynamics-Roboter-Spot-fuer-74-500-US-Dollar-zu-kaufen-4786299.html.

67 Smajstrla, A.: Ford deploys Boston Dynamics' Spot robots to survey Michigan plant. engaged, July 27, 2020; https://www.engadget.com/ford-boston-dynamics-spot-robots-michigan-plant-153343909.html.

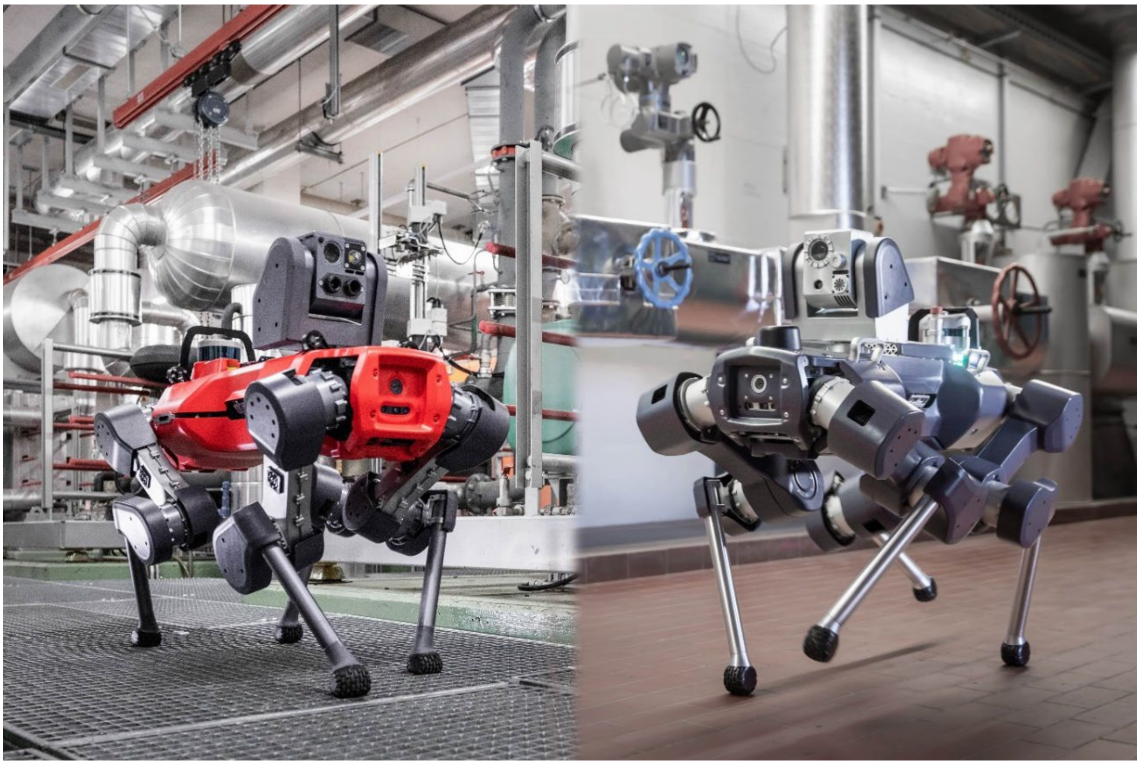

Figure 2.39: Anymal, the autonomous legged robots perform inspection missions in complex industrial environments (Anymal – left) and in potentially hazardous and explosive environments (Anymal X, an Ex-proof legged robot – right). Image credit: Anybotics AG.

A further development of Spot is the Anymal[68] robot from Anybotics, which is used for different inspection areas, from chemical process plants to underground mines. Deeprobotics presented their quadruped robot series Jueying, which contains four different robots for various inspection tasks. Besides these products, development is still ongoing with, e.g., prototypes like the Leonardo from Caltech University or the mini Cheetah from the Massachusetts Institute of Technology (MIT). These multi-legged mobile robots can be used in various environments, even in explosive and high-voltage environments, as long as they fulfill the necessary certificates.

The remote and autonomous inspection of offshore equipment or chemical plants imposes such requirements on the explosion-proof design of a robot. An example is Mimroex, a prototype inspection robot designed by Fraunhofer IPA. It is equipped with a robotic arm that carries a camera for visual inspection as well as various application sensors, such as microphones, gas and fire sensors, and laser scanners. The robot can be set to remote or autonomous mode; the latter enabling safe driving through industrial plants, which means that the robot will stop or take evasive action if people walk in its path or if it encounters any fixed or moving obstacles. Future developments are aimed

[68] Edwards, D.: ANYmal robot being put to work inspecting BASF facility, March 30, 2021; https://roboticsandautomationnews.com/2021/03/30/anymal-robot-being-put-to-work-inspecting-basf-facility/41990/.

at physical intervention using process equipment for sample taking, valve turning, cleaning up minor obstructions, and even operating control panels.

For nuclear sites, a large variety of robot systems has been developed, too: Both robots for special tasks, such as the inspection of reactor cores, steam generator inspection, and surface and tank clean-ups, as well as mobile robot arms that are tele-operated or operated semi-autonomously for general inspection tasks.[69] Often, these costly inspection robots are made available to nuclear power stations by service providers who maintain a pool of different robot systems. Inspection in nuclear power plants has received increased attention following the Fukushima reactor disaster.

A critical feature is the tactile feedback of robot arms or gripper forces to the operator, which results in technically expensive solutions. These can be one-armed or even two-armed for precision handling. Examples of current products include the flexible and slim robot arms produced by Cybernétix, now Technipfmc. These arms are manufactured in considerable quantities and are usually integrated into customized solutions for nuclear power plant maintenance. Technology and applications of robots in the nuclear industry are documented in regular publications.[70]

Radiation-proof mobile platforms as carriers for manipulator arms or sensor equipment are mostly tele-operated. These platforms are usually tracked or even equipped with segmented tracks for climbing stairs or negotiating uneven floors. Groupe INTRA (Intervention Robotique sur Accident) in France has developed robotic vehicles for the remote analysis and clean-up of radioactive sites. Groupe INTRA maintains a selection of inspection and intervention robots which are chartered to respond to a nuclear accident within 24 hours for its member organizations, very similar to Kerntechnische Hilfsdienst GmbH in Germany or Savannah River Remediation in the U.S.[71]

Extreme safety standards in nuclear power stations require regular inspections of weld seams in reactor cores and pipes by ultrasonic and eddy-current systems. The inspection equipment is squeezed in a narrow gap between the biological shield and the reactor core. The gap size is about 15mm wide and between 250mm and 500mm deep. Only automated inspection systems can gain access to the inspection area. OC Robotics has presented a foldable, modular robotic system for this purpose which is introduced into the gap on a rail system. The robot scans the areas to be inspected with an array of inspection sensors. The robot moves along the rails of the reactor, and thus covers the entire surface in segments. The inspection trajectories are generated by offline

[69] Bendale, T., Kharat, V.: Comparative analysis and future trends of robotics in nuclear power plants, *2017 International Conference on Intelligent Sustainable Systems (ICISS),* Palladam, 2017, pp. 400-405; https://dl.acm.org/doi/abs/10.1145/3529763.3529769.

[70] Sattar, T. P.: Robotics for Inspection and Decommissioning of Nuclear Power Plant; http://researchopen.lsbu.ac.uk/1594/1/Robotics%20for%20Nuclear%20work.pdf.

[71] Kerntechnische Hilfsdienst GmbH; https://khg.bgz.de/en/.

[72] Robotic Technology at the U.S. Department of Energy, Savannah River Site; http://www.srs.gov/general/news/factsheets/srr_robotics.pdf.

programming systems. The reactor core is scanned and the material pattern mapped, so that the growth of material flaws can be monitored. Both programming and operator training are supported by full offline functionality. All controllers and electrical equipment are integrated into the robot's structure or on the servo-drives to work independently of a switching cabinet.

Power generation and power line infrastructure

Figure 2.40: Risk of electric shock in the switchroom can be prevented by automatic inspection and operation solutions with Youibot's robot. Image credit: Shenzhen Youibot Robotics Co., Ltd.

Surveillance of power substations, electrical substations, high-voltage overhead transmission lines, and power plants need regular monitoring and inspection. In the hydropower industry, in situ inspection and maintenance work of turbine runners, ducts, tubes, etc. are of major importance, e.g., to detect cavitation, damage, and cracking.[73] A 2018 study identified robotic transmission line inspection as the most beneficial application for this industry.[74]

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73 Menendez, O., Cheein, F. A. A., Perez, M., Kouro, S.: Robotics in Power Systems: Enabling a More Reliable and Safe Grid. IEEE Industrial Electronics Magazine, vol. 11, no. 2, pp. 22-34, 2017; https://researchers.unab.cl/en/publications/robotics-in-power-systems-enabling-a-more-reliable-and-safe-grid.

74 Daim, T. U.; Yoon, B.-S.; Lindenberg, J., Grizzi, R.; Estep, J., Oliver, T.: Strategic roadmapping of robotics technologies for the power industry: A multicriteria technology assessment. Technological Forecasting and Social Change, vol. 131, pp. 49-66, 2018; https://ideas.repec.org/a/eee/tefoso/v131y2018icp49-66.html.

The inspection and maintenance of the high-voltage overhead transmission infrastructure still focuses mainly on the development of tele-operated robots; and only the few autonomous robot solutions will be presented in the following. In contrast, robots and uncrewed ground vehicles (UGVs) have been introduced more widely in power plants and substations to save valuable time and effort in the inspection process on the ground.[75, 76]

Scompi is a miniature six degree-of-freedom, track-based robot for inspection in hydraulic turbines developed by Hydro Québec.[77] A set of miniature inspection robots has jointly been developed by the Swiss Federal Institute of Technology (ETH) Zurich and Alstom Inspection Robotics (now Inspection Robotics and owned by Waygate Technologies). These devices are able to move autonomously or semi-autonomously on a large spectrum of different surfaces and structures, such as rotors, vessels, or pipes.[78, 79] Today, Inspection Robotics still develops and sells several inspection robots for a variety of use cases.

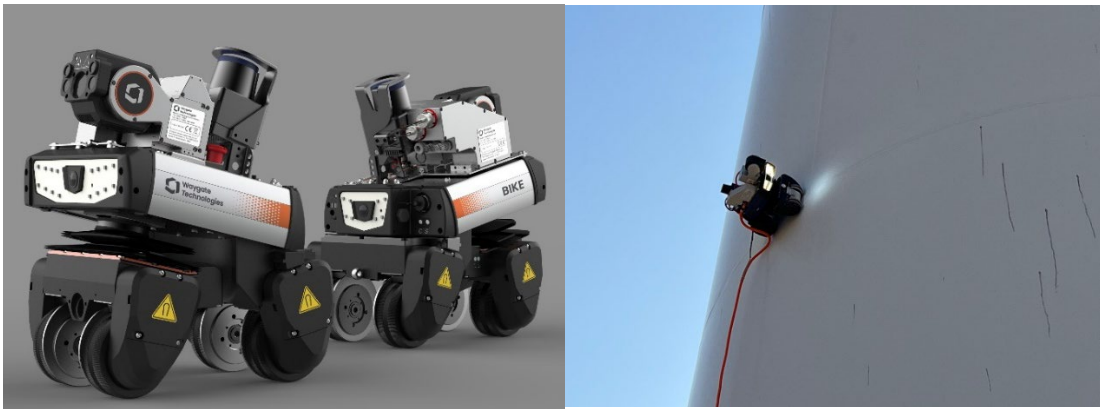

Figure 2.41: The Bike platform is a magnetic wheeled robot capable of inspecting power plant facilities and multiple applications in the oil and gas industry, such as vessel or pipe inspection. The locomotion concept allows the robot to climb obstacles like stairs and 90-degree corners (convex and concave). With integrated navigation cameras and 3D

75 Li, L., Li, D., Li, Y., Zhang, B., Zhao, J., Zhang, C., Dai, Z.: A state-of-the-art survey of the robotics applied for the power industry in China, Applied Robotics for the Power Industry (CARPI), 2016, pp. 1-5; https://ieeexplore.ieee.org/document/7745634.

76 Menendez, O., Auat Cheein, F. A., Perez, M., Kouro, S.: Robotics in Power Systems: Enabling a More Reliable and Safe Grid, in IEEE Industrial Electronics Magazine, vol. 11, 2017, no. 2, pp. 22-34, doi: 10.1109/MIE.2017.2686458; https://ieeexplore.ieee.org/document/7956250.

77 http://www.hydroquebec.com/robotics/generation-solutions-scompi.html.

78 Hess, S.; Siegwart, R. Y.: University Technology Incubator: Technology Transfer of Early Stage Technologies in Cross-Border Collaboration with Industry, Business and Management Research, vol. 2, no. 2, 2013; http://www.sciedu.ca/journal/index.php/bmr/article/download/2859/1693.

79 Capari, G. et al.: Highly Compact Robots for Inspection in Power Plants, Journal of Field Robotics, vol. 29, 2012, no. 1, pp. 47-69; https://www.research-collection.ethz.ch/bitstream/handle/20.500.11850/82240/eth-7796-01.pdf;jsessionid=65694A4B80C5660382F8E2585F955ABC?sequence=1.

position sensors, the operator receives precise information about the robot's position. Image credit: Waygate Technologies.

Figure 2.42: The service called BRIC (boiler robotic inspection & cleaning) will eliminate any physical risk to inspectors, provide precise data, and cut inspection costs for customers in sectors such as the chemical industry, paper manufacturing, or energy. Image credit: Waygate Technologies.

Robotic devices have been successfully introduced for assessing live power lines for defects, such as corrosion, degradation, or mechanical damage. Specific applications include checking compression splices for mechanical degradation by measuring resistance, detecting corrosion in the steel core of the aluminum conductor's steel-reinforced cable, or using infrared imaging to detect possible defects in power line components.

Additionally, various designs of power line inspection robots and robotic devices have been presented.[80, 81] Hibot and the Electric Power Research Institute in the United States

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[80] Pagnano, A. et al.: A Roadmap for Automated Power Line Inspection, Maintenance and Repair, Proceedings of the 8th CIRP Conference on Intelligent Computation in Manufacturing Engineering, 2012; https://www.sciencedirect.com/science/article/pii/S2212827113006823.

[81] Richard P. et al.: LineRanger: Analysis and Field Testing of an Innovative Robot for Efficient Assessment of Bundled High-Voltage Powerlines, *2019 International Conference on Robotics and Automation (ICRA),* Montreal, QC, Canada, 2019, pp. 9130-9136; https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=8794397.

have been developing power line inspection robots.[82] The Electric Power Research Institute's Ti robot has high-definition visual and infrared cameras. The robot inspects rights of way and components and determines clearances between power lines and trees. Ti can move at up to 5 miles per hour. The inspection robot from SMP Robotics Systems Corp. is a UGV equipped with an application-dependent sensor setup to perform thermal image inspection for electrical substations or gas leak detection. It is equipped with a graphics processing unit (GPU) to deploy machine learning algorithms for data analysis. The ground inspection robots from Energy Robotics perform visual analyses, e.g. reading analog measuring instruments.

2.4.1.3. COST-BENEFIT CONSIDERATIONS AND MARKETING CHALLENGES

Robots are one way to relieve the human worker from exposure to potential hazards, particularly in environments that are characterized by biological, chemical, and nuclear hazards. Additionally, the cost of human operations can be quite expensive. Offshore platforms are one of the most expensive work environments as logistics, work rhythms, safety, and qualification costs are part of the extreme overhead costs. The introduction of robots on offshore platforms and in chemical plants to take over routine work, such as inspection and maintenance, either tele-operated or autonomous, may result in short pay-off periods. At nuclear sites, their usage increases the safety of the human workers and productivity, due to the longer time periods that the robot can operate in these areas.

As an example, with over 300,000 km of transmission lines in the U.S., transmission line inspection is a costly and sometimes dangerous proposition. Corrosion and reliability of overhead power lines is a considerable industrial problem. As transmission line assets age, obtaining data on their condition is necessary to maintain high reliability. Internal damage of aluminum wires and bulges are due to corrosion and defects within cables. Deployment of transmission line inspection robots along with a new generation of low-cost RF sensors can enable system operators to remotely obtain detailed up-to-date knowledge of transmission line components and right-of-way conditions, thus increasing reliability while reducing operation and maintenance costs. In some cases, purchase of the robots to defer maintenance can shift operation and maintenance costs to capital costs, allowing a return on investment and depreciation.[83]

Overall, the use of robots in inspection and maintenance has been below its potential during the last years. Initiatives such as the Sprint Robotics Collaborative aim to achieve field use of robotics for inspection and maintenance of capital-intensive infrastructure assets on a very large scale within the next ten years. This initiative, which is formed by

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[82] Barker, B.: Robots Take on Tough Tasks in Transmission and Distribution, EPRI Journal, 2020; https://eprijournal.com/robots-take-on-tough-tasks-in-transmission-and-distribution/.

[83] Stevens, K. J., Lichti, K., Minchington, I. A., Janke-Gilman, N., Mactutis, T., Rook, D., Bondurant, P.: Conductor Damage Inspection System for overhead ACSR power cables CDIS on ACSR, 2013 Seventh International Conference on Sensing Technology (ICST), IEEE, pp. 901-905; https://ieeexplore.ieee.org/abstract/document/6727780.

several large asset owners from the petrochemical industry, claims that using robotics in the domain of technical inspection and maintenance of capital-intensive infrastructure is of vital importance due to the urgency to minimize the impact on the environment and increase safety. Additionally, robotic inspection and maintenance may reduce shutdown times, prevent human entry to vessels and other equipment, as well as cut costs related to services required to enable human entry.[84]

2.4.1.4. PRODUCERS

ANYbotics, ART Robotics, Baltrobotics, Boston Dynamics, Cablewalker, Deep Robotics, Diakont, DJI, Eddyfi Technologies, Efy Technology, Empire Unmanned, Energy Robotics, Ex Robotics, Gecko Robotics, Ghost Robotics, Groupe Intra, Hausbots, Hydro-Quebec, Inspector Systems, International Robotics Solutions, Invert Robotics, Kemaro, Mrobot, Nimbl'bot, Ogawayuki, Orano, PreNav, QI, Robosea, Ross Robotics, SeaRobotics, Sevnce, Shandong Guo Xing Intelligent Technology, SkySpecs, SMP Robotics, Taurob, Topy Industries, ULC Robotics, Youibot

[84] Miller, R., Abbasi, F., Mohammadpour, J.: Power line robotic device for overhead line inspection and maintenance, Industrial Robot: An International Journal, vol. 44, no. 1, 2017, pp. 75-84; https://www.researchgate.net/publication/312956959_Power_line_robotic_device_for_overhead_line_inspection_and_maintenance.

2.4.2 AP32: TANK, TUBES, PIPES, AND SEWERS

2.4.2.1. TYPES OF OPERATIONS CARRIED OUT BY THE ROBOT

Types of operations for robots may include pipe and sewer inspection, sewer cleaning, pipe cleaning, descaling, leak detection, and simple repair jobs. The inspection and maintenance of tanks, tubes, and pipes is a task that is clearly suitable for robots to bring humans out of the inspection and maintenance zones. Typical operations include conventional non-destructive inspection and advanced sensor techniques for condition monitoring. Pipe and sewer maintenance with service robots is becoming more and more of a necessity. The reasons for this are the following:[85]

- Environmental requirements: A sewer system must be demonstrably leak-tight.
- Resource conservation: The necessity of open repairs must be avoided by preventive measures.
- Safety: Formation of cavities underneath trafficable areas must be prevented at all costs.

Most of the tube, sewer, and pipe robots are segmented robots equipped with either wheels, tracks, or multiple legs for crawling inside oil, gas, or other media pipes, sewers or fresh-water pipes, industrial piping, or air ducts. Besides quickly detecting problems within pipe systems, such as failures at weld seams, corrosion, erosion, breakages, deposits, loose parts, faulty interior coatings, etc., the tasks may comprise grinding or milling which require special tools. Typical robot systems for pipe inspection come in various types:

- Mobile robot scanners (wheeled and tracked) which can be made up of segments to follow narrow bends. Their signal and energy transmission may be tethered or untethered.
- Floating robots which are washed through the pipes or ducts.
- Arm kinematics, often in the form of snake arms, to provide access to cluttered inspection environments through keyholes.

Today, most of the commercially available tank, tube, pipe, and sewer inspection systems are fully or partially tele-operated which requires an operator to be at least in proximity to an uncomfortable and dangerous environment. In some cases, the information obtained from the inspection may be insufficient to make a full assessment of the tunnel and additional inspections involving human operators are required. Therefore, current research and development (R&D) efforts are geared towards making the inspection robots fully autonomous. A completely autonomous system can perform the inspection of the tunnel without being controlled and monitored by an operator.

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[85] Shao, L., Wang, Y., Guo, B.; Chen, X.: A review over state of the art of in-pipe robot, Mechatronics and Automation (ICMA), 2015, pp. 2180-2185; https://www.semanticscholar.org/paper/A-review-over-state-of-the-art-of-in-pipe-robot-ShaoWang/38658dbd617e61c0e083e72a66d766e845a20ea4.

2.4.2.2. LEVEL OF DISTRIBUTION

Example of systems for sewer inspection:

As water mains age, they are increasingly exposed to stress from operational and environmental conditions. In consequence, these mains deteriorate structurally and hydraulically, thus adversely impacting water quality, leakage, and reliability. Effective management of these assets requires condition assessment, which includes the collection of information about their condition, analysis of this information, and ultimately transformation of this information into knowledge leading to effective decision-making about renewal. Numerous robot developments for sewers, pipes, and mains have been investigated in the past.[86]

In this domain, robot manufacturers offer rehabilitation equipment that helps restore sewers, which is significantly easier and cheaper than replacing sewer pipes using traditional methods. Sewer robots can clean pipes with typical inside diameters of 200mm to 600mm, which are inaccessible for humans.

A wide range of sewer inspection robotic devices for various diameters are available on the market for sewer mapping, wastewater assessment, and repair work. Most of them are tele-operated by a human operator, like Surveyor from Sewervue Technology, but some robots can navigate autonomously inside the sewers.

For example, the autonomous crawling robot Solo from Redzone Robotics executes a provided plan autonomously, maps the pipe system using radar, sonar, and video cameras, and highlights problem areas in the map.

Inspector Systems has several robots for inspecting pipes, which they call pipe crawler robots. Its sewer inspection robot is based on ultrasonic sensors and is able to travel in vertical and horizontal pipes at a speed of up to 200 m/h. The robot consists of three drive elements, which are connected by using flexible folding bellows and one ultrasonic module. Similar robots, which are additionally equipped with small robot arms for guiding, cutting, and grinding tools, are used for systematic sewer repair work as offered by IbakJS Robotics. IMS Robotics provides similar products. Sewervue Technology offers Surveyor, a tracked robot featuring sensor equipment, e.g. LiDAR, closed circuit TV, and a pipe penetrating radar.

The Fraunhofer Institute for Factory Operation and Automation IFF has deployed the automated sewer inspection system for the German river and canal system Emscher, which is the largest residential water management facility in Europe and the heart of future sewage disposal in the Ruhr region. The automated sewer inspection system must detect and map typical damage in the sewer system (corrosion; mechanical wear;

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[86] Siqueira, E. B., Azzolin, R. Z., da Costa Botelho, S., Oliveira, V. M.: Inside Pipe Inspection: A Review Considering the Locomotion Systems, In: Garrido, P. et al. (eds.): CONTROLO 2016. Proceedings of the 12th Portuguese Conference on Automatic Control. Springer, 2017, pp. 449-458; https://www.researchgate.net/publication/307623670_Inside_Pipe_Inspection_A_Review_Considering_the_Locomotion_Systems"

inhibition of flow like obstacles, deposits, and incrustations; deviation of position in means of horizontal, vertical, axial displacements; cracks and leaks) reliably through its various sensors. Furthermore, cleaning jets free the sewer from deposits and sludge.

An example of the ongoing developments in this area is the Submerge inspection robot, which is still in a prototype phase, but has already won an innovation award.[87]

Example of systems for gas and oil pipes

Pipelines are exposed to corrosion, mechanical stress, deposits, incrustations, and external impacts, which may all contribute to reduced flow or even explosion accidents. Regular maintenance by robots is necessary. In most cases, large pipelines have built-in cleaning and inspection devices ("pigs"). For smaller pipes, robots may be a flexible instrument to account for the state of the pipes. However, in most cases, robots have to be explosion-proof. Sensor-equipped inspection robots are inserted into gas or petroleum pipes to determine their condition.[88, 89] Even though the inspection tasks are similar, available robots vary in size and mobility concept depending on the gas pipe's diameter and geometric attributes. Also, the selection of sensor equipment varies from ultrasonic, LiDAR, or radar sensor to near-infrared or red green blue cameras and pH meters.

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87 Koomen, A.: Aquatech Innovation award winners announced, November 2, 2021; https://www.aquatechtrade.com/news/event/autonomous-robot-wins-aquatech-innovation-award.

88 Shukla, A.; Karki, H.: Application of robotics in onshore oil and gas industry – A review Part I, Robotics and Autonomous Systems, vol. 75, 2016, pp. 490-507; https://www.sciencedirect.com/science/article/pii/S0921889015002006.

89 Lattanzi, D., Miller, G.: Review of robotic infrastructure inspection systems, Journal of Infrastructure Systems, vol. 23, no. 3, 2017; https://ascelibrary.org/doi/10.1061/%28ASCE%29IS.1943-555X.0000353.

Figure 2.43: Eddyfi Technologies' Versatrax™ P-Series pipe inspection robotic crawler for long-range inspections. Image credit: Eddyfi Technologies.

A wide range of similar-sized inspection systems for internally inspecting and repairing pressurized gas mains is offered by ULC Robotics. As an example, Pipetel offers a tetherless, battery-powered robot to inspect unpiggable pipelines to achieve uninterrupted gas service even in challenging pipeline configurations, such as bends and back-to-back bends. Engineering Services Inc. has developed a technique to perform cast iron bell and spigot joint sealing from inside the pipe using a tele-operated robotic device. The device enters and travels along the interior of the pipe until a desired joint is reached and drills a hole into the joint spigot. Joint sealing is performed by injecting an anaerobic sealant into the jute packing of the joint, thus replicating the repair procedure currently done externally.

The responder platform from Redzone Robotics performs inspection and rehabilitation tasks in interceptor and tunnel pipes ranging from 90cm to 15m or more in diameter. The responder can be deployed for up to 1.5km through a single 60cm maintenance hole. With its on-board hydraulics and ability to navigate by sonar, laser, or video, the robot can access the most challenging environments.

Spherical storage tanks (spherical gasholders and liquid petroleum *gas* (LPG) storage tanks) have to be inspected periodically. One of the inspection methods is called 'in-service inspection' for inspecting the weld seams from the outside based on ultrasonic waves. It is reported that the robot can cut maintenance costs by reducing the inspection time by about one week from the conventional 23 days and decrease the conventional number of inspectors required by two.[90]

In pipeline inspection, a number of differently sized products (according to diameter or shape) have been introduced to the market. The purpose of these robots is to:

- Carry out short and long-range uncrewed inspections under various operating conditions at speeds of up to 1.8km/minute
- Accommodate dedicated tools for both water and wastewater applications
- Perform high-definition closed circuit TV and sound navigation and ranging (SONAR) inspections using a tracked robotic crawler or a flotation system

One application is their use in the Alaska pipeline where the Rodis crawler from Diakont braces itself against the inside of pipes to move forward and search for anomalies. The system has been successful on three Alaska pipelines and saved the project USD 70m.[91]

Other types of tank, tube, and pipe inspection robots

Nanomag™ and Magg™ from Inuktun Services (owned by Eddyfi Technologies) are designed to adhere magnetically to metal surfaces: Horizontally, vertically, and even upside down. Cameras in the front acquire high-quality images while the rear camera is used mainly for tether management. Another design, the variable geometry tracked vehicle, is a tethered (100m) miniature inspection system designed to access confined spaces and challenging terrain in a variety of applications, including search and rescue, nuclear, and duct inspection.

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[90] Sogi, T., Kawaguchi, Y., Morisaki, H., Ohkawa, K., Kai, N., Hayakawa, H.: Inspection robot for spherical storage tanks, Proceedings of the IEEE IECON 2000 26th Annual Conference (Nagoya), vol. 1, October 22-28, 2000, pp. 393-398.

[91] Abaffy, L.:Pipe Inspection Robot Saves Alaska Pipeline Millions, August 19, 2015; http://enr.construction.com/technology/construction_technology/2015/0819-pipe-inspection-robot-saves-alaskan-pipeline-millions.asp.

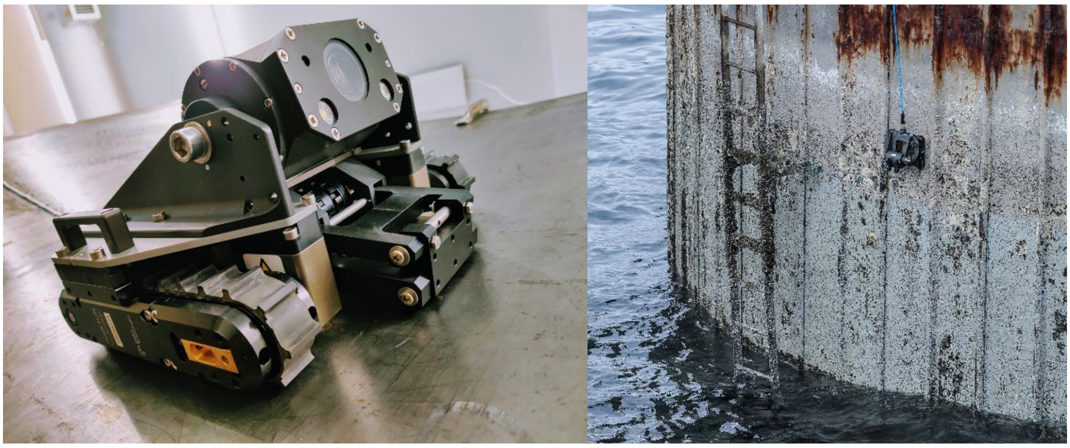

Figure 2.44: Eddyfi Technologies' Versatrax™ M-Series magnetic crawler for advanced non-destructive testing remote operations (right: performing offshore asset remote visual inspection). Image credit: Eddyfi Technologies.

Extremely dexterous snake arms for accessing and exploring confined spaces have been introduced by GE Aviation, formerly OC Robotics. Confined spaces are ubiquitous, ranging from storage to construction, and can be found in hazardous environments, such as underwater, radioactive enclosures, or toxic or corrosive fluids. These robots have multiple sequential joints, so unlike conventional robots, they do not have prominent elbows. Thus, the whole device can follow the robot's tip. Further developments resulted in the Pipe-worm robot, which performs the inspection tasks all on its own in an unknown pipeline network.

A large variety of different systems for sewer inspection and repair work has been suggested and introduced to the market. Usually, these systems are tele-operated tracked or wheeled mobile platforms and carry cameras, sensors, or simple tools. An example of a drone for inspection tasks comes from Flyability.

Most of the existing inspection systems for tanks, tubes, or pipes are still customized solutions. Other systems have been developed to inspect vents and ducts of air systems, but few have so far progressed beyond the prototype stage. Similarly, these systems have to negotiate sharp inclines, bends, and junctions.

Sewer robots are all still an active research area characterized by many prototypes and an increasingly strong product number.

Duct inspection

A contaminated ventilation duct can spread biological and non-biological pollutants throughout the building and result in sick building syndrome. Accumulated dust can be the spreading medium for contaminants. Numerous inspection robots for ducts have been presented for the maintenance of heating, ventilation, and air condition ducting systems. Besides inspection modules, these robots carry cleaning modules (brushes, dry ice blasting), disinfection spray guns, and/or HD video cameras. Furthermore, their mobility should allow negotiation of all duct shapes, as well as horizontal and vertical ascent and decent.

Besides tele-operated robotic devices that have to be controlled remotely by an inspector and are performing inspection and cleaning tasks, autonomous robots are still an active research area. The robotic devices typically clean and inspect air-conditioning ducts, kitchen and industrial air vents, air-conditioning vents, or any spaces where cleaning is strenuous or impossible without dismantling. Typically, the robotic devices are designed to easily pass through, inspect, and clean circular, rectangular, or square-shaped ducts. They should be operational in horizontal, vertical, or sloping ducting, including C-turns.

2.4.2.3. COST-BENEFIT CONSIDERATIONS AND MARKETING CHALLENGES

The cost of a typical pipe and sewer inspection robot is currently around €100k for a simple sewer TV robot and up to €250k for pipe-cleaning equipment. The different operation modes of the robots specify the benefit of the inspection solution:

Tele-operated inspection robot:

- The mobile platform is controlled via remote access by a human operator. Most robots are connected via wire, but some are also wireless.
- When an additional manipulator is available, the operator can perform maintenance tasks remotely.
- Sensor data of the whole inspection process are saved automatically.

Autonomous inspection robot:

- The mobile platform navigates autonomously through the pipe network, based on a scheduled path and collects all sensor data corresponding to its location.
- Additional manipulators are rare; they focus mostly on data acquisition.

Using sewer robots with wireless remote access, productivity improvements are attained mainly through a) their more mobile operation, which allows the robot to work without dragging cables behind it; and b) their increased mobility, which widens the range of operation, thus allowing for longer working periods without resetting. The whole cleaning process is thus more rapid and economical. Using autonomous sewer robots avoids the need for a permanent operator and is therefore less expensive during execution. In some cities, there is a lack of detailed plans of the complete sewer system. In this case, robots can also be used for mapping the sewer system to ensure that information is easily accessible when a leakage is detected. The major constraint on commercial viability is the usage limitation to pipes with an inside diameter of 200mm to 600mm. In particular, for smaller operators, this specialization can make it difficult to attain a sufficient degree of utilization.

Inspections and thickness measurements of the tank walls can be carried out manually with the inspector in a lift or hanging down from the top. However, a much safer way to carry out an inspection is to use a crawling robot. Usually, these robots have magnetic wheels that allow them to cling to the tank walls. The floor is particularly prone to thinning due to corrosion attack and tank owners must find the weak spots in the floors before they breach the tank's integrity. This often involves the costly process of draining the contents, removing the layer of sludge from the bottom, and cleaning the tanks so that inspection personnel may enter them. In the EFFIROB study (scenario "Sewer inspection"), the cost-effectiveness was demonstrated, concluding that robotic sewer inspection costs are still lower than the conventional alternatives – and amortization is still possible within the service life.[92] Such a length of sewers will probably be reached in any urban region with an area of over 3km². Against this background, a high level of market acceptance can be expected for the service robot solutions.

Customized inspection solutions for pipes, tubes, and tanks have been developed as part of the maintenance services offered by numerous companies.

The inspection of gas and oil pipes is at least as pressing: An array of four robots for oil pipeline inspection was used in 2017 to inspect a 40-year-old branch of the Trans-Alaska pipeline system at the Valdez terminal. The mostly tele-operated robotic devices from Diakont supply real-time data of 550m (1,800ft) of pipes with diameters ranging between 20cm and 140cm (8in and 55in).[93]

2.4.2.4. PRODUCERS

BakerHughes (Waygate Technologies), Berkeley Springs Instruments, Deep Trekker, Diakont, Eddyfi Technologies, Energy Robotics, GE Hitachi Nuclear Energy, Gecko Robotics, Gerotto Federico, Gridbots Technologies, HiBot, Honeybee Robotics, IBAK, IdMind, IMS Robotics, Inspector Systems, IntroScan Technology, Ishikawa Iron Works, NDT Global, Nimbl'bot, Ocius, PTTEP, Qiteng Robot, RedZone Robotics, Robot++, Robotics Design, SewerVUE technology, SMP Robotics, Taris, Taurob, ULC Robotics

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92 EFFIROB study: https://www.ipa.fraunhofer.de/en/reference_projects/EFFIROB.html (Study content is German).

93 Love, A.: Piping inspections near completion, August 13, 2018; http://www.pwsrcac.org/observer/piping-inspections-near-completion.

2.4.3 AP39: OTHER INSPECTION AND MAINTENANCE ROBOTS

2.4.3.1.1. TYPES OF OPERATIONS CARRIED OUT BY THE ROBOT

This class addresses the inspection robots that are not covered by the above-mentioned classes, such as autonomous water vehicles or autonomous drones. Besides the developments for robots on the ground or inside or outside of pipes, several robots are being developed to inspect plants or pipes from the air or from underwater.

Autonomous drones mostly inspect whole plant sites from above with different sensor equipment, such as LiDAR sensors, thermal imaging or optical gas imaging cameras, and perform mapping tasks. Underwater robots are used for inspecting offshore plants or underwater pipes from the outside.

2.4.3.1.2. LEVEL OF DISTRIBUTION

The usage of autonomous drones for inspection tasks has increased in recent years. Percepto offers several different sized drones for linear inspection tasks for pipes or power lines or coverage inspections of whole plants. A major difference to previously developed drones is the autonomy of these drones. For example, Percepto Air Max follows scheduled inspection routes autonomously and maps the environment at chemical or energy plants. Perceptual Robotics focuses on the blade inspection of onshore and offshore wind power plants with autonomous drones. They provide high resolution images of up to 3 pixels per mm to interpret the status of the blades. Another focus lies on the inspection of buildings and their facades. Leica BLK2FLY is equipped with a LiDAR sensor and autonomously covers the whole front of a selected building to create 3D digital twins. Some drones are also used in indoor environments like Elios 2 from Flyability, which is mainly controlled remotely but has semi-autonomous features to follow certain structures or to keep a certain distance to walls.

Figure 2.45: The Elios 3 created by Swiss drone company Flyability, designed for challenging, confined space inspections with a modular payload bay enabling a variety of applications across industries. Image credit: Flyability SA.

The development of autonomous underwater vehicles (AUV) has also been on the rise recently. Kongsberg Maritime developed the AUV Hugin, which can perform pipeline inspections and other tasks at a depth of up to 6,000m. It offers different operation modes from a fully autonomous mode to a supervised mode. Argos ROV from Forssea Robotics is currently still a remotely operated vehicle (ROV), but the company is also looking at implementing more advanced autonomous features.

Another form of underwater vehicles are snake-like robots, of which several systems are currently being developed or are in the prototype phase, e.g. the snake robot from Eelume or the Robofish from Verlume. These robots move like fish and should perform inspection tasks for offshore oil/gas and wind parks or pipelines.[94]

94 Offshore Network: Verlume progresses development of the RoboFish for efficient offshore inspections, March 2022; https://offsnet.com/content/gulf-of-mexico/verlume-progresses-development-of-the-robofish-for-efficient-offshore-inspections.

Figure 2.46: The Eelume vehicle, a self-propelled, autonomous robotic arm, inspects subsea structures. Image credit: Eelume.

Besides underwater robots, there are also uncrewed surface vessels, which are used for different underwater and above water inspection tasks like the uncrewed surface vehicle (USV) from Demcon.

2.4.3.1.3. COST-BENEFIT CONSIDERATIONS AND MARKETING CHALLENGES

The information gained from drone images and inspection analysis helps the maintenance personnel to detect all kinds of problems, from leakages in chemical plants and ruptures on wind turbine blades to increased thermal activity in power plants or gas leakages, and to initiate the right maintenance tasks before the problems result in plant downtime. Alternatives, like the use of helicopters, are more expensive or, e.g., the use of manual human inspection would often require production downtime to secure the safety of the human inspector. The advantages of autonomous drone application in contrast to the remotely controlled ones lie in the reliability and repeatability of inspections and the significantly reduced working hours for controlling and monitoring them.

The AUVs have several advantages compared to the assignment of diving human inspectors. They can travel faster and longer and can be equipped with several sensors. This also allows a more frequent inspection rate, which results in earlier maintenance activities and less harm to the infrastructure. In comparison to the remotely operated underwater vehicles, AUVs deliver similar advantages to the autonomous drones over their counterparts.

These fields are still fast changing due to their novelty and the number of new developments in comparison to the amount of commercially available products.

2.4.3.1.4. PRODUCERS

AiDrones, Australian Droid + Robot, Blue Atlas Robotics, Capra Robotics, Delair Marine, Demcon, Eddyfi Technologies, Eelume, Empire Unmanned, Flyability, Forssea Robotics, Gecko Robotics, Independent Robotics, Innok Robotics, Kongsberg Maritime, Nordic Unmanned, Ogawayuki, Perceptual Robotics, QI, Qiteng Robot, Running Brains

2.5 AP4: CONSTRUCTION AND DEMOLITION

Author: Tobias Rainer Schäfle, PhD.

The application area of construction robots was initiated in the 1980s, especially in Japan, as a way of improving human working conditions and thereby adding attractiveness to an often less-appreciated profession.[95] Numerous applications for construction robots have been suggested, such as:[96]

- Large (nuclear) facility decommissioning, demolition, and dismantling
- Building construction
- Road construction
- Robots for heavy/civil construction (drilling, tunnel building, earthmoving, etc.)
- Maintenance operations

The initial visions from the 1980s and 1990s turned out to be overly optimistic and the field of construction robotics has advanced in a much slower and technologically less radical fashion. Generally speaking, construction robots have produced significantly lower robot installation numbers than initially expected. However, with the advent of customization, the rapid take-up of additive manufacturing processes, networked manufacturing equipment, and increasing data integration, building construction was picking up speed in industrial activity and public appearance in the last years.[97]

A good overview of current research activities in construction robotics may be obtained from the annual International Symposium on Automation and Robotics in Construction (ISARC) or publications by the International Association for Automation and Robotics in Construction (I.A.A.R.C).[98] Surveys on the topic can be found in the journals "Construction Robot" or "Automation in Construction".[99, 100, 101]

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95 Cousineau, L.; Miura, N.: Construction robots. The Search for New Building Technology in Japan. Reston, VA: ASCE Press, 1998;
https://www.semanticscholar.org/paper/Construction-Robots%3A-The-Search-for-New-Building-in-CousineauMiura/a4960fc13b835e783eb853cec0071eb67eea4316.

96 Bock, T.; Linner, T.: Robot Oriented Design: Design and Management Tools for the Deployment of Automation and Robotics in Construction. The Cambridge Handbooks in Construction Robotics, Cambridge University Press, 2015.

97 Wakefield, J.: Tomorrow's Buildings: Construction industry goes robotic. BBC, May 4, 2016; http://www.bbc.com/news/technology-35746648.

98 International Association for Automation and Robotics in Construction (I.A.A.R.C.); their ISARC conference proceedings since 1984 are freely accessible through http://www.iaarc.org/pe_publications.htm. In 2024, the 41st edition will be in Lille/France.

99 Automation in Construction; https://www.sciencedirect.com/journal/automation-in-construction.

100 Construction Robotics; http://www.springer.com/engineering/control/journal/41693.

101 Li, R. Y. M.: Robots for the Construction Industry. In: Li, R. Y. M. (ed.): An Economic Analysis on Automated Construction Safety. Springer, Singapore, 2018, pp. 23-46; https://link.springer.com/book/10.1007/978-981-10-5771-7.

IFR statistics

Many products for construction or demolition are robotic devices. Service robots for **construction or demolition** (AP4) enjoyed a considerable growth rate of 58% in 2023. Coming from low absolute numbers, though, this high double-digit growth rate should not be overinterpreted.

Table 2.8

Professional service robots for construction and demolition (2022 and 2023)

	Application	2022	2023	2023/2022	2022	2023	2023/2022
		units sold		growth rate	RaaS fleet (in units)		growth rate
AP4	Construction and demolition*	26	41	+58%	**	**	-
AP41	Construction*	**	**	-	**	**	-
AP42	Demolition*	**	**	-	**	**	-

Source: World Robotics 2024
Results of IFR's annual survey and desktop research (8 robot companies for construction and demolition)
*Regional breakdown cannot be revealed (minimum number of non-zero observations not reached).
**Results cannot be revealed (minimum number of non-zero observations not reached). Data included in application group total (AP1, AP2, etc.).

2.5.1 AP41: CONSTRUCTION

2.5.1.1. TYPES OF OPERATIONS CARRIED OUT BY THE ROBOT

Most of the processes in automated building construction can be grouped into several types of functional operations:

- Materials handling (by bulk and unit load)
- Materials shaping (cutting, breaking, compacting, brick laying, and machining, sometimes in a collaboration between worker and robot)
- Structural joining (assembly)
- Cable robot prototype for 3D concrete printing[102]
- Planning and monitoring

102 https://cordis.europa.eu/project/id/723611/de.

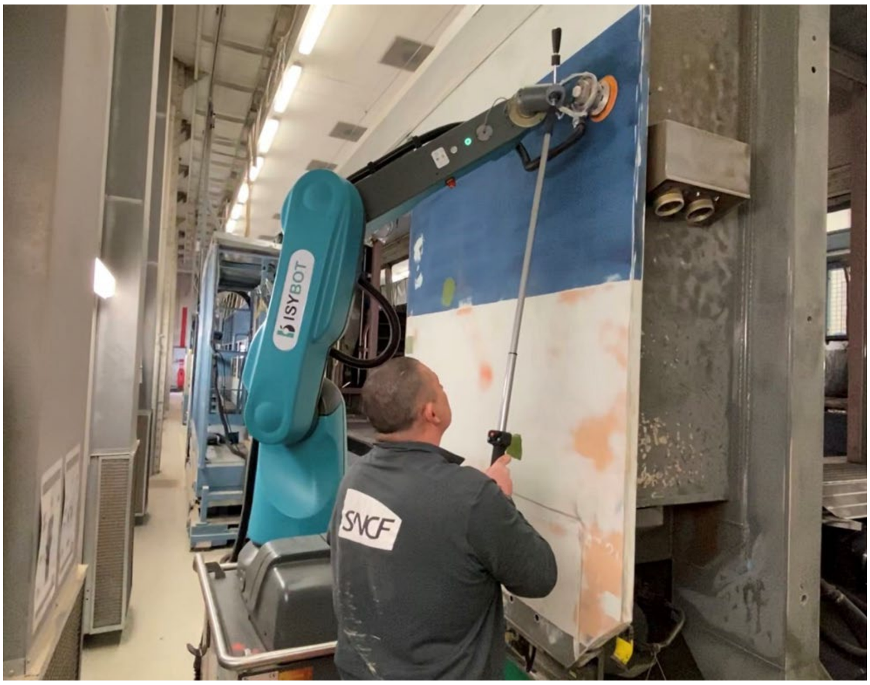

Figure 2.47: The Isybot collaborative system relieves the operator and increases the productivity in a variety of tasks, e.g. in the field of building construction. Here, a picture of the cobot SYB3 is shown in a configuration for a sanding application with the integrated vacuum system. This configuration of the cobot is currently used to sand walls in preparation for the final painting process. Image credit: Isybot.

Robots for material handling include programmable cranes and mobile robots to perform concrete panel handling and brick laying tasks at construction sites. Structural joining by robots has been suggested in the case of high-rise steel buildings, as industrial robot technology could be easily adapted to this task. Often, construction automation favors a divided approach: robots automatically prefabricate building elements (walls, ceilings, room cells, stairways, etc.) offsite in factories and the elements are then shipped to construction sites where structural joining is performed manually.[103, 104]

Regarding service robotics, the focus of use in the construction industry is on onsite application. The robots are engaged in steel welding, reinforcement manufacturing and positioning, concrete distribution, customized construction (masonry), interior finishing, onsite logistics, and facade operation.[105] A concise overview is given in the Springer Handbook of Robotics.[106]

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103 Kahane, B.; Rosenfeld, Y.: Balancing Human-and-Robot Integration in Building Tasks. Computer-Aided Civil and Infrastructure Engineering, vol. 19, no. 6, 2004, pp. 393-410; https://onlinelibrary.wiley.com/doi/abs/10.1111/j.1467-8667.2004.00365.x.

104 Built Offsite: ABB Robotics targets prefabrication construction industry with advanced building technology; May 2021; https://builtoffsite.com.au/news/robotics-prefabrication/.

105 See for example the cable robot for facade operations in the European Hephaestus Project: https://www.hephaestus-project.eu.

106 Saidi, K. S.; Bock, T.; Georgoulas, C.: Robotics in Construction. In: Siciliano, B. and Khatib, O. (eds.): Springer Handbook of Robotics, 2nd Edition. Berlin, Heidelberg: Springer, 2016, pp. 1493-1591; http://handbookofrobotics.org/.

For general or civil construction tasks, partly autonomous robotic devices are being increasingly considered. In addition, some of these device types are shared with the mining industry.

Earth moving equipment

Fujita Corporation, a Tokyo-based construction company, developed the uncrewed Tele-Earthwork System in the mid-1990s. Tele-operated construction machines were used by incorporating commercially available wireless communication systems into construction vehicles. The system comprised a set of components that can be installed quickly onto most conventional backhoes to allow uncrewed operation. This, together with the installation of monitoring cameras and wireless image communication systems on the construction machines and at various locations around the site, enabled operators to control these vehicles from control rooms without the need to see the machinery directly. The maximum distance between the control rooms and sites is around 2km. It has been reported that Fujita's uncrewed construction method has been used for the construction of a series of check-dams at Mount Fugen (Japan). One of the motivations to use the tele-operated construction method was the protection of the workers from disasters or risks in the vicinity of active volcano sites.[107]

In September 2019, the startup Built Robotics raised USD 33m for its autonomy stack that turns construction vehicles into autonomous robots.[108] Core technology is to retrofit existing construction vehicles with different types of sensors and actor equipment and orchestrate these robots in autonomous fleets. These fleets can be operated remotely by uploading blueprint metrics into the heavy machinery, such as dozers and excavators.[109] In 2022, Built Robotics was able to raise another USD 64m for its autonomy kits.[110]

Drilling and forepoling

Drilling has to be done for various reasons, for example when installing telephone cables or electricity wires under riverbeds, etc. To achieve this, the surface has to be removed along the route. A company in this field is Nlink from Norway, founded in 2012, which uses industrial robot arms for drilling on construction sites. In the meantime, Nlink has received several awards for its ceiling drilling robot. The precise drilling process is

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[107] Kusuda, Y.: A remotely controlled robot operates construction machines, Industrial Robot, vol. 30, no. 5, 2003, pp. 422-425.

[108] Crowe, S.: Built Robotics raises $33M for autonomous construction vehicles, September 19, 2019;
https://www.therobotreport.com/built-robotics-33m-autonomous-construction-equipment/.

[109] http://www.builtrobotics.com.

[110] Wessling, B.: Built Robotics digs up $64M for construction vehicle autonomy kits April 6, 2022; https://www.therobotreport.com/built-robotics-digs-up-64m-for-construction-vehicle-autonomy-kits/.

controlled and guided by an app and a laser. The global tool manufacturer Hilti introduced Jaibot, a drilling robot that is capable of drilling holes into ceilings according to CAD files uploaded to a cloud platform. To achieve high accuracy, the robot must be referenced by a worker before starting the drilling process.[111]

The trenchless drilling method first drills along a predefined route and then washes and widens the tunnel with a reamer. When the cavity has the correct size, the product gas or water tube, for example, is fitted through it. Such trenchless drilling, sometimes referred to as “micro-tunneling”, can be used on crossings up to 2,000m in length and 300m in depth with a diameter below 1.50m. This method is environmentally friendly as there is less damage to tree roots and other underground objects. There is less dust, dirt, and noise, and it requires 20% less operating space.

Furthermore, it is cost-effective as it is faster and streets or other nearby facilities do not have to be closed off. Although fewer workers are needed, they have to be well-trained, since the robots require more operational knowledge than conventional machines.

Just as in road construction, the application area of drilling robots is more or less limited to new drillings, as repairs and other maintenance tasks on pipelines often require a full opening. A trenchless drilling robot is produced by Tracto-Technik. The use of robotic technologies in these drilling machines yields advanced maneuverability and motion capability. The integration of perception, localization, and mapping techniques allows precise motions. Other manufacturers of similar technologies also cater to this interesting market.

Heavy-duty tunnel digging machines, as produced by Casagrande s.p.a., consist of a crawler with two hydraulically powered robotic arms to support the large rail, which guides the drilling mechanism. The award-winning control of this closed spatial kinematic chain contributes significantly to improving the precision and the cost-effectiveness of tunnel forepoling. Both the robot’s kinematic design and control support fast positioning procedures and improved positioning precision of less than 1cm.

Automated offshore drilling has entered the focus of mineral oil companies following the Gulf of Mexico disaster in spring 2010. A new, safer exploration rig is being developed by the Norwegian company Nabors Industries. It is operated by sophisticated, intelligent robots that are controlled with software provided by Energid Technologies Corporation. The rig is reported to consist of a patented encapsulated and pressure-compensated design that ensures an environmentally friendly solution with zero discharge to sea and the same safety barriers as for conventional drilling. Remote control from an interactive 3D interface allows uncrewed operation.[112]

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[111] https://www.hilti.de/content/hilti/E3/DE/de/business/business/productivity/semi-autonomer-baustellenroboter-jaibot.html.

[112] Seabed Rig and Energid Technologies Developing a Safer Oil Drilling System, PR Newswire, May 13, 2010; https://www.prnewswire.com/news-releases/seabed-rig-and-energid-technologies-developing-a-safer-oil-drilling-system-93678419.html.

In 2018, the elevator manufacturer Schindler AG started a project featuring a conventional six degree-of-freedom robot from ABB for autonomous drilling in elevator shafts.[113] Schindler AG and the Council of Tall Buildings and Urban Habitat (CTBUH) entered into a partnership focusing on the research of robotics in construction.[114] At the end of 2021, the R.I.S.E. system from Schindler was used for the first time in China to perform drilling, mounting, and climbing tasks in elevator shafts autonomously.[115]

Another benefit of automation in construction applications in general is the avoidance of errors. Especially in larger projects, errors can cause immense financial damage. Therefore, mobile robots are equipped with printers, which mark the existing floor with hints and layouts for manual workers. Mobile robots are used in onsite construction, not only for work preparation but also for process monitoring. For example, the startup Scaled Robotics equips mobile robots with sensors to create 3D maps to detect errors and verify the process of the construction.

Another company which performs automated tasks for error avoidance is Rugged Robotics, which prints layouts onto the floor and assists workers with its technology rather than replacing workers. This technology is seen as the intersection of the digital and physical world in construction.[116] The mobile robot of Rugged Robotics is equipped with an inkjet based printer and an omnidirectional drivetrain with four drive-steer-units to perform its tasks.

Similar to Rugged Robotics, the start-up Dusty Robotics prints layouts onto the unfinished floors but in contrast to Rugged Robotics, the localization of the robot is done externally by a base station on a tripod. Fieldprinter from Dusty Robotics is pre-loaded with the building plans and does not need to perform a SLAM, an algorithm to map the environment. Fieldprinter is commercialized as a Robot-as-a-Service (RAAS) model and was used to layout the luxury suites in the National Football League Allegiant Stadium in Las Vegas.[117]

Strabag, an Austrian construction company, started to use the four-legged Spot robots from Boston Dynamics for documentation of their construction sites. They are equipped

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[113] Autonomous drilling robot debut, ABB robotics, December 19, 2019; https://new.abb.com/news/detail/53854/autonomous-drilling-robot-debut.

[114] Schindler debuts breakthrough robotic system for elevators, October 2018; https://www.schindler.com/com/internet/en/media/press-releases-english/press-releases-2018/schindler-debuts-breakthrough-robotic-system-for-elevators.html.

[115] Thornton, J.: Schindler elevator installation robot deployed in Asia-Pacific, March 2022; https://www.roboticsandinnovation.co.uk/news/construction/schindler-elevator-installation-robot-deployed-in-asia-pacific.html.

[116] Heater, B.: Rugged’s construction layout robots land $9.4M; TechCrunch; March 2022; https://techcrunch.com/2022/03/23/ruggeds-construction-layout-robots-land-9-4m/.

[117] Crowe, S.: Dusty Robotics FieldPrinter automates building layout, December 2019; https://www.therobotreport.com/dusty-robotics-fieldprinter-automates-building-layout/.

with different types of sensors to generate 3D maps, for example at the construction site of the train station in Stuttgart, Germany.[118]

Mobile robotic platforms for onsite construction are also part of research, as researchers from Fraunhofer Italia Innovation Engineering Center have developed a prototype for logistic handling tasks in construction environments.[119]

2.5.1.2. LEVEL OF DISTRIBUTION

During the first robotic boom in the 1980s and 1990s, large sums were invested, particularly in Japan, in developing robots that could address the shortage of construction labor while increasing quality. However, this euphoria wore off as soon as automation in construction affected any aspect of construction materials, processes, logistics, and operations. Instead of a revolution, a much slower evolution in building construction has set in, focusing on the development of specialized machinery for specific high-performance applications, such as tunnel drilling, construction site transport (e.g. wheel loaders), and material handling systems for local use of semi-automated cranes.[120]

Taisei Corporation (Japan) reported a robot development for asbestos removal from elevator shafts that was commissioned by the New Energy and Industrial Technology Development Organization (NEDO, Japan). The remotely controlled robotic devices remove and collect dry-sprayed asbestos used on beams, ceilings, columns, and walls of buildings. This system allows an operator in a separate room to remotely control a robotic device using a video monitor to remove and collect sprayed asbestos by spraying water mixed with abrasives and super-absorbent polymer from a nozzle attached to the end of the robot's arm. The first experiments were conducted at a warehouse demolition site in Tokyo in October 2007.[121] A tele-operated asbestos removal robotic device has also been in use for blasting off the asbestos infested layer of stucco on building facades. It was claimed that cost and time for using the robot were about the same as with an all-manual process, although manual removal is still required on the tops and bottoms of the facades that the robot cannot access.

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[118] Wessling, B.: Built Robotics digs up $64M for construction vehicle autonomy kits April 6, 2022 https://www.reddit.com/r/Wevolver/comments/sevalr/z%C3%BCblin_and_strabag_are_testing_ the_robot_dog_spot/.

[119] https://www.fraunhofer.it/en/Application-Centre-ARENA/Preliminary-research-and-applications/rosbim.html.

[120] Yanagihara, Y.; Yoshinada, H.; Inoue, F.: Special Issue on Construction Robot, Journal of Robotics and Mechatronics, vol. 24, no. 6, 2012, p. 923; https://www.fujipress.jp/jrm/rb/robot002400060923/.

[121] Mori, N.; Nagase, K.; Oyama, Y.; Kuboki, K.; Murata, T; Ishihara, S.: Remote System to Remove and Collect Dry Sprayed Asbestos, Taisei Technology Center, no. 40, 2007; http://www.taisei.co.jp/giken/report/2007_40/abstract/B040_011.htm.

The Austrian start-up Baubot is one of the first companies to develop a multi-purpose robot for construction tasks. The mobile robot is capable of concrete 3D printing, material handling, welding, milling, painting, and several more tasks.[122]

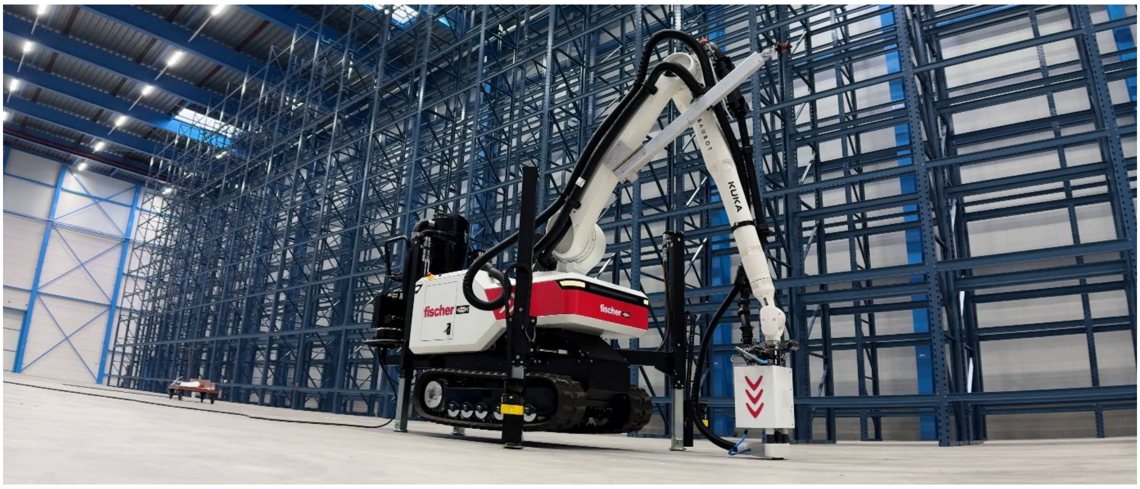

Figure 2.48: Baubot from Austria offers fully mobile systems to perform various tasks on construction sites and manufacturing facilities. Image credit: Baubot GmbH.

First prototypes of robotic road rollers and paving machines have been introduced, but only a few products are currently commercially available. An initial development, suggested in the 1990s, the road robot from Voegele (now part of the Wirtgen Group, Germany) navigated automatically without the need for guidance from workers. It combined the tasks of several conventional machines so that instead of engaging in several consecutive work steps and phases, the robot immediately produced the final pavement. So far, the robot system has not been commercialized. Other robotic designs for road maintenance have been designed and evaluated as prototypes: intelligent highway safety markers may replace the traditional base of the standard orange-and-white safety barrels with a mobile robot. The barrel robots can then self-deploy and self-retrieve, removing workers from this dangerous task. Key components of these mobile construction machines are 2D or 3D navigation modules, which can be interfaced to specific machines.

Robotic cranes and booms

The robot company Brokk (now part of Neerja) offers different types of robots in construction applications. With their demolition robot segment, Brokk offers 16 different types of robotic booms and various attachments like drills or saws.[123]

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[122] Katz, S.: Baubot comes out with two new robots to aid in construction projects, TechXplore, April 15, 2021; https://techxplore.com/news/2021-04-baubot-robots-aid.html.

[123] https://www.neerjagroup.com/product/brokk/remote-controlled-demolition-robots.

Putzmeister Concrete Pumps (now part of Sany, China) have marketed an example of a computer-controlled crane or boom since 2001. Their mobile concrete booms can be equipped with a computer control (Ergonic 2.0) to efficiently guide and program a hydraulically powered redundant kinematic chain (the multi-joint arm). It is reported that time effectiveness, damage reduction, and the quality of concrete delivery was dramatically improved, thus ensuring a very good return on investments. The controller is a spin-off of the Skywash aircraft-cleaning system.

Robotic manipulators for bricklaying and fabricating

Meyco ME5 Logica, now Epiroc (Sweden), is based on the kinematic principles of existing shotcrete pumps (concrete which is sprayed onto surfaces). A laser scanner sensor measures heading geometry and this information is then used to automatically control the standoff distance and the angle of the spraying jet.

Bricklaying robots on construction sites have not yet left the prototype stage. However, conventional industrial robots are used in the pre-manufacturing of brick walls and other parts, such as in the solution by Construction Robotics. Efforts to use robots for producing surprising architectural shapes have received significant recognition.[124] Housed in a modified freight container, the robot mobile fabrication unit can be used anywhere. It combines the advantages of prefabrication – precision and consistent high quality – with the benefits of short transport routes and just-in-time production on construction sites. A different design, making use of parallel arms, has been introduced by a team of Australian engineers. The Hadrian prototype is reportedly capable of setting 1,000 bricks an hour. In 2019, the new Hadrian X prototype was presented.[125] With 200 bricks an hour, Fastbrick Robotics increased the performance of the prototype and made a step forward towards commercialization.[126] In October 2020, the first two-story house was built by Hadrian X.[127] In 2021, FBR signed a contract to use Hadrian X to build walls for up to 5,000 homes in Mexico.[128] FBR has recently deployed its first next-generation Hadrian X to the US. The company plans to offer the robot as a RaaS solution.[129]

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[124] Würtsen, F.; Hodel, C.: Revolutionising building sites, ETH Zürich, March 9, 2015; https://www.ethz.ch/en/news-and-events/eth-news/news/2015/03/revolutionising-building-sites.html.

[125] Caballar, R. D.: This Bricklaying Robot Is Changing the Future of Construction, Autodesk.com, May 29, 2019; https://www.autodesk.com/design-make/articles/bricklaying-robot.

[126] Hayes, M.: Bricklaying robot hits 200 blocks per hour, construction europe, June 8, 2020; https://www.khl.com/construction-europe/bricklaying-robot-hits-200-blocks-per-hour/144453.article.

[127] Sweet, R.: Block-laying robot Hadrian builds first two-storey house, October 28, 2020; https://www.globalconstructionreview.com/innovation/block-laying-robot-hadrian-builds-first-two-storey/.

[128] Quirke, J.: Hadrian the bricklaying robot to build thousands of walls in Mexico, November 2021; https://www.globalconstructionreview.com/hadrian-the-bricklaying-robot-to-build-thousands-of-walls-in-mexico.

[129] Oitzman, M.: 1st Hadrian X bricklaying robot arrives in U.S., July 12, 2024; https://www.therobotreport.com/1st-hadrian-x-bricklaying-robot-arrives-in-us/.

Figure 2.49: Hadrian X® is a blocklaying machine and system, capable of safely working outdoors in uncontrolled environments with speed and accuracy. Hadrian X® is pictured here during construction of a 16 two-story townhouse development in Western Australia, the largest construction project ever undertaken by the robot to date. Image credit: FBR Limited.

The Japanese company Aist (marketed by Intelligent Systems) is working on an autonomous robot which can perform the entire process of mounting boards on walls.[130] Unlike most robots and assistive systems in automated construction, HRP-5P is designed as a humanoid robot with legged locomotion and two arms for grasping, transporting, and mounting boards.

With digitization on the rise, robotics is increasingly seen as an enabler for surprising architectural designs which are inspired by new materials, bionic structures, and novel manufacturing processes, allowing for a one-of-a-kind, sometimes additive, build-up of complex structures.

Examples are:[131, 132]

- A segmented shell-like structure based on the anatomy of a sea urchin robot which is stitched together of molded beech plywood components. Another

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130 Development of a Humanoid Robot Prototype, HRP-5P, Capable of Heavy Labor, AIST, November 16, 2018; https://www.aist.go.jp/aist_e/list/latest_research/2018/20181116/en20181116.html.

131 Frearson, A.: 10 projects paving the way to a future robot-built architecture, dezeen magazine, May 10, 2016; http://www.dezeen.com/2016/05/10/10-projects-that-look-future-robotic-construction-robots-architecture.

132 Ackermann, E.: Robotic Construction Platform Creates Large Buildings on Demand, IEEE Spectrum, April 26, 2017; https://spectrum.ieee.org/automaton/robotics/industrial-robots/robotic-construction-platform-creates-large-buildings-on-demand.

example is a web-like pavilion based on the lightweight shell of a beetle (University of Stuttgart).

- A 3D-printed steel bridge that creates a load-bearing structure that supports the robot's own weight as it works.
- The DFAB House is the first house in the world to be designed, planned, and constructed using predominantly digital processes.[133]
- A fleet of drones was programmed to lift and stack thousands of polystyrene bricks, creating a series of towers at the FRAC Centre in Orléans, France.

However, construction automation activities and the diffusion of actual construction robots for increasing the worker's productivity have been lower than anticipated, partly because of the industry's aversion to the risks associated with the introduction of new technologies, particularly robots. In addition, unlike their manufacturing counterparts, construction sites are for the most part unstructured, cluttered, and congested, making them difficult environments for robots to operate in. While certain robots with limited intelligence are slowly finding their way onto construction sites, others remain scaled-down prototypes.

In heavy and civil construction, there is a large potential for robotics and automation due to the hazardous conditions. Initial products for earth moving equipment are, for example, available from CAT in four different levels of autonomy, ranging from assistive task execution to fully autonomous vehicles. Vehicles like dozers or excavators have been in operation for several years, mainly in mining.

2.5.1.3. COST-BENEFIT CONSIDERATIONS AND MARKETING CHALLENGES

The robot transports material partly or fully autonomously, making the time and labor-intensive usage of cranes superfluous. Robot construction is thus up to 30% faster. It is not reliant on weather conditions as construction activities take place indoors, which also makes it less dirty and noisy.

The building architecture has to be adapted to suit the method of construction. Hydraulic cylinders have to be placed in the building foundations to allow the transport unit to glide up and down. A sufficient demand for such uniform buildings is essential to amortize the costs of construction robots.

The main motivational factors for using robotics in construction work are to ease working conditions, to make digital and sensory data at construction sites available to robotics equipment, to increase precision, and to spur innovation in this economically large sector instead of relying on cheap labor. Particularly semi-automated or even remotely

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[133] Robotic collaboration in timber construction, press release by ETH Zurich, March 22, 2017; https://www.ethz.ch/en/news-and-events/eth-news/news/2018/03/spatial-timber-assemblies.html.

controlled uncrewed construction equipment could play a valuable role in performing construction work, making it safe for human construction workers.

The major benefits of introducing robots in this area are the reduction of manual work and the increase in work safety.

2.5.1.4. PRODUCERS

Aeditive, Amyrobotics, BBZ, Canvas Construction, Conbotics, Dusty Robotics, Easy Floor Robotics, Effidence, FastBrick Robotics, Fujita Corporation, Isybot, JMU Defense Systems, Kajima, Kobots, Ogawayuki, Okibo, Panasonic, Q-bot, Taisei, TinyMobileRobots

2.5.2 AP42: DEMOLITION

This category includes demolition robots and robots for deactivating or decommissioning nuclear, chemical, refuse, military, and other hazardous complexes. Deactivation and decommissioning (D&D) as well as post-accidental activities are generally carried out via remote handling. The operator is usually either in a safe cabin or operating the robots/manipulators from a safe distance. Robots are frequently used for decommissioning nuclear power stations.

2.5.2.1. TYPES OF OPERATIONS CARRIED OUT BY THE ROBOT

To date, about 180 commercial nuclear power reactors, experimental or prototype facilities, and more than 500 research reactors have been retired from operation. Most parts of a nuclear power plant do not become radioactive or demonstrate only very low levels of contamination.[134]

Proven techniques and equipment are available to dismantle nuclear facilities safely and have been well demonstrated in several parts of the world. Decommissioning costs for nuclear power plants, including disposal of associated wastes, are decreasing and are only a small fraction of the total cost of electricity generation.

Currently, 18 commercial power reactors are being decommissioned and about 400 civilian nuclear power reactors will be closed down in the next two decades, of which approximately half will be decommissioned.[135] The demolition of structures often involves considerable risks, especially when the different pieces come apart.

Typical tasks comprise:

- Active decontamination through physical/chemical surface treatments (collecting, removing, surface depositing, removing contamination penetrated into concrete)
- Collecting decontaminated fluids, debris, waste, and materials
- Collecting and handling (secondary) waste from decontamination
- Transporting and depositing contaminated materials
- Surface processing (e.g. for applying sealing) materials
- Physical processes (cutting, drilling, milling, etc.) for dismantling structures
- Probing and active measurements (geometry, contamination, etc.)

Some operations are quite crude, such as knocking down building structures and debris removal. Other operations may involve careful disassembly of equipment and devices,

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[134] Decommissioning Nuclear Facilities, World Nuclear Association, May 2021; http://www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-wastes/decommissioning-nuclear-facilities.aspx.

[135] Iurchak, D.: 200-400 Nuclear reactors to be decommissioned by 2040, February 2020; https://energypost.eu/200-400-nuclear-reactors-to-be-decommissioned-by-2040/.

size reduction, and packaging of handling/storage. Often, tools such as hydraulic shears and impact wrenches are used. In most cases, these robots consist of a mobile part with an on-board hydraulic manipulator that has a tool for demolition mounted at the end. A good overview of robotics-related decommissioning processes and equipment is presented in overview articles.[136, 137]

Brokk has developed a series of electrically driven, hydraulic machines that can navigate through narrow doorways, down staircases, and into very high dose areas. They are being used at Fukushima to survey, videotape, and remove debris from the very high exposure areas of the damaged reactors. Brokk has added manipulator end effectors, similar to a hot cell manipulator, with load carrying capacities exceeding 75kg. The application of robotics for cutting pipes, electrical conduits, cable trays, and structural steel and for scarifying (scabbling) concrete are virtually limitless.

Numerous manufacturers offer manipulators either fixed in place or mounted on a gantry or a mobile platform for object grasping, manipulation, or guidance of tools. LMF (Easy Manipulator Vehicle) manufactured by Cybernétix (now Technip) is a modular vehicle for tele-operated intervention in nuclear facilities. The mobile platform, which can navigate obstacles such as stairs, is equipped with a heavy-duty hydraulic tele-manipulator (force feedback). Control, data, and video images are transmitted by an umbilical cable or by a radio system using spread-spectrum technology. Garrec and Perrot have presented a good survey of the progress made in force feedback systems in nuclear tele-robotics.[138] Cybernétix has also developed a range of carriers equipped with hydraulically or electrically powered manipulator arms, both with and without force reflection. A selection of tele-operated arms for decommissioning is produced by Wälischmiller Engineering. A concise overview of the current state of the art in this field can be retrieved from a NIST workshop on the use of robotic technologies at nuclear facilities.[139]

[136] Hornyak, T.: How robots are becoming critical players in nuclear disaster cleanup. Science, March 3, 2016; http://www.sciencemag.org/news/2016/03/how-robots-are-becoming-critical-players-nuclear-disaster-cleanup.

[137] Iqbal, J.; Tahir, A. M.; Islam, R. ul; Riaz-un-Nabi: Robotics for Nuclear Power Plants – Challenges and Future Perspectives. In: Proceedings of the 2012 IEEE Second International Conference on Applied Robotics for the Power Industry (CARPI), ETH Zurich, Switzerland, September 11-13, 2012; https://www.semanticscholar.org/paper/Robotics-for-Nuclear-Power-Plants-%E2%80%94-Challenges-and-Iqbal-Tahir/c18978908cab97b173efd1d41fbf78ec74ec0885.

[138] Garrec, P.; Perrot, Y.: Force Feedback Nuclear Telerobotics in France: R&D Results and Industrial Achievements, In: Puresafe Final Conference, CERN, Switzerland, January 2015; https://indico.cern.ch/event/346833/contributions/1751182/attachments/684457/940211/PURESAFE_CERN_january_2015_Garrec_Perrot.pdf.

[139] International Workshop on the Use of Robotic Technologies at Nuclear Facilities; Gaithersburg, USA, February 2-4, 2016; https://www.nist.gov/news-events/events/2016/02/international-workshop-use-robotic-technologies-nuclear-facilities.

Figure 2.50: Power Manipulator equipped with a robotic arm type A1000S. Image credit: Wälischmiller Engineering GmbH.

Laser cutting operations in the reactor vessel of the Superphénix fast neutron reactor (which was dismantled at Creys-Malville, France) were performed with the help of Charli, a small remote-operated vehicle (ROV) that is equipped with a robotic arm fitted with a laser cutting head and multiple vision cameras. It has been specially designed to move around inside confined pipework structures and to withstand very harsh environments with high levels of radiation and temperatures, as well as the presence of sodium, aerosols, and argon.[140]

In Chernobyl's Reactor 4, the legged Spot robot from Boston Dynamics was used to generate a heat map of the radiation that leaked out of the sarcophagus made of concrete and steel, in which the reactor was covered. The robot was equipped with a collimated radiation sensor and operated by researchers of the University of Bristol, the

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[140] Charli cleans up at Creys-Malville, World Nuclear News, December 4, 2013; http://www.world-nuclear-news.org/C-Charli-cleans-up-at-Creys-Malville-0612137.html.

U.K. Atomic Energy Authority, the Robotics and Artificial Intelligence in Nuclear initiative, and the National Centre for Nuclear Robotics.[141]

Preparatory work for decommissioning the Fukushima-Daiichi nuclear power plant is still in progress: Various robot technologies have been considered essential for success; therefore, public offerings of applicable technologies as a technical catalog were solicited by the Ministry of Economy, Trade and Industry of Japan in 2012. Robots have been introduced to the disaster site for clean-up and decommissioning.[142] Due to the COVID-19 pandemic, the removal of debris was postponed by about one year and was restarted in early 2022.[143,144] A description of possible technical approaches and their challenges can be accessed through a website.[145, 146] Another robot which can resist the harsh environment of nuclear facilities was developed by Hitachi for decommissioning the Fukushima plant. The Astaco-Sora robot is equipped with a crawler and two arms.[147] More information on the actual rescue and security operations at the Fukushima disaster site can be accessed in chapter 2.7.2.

To date, road construction is still mainly done by manually guided or partly automated machines. Working next to highway lanes is a noisy and dangerous job, thus making it suitable for automation.

An example of a new method of road and wall demolition is offered by Conjet, which produces automated high-pressure water-jetting machines. This process, called hydro-demolition, uses a high-pressure water jet to remove concrete from sensitive structures, such as bridges, parking decks, dams, canals, tunnels, quays, and jetties, in conjunction with concrete repair. These robots are also used for other water jet applications, such as scarifying or roughening surfaces, cleaning, and paint removal. Alternatively, power drills can be attached to the robot arms.

Strong water jets can be applied for effective road repair and deconstruction. Robots can accurately guide high-pressure water jets to cut and remove concrete from bridges, roads, and building walls. Owing to the recoil, precision, and noise emission associated

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[141] Ackermann, E.: Boston Dynamics' Spot Is Helping Chernobyl Move Towards Safe Decommissioning, November 23, 2020; https://spectrum.ieee.org/automaton/robotics/robotics-hardware/boston-dynamics-spot-chernobyl.

[142] Japan to start Fukushima fuel debris retrieval in 2021, World Nuclear News, June 4, 2015; http://www.world-nuclear-news.org/WR-Japan-to-start-Fukushima-fuel-debris-removal-in-2021-04061501.html.

[143] Melted fuel removal at Fukushima delayed by pandemic, December 24, 2020 https://techxplore.com/news/2020-12-fukushima-nuclear-debris-virus.html.

[144] 11 Years On: TEPCO to Begin Fukushima N-Fuel Debris Removal, March 2022, https://sp.m.jiji.com/english/show/18342.

[145] R&D on fuel debris retrieval – IRID Research report FY 2019; https://irid.or.jp/en/research/20190000-2/.

[146] Mid-and-Long-Term Roadmap towards the Decommissioning of Fukushima Daiichi Nuclear Power Units 1-4, Ministry of Economy, Trade and Industry Japan; http://www.meti.go.jp/english/earthquake/nuclear/decommissioning.

[147] https://www.hitachi.com/rev/archive/2020/r2020_04/04d02/index.html.

with such machines, they are operated automatically. For tearing down steel and metal structures, the robot arm can also be equipped with oxy fuel torches.

2.5.2.2. LEVEL OF DISTRIBUTION

The nuclear power industry is clearly a significant user of robots, although they are usually highly specialized units produced in relatively small quantities. With the anticipated construction of new plants in many territories, combined with the massive decommissioning tasks ahead, the prospects for innovative robotic solutions in this industry look promising. Therefore, robots for general demolition of construction complexes and for dismantling or servicing nuclear plants, chemical facilities, waste treatment systems, or military complexes have a significant market potential.

2.5.2.3. COST-BENEFIT CONSIDERATIONS AND MARKETING CHALLENGES

Dismantling a nuclear site is expensive: whereas in Germany €38bn have been set aside to decommission 17 nuclear reactors, the UK Nuclear Decommissioning Authority estimates that clean-up of the UK's 17 nuclear sites will cost between €109 and €250bn over the next 120 years which means €1.4bn to €2.7bn per Giga Watt. [148] France has set aside just €23bn to decommission its 58 reactors.

When dismantling nuclear power plants, it is often difficult or impossible to use manual labor due to the risk of radiation or chemical contamination. Conversely, it is possible in such cases to use a demolition robot in the area to be decontaminated, dismantled, or demolished. To be truly effective, the robot must be agile in the sense that it must be able to cut pipes and package materials into containers, demolish walls, or haul materials, etc. Finally, it must itself be dismantled for transportation to a storage area. A major challenge here is that the robot must be extremely reliable as it is virtually impossible to repair or upgrade the system once it has been deployed. Due to the respective safety considerations and the complexity of the task, these robots are typically tele-operated with a very limited degree of autonomy. The challenge of combining robust sensing/feedback with high durability and flexibility represents a significant obstacle to wider deployment.

Most current robotic devices employ little autonomy or even programmed motion; invariably, there is a human in the control loop, and this is likely to continue. Most systems employ simple tele-operation or master/slave manipulation and generally fall into one of three following broad categories:

- Relatively costly, customized solutions to specific problems
- General purpose equipment, modified for this use

[148] Dorfman, P.: How much will it really cost to decommission the aging French nuclear fleet? Energy Post, March 15, 2017; http://energypost.eu/how-much-will-it-really-cost-to-decommission-the-aging-french-nuclear-fleet.

- Systems produced from “off-the-shelf” components such as heavy-duty (hydraulically driven) manipulator arms

The nuclear power industry uses robots during plant construction and decommissioning, in maintenance operations and in waste disposal.

In a 2011 OECD report, the Nuclear Energy Agency (NEA) explains the Co-operative Programme on Decommissioning (CPD): “Regarding the use of robotics, the CPD observed that […] robots may have a limited practical applicability in decommissioning contrary to earlier expectations that robotic methods would be extensively used in the decontamination and dismantling of radioactive structures and components although they will remain necessary for some applications especially in the high radiation areas. The clean-up and verification for the release or declassification of alpha contaminated concrete structures where seepage of contamination into cracks and along pipe penetrations has proved to be very challenging and in fact in some cases has prompted authorities to impose much more stringent release criteria...”.[149] However, in December 2019, the NEA established the “Expert Group on the Application of Robotics and Remote Systems in the Nuclear Back-end” with 40 experts representing 14 member countries and three international organizations to exchange information and explore potential joint activities.[150]

Means to overcome these limitations have been identified as “…high cost of development of robotics technology as an obstacle to obtaining a suite of robotic and/or remote technologies (platforms and tools) for efficient operations in high radiation or contaminated areas. Key challenges that need to be addressed in order to overcome high costs and integrate robotics into decommissioning projects include:

- Develop a fuller and more broadly held knowledge and appreciation of the robotics capabilities that currently exist and where they have been used successfully on decommissioning projects.
- Stop re-inventing technologies that already exist, then abandoning the equipment when the project is over. If every decommissioning project insisted on designing and fabricating their own excavators, cranes, and other equipment from scratch they would also be prohibitively expensive.
- Manage decommissioning to become a consistent reliable patron of the robotics industry and enable the costs of new developments and advances to be spread over multiple decommissioning projects.

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[149] Radioactive Waste Management Committee: The NEA co-operative programme on decommissioning; twenty-five years of progress; the last five years 2006 through 2010. Nuclear Energy Agency, September 21, 2011; https://www.oecd-nea.org/rwm/docs/2011/rwm-r2011-3.pdf.

[150] Annual Report 2019. Nuclear Energy Agency, May 2020; http://www.oecd-nea.org/pub/activities/ar2019/ar2019.pdf.

- Integrate the newer, more technically adept generation into the current older and vested generation of D&D managers who mistrust the technology and think it is simpler and more cost-effective to throw human power at a task.
- Fund research further down the research & development (R&D) pipeline to influence development and testing of robotic capabilities that are applicable to nuclear D&D instead of trying to back-fit them after they have been developed for other applications in other industries and the military.

An analysis of the reasons why Japanese robots did not play a prominent role in the Fukushima nuclear disaster response is instructive regarding the above challenges."[151]

However, there is a strong tendency to use more versatile systems, regarding both the degree of automation and mobility. Advanced sensors, augmented reality, and largely improved human-machine interaction or usability have increased the practical benefit in using robot technology. Particularly regarding the Fukushima disaster, this decommissioning project is expected to become one of the biggest engineering challenges of our time: It is claimed to take likely 40 years to complete at a cost of USD 15bn. The operation will involve squadrons of advanced robots.[152, 153, 154] During the first half of 2017, a series of visual investigations using remotely controlled equipment and robots was performed to identify the condition of vessels inside as well as the distribution of fuel debris in all three units. In the summer of 2017, as stated in the government roadmap, policies for fuel debris retrieval from each unit were presented and resulted in a discussion on which unit should be the first to undergo fuel debris retrieval in 2018.[155] In 2019, the first test was conducted which included the lifting and moving of fuel debris by a robot arm. Even though the test ended with positive results, the clean-up operation is not expected to begin until 2022, since the initial plans of starting in 2021 had to be postponed due to the COVID-19 pandemic.[156, 157] In May 2020, however, Tepco held training sessions at the Fukushima test field in preparation for the upcoming removal of

[151] R&D and innovation needs for decommissioning nuclear facilities. Nuclear Energy Agency. OECD, 2014; https://www.oecd-nea.org/rwm/pubs/2014/7191-rd-innovation-needs.pdf.

[152] Strickland, E.: Fukushima's next 40 years, IEEE Spectrum, vol. 51, no. 3, March 2014, pp. 46-53; https://ieeexplore.ieee.org/document/6745884.

[153] Application of Robot Technology, Tepco; http://www.tepco.co.jp/en/decommision/principles/robot/index-e.html.

[154] Fukushima Daiichi Nuclear Power Plant Accident, Ten Years On, 2021; https://www.oecd-nea.org/jcms/pl_56742/fukushima-daiichi-nuclear-power-plant-accident-ten-years-on.

[155] Weber, I.; Funaki, K.; Sandberg, N.; Otsuka, I.: NEA support to Fukushima Daiichi decommissioning strategy planning, NEA News, no. 35.1, 2017; https://www.oecd-nea.org/nea-news/2017/35-1/nea-news-35-1.pdf.

[156] Robot lifts bits of melted fuel at Japan's Fukushima plant, Phys.org, February 14, 2019; https://phys.org/news/2019-02-robot-bits-fuel-japan-fukushima.html.

[157] Melted fuel removal at Fukushima delayed by pandemic, December 24, 2020; https://techxplore.com/news/2020-12-fukushima-nuclear-debris-virus.html.

fuel assemblies.[158] In early 2022, a robot captured the first images of fuel debris in preparation of the removal.[159]

It should be noted that the Fukushima disaster motivated the DARPA Robotics Challenge (Defense Advanced Research Projects Agency) to a significant extent. The DARPA challenge in 2020 focused on subterranean robots, which are able to operate in complex underground environments. Further information on this most important challenge for robotics technology can be found in the abundant literature accompanying this international initiative.[160, 161] However, in 2024 the focus will be on "artificial intelligence-enabled cyber reasoning systems that can automatically find and fix software vulnerabilities in real-time and at scale in widely used, critical code" and not on robotics anymore.[162] Fukushima also motivated the Disaster Challenge at the World Robot Summit 2018 in Tokyo.

Even in non-nuclear environments, there is often a considerable risk associated with the demolition of structures, for example the tearing down of a ceiling. To this end, a special breed of robots has been developed. The robots are typically tele-operated from a wireless operator panel. It is, however, characteristic that this is a niche market and many of the providers do not consider their vehicles to be robotic systems but rather a demolition vehicle with a hydraulic crane for handling walls, ceilings, pipes, etc.

2.5.2.4. PRODUCERS

Autonomous Solutions, Brokk, Caterpillar, Conjet, Epiroc, Husqvarna, Kowa Tech

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[158] Tepco prepares to survey Fukushima Daiichi unit 2 fuel pool, May 14, 2020; https://www.world-nuclear-news.org/Articles/Tepco-readies-to-survey-Fukushima-Daiichi-unit-2-f.

[159] Yamaguchi, M.: Robot photos appear to show melted fuel at Fukushima reactor, February 2022; https://www.news4jax.com/tech/2022/02/10/robot-photos-appear-to-show-melted-fuel-at-fukushima-reactor/.

[160] Chung, T.: DARPA Subterranean (SubT) Challenge:
https://www.darpa.mil/program/darpa-subterranean-challenge.

[161] Ackermann, E.; Guizzo, E.: DARPA Robotics Challenge: Amazing Moments, Lessons Learned, and What's Next, IEEE Spectrum, June 11, 2015;
http://spectrum.ieee.org/automaton/robotics/humanoids/darpa-robotics-challenge-amazing-moments-lessons-learned-whats-next.

[162] https://www.darpa.mil/news-events/2023-12-14.

2.6 AP5: TRANSPORTATION AND LOGISTICS

Authors: Nikhil Srinath Betgov, M.Sc.; Florenz Graf, M.Sc.; Florian Jordan, M.Sc.; Max Kirchhoff, M.Sc.; Tobias Rainer Schaefle, Ph.D.

Logistics systems cover the management of the flow of goods, as well as their transport, handling, and packaging. Most logistics systems require mobility, either in indoor or outdoor environments (exceptions are goods-to-robot systems, pick-and-place robots, and palletizers, which classify as industrial robots and are treated in “World Robotics Industrial Robots”). Autonomous mobile robots (AMRs) are mobile robots (see definition in chapter 1.2.1) used in industrial and non-manufacturing applications to move materials autonomously from one point to the next. AMRs do not perform long distance transportation, which is typically carried out by truck, train, ship, or plane.

Some companies use the term AGV (automated/autonomously guided vehicle) interchangeably with the term AMR. Nevertheless, it is important to differentiate between traditional AGVs that navigate on predefined paths, either virtual ones or paths that use some kind of external guidance (e.g. colored markings, rails, or beacons) for navigation, and AMRs that can navigate freely in a predefined operation area. Traditional AGVs do not classify as robots. However, it is sometimes not possible to make a clear distinction between AGVs and AMRs, since the technological components used may enable a certain degree of autonomy in functions such as navigation. For example, some of them still navigate on predefined paths but come with obstacle avoidance functions that allow them to leave the path within predefined boundaries in case it is blocked. A new trend among several companies has emerged in mobile platforms that can be used as both AGVs and AMRs. An example of this is provided by Ek Robotics with its product X Move. These mobile platforms do not really differ in terms of hardware but in their navigation and integration at the customer’s site. The AMR navigates freely in space, avoids detected obstacles, and even stops sometimes, but is thus not as precise as an AGV, which follows a programmed fixed route. The AMR configuration allows for fast integration at the customer’s site, whereas the AGV configuration delivers the highest degree of predictability and reliability. With a platform that can function as both, the user can switch between the modes or run both types in parallel without any changes to the hardware or infrastructure.

Figure 2.51: The X Move 2-in-1 transport platform can be equipped with a variety of load handling attachments. Three of the five models, with payloads from 150 kg to 1,900 kg, can be used either as AGVs or AMRs. The X Move transport robot supports the VDA 5050 interface and can be used in combination with other transport robotic systems. The image shows the X Move 1200. Image credit: Ek Robotics.

Applications of AMRs comprise transportation and, depending on the specific application scenario, handling, packaging, sorting, and delivery. Typically, AMRs are installed in:

- Indoor environments without any public traffic, mainly in manufacturing environments, warehouses, or logistics centers; see chapter 2.6.1
- Indoor environments accessible to the public, such as hospitals, hotels, and public buildings; see chapter 2.6.2
- Outdoor environments without any public traffic, mainly harbors, airports, parking decks, production sites, and trans-shipment centers; see chapter 2.6.3
- Outdoor environments that overlap with streets and walkways in which AMRs navigate the "last mile" for the delivery of food or consumables; see chapter 2.6.4.

An overview of the technology and the future of robotic logistics systems is given in the quoted literature.[163, 164, 165] Relevant startup activities have been happening in the

163 Bechtsis, D.; Tsolakis, N.; Vlachos, D.; Iakovou, E.: Sustainable supply chain management in the digitalisation era: The impact of Automated Guided Vehicles, Journal of Cleaner Production, vol. 142, 2017; pp. 3970-3984.

164 Fazlollahtabar, H.; Saidi-Mehrabad, M.: Autonomous Guided Vehicles. Methods and Models for Optimal Path Planning, Studies in Systems, Decision and Control, vol. 20, Springer, 2015.

165 The 2022 IFAC Intelligent Autonomous Vehicles Symposium, Prague, July 6 to July 8, 2022; https://www.iav2022.eu. See also IFAC Technical Committee on Intelligent Autonomous Vehicles TC7.5: http://tc.ifac-control.org/7/5.

logistics sector; an abundance of market studies confirm this global growth market. In 2022, the transportation and logistics application area was the second fastest growing application for professional service robots according to the IFR statistics.

An interesting discussion is to what extent autonomous cars or trucks fall into this category. Technically, these systems show a high resemblance to AMRs. However, according to the definition of service robots, the statistics strictly count (fully autonomous) AMRs that are used for commercial tasks and operated by properly trained personnel. According to the IFR, passenger transportation is part of the automotive industry and therefore not covered by the IFR statistics (see chapter 1.2.4). Admittedly, technical boundaries are somewhat blurred in this area.

IFR statistics

With more than 112,000 units (+35%) sold in 2023, more than every other professional service robot was built for the application class **transportation and logistics** (AP5). While traditional sales remain the main channel of monetarization, RaaS business models enjoy growing popularity with a growth rate of 20% to more than 5,000 units in 2023. Most units in the application group AP5, around 80% in total, were originated in the Asia + Pacific region. Growth rate-wise, the Americas enjoyed a strong +179% rate while sales in absolute numbers were significantly lower (almost 7,700 units, compared to Europe with 11,000 units sold in 2023).

Transportation in **indoor environments without public traffic** (AP51) qualify with 71% of all units sold as the most important application class within the segment. Here the same applies regarding the regional breakdown: Most robots are from the Asia + Pacific region (close to 66,400 units; +20%) in 2023, while sales in the Americas are growing by an exceptional +220% to almost 5,500 units in 2023. Transportation **in indoor environments with public traffic** (AP52) are catching up with a strong +76% growth rate amounting to almost 30,000 units sold in 2023. This development is attributable to the strong demand for food and beverage delivery in restaurants, at airports, and indoor malls. These delivery robots are mainly built in the Asia + Pacific region (around 26,500 units sold in 2023). Growth rates in the Americas are similar to Asia+ Pacific (both around +82%) with much lower absolute numbers, though (1,739 units sold), while Europe's growth rate is more moderate with +19% and almost 1,700 units sold in 2023. The business model RaaS is especially prevalent in this application class (AP 52) with a +41% growth rate as it does not require capital investments. Hardly any sales in transportation in **outdoor environments without public traffic** (AP53) were reported whereas sales in **transportation in outdoor environments with public traffic** (AP54) amount to 1,352 units in 2023 and a strong growth rate of +31%. **Inventory and other transportation and logistics** (AP55 and AP59) are comparable in both units sold and growth rate (close to 1,400 units sold and +28%).

Table 2.9

Professional service robots for transportation and logistics (2022 and 2023)

	Application	Region	2022	2023	2023/2022	2022	2023	2023/2022
			units sold		growth rate	RaaS fleet (in units)		growth rate
AP5	Transportation and logistics	Total	83,582	112,971	+35%	4,180	5,007	+20%
		Europe+MENA	9,753	11,034	+13%	90	253	+181%
		The Americas	2,740	7,656	+179%	**	**	-
		Asia+Pacific	71,089	94,281	+33%	**	**	-
AP51	Indoor environments without public traffic	Total	64,477	80,260	+24%	**	**	-
		Europe+MENA	7,294	8,347	+14%	**	**	-
		The Americas	1,718	5,492	+220%	**	**	-
		Asia+Pacific	55,465	66,421	+20%	**	**	-
AP52	Indoor environments with public traffic	Total	16,968	29,940	+76%	1,561	2,198	+41%
		Europe+MENA	1,406	1,668	+19%	**	**	-
		The Americas	949	1,739	+83%	0	0	-
		Asia+Pacific	14,613	26,533	+82%	**	**	-
AP53	Outdoor environments without public traffic	Total	24	35	+46%	**	**	-
		Europe+MENA	24	35	+46%	0	0	-
		The Americas	**	**	-	**	**	-
		Asia	**	**	-	**	**	-
AP54	Outdoor environments with public traffic*		1,031	1,352	+31%	**	**	-
AP55+AP59	Inventory, other transportation and logistics*		1,082	1,384	+28%	**	**	-

Source: World Robotics 2024
Results of IFR's annual survey and desktop research (109 robot companies for transportation and logistics)
*Regional breakdown cannot be revealed (minimum number of non-zero observations not reached).
**Results cannot be revealed (minimum number of non-zero observations not reached). Data included in application group total (AP1, AP2, etc.).

2.6.1 AP51: INDOOR ENVIRONMENTS WITHOUT PUBLIC TRAFFIC

A significant number of AMRs are utilized in indoor environments that are restricted from public access, primarily in manufacturing warehouses where only authorized personnel are allowed. The dynamics of the environment, the amount of traffic, and the autonomy of the AMRs are diverse.

AMRs play a crucial role in the concept of the smart factory and the Industry 4.0/smart factory paradigm thanks to their exceptional routing flexibility. For many years, AMRs were not able to achieve the level of acceptance they deserve in industrial factory logistics; a circumstance that is now changing drastically. Reasons for the effective operation of AMRs are their acclaimed performance and reliability, as well as the increased degree of digitalization of factories, even in challenging environments.[166] A relatively new field of application is robot-based truck loading and unloading, which is typically done in environments that most likely incorporate indoor applications. This chapter focuses widely on this field of application thanks to an extensive revision in 2024.

2.6.1.1. TYPES OF OPERATIONS CARRIED OUT BY THE ROBOT

Apart from their mobile base, AMRs can be equipped with containers for storing goods, with transferring devices such as forklifts (“fork types”), transfer belts, slides, or arms (manipulators) for loading and unloading (“mobile manipulation types”). Other AMRs are used to tow carts (“tow types”).

Figure 2.52: A fleet of Effibot-XS AMRs equipped with lift modules to enhance productivity. Image credit: Effidence.

[166] US Roadmap 2.0, Material Handling & Logistics, April 2017; https://www.supplychain247.com/paper/material_handling_logistics_us_roadmap_2_0/apics.

Initially, AGVs relied on prepared floors, such as embedded wires or magnets, for motion guidance. While many systems still utilize cost-effective methods, like magnetic beacons or floor tapes, to create a suitable environment for navigation, there is a growing trend toward freely navigating AMRs in large-scale manufacturing and logistics. To emphasize this distinction, the term AMR (autonomous mobile robot) has been coined.

Usually, their navigation is based on laser scanners, which are used to provide an accurate 2D map of the environment for self-localization and obstacle avoidance. Initial solutions relied on reflector markers in fixed locations to determine the exact position. Newer developments no longer depend on such markers and are more robust for use in dynamic environments. Lidar and other optical sensors form the basis of this technological leap.

Early on, combinations of AMRs and robotic arms were implemented to automatically load and unload machine tools. In recent years, these mobile manipulator robots have gained significant popularity. This can be attributed to several factors, including the increasing labor costs in developed nations, a strong emphasis on productivity, a scarcity of skilled labor, and the exponential growth of the e-commerce industry.

Mobile robots are applied in typical branches of industrial robot automation: automotive, electrical/electronics, metal, chemical, rubber and plastics, food and beverages, etc.[167]

Figure 2.53: Evocart mobile robots from the Italian producer Oppent are used around the world to improve efficiency in logistics. Image credit: Oppent SPA.

[167] Ullrich, G.; Albrecht, T.: Automated guided vehicle systems. Berlin, Heidelberg, Springer, 2023; https://link.springer.com/book/10.1007/978-3-658-35387-2.

Automotive industries, however, are clearly dominant in terms of the number of installations. They are increasingly using mobile robots as part of their lean and agile manufacturing concepts, which replace conveyor belts and fixed cycle times. These mobile robots play a vital role in ensuring just-in-time and just-in-sequence deliveries, further enhancing the efficiency of automotive manufacturing processes.

Numerous publications point out the immense future potential of mobile robot use.[168] Typical tasks for AMRs today are:

- Assembling: moving products through production processes
- Kitting: collecting parts for assembly
- Transporting: loading pallets and loose parts
- Staging: delivering pallets for production processes
- Warehousing: moving products from stretch wrappers to docks or storage facilities
- Order picking: moving ordered products to trailer-loading areas for distribution
- Parts/Just-in-time delivery: towing trailers loaded with parts and materials to the point of consumption
- Truck loading and unloading tasks are now also frequently delegated to AMRs.

Additionally, the use of AMRs in automotive production for transporting chassis has shown promising growth. This application enables more flexible and agile production compared to traditional conveyor belt systems. Fraunhofer IPA already developed such a solution together with Bär Automation GmbH back in 2014.[169] Further developments from other companies and startups have also followed suit.

Truck loading and unloading

In logistics, truck loading and unloading are two processes that go hand in hand and have largely been carried out manually for many years. With advancements in technology, these processes are now being automated also with robots in many logistics chains to minimize manual labor and to reduce the time it takes to load and unload goods, thereby increasing throughput. Theoretically, the procedure for loading trucks is not very complicated: starting off with the inspection of goods, followed by labelling, arranging, loading, and securing of the goods in trucks or trailers. Unloading at the destination is carried out in reverse: commencing with the removal of goods, followed by inspecting, sorting, and finally transporting the goods to storage locations for further distribution.

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[168] Robotics in Logistics: A DPDHL perspective on implications and use cases for the logistics industry, DHL Customer Solutions & Innovation, March 2016; https://www.dhl.com/global-en/home/insights-and-innovation/thought-leadership/trend-reports/robotics-in-logistics.html.

[169] https://www.ipa.fraunhofer.de/en/reference_projects/free_navigation.html.

The most common types of payloads for truck loading and unloading are cartons or boxes of goods and palletized goods, which in turn results in two main types of trucks that need loading and unloading in most scenarios:

- The first type of truck has its floors stacked with cartons or boxes. Sometimes, there is no space between the boxes and little or no gaps between the top of the truck and the boxes. This kind of arrangement minimizes delivery costs and maximizes the shipment volume. It is also beneficial, especially when there are variabilities in load sizes. However, it must be noted that this arrangement is not very stable, as the boxes may shift during transit, thus causing damage to the goods.
- The second type of truck is stacked with palletized goods. A palletized arrangement ensures a more stable transit of goods and reduces the risk of damage since the goods are secured more firmly on pallets. This kind of arrangement, however, offers less flexibility when dealing with variable load sizes and thus limits the loads to standard sizes that can be shipped. As a result, the shipping space may not be fully and efficiently utilized. Palletized shipping can also lead to additional packaging costs.

Generally, truck loading and unloading processes are efficient when carried out with the right kind of equipment. Forklifts, conveyers, cranes, and automated systems, to name just a few, help make the loading and unloading of trucks and trailers as efficient and as safe as possible. However, even with the use of the right kind of equipment, truck loading and unloading comes with its own set of hazards. This can include falling load and cargo, which could be heavy and not fastened securely. Improper weight distribution and poor visibility can also lead to falling cargo. Spills from wet cargo, slippery floors, and falls are also common hazards. Unattended vehicles and machinery result in disasters. Poor management of the warehouse infrastructure as well as unorganized warehouse items, tools, and other artifacts may also lead to injuries and accidents.

There are many strategies for loading and unloading trucks, but the most common ones include rear and side loading and unloading. Rear loading involves loading a truck from a loading dock situated at the rear of the truck and can be done either manually by humans or with automation tools. The same applies for side loading, except that trucks have a provision for being loaded from the side at the loading docks. Unloading is also either done manually or is partially or fully automated. Recent trends indicate that both loading and unloading are now automated to a large extent using robots. Robot usage has not only simplified loading and unloading processes but has also helped minimize the hazards for humans at warehouses and production sites.

There are various approaches to truck loading and unloading.

Autonomous robotic forklifts

The easiest way to load and unload trucks is using a forklift that has been made autonomous. It is safe to categorize these forklifts into autonomous mobile robots (AMRs), since they need little to no assistance for carrying out navigation as well as loading and unloading tasks. SLAM (simultaneous localization and mapping), AI, and modern perception systems are implemented that rely on LiDAR (light detection and ranging) and camera sensors to assist with navigation. These technologies make the forklifts navigate autonomously. One important aspect of these AMRs is that they are mainly used to load/unload goods that are palletized but unsuitable, in most cases, for loading/unloading other kinds of items from trucks.

For the loading process, these autonomous forklifts initially locate the palletizing area or a staging point. By identifying palletized loads using perception technology, a forklift positions itself appropriately below a chosen pallet and loads it onto the forks. After deciding on a suitable loading strategy or pattern, it finally carries the pallet into a truck for loading. All these operations are carried out by the robot after accurately localizing itself and planning the path. Once a palletized load has been loaded into the truck, the forklift drives out again, autonomously, and identifies the next palletized load to be shipped. This process continues until all the palletized loads have been loaded into the truck. The reverse operation of unloading is also carried out autonomously by the forklifts. As soon as a truck arrives at the destination and is positioned at the loading dock, the autonomous forklifts come into play. In the first step, a forklift positions itself in front of the truck(s) to be unloaded. After that, a suitable unloading strategy or pattern is selected to remove the palletized loads from the truck. Pallets are identified by means of perception algorithms, and the unloading order is also decided by intelligent algorithms. The forklift autonomously navigates to the pallets after accurately localizing itself in the environment and then positions itself correctly to carry the palletized load. Once loaded onto the forklift, the forklift navigates autonomously to the staging area where the palletized load is dropped off. This process continues until all the palletized goods have been dropped off at the staging area for further processing by other robots or human operators.

There are a variety of robotic forklifts, and not every forklift is suitable for loading and unloading trucks, trailers, and containers. Each forklift is categorized by the type of operation it performs, its load capacity, its maximum height reach, and its aisle width traversabilty, to name just a few criteria.[170] Different forklifts include pallet movers (pallet jacks), pallet stackers, counterbalanced fork trucks, straddle vehicles, very narrow aisle (VNA) vehicles, and reach trucks. Counterbalanced forklifts are more commonly used for loading and unloading trucks.[171, 172]

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170 A detailed overview of the different types can be found here: https://www.toyotaforklift.com/resource-library/blog/toyota-products/forklift-types-and-classes; and here: https://www.agvnetwork.com/types-of-agv/types-of-robot-forklift.

171 https://www.agvnetwork.com/types-of-agv/types-of-robot-forklift.

172 https://www.meilirobots.com/resources-list/robot-guide.

Since the forklifts are intelligent, they are aware of their surroundings and can detect various objects, as well as obstacles and humans. They can maneuver themselves in warehouses, avoiding obstacles in real time and planning their routes on the fly with dynamically changing scenarios. Robotic forklifts are also designed in such a way that they can be operated manually by humans or autonomously without any human intervention.[173] In very complex scenarios where human input is necessary or in emergency situations, humans can assume operation thanks to a manual override option.

Mobile manipulators and other solutions

In the realm of non-robotic systems, automated truck loading systems (ATLSs) play a major role. They streamline the process of loading and unloading cargo from trucks using various mechanisms, like rollers, chains, and conveyors. They are designed based on specific criteria, such as cargo type, dock requirements, and system dimensions, to maximize efficiency. ATLS setups usually have two components, one inside the truck and one at the dock, though configurations may vary depending on whether the truck can be modified or not. These systems facilitate the rapid and single-shot transfer of goods to and from the truck, thereby enhancing operational flexibility and efficiency. Different systems, like chain, slat, and belt conveyors, cater to varying cargo types, from palletized to loose cartons, while other systems, like skate loaders, do not require truck modification and include advanced hardware and software features with sensor support for optimal operation.

Where forklift AMRs and ATLSs are not feasible, other alternative solutions are available for loading and unloading trucks. Most of these other solutions usually employ a combination of AMRs and conveyors, thus resulting in a hybrid concept. Other approaches use a combination of conveyors and autonomous forklifts or rely completely on AMRs. Human input is minimal and often not required at all. Truck modification is not necessary in most cases, as the AMRs are able to load/unload trucks.

The most widely used hybrid solution is a mobile manipulator that works autonomously in tandem with a conveyor system. This type of solution includes AI algorithms and real-time motion planning. The mobile manipulator functions exactly the same as an autonomous forklift, as described in the section above, with the minor difference of the manipulator being situated at the loading dock upstream of the conveyor system. Sometimes, the mobile manipulator comes with an integrated conveyor system. The manipulator arm is equipped with suction vacuum pads or grippers that can grasp cartons firmly. It, of course, has a predefined payload that it can withstand. For the loading process, cartons are transported on a conveyor system to the loading dock where the autonomous mobile manipulator is situated. As soon as the manipulator arm identifies the incoming cargo with the help of AI and machine vision technology, it picks

[173] https://www.apexwarehousesystems.com/its-a-forklift-its-a-robot-no-its-a-robotic-forklift/.

up the cargo with its vacuum gripper and loads the truck. This process continues for all the incoming cartons. For the unloading process, the operations are carried out in reverse, with the cartons first being identified with AI and machine vision technology. They are then picked up by the manipulator and placed one after the other on the conveyor system before finally making their way to a staging area for further processing. The kind of load is mostly limited to cartons or boxes that can be grasped by the manipulator. An interesting feature of these autonomous manipulators is that they can recover from failures, e.g. accidently dropping cartons during loading and unloading. They attempt to pick up dropped packages and resume from where they left off prior to the failure. Another less common hybrid solution utilizes conveyors to transport loads up to the loading dock but uses an autonomous forklift instead of mobile manipulator AMRs for the final loading and unloading task.

A different yet effective approach is using articulating or roaming conveyors to load and unload trucks. This approach combines active conveyors and grippers/end arm tools in a single system on a vehicle or AMR. The kind of load that can be loaded/unloaded is usually limited to cartons or boxes. For the loading process, boxes from the staging area or stacked location arrive on the conveyor system and are then arranged on the floor of the truck bottom-up by means of an end effector. Unloading happens in reverse with the gripper or end effector grasping the boxes and transporting the load back onto the roaming conveyor. Navigational methods, similar to the autonomous forklifts described in a previous section, help to ensure accurate localization inside the truck and at the loading dock. AI and 3D machine vision technology help in identifying and detecting boxes.

2.6.1.2. LEVEL OF DISTRIBUTION

Despite the large number of suppliers, freely navigating AMRs (without fixed wires or other methods for preparing floors) have only recently become industrial practice. Furthermore, Industry 4.0 or IoT scenarios very much favor the diffusion of AMR technology in manufacturing practice. It is expected that forklifts, a standard tool in logistics, will increasingly be operated autonomously as autonomous forklifts.[174] All major forklift manufacturers are currently experimenting with autonomous navigation as well as environmental and pallet recognition or have already launched interesting products.[175]

Kuka offers mobile manipulator platforms equipped with various robotic arms depending on the task at hand. KMR Quantec is a combination of the omniMove platform with Mecanum wheels for omnidirectional maneuvers and the KR Quantec arm for heavy-

[174] Banker, S.: The Intelligent Forklift in the Age of the Industrial Internet of Things, Forbes, March 16, 2015; http://www.forbes.com/sites/stevebanker/2015/03/16/the-intelligent-forklift-in-the-age-of-the-industrial-internet-of-things/#21f526f57635.

[175] Myers, A.: How ‘every day’ AGV forklifts and fork trucks may bring warehouse automation to every company, Lantech Blog, February 9, 2017; https://www.lantech.com/blog/agv-forklifts-and-fork-trucks-and-warehouse-automation?region=2.

duty tasks. KMR iiwa is an autonomous mobile platform with a lightweight LBR iiwa arm for intricate assembly work.

Further developments include the MiR family of multi-purpose mobile platforms from Mobile Industrial Robots and Otto from Clearpath Robotics. Both are freely configurable, modular platforms, preferably for general indoor logistics. The two systems strongly depend on the open-source platform Robot Operating System (ROS) and promise easy configuration and integration into a range of varying environments.

Figure 2.54: A fleet of MiR robots ensures a fully automated palletizing process at Kinrise Snackfoods. Image credit: MiR.

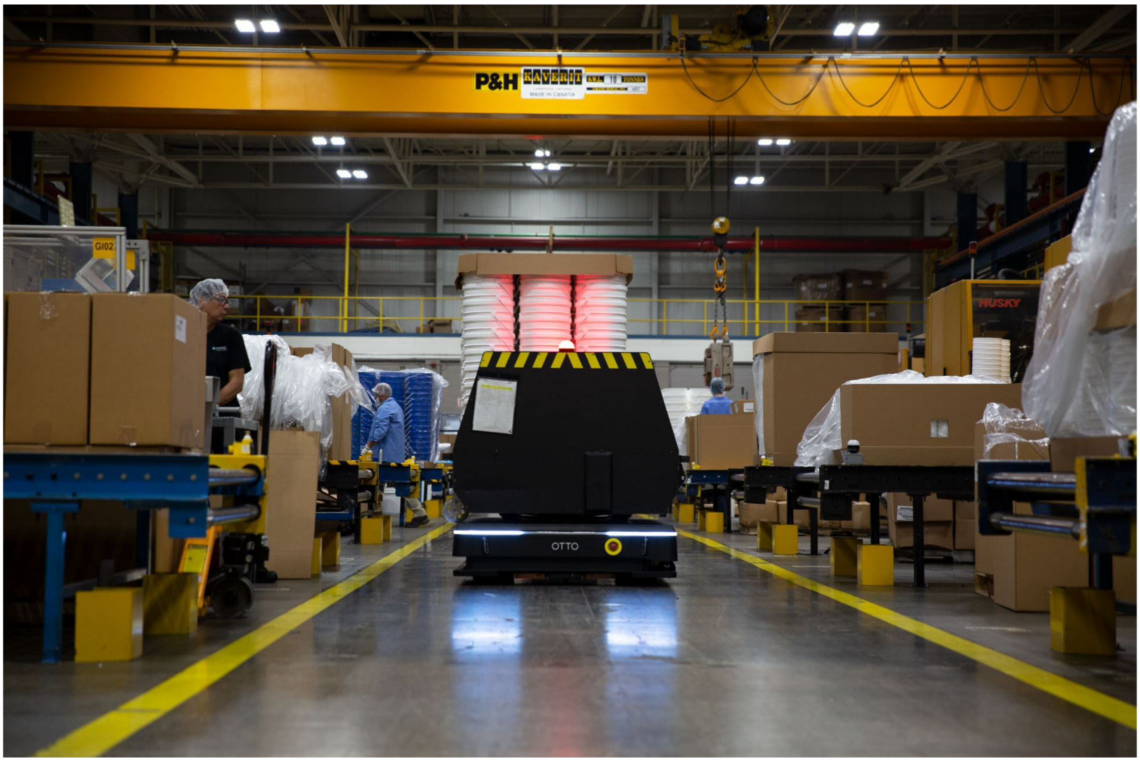

Figure 2.55: The Otto 1500 AMR delivers payloads of up to 1900 kg for Mauser Packaging. Image credit: Otto Motors.

Omron offers LD-60/90, LD-250, and since 2020 also LD-1500 with a maximum payload of 90 kg, 250 kg, and 1,500 kg respectively. According to the company's website, they are designed to drastically increase productivity in manufacturing and logistics operations. All of the platforms offer state-of-the-art navigation and safety features.

Bluebotics offer different variations of its AMR platform mini, driven by the separately available ANT navigation technology. ANT is a commercially available solution that enables autonomous navigation for any mobile platform using natural structures in the environment as a localization reference. Therefore, no infrastructure, such as inductive wires, magnets, or reflectors for triangulation, is required.

In June 2022, after a decade of running the barcode-guided Kiva AGV in its warehouses, Amazon announced its first AMR, called Proteus, which can safely navigate autonomously amongst human workers.

Figure 2.56: One more example of an AMR: Cary transports floor rollers autonomously through factories. Image credit: Metralabs.

Truck loading and unloading

Autonomous robotic forklifts

Autonomous forklifts have advanced technologically over the past few years and are still improving and evolving. Their applications are profound in warehouse settings.

Gideon, a robotics company from Croatia, launched Trey, an AMR for truck loading and unloading, in 2022. Trey is a counterbalanced forklift built by Infinity Machine & Engineering Corp. With the help of a vision module that is facilitated by AI and 3D vision, Trey can perceive its environment. Thanks to the built-in user interface for human workers, they can start and stop Trey's operations and optimize workflows. Trey uses robust 3D mapping, object tracking, semantic understanding, and pose estimation. All of this ensures that Trey operates completely autonomously and is aware of its surroundings. Thanks to opportunity charging, Trey can work round the clock. The company claims to save 80% of the workers' time and that Trey is capable of loading and unloading around 25 pallets per hour. Further, Trey can be integrated into any warehouse management system (WMS).

Fox Robotics is another popular company in the USA that launched an autonomous trailer loading/unloading (ATL) forklift to speed up operations at loading docks. The AMR, called Foxbot can also unload up to 25 pallets per hour. It is possible for a single operator to manage up to six Foxbots at once. In addition, a single operator can unload from 20 to 100 trailers per shift with several Foxbots. Foxbot is equipped with real-time vision and LiDAR perception technologies, thereby allowing it to detect different types of pallets and avoid obstacles and humans in the vicinity. Foxbot does not require a WMS or IT integration. The company raised around USD 20 million in 2022, saving up to 60% on labor costs.[176] Walmart has decided to roll out 19 Foxbots across four high-tech distribution centers to fully automate the warehouse loading docks and bought an ownership stake in Fox Robotics.[177]

Visionnav, a popular industrial supplier of autonomous forklifts and automation solutions, has developed a variety of driverless forklifts that are suited for tasks expected of manual forklifts in a logistics and warehouse setting. These include container loading and unloading, pallet drop and retrieval, very narrow aisle operations, and pallet transportation in warehouses. In 2024, Visionnav exhibited their newest autonomous forklift VNST20 Pro at Logimat, an international trade show for intralogistics solutions and process management in Stuttgart, Germany. The VNST20 Pro designed for floor operations is capable of generating loading and unloading strategies for trucks and trailers. Equipped with 3D perception systems, which make use of 3D SLAM navigation and a 3D stereoscopic protection laser and laser scanners for obstacle avoidance, the VNST20 Pro can adapt itself to various environments. It will be available in Europe from 2025.

Another competitor in the autonomous forklift sector is Navflex, a US-based company with German roots and German development. Navflex offers robotic solutions for truck loading and unloading. They can either be integrated into a WMS or deployed as a stand-alone solution. Their AMRs come in two variants: AMR Pallet Jack and AMR Counterbalance Truck. The Counterbalance Truck can be equipped with double forks to speed up loading and unloading operations. Like every other autonomous forklift, Navflex AMRs possess all the capabilities to work without human supervision. Additionally, they can be used in low-light conditions and in dark, humid, hot, and cold docks according to the company. Navflex AMRs are also capable of running on uneven floors, imperfect trucks and trailers, and dock plates.[178] Navflex claims that its AMRs have an ROI of twelve months or less. They can either be purchased, leased, or used as RaaS (Robots-as-a-Service). Their prominent success story is that of Altmühltaler, one of the largest beverage producers in Germany. Altmühltaler's existing pallet jacks have been converted into autonomous AMRs with Navflex technology and software, without the need for any changes to the existing infrastructure.[179]

Multiway Robotics, a company based out of China, adopts a different strategy compared to other big players in the autonomous forklift market. Its truck loading and unloading forklifts are also autonomous but differ in the fact that they load and unload trucks from the sides and not the rear. Utilizing a fleet of these autonomous forklifts, a truck can be

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176 https://www.robotics247.com/article/fox_robotics_surpasses_2.5_million_pallet_pulls_with_foxbot_autonomous_trailer_loader_unloader.

177 https://corporate.walmart.com/news/2024/04/11/a-fork-in-the-road-walmart-bets-on-associates-automation.

178 https://www.logisticstechoutlook.com/navflex.

179 https://www.navflex.com/references.

loaded and unloaded from the sides relatively quickly compared to just one forklift. It uses both vehicle-mounted and external vision systems for precise positioning.

Mobile manipulators and other solutions

There is no one-fits-all solution when it comes to loading and unloading trucks. Automated robotic forklifts are suitable in some scenarios, where AMR forklifts are deployed at the warehouse. A few warehouses are dependent on one-shot loading and unloading solutions to minimize the time spent on these operations at the dock, for which the warehouses are adapted accordingly. A few custom solutions exist that are tailored to the specific requirements of customers. While all these approaches perform loading and unloading, they accomplish this task in different ways. Some approaches that are a hybrid of conveyors, AMRs, and manipulator arms are also gaining widespread attention.

To provide a very quick and hassle-free one-shot loading and unloading experience and to also take into account efficiency, safety, and costs, ATLSs were developed and have been evolving over the years. Their ability to handle different types of loads, weights, and sizes makes them ideal for a variety of applications, including truck loading and unloading. Joloda Hydraroll and Ancra Systems are prominent players in the European ATLS market, providing a wide range of loading solutions tailored to customer needs. Joloda offers manual, semi-automatic, and automatic systems, including a moving floor system, a slipchain system, and a trailerskate system, that all require some truck and dock modifications. Ancra's offerings include various conveyor systems and an adaptable AGV system. The skateloader system developed by Ancra is notable for its compatibility with non-modified trucks and automated alignment and monitoring features for efficient loading.

In 2021, Boston Dynamics first announced Stretch, a robot that has a manipulator-like arm mounted on a mobile AMR base. It makes decisions in real time and can work up to 16 hours on a single charge. Stretch is capable of handling a wide range of package types and sizes, up to 50 pounds.[180] Fitted with custom vacuum grippers at the end of the manipulator, Stretch unloads packages from trucks and trailers with a consistent throughput and drops off packages on a conveyor that transports them into the warehouse for further processing. In January 2022, Boston Dynamics announced Stretch's first customer, DHL, who pre-ordered USD 15 million worth of Stretch robots for warehouse automation.[181]

Pickle Robot developed a similar solution. Its robot also has vacuum grippers that drop off boxes on an outfeed conveyor. According to the company, the robot is equipped with advanced software-enabled hardware that incorporates generative AI, machine vision, foundation models, and advanced robotic manipulation. More recently, Pickle Robot has

[180] https://bostondynamics.com/products/stretch.

[181] https://mobilerobotguide.com/2022/03/28/boston-dynamics-stretch-ready-to-automate-trailer-unloading/.

started providing its robots as Robots-as-a-Service (RaaS) and has successfully partnered with Yusen Logistics, who now leverage robots from Pickle Robot as an RaaS model in its cargo unloading operations from ocean containers.[182]

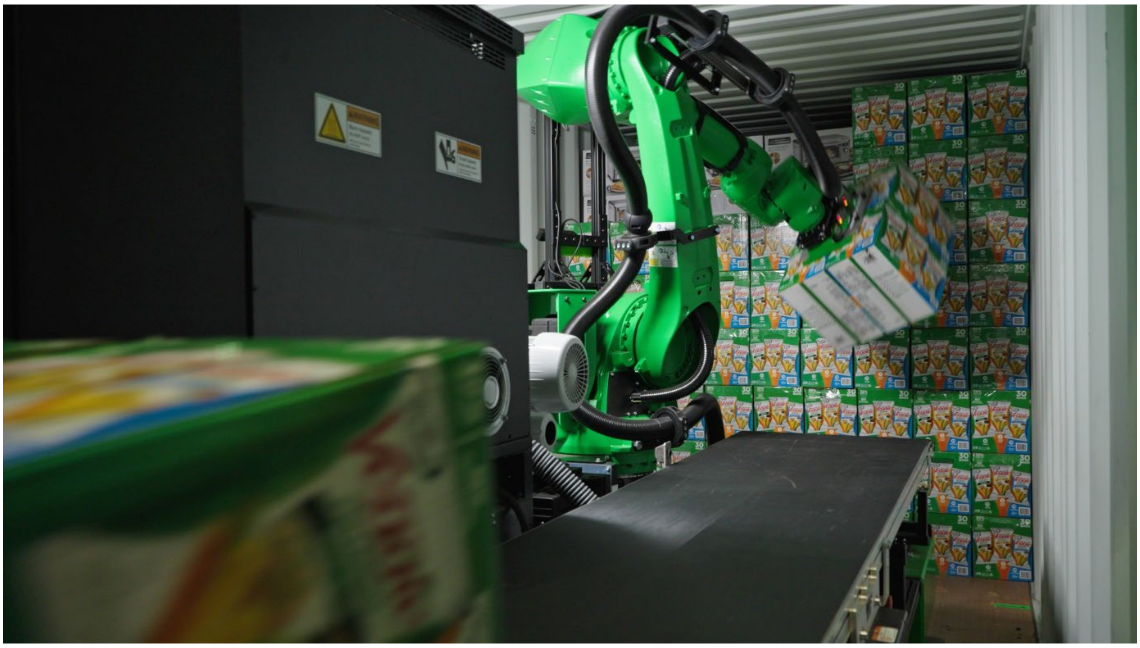

Figure 2.57: A robot from Pickle Robot unloading four food boxes. Image credit: Pickle Robot.

Dexterity, whose experience lies in singulation and induction, palletization and depalletization, has now developed a robot named Dexr for truck loading and unloading. Dexr has an AMR platform with a dual arm manipulator design mounted on it.[183] This design helps to give Dexr a human parity and enables it to perform its operations faster. In 2023, Dexterity announced its partnership with Fedex to utilize its AI-powered robotic technology in truck loading.[184]

A different but effective container loading and unloading approach makes use of roaming or articulated conveyors. Bastian Solutions has come up with a one-of-its-kind truck loading system, called Ultra Blue.[185] The mobile autonomous robot was designed to load a high volume of boxes with uniform dimensions. It consists of a retractable mast, custom end of arm tool, and articulating conveyors, all combined in a single autonomous platform. On reaching a dock and after navigating inside a truck autonomously, Ultra Blue starts the loading process. Packages arrive by means of an extendable conveyor

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182 https://www.therobotreport.com/yusen-logistics-pickle-robot-collaborate-streamline-container-unloading/.

183 https://www.dexterity.ai/product/robotic-truck-loading.

184 https://www.dexterity.ai/blog/dexterity-ai-and-fedex-unveilfirst-of-its-kind-robotics-trailer-loading-technology.

185 https://www.bastiansolutions.com/solutions/technology/industrial-robotics/robotic-truck-loading/.

onto its retractable mast and finally to the custom end of arm tool, which places the packages one by one, bottom to top.

Mujin's Truckbot[186], a roaming conveyor-type system that was specifically designed for unloading boxes and cartons from trucks, is a stationary robot placed at loading docks. With the help of movable and retractable conveyors, in addition to the suction grippers at its end capable of opportunistic multi-picking, it reaches into trucks and unloads boxes with a high throughput. Truckbot attaches to standard telescoping conveyors available at existing loading docks. The controller also developed by Mujin is the heart and brain of Truckbot and helps it to make decisions autonomously in real time. It is responsible for calculating real-time optimal routes and movements, using data from the 3D vision system, and performing other major functionalities. Truckbot was unveiled at Promat 2023.

Honeywell's robotic unloader, known as the Honeywell Intelligrated Unloader[187], combines a robotic arm that has an end of arm tool with suction cups, conveyors, and an autonomous vehicle in a single system. The robotic arm moves to the boxes to be unloaded after which the suction cups gently extract a row of boxes from a stack and place it on the integrated outfeed conveyor, below the arm. The unloader also has a kicker roller at the edge of the conveyor, which assists in direct extraction of boxes at the bottom of a stack. Equipped with vision-guided robotic technology, AI, and machine learning-based decision-making, the Honeywell Intelligrated Unloader is fully autonomous, and truck modifications are not necessary.

A different approach adopted by Slip Robotics is having a robot carry pallets into and out of trucks while also traveling to the destination inside the truck. Slipbots, as Slip Robotics calls them, are capable of carrying up to eight pallets of load into and out of trucks autonomously, thus eliminating the need for forklift loading and unloading inside the trucks. Their design allows around three Slipbots to fit inside a typical truck/trailer. For the onward journey, the Slipbots travel with the load in the truck to the destination, where they drive out of the truck to the loading dock for unloading. Another set of loaded Slipbots then enter the truck for departure to another destination.[188] Slipbots do not need special integration or installation and can be used as RaaS.

Over the years, advanced robots that look and act like humans have been developed. These humanoids, as they are called, emulate a human's skills to help perform typical operations normally done by humans. Leveraging this concept, many startups have already begun implementing humanoids to carry out manual tasks that are often repetitive, tiring, and unappealing to humans. Apptronik is one such company that has developed a general-purpose humanoid, called Apollo, that can be used for a wide range of tasks. Not surprisingly, truck unloading is a task that Apollo can carry out.[189] At the

[186] https://mujin-corp.com/truckbot-automated-truck-unloader/.

[187] https://sps.honeywell.com/us/en/support/automation/resources/brochures/robotic-unloader.

[188] https://www.therobotreport.com/slip-robotics-launches-new-trailer-pallet-unloading-solution/.

[189] https://apptronik.com/solutions/trailer-unloading.

moment, it is being used as a pilot with selected retail customers, manufacturers, and logistics providers for loading and unloading tasks.[190]

2.6.1.3. COST-BENEFIT CONSIDERATIONS AND MARKETING CHALLENGES

The main benefit of robotic solutions for factory logistics is the reduced need for manual workers, the elimination of human errors, and workplace safety. A detailed scheme on how to plan AMR systems to achieve profitability and benefits is subject to several guidelines.[191]

AMRs heavily rely on digital data for mission control and environment layouts, which can be challenging to obtain, particularly for smaller companies. While the predicted levels of AMR adoption and industrial diffusion have not yet been fully achieved, they still offer significant benefits, such as improved safety, and are key enablers for innovative developments, like automatic truck unloading systems (see chapter AP 51).

Many suppliers have started to address the cost problem by minimizing the unit costs of AMRs and offering leasing options to reduce company investments in non-value-adding processes, such as logistics, and to reduce their dependence on complex data for mission management. A systematic method and practical tool set for systems planning and cost analysis for AGV/AMR installation is available through VDI 2510 and ANSI/ITSDF B56.5-2019.[192, 193] AGV-related standards, which mostly cover functional and machinery safety, are well established with a good overview of further reading and resources given in the footnotes.[194, 195] It is worth noting that standard EN 1525 has been withdrawn and may not be used for declarations of conformity.

Currently, the world market is growing with strong double-digit rates (+35% in 2023, see IFR statistic). It can be safely conjected that this trend will continue over the next few

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[190] https://eu.statesman.com/story/business/technology/2023/08/29/apptronik-robotics-company-austin-humanoid-robot-apollo-commercialize-work-alongside-humans/70618882007/.

[191] Using autonomous robots to drive supply chain innovation, Deloitte Development, 2017; https://www2.deloitte.com/content/dam/Deloitte/us/Documents/manufacturing/us-manufacturing-autonomous-robots-supply-chain-innovation.pdf.

[192] VDI-Fachbereich Technische Logistik VDI; https://www.vdi.de/richtlinien/details/vdi-2510-fahrerlose-transportsysteme-fts (partly in German).

[193] ANSI/ITSDF B56.1 - 2020, Safety Standard for Driverless, Automatic Guided Industrial Vehicles and Automated Functions of Manned Industrial Vehicles EFFECTIVE, March 3, 2022; http://www.itsdf.org/cue/b56-standards.html.

[194] Moretz, L.: Mobile Robot Standard R15.08-1-2020 — What You Need to Know, Association for Advancing Automation Online, February 15, 2021; https://www.automate.org/industry-insights/mobile-robot-standard-r15-08-1-2020-what-you-need-to-know.

[195] Markis, A. et al.: Safety of Mobile Robot Systems in Industrial Applications, Proceedings of the ARW & OAGM Workshop, 2019; https://workshops.aapr.at/wp-content/uploads/2019/05/ARW-OAGM19_04.pdf.

years, as important preconditions for investment in AMRs are being increasingly met, such as:[196]

- Digitalization of the factory floor. AMRs depend on digital data for routing and missions. Concepts of digitalizing and networking environments, as addressed by initiatives in this direction ("Internet of Things/Services", Industrial Internet, "Industry 4.0", etc.), favor the acceptance of AMRs in target environments. AMRs can be seen as typical cyber-physical systems (CPSs).
- Performance and flexibility of the actual AMRs. With fully autonomous navigation, changes to the infrastructure, such as the installation of markers or beacons, are no longer required.
- Increased uptimes through smaller recharging cycles, as energy storage technologies improve (batteries, super capacitors, etc.).
- Rapid and intuitive changeover and configuration, easy maintenance.
- Increased positive reputation of AMR applications (mean time between failure (MTBF) rates and dependability), ease of use, etc.

Literature on the potentials of AMRs, both technologically and from an application point of view, is widely available and stated in the footnotes.[197]

[196] 2016 MHI Annual Industry Report – Accelerating change: How innovation is driving digital, always-on supply chains; http://cpbucket.fiu.edu/1168-geb6368x81168_emba-97075%2F2016-industry-report-2016-(1).pdf.

[197] Andreasson, H. et al.: Autonomous transport vehicles: Where we are and what is missing, IEEE Robotics & Automation Magazine, March 2015, pp. 64-75; https://ieeexplore.ieee.org/abstract/document/7059356.

Figure 2.58: Mobot Flatrunner MW Light with gravity conveyor for the automotive industry. Image credit: Wobit.

The return on investment (ROI) in service robots for logistics in manufacturing processes depends highly on the actual use case. If 24/7 operation and ubiquitous use with a high focus on transportation compared to handling processes can be assumed, an ROI may typically be achieved within two to three years according to experience. Given a lifetime of fifteen years, operating costs, including software licenses, maintenance, and wearing parts, may account for 20% of the investment each year.

Truck loading and unloading

One of the biggest motivations for using automated/robotic loading and unloading solutions is increased efficiency, since they operate round the clock and tirelessly as opposed to humans. This is a general driver for the use of professional service robots: Their sales for the transportation of goods or cargo grew by 44% year-on-year (2021-2022), as stated in the IFR statistics in 2023.

Robotic forklifts can load/unload up to 25 pallets per hour and within 45 minutes to one hour for an entire truck as claimed by many companies.[198] ATLS-based solutions achieve

[198] Several companies claim these numbers, see, e.g. https://www.gideon.ai/solutions/trey or http://foxrobotics.com.

loading and unloading within just a few minutes with the only requirement being that the load must be prepared by hand for loading. Some other hybrid conveyor-robotic systems are capable of loading/unloading more than 100 packages per hour. Productivity is increased as the need for taking breaks by human operators is largely eliminated. Labor costs are also reduced, since fewer manual operations are required. Regarding safety, which is often an attribute that is neglected, the Bureau of Labor Statistics reported around 64,930[199] non-fatal injuries at workplaces resulting in days off work, as well as around 79,360[200] overexertion injuries due to lifting/lowering at work (data from 2016 to 2020). With the introduction of automated/robotic loading and unloading in warehouses and loading docks, accidents and injuries are largely minimized. Human workers no longer have to put themselves at risk when lifting sharp and heavy pallets of goods or other cargo. As far as the precision of the tasks is concerned, these automated/robotic systems are highly accurate and sometimes even better than humans. They are also sensitive to the loads and handle them with care, often surpassing humans in this regard, too. This ensures consistent quality material handling. The systems also adapt to changing scenarios and avoid collisions.

The robotic forklift and ATLS markets have seen a sharp rise in use and distribution and are expected to increase significantly in the coming years. By using robotic loading and unloading solutions, companies can benefit from their numerous offerings. The development of these solutions is happening at a fast pace. Marketwide Research has conducted an extensive market analysis of automated truck loading systems and robotic forklifts and shared its insights and forecasts for the years 2024-2032.[201, 202] According to the research, the key market trends of truck loading and unloading are:

- AI and machine learning integration: Making an automated system/robot intelligent and aware of its surroundings takes its capabilities to the next level.
- Sensor technology improvement: The continuous development of sensors, like LiDAR, and cameras improves general perception and navigation abilities of AMRs.
- Warehouse management system integration: Integration of automated systems with a WMS allows for real-time exchange and proper management.
- Human-robot collaboration: The focus on the development of collaborative robotics leads to increased productivity and safety in the long run.
- Eco-friendliness: Manufacturers are focusing on developing energy-efficient loading/unloading solutions to reduce the environmental impact and achieve sustainability goals.

199 https://www.bls.gov/iif/snapshots/osn-laborers-and-freight-stock-and-material-movers-hand-2016-20.htm.

200 https://www.bls.gov/iif/nonfatal-injuries-and-illnesses-tables/case-and-demographic-characteristics-table-r31-2020.htm.

201 https://markwideresearch.com/automated-forklift-trucks-market/.

202 https://markwideresearch.com/global-automated-truck-loading-system-market/.

Even with the benefits provided by ATLSs and robotic loading and unloading, it is obvious that these systems come with their own set of challenges. One of the major challenges and marketing restraints is the high initial investment. Robotic forklift solutions require the purchase of the forklifts, which are not cheap. They can cost anything in the range of USD 45,000 to USD 200,000, as a rough estimate.[203] It depends on various factors like payload capacity, lifting height, batteries, charging system, safety system, and so on. Other hybrid solutions may also require the purchase of additional manipulator arms or conveyor systems to make them work as a holistic unit. ATLS-based solutions require additional infrastructure modifications and can demand changes to the truck, which can again be costly. Integration of these systems into existing warehouses can lead to more costs and can be a time-consuming challenge. Regular maintenance of these systems is crucial to ensure smooth and uninterrupted operation. Another challenge is the requirement of skilled labor. To operate and troubleshoot these systems, skilled personnel and operators are necessary. Companies implementing these systems may face a shortage of such personnel and expertise.

A whitepaper by Yale Lift Truck Technologies[204] highlights that labor generally accounts for 40-60% of a company's warehousing budget. Severe labor shortages and high turnover force companies to increase wages and provide other benefits to retain workers. This is an endless cycle where workers are hired and retrained, amounting to high operating costs. To counteract this, improving satisfaction amongst workers and retaining employees you already have instead of hiring new ones help reduce operating costs. Academic research[205] shows that organizations augmented by automation technologies are 33% more likely to be 'human-friendly' workplaces, in which employees are 31% more productive. This makes sense as robots can take up most of the monotonous and repetitive work, thus allowing humans to focus on more rewarding and challenging tasks. In this context, the introduction of robotic forklifts in a loading/unloading setting within a warehouse can help workers greatly by doing the time and energy-consuming repetitive tasks in a shorter amount of time, thereby enabling workers to focus on fruitful and valuable work.

The whitepaper further highlights that the introduction of robotic forklifts in warehouses helps cut operating expenses by up to 70%. While this number is suggestive, it highly depends on several variables like the number of manual trucks replaced, the number of robotic units introduced, operating hours, and burdened labor rate. Often, the initial high cost of investment is the reason why companies hesitate to implement or adopt automated/robotic loading and unloading systems. However, as touched upon previously, what is important is that shorter loading and unloading times allow for significant cost savings in a long-term strategy, thereby achieving lower total costs

203 https://www.agvnetwork.com/autonomous-forklift-costs.

204 https://og.mhi.org/media/members/14259/133294184720615242.pdf.

205 https://www.prnewswire.com/news-releases/automation-is-making-work-more-human-global-research-reveals-300714154.html.

compared to manual loading/unloading. According to a whitepaper by Ancra Systems[206], the return-on-investment times for an ATLS solution depend on two main factors: volume and driving time. The profit obtained from an ATLS increases with the volume shipped for short distances with high frequency. Secondly, the profitability increases with a decrease in driving time. This is because the impact of loading times on the total costs is high with short driving times.

In 2023, the IFR gave insights into a particular market with respect to truck loading. It claimed that Japan would face a labor shortage in 2024 due to new overtime regulations for truck drivers, which is termed the “2024 problem”.[207] With potential disruptions taking place, the IFR says that the introduction of mobile robots can help truck drivers by cutting the time it takes them to load and unload cargo in a daily shift by up to 25%.

[206] https://www.ancra.nl/upload/docs/whitepaper-atls-technology-information-ancra-systems.pdf.
[207] https://ifr.org/ifr-press-releases/news/robots-help-to-solve-japans-2024-problem.

2.6.1.4. EXPERT VIEW

Two interviews with the companies Pickle Robot Co. and Mujin-Corp, both from the USA, are presented below. The interviews were conducted in 2024 as part of the major focus chapter revision by Fraunhofer IPA.

2.6.1.4.1. INTERVIEW WITH PICKLE ROBOT CO.

Company:	Pickle Robot Co., USA
No. of employees:	11-50
Products:	Truck unloading robots (Pickle Robot)
Interview partner:	Peter Blair (VP Product, Marketing & Sales)

Why did you choose to develop truck unloading robots?

The founders of Pickle Robot, who come from different generations of MIT with expertise in artificial intelligence, robotics, and software, chose to develop truck unloading robots because they wanted to apply their backgrounds to a real need. Initially, the company started with creating a sorting robot for small package sortation in e-commerce, but the long-term intention was to identify where in the warehouse robotic technology could add value and be easily implemented. They found that the dock area was a pain point for many customers, as the task of unloading trucks was both physically demanding and unpleasant. The dock doors have a limited number of configurations, making it a fairly standard and repeatable process. This made it an ideal place to apply AI, robotics, and the experience of the team. The hypothesis that customers would actually want a robot to handle the unloading process also played a significant role in their decision to focus on this area. Overall, the founders saw the truck unloading process as a prime opportunity to leverage their expertise and address a common pain point in the logistics industry.

What was the most impactful decision for your product development?

The most impactful decision for the product development of the truck unloading robots was two-fold. Firstly, Pickle Robot recognized that the software side was the “secret sauce” and crucial to the success of the product. We focused on developing robust software that encompassed vision systems, interpretation, path planning, and other essential aspects, including AI built on trained foundation models. Secondly, we made the strategic decision to not create our own hardware components if we didn’t have to. Instead, we opted to utilize existing reliable and readily available industrial components such as Kuka robot arms and a heavy-duty belt conveyor. We designed and fabricated certain components ourselves, but overall, we integrated industrial components into our own hardware platform. This approach allowed us to develop the hardware and software in parallel, enabling seamless integration and optimization. There is a lot of interconnectivity between hardware and software, and developing both simultaneously is really essential. By leveraging existing industrial components while building our own platform and software, we were able to create a powerful and cohesive solution.

What are the biggest hurdles in terms of bringing your robots to the market?

The biggest hurdles in bringing the truck unloading robots to the market are the novelty of the product category and the apprehension of potential customers to be early adopters. Overcoming this hurdle requires gaining traction and proving the effectiveness of the robots through successful implementations and testimonials from early customers. Another challenge is the varying complexity of unloading tasks, with some containers containing uniform items that are easier to handle, while others have a mix of small and complex items that require more advanced capabilities. Managing customer expectations and ensuring the eligibility and volume of tasks align with the ROI are also significant considerations.

Looking into the future, what are the biggest challenges ahead for your customers?

The biggest challenge ahead for customers in the truck unloading industry is the shortage of labor and the aging workforce. The next generation does not seem interested in these types of jobs, leading to a limited pool of available workers. Additionally, geographical hot spots such as Cincinnati in the United States face intense competition for labor due to the concentration of distribution facilities in those areas. As a result, wages are increasing, making automation more appealing. Pickle Robot also plans to expand to Europe and is working toward CE certification to support that entry.

How are you planning to further develop your products to tackle these challenges?

Our plan is to further develop products by focusing on both hardware and software improvements. We aim to enhance performance, such as increasing speed and expanding the eligibility of items the robots can handle, including polybags and different types of containers. We have already made significant progress in reducing unloading times and see further potential for performance improvements. Additionally, we are exploring additional applications, such as truck loading and palletization, based on customer needs and feedback. Our approach is to excel in our core functionality before branching out into new areas.

2.6.1.4.2. INTERVIEW WITH MUJIN-CORP

Company:	Mujin-Corp, USA
No. of employees:	51-200
Products:	Truck unloading robots (Truckbot)
Interview partner:	Josh Cloer (Director of Sales)

Why did you choose to develop truck unloading robots?

The decision to develop truck unloading robots was driven by Mujin's core purpose of creating a better situation for humanity. Manual truck unloading is a challenging and physically demanding job with high turnover rates. Mujin wanted to empower humans to engage in more creative and fulfilling work by automating this labor-intensive task. Additionally, our company already had the capability with our own Mujin Controller platform, which had been used for various robotic systems in the past. We recognized that truck unloading automation was a difficult problem to solve and saw it as a significant opportunity in the warehouse automation market. We have been working on truck unloading robots since 2016 and have continued to grow in this area.

What was the most impactful decision for your product development?

The most impactful decision for the product development of Mujin's truck unloading robots was to move away from the initial 6-axis robot design and develop a new solution called Truckbot. The decision came after realizing that the previous design was too slow and did not meet customer expectations. Leveraging the Mujin Controller platform, the team looked at the problem from a different perspective and focused on developing the right hardware for the challenge. We took inspiration from manual unloading processes and built Truckbot, a unique conveyor-like 5-axis robot with an end-of-arm tool. This specific hardware design, different from standard 6-axis robots, was chosen to optimize speed and efficiency based on the economic requirements of the application. Truckbot is the first fully hardware product that Mujin has designed and built for truck unloading.

What are the biggest hurdles in terms of bringing your robots to the market?

The biggest hurdle in bringing our truck unloading robot to the market is finding the right partners to implement our systems without taking on excessive complexity or risk. While we have identified and targeted a specific market segment, there is potential for expansion into other areas with varying load complexity. The challenge lies in solving the different levels of complexity that may exist, such as handling diverse items like tires, rolls of carpet, or large bags for airports. Mujin's Truckbot can handle such tasks by changing the tool at the end, but it requires available resources and market demand to focus on these specific problems. The complexity of loads will be a significant hurdle for both robot manufacturers and user adoption of truck unloading systems.

Looking into the future, what are the biggest challenges ahead for your customers?

The biggest challenge ahead for customers is in the adoption of our truck unloading systems. There are two main areas. Firstly, there is the technical challenge of identifying the correct market to target and understanding the specific load complexities within that market. This requires developing solutions that can handle a wide range of load types efficiently. Secondly, there is a commercial challenge related to the low wages typically associated with manual truck unloading. The business case for automation needs to consider the additional costs incurred by relying on low-paid temporary labor, such as damages and equipment validation issues. Developing a compelling business case and finding the right fit within customer organizations will be crucial for successful adoption of truck unloading automation.

How are you planning to further develop your products to tackle these challenges?

Mujin's plan for further developing products to tackle challenges like load complexity involves leveraging the versatility of the TruckBot platform. The focus will be on adapting the tooling on the robot's end to cater to different work pieces and applications. While specific details of the roadmap cannot be shared, we will incorporate improvements based on the insights gained from pilot programs and real-world deployments.

2.6.1.5. PRODUCERS

4am Robotics, 6 River Systems, Addverb Technologies, Agilox, Agora Robotics, AGV International, AGVE, Aiut, Alog, Alstef Group, Alta Material Handling, Amazon Robotics, Amerden Agvs, American In Motion, Anscer, Anyware Robotics, Asseco Ceit , Astro, Atlas Robotics, Avenof, Balyo, Bama Sistemas, Bär Automation, BEC, Big Joe , Bila, BionicHIVE, BlueBotics, Bluepath Robotics, Boston Dynamics, Brightpick, Caja, Cassioli, Casun, Coalescent Mobile Robotics, Comau, Co-Robotics, CoTek, CSG, CtrlWorks, Cyberworks Robotics, Dane Technologies, Dematic, Dexterity, DF Automation & Robotics, Doog, DS Automotion, Eceon, Effidence, Eiratech Robotics, Ek Robotics, Elettric80, Emayor Synersight Technologies, Esatroll, EV Soosung, Exotec, Fabric, Floatic, Follow Inspiration, ForwardX Robotics, Fox Robotics, GAM Soluciones, Gebhardt, Geek+, Ger4tech, Gessmann, Gideon Brothers, Gieicom, Global Tech Co, Grenzebach, GreyOrange, Gridbots Technologies, Ground, Guangdong Jaten Robot & Automation, Guozi, Hai Robotics, Hangcha Forklift, Hikrobot, HIT Robot Group, Honeywell International, Hyster-Yale, Hyundai-wia, IBG Automation, Idealworks, Infocom, Innok Robotics, Inovasyon Mühendislik, Invata, inVia Robotics, Invio Automation, Iplusmobot, IQ Robotics, iRob, Jaso Industrial, JBT, JD, JNOV Tech, Joloda, Jungheinrich, Kelo Robotics, Kion, Kivnon, Knapp, LexxPluss, LG Electronics, Libiao, Locus Robotics, Lodamaster , Lödige Industries, Lowpad, Mabi Robotics, Mabo Engineering&Automation, Machinery Technology Development, Mad Automation, Marorobottech, Max AGV, Meanwhile, Megvii, MetraLabs, MG Tech, MHS, Milvus Robotics, MIR Mobile Industrial Robots, Mircolomay, Modoya, Morello , MoviĜo, Movu Robotics, Movvo, Mrobot, MSI International, MT Robot, Mujin Corp., Mul Technology, Multiway Robotics, Muratec, Mushiny, MyBull, Nakanishi Metal Works, Navflex, Neobotix, Neumaier Industry, Neura Robotics, New Kinpo Group, Nipper production logistics, Novus Hitech, Oceaneering, Ocme, Okagv, Omron, Onward Robotics, Oppent, Otsaw Digital, Patika Robotics, PBA, Peer Robotics, Peppermint Robotics, Piaggio fast forward, Pneumax (Automationware), Potenit, Prime Robotics, Qenvi, Qingdao Kingerobot, Quasi Robotics, Quest , Quicktron, Rainbow Robot, Rapyuta Robotics, Rexroth, Rightbot, RoboCV, Robotize, Rockwell Automation, Rocla, Russell Robotics, Safelog, Scott, Seasony, Seegrid, Seer Robotics, Servus Robotics, Sesto, SEW Eurodrive, Shanghai Triowin Intelligent Machinery, ShenZhen Wellwit Robotics, Sherpa Mobile Robotics, Shintec Hozumi, Siasun Robot & Automation, Slip Robotics, Smart Robotics, Smart Technology SA (Smarlogy), Soft Design RTS, Solving Oy, SSI Schäfer, Stäubli, Steering Machines, Storojet, Studio 3S, Suzhou i-Cow, Syrius, Syscon Robotics, System Logistics, Tarqan, Techmetics Robotics, Tecnoferrari, Thira Robotics, Tompkins Robotics, Tractonomy, Trapo, Twinny, Ubiquity Robotics, UBT Robot, Vecna Robotics, Versa Box, Visionnav Robotics, Volume Lagersysteme, Wewo Techmotion, Wobit, Yeefung , Youibot, Yujin Robot, Zebra Technologies, Zhejiang Libiao Robot

2.6.2 AP52: INDOOR ENVIRONMENTS WITH PUBLIC TRAFFIC

Autonomous robots have made significant progress in recent years and are now able to navigate autonomously through highly dynamic environments with their obstacles. This has opened up new possibilities for AMRs, which were previously limited to operating only in areas isolated from public traffic. The advancements now allow their operation in environments with public traffic, i.e. in environments where AMRs act near non-instructed people without a physical boundary, such as in hospitals, restaurants, offices, or airports. Most applications offer automated delivery services through the transport of food, beverages, care utensils, mail, or medication.

For AMRs to function effectively in public buildings, it is essential to have a digital network environment that enables seamless communication with the infrastructure (such as automated doors and elevators) and other robots (since they typically operate in fleets). This network also facilitates real-time monitoring of the robots' location and status, making it easier to manage and assign tasks to them efficiently. By having a robust digital infrastructure in place, buildings can harness the full potential of AMRs to improve productivity and efficiency. With a broader distribution of technical systems, a few initiatives are currently underway to standardize these digital interfaces in public buildings. One notable example is the Digital Service Standards (DSS)[208] initiative in Singapore, which seeks to establish guidelines and requirements for user-centric digital services across the country's public sector.

Finally, yet importantly, robot deployment must be aligned with local regulations regarding robot safety, certification, and data security.

2.6.2.1. TYPES OF OPERATIONS CARRIED OUT BY THE ROBOT

Transportation in hospitals and care facilities

Hospitals and care facilities often involve repetitive service tasks, such as circulating mail and transporting laundry, food, or waste. While these activities are relatively simple, they can be time consuming and physically demanding for employees who have to move around the premises with trolleys. Although newer buildings have partly automated the delivery of goods using pneumatic tubes or AGVs in separated sectors, there is still a pressing need for automated solutions in post-installation, particularly in older buildings.

The already predominantly barrier-free environments in hospitals and care facilities favor the use of logistics robots outside the supply areas as well. This allows goods to be brought closer to their actual destination in the rooms of patients and residents, thereby also supporting the "last mile" of the flow of goods. For this, it is necessary that the robots can also operate safely where non-residents are present. In addition to localization with

[208] Digital Service Standards (DSS); https://www.developer.tech.gov.sg/guidelines/standards-and-best-practices/digital-service-standards.

natural landmarks, functions for automatic obstacle detection and avoidance are crucial in this context.

In recent years, manufacturers that previously focused on logistics applications without public traffic have entered this new market with more sophisticated solutions to tackle these new challenges. Today, a rapidly growing market of transport robots offers a range of operations, including:

- Automatic pick-up/loading of objects using the detection of transport goods (containers, beds, etc.); where necessary, with human assistance – "call from unit terminal"
- Transport of objects; where necessary, with elevator and automatic door integration (scheduled or ad-hoc)
- Optimization and adaption of transport routes (restricted areas, fleet management)
- Unloading of objects in the destination area (objects segregated)

Various hospitals have implemented innovative solutions, where robots are utilized for efficient point-to-point delivery. Typical transport tasks include meal distribution, linen, waste, and laboratory samples. While some solutions automate the loading and unloading of the transport goods by picking up mobile units, other solutions still require staff to carry out loading and unloading.

Most commonly, transport between different stations located throughout a facility is enabled by autonomous navigation using laser scanners and ultrasound sensors, sometimes supported by strategically located landmarks (often placed in the ceiling).

Today, transport is limited to areas without physical barriers, since the opening of non-automated doors is not yet established due to technical (complexity), economical (need of a manipulator), and safety (use of a manipulator) reasons. Moreover, the transport tasks are limited to corridors across multiple levels of the same building complex, as current products are designed for indoor use only.

The installation of AMRs in elderly care facilities is still rare, since their buildings are typically smaller, i.e. without underground logistic transport possibilities and narrow corridors. This makes deployment technically more challenging and less efficient. However, field trials have already been conducted successfully.[209]

Delivery and courier robots for restaurants, hotels, and other public spaces

Generally, with the rise of technology, the use of mobile transport robots in public spaces is gaining popularity due to their ability to improve efficiency and reduce operational

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[209] Graf, B.; King, R. S.; Schiller, C.: Development of an intelligent care cart and new supplies concepts for care homes and hospitals. In: 47th International Symposium on Robotics: Robotics in the Era of Digitalization. June 21-22, 2016, Munich, Germany. Berlin; Offenbach, 2016, pp. 446-451.

costs. Additionally, these robots can provide a safer and more reliable mode of transportation in crowded areas.

One current application field for mobile service robots is food and beverage delivery in restaurants. These robots are designed to transport meals and drinks from the kitchen to tables on demand. In addition, they can transport used tableware and cutlery back to the kitchen for cleaning after customers have finished their meals. By utilizing mobile service robots, the restaurant can improve the efficiency of its operations and relieve the physical burden on staff by eliminating the need to carry heavy orders.

Mobile robots are equipped with sensors and navigation systems that enable them to move around the restaurant without colliding with obstacles or customers. They can also communicate with the restaurant's computer systems to receive information about the orders they need to deliver. By providing an interface to restaurant staff, e.g. on a smartphone or tablet, the robot can be called to a certain position on the premises when needed. Mobile robots can carry multiple orders at once, making the delivery process faster and more efficient. Especially returning the used tableware after the customers have left can be done in one go, without the need to go back and forth to the table multiple times. While the robot is returning the tableware, the human worker can directly clean the table and prepare it for the next customers.

The delivery of goods and services in hotels is another common use case in which robots operate very similar to restaurant delivery robots. These robots are designed to navigate their way around the hotel, delivering items such as food, drinks, amenities, or luggage to guests.[210,211] One of the key advantages of mobile robots is their ability to operate 24/7, providing a consistent and reliable service to guests. Additionally, mobile robots can reduce the workload on hotel staff, allowing them to focus on more complex tasks that require human intervention.

Another common application of mobile transport robots is in airports, where they are used to transport luggage between check-in counters, baggage claim areas, and planes. These robots can navigate through crowded airports and operate 24/7, providing a reliable and efficient service to passengers.

In addition to these fields, mobile transport robots are being explored in various other fields, including shopping malls, where they facilitate the transfer of goods between stores and storage areas. However, these systems are still in the development stage and are expected to take some time before they can be widely implemented.

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[210] Hertzfeld, E.: Singapore Hotel Jen properties install Relay autonomous robots, Hotel Management, November 21, 2017; https://www.hotelmanagement.net/tech/hotel-jen-installs-relay-autonomous-robots.

[211] Tokumatsu, G.: At Your Service! Hotel Robot Becomes Essential Amid Coronavirus Pandemic, NBC Los Angeles, June 23, 2020;

https://www.nbclosangeles.com/news/local/at-your-service-hotel-robot-becomes-essential-amid-coronavirus-pandemic/2384865/.

2.6.2.2. LEVEL OF DISTRIBUTION

Transportation in hospitals and care facilities

The pioneering robot used in hospitals was Helpmate, first developed by TRC at the beginning of the 1990s and then promoted by Cardinal Health. It was reported that more than 100 units, including interfacing with doors and elevators, had been installed (now discontinued). Helpmate transported meals to patients, drugs to other departments, etc. Its main benefit was to free skilled staff from doing unskilled courier tasks.[212] The system was way ahead of its time and successfully paved the way for several courier systems in hospitals and indoor environments.[213] Another early example, announced in 2004 by Panasonic, was Hospi, a 24/7 delivery robot for medicine, specimens, and medical records.[214] From the same supplier, the robotic blood sample courier system controls a fleet of autonomous mobile robots working together in a coordinated fashion. The system automatically controls a series of blood sample deliveries and courier tasks, including pick-up, transfer to the automatic analyzer, and collection of products by having a group control computer assign appropriate tasks to each individual robot.

Currently, the market offers three types of robots for healthcare applications aiming to transport typical hospital goods, such as dietary trays, medications, linen, blood samples, medical records, or pharmacy drugs:

1. AMRs with an integrated cabinet as a storage unit, partially with a modular design
2. AMRs without a storage unit that can automatically drop off and pick up a transport unit
3. AMRs with a manipulator and a small storage unit

The first category is the most popular one. Users benefit from the flexibility in the cabinet design that offers an individual solution for selected transport tasks. These AMRs are affordable, since they employ differential instead of omnidirectional kinematics. However, this does not compromise their effectiveness in carrying out simple A to B transport tasks.

Aethon from the USA and Oppent from Italy represent two popular examples of companies that previously concentrated on logistics without public traffic but due to the technical progress now offer transport robots also for last mile deliveries. Aethon has a large portfolio of Tug robots for various logistics tasks. Their models Tug Door and Tug Drawer share an identical base but use different cabinets to offer an optimal solution for transporting goods along the last mile. It is claimed that in total TUGs move materials

[212] Engelberger, J. F.: HelpMate, a service robot with experience, Industrial Robot: An International Journal, vol. 25, no. 2, 1998, pp. 101-104.

[213] Pinto, A. C. P.: Advanced Mobile Manipulation for Logistics in Hospitals or Laboratories, M. Eng. Thesis, University of Porto, July 24, 2016.
https://repositorio-aberto.up.pt/bitstream/10216/84607/2/138902.pdf.

[214] Ackermann, E.: Panasonic Revives Hospital Delivery Robot, IEEE Spectrum, May 15, 2014, http://spectrum.ieee.org/automaton/robotics/medical-robots/panasonic-hospital-delivery-robot.

and supplies over 370 miles every week. Similarly, Oppent from Italy offers Evocart, a fleet of AMRs that have been deployed in the past only in logistics applications without public traffic. One of the main features of the Evocarts is their flexibility and adaptability, since they can be customized to suit the specific needs of a healthcare facility, with various configurations available for carrying different types of equipment and supplies. Today, the Evocabinet model is deployed in multiple hospitals across Europe to transport various items, such as medical equipment, supplies, and medical records.

Figure 2.59: Aethon Tug in operation at the Hospital of Southern Jutland, Denmark. Image credit: Danish Technological Institute (DTI).

A different approach is followed by Pal Robotics with its adaptation of Tiago, a humanoid service robot with manipulators for the healthcare sector. The company uses only the mobile robot base with a re-designed construction on top to transport medical equipment, supplies, and medication. A comprehensive fleet of transport robots is offered by the Chinese company Noah Hospital Logistics Robot with 17 different AMRs for 21 scenarios featuring a modular design. It cooperates with Huawei for 5G.[215] Noah's products are widely used in Asia and have been deployed in over 100 hospitals. The Chinese company Saite Intelligence offers a fleet of robots with an integrated design. Its delivery robots, called Smart Sala, come in various sizes and storage designs for the optimal transport of goods in hospitals. Another example is Sally from DS Automotion. By means of mechatronic interfaces, Sally can be equipped with different superstructures, e.g. with

[215] Wang, F.; Ma, Y.: Noah Hospital Logistics Robot Received over Ten Million CNY in Series B+ Round, Equalocean, June 22, 2022; https://equalocean.com/news/2022062218322.

a small cabinet or a roller conveyor for picking up small loads, and thus flexibly adapted to varying transport tasks.

Figure 2.60: Delivery robot for hospitals or care facilities. Image credit: DS Automotion.

The transport robots Relay and Jeeves from Robotise take similar approaches and were both developed specifically for transporting smaller items. Originally intended as “mobile minibars” for hotels, they are now also being used in the healthcare sector. For instance, the Relay robot marketed by Swisslog in the EU is currently deployed in multiple hospitals in the Netherlands, executing ad-hoc deliveries of medicine and laboratory samples. Similarly, the size and shape of the Jeeves drawers can be individually adapted to the application, for example to transport laboratory samples, medicines, or work materials in the clinic. These robots supply both nursing staff and, in some cases, patients.

Figure 2.61: The delivery robot Jeeves is capable of delivering goods to nursing staff or patients. Image credit: Robotise AG.

With Gogo, Yunji Technology offers a particularly small and compact example of a multifunctional delivery robot. Due to its narrow design, it can pass through narrow spaces measuring just 0.55 meters in width. Further, it can be deployed as a butler for various use cases, such as in hospitals, restaurants, and other food service businesses. It is also worth mentioning that many delivery robots for restaurants described in the following section are potentially suitable for designated transport tasks in hospitals, too.

In contrast to the previous examples, where a fleet of robots with the company's own robot hardware is offered, there is now a trend in SMEs to use established robot bases of other manufacturers. The bases MiR100 and MiR250 from Mobile Industrial Robots are a prime example of this. Not only this manufacturer has deployed the robot successfully in hospitals[216]; other companies, such as Medimobil and Roeq, are also using the base with customized shelf storage in the same environments. A second example is the LD60/LD90 base from Omron. Like before, the manufacturer provides modular OEM solutions, while other companies are using it to develop their own transport solutions for hospitals. For instance, the French company Meanwhile offers the XuP-Med and XuP-Lift models that combine a cabinet with the Omron base. These AMRs have been deployed successfully in multiple hospitals throughout France to transport small care utensils, e.g. blood samples and medicine. Similarly, Techmetics Robotics offers a fleet of robots based on the Omron base with various storage designs and cabinets.

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216 https://www.mm-logistik.vogel.de/ejner-versorgt-daenische-patienten-a-500471/.

Figure 2.62: At Cholet Hospital, an XuP-Med robot transports medicines to the wards, among other things. Image credit: Meanwhile.

The second category comprises robots without a storage unit that enables automatic drop-off and pick-up of a transport. Their advantage is that they can handle multiple carts with a single robot. Aethon and Ceterio offer robots with an integrated lifting mechanism in a range of sizes, thus enabling the transport of various carts, roller cages, or pallets; this is required if existing transport solutions are to be automated. Oppent offers a towing robot, called "Evotug", that guarantees similar flexibility in the selection of transported carts. The docking process requires sufficient navigation space in front of the transport unit to align the robot before docking. This must be carried out precisely. In contrast, some robots use omnidirectional kinematics, are less affordable, but offer a higher degree of freedom while adjusting the robot. Although they are not yet popular for last mile deliveries, their concept is highly relevant to align with current processes in hospitals and care facilities.

The third category includes robots with a manipulator that enables them to pick up, transport, and drop off arbitrary objects without any human help. However, their manipulation requires the successful detection and grasping of the objects of interest, which represents a challenge for the software, hardware, and safety. Moreover, the manipulator increases the costs. Therefore, due to their technical complexity and high costs, they are not that popular yet but nevertheless offer high potential beyond transport tasks.

One example is, for instance, Moxi from Diligent Robotics, a mobile service robot equipped with sensors, a manipulator, and a graphical interface. It can assist care staff in finding and fetching various small items. This kind of assistance can be especially useful in situations or areas with a high risk of infection, like during the COVID-19 pandemic or similar crises, to lower the infection risk, as the robot itself cannot become infected.[217] The robot uses machine learning for object recognition, grasping, and learning tasks in real time. Another example is Lio from F&P Personal Robotics, which comes with similar features. The professional personal robot features sensors for navigation and perception, as well as a mobile platform and a robotic arm, both fitted with a soft cover. The robot can assist with several tasks, like fetch and carry, guidance, patient interaction, and entertainment. Lio is being deployed in nursing homes and rehabilitation centers.

Figure 2.63: Lio is a service robot for various purposes in close contact with patients. Image credit: F&P Robotics.

Both examples are targeting multifunctional service robots with a focus on human-robot interaction (HRI), thus having a limited storage area. In contrast, Hope Technik offers a last mile delivery robot that combines a large shelf-like storage unit with a manipulator on top for the automatic unloading and loading of shelf trays. The robots use a “safety bubble” while delivering medical and daily items that do not require human-to-human contact.

The growing demand motivates existing companies and startups to develop transport robots for healthcare facilities. For instance, Yuman Robots from Denmark won the euRobotics Entrepreneurship Award at the European Robotics Forum 2022 with its concept of a transport assistant for caregivers. Similarly, the Solteq spin-off Ceterio has started developing transport robots for hospitals. Its Karter robots are modular lifting robots available in various sizes, thus allowing for the transportation of various carts, roller cages, or pallets; this is required if existing transport solutions are to be automated.

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217 Johnson, K.: Hospital Robots Are Helping Combat a Wave of Nurse Burnout, Wired, April 19, 2022; https://www.wired.com/story/moxi-hospital-robot-nurse-burnout-health-care.

Exciting ongoing research is exploring novel applications and technologies for the healthcare sector that could revolutionize the way medical facilities operate. For instance, Fraunhofer IPA presented the prototype of a flexible transport robot that can lift various carts, roller cages, and containers, tackling the challenge of handling existing solutions. The robot chassis can adjust in width and length before lifting and bringing the items in front of the patients' or residents' rooms in which they are needed. Another prototype, named “Intelligent Care Cart”, was built in a collaborative project and transports care utensils across multiple levels in hospitals and elderly care facilities. A unique feature is its integration with a documentation system that tracks the stock of care utensils using an object recognition system on top of the robot. This AMR was tested in several care institutions, showing promising benefits regarding process optimization.

Figure 2.64: Thanks to its base that is adjustable in both width and length, the flexible transport robot can pick up various care carts and containers and transport them autonomously (left). The Intelligent Care Cart uses an object recognition system to monitor the stock of care utensils (right). Image credit: Fraunhofer IPA.

Delivery robots for restaurants

Delivery robots are increasingly becoming a common sight in restaurants, as they offer a convenient and efficient way of delivering food to customers and retrieving used tableware. These robots are designed to navigate through tight restaurant spaces and to move to tables or designated pick-up areas. To do so, they are always equipped with a mobile base, utilizing different means of localization in the environment. At present, mostly laser or visual SLAM technologies are used to allow the robot to determine its position in the environment and to find its way to the customer. All of these systems have a shelf-like structure on the mobile base, with a varying number of trays. Thanks to their ability to ease the workload on humans and to further increase efficiency, delivery robots are set to revolutionize the way we experience dining out. They are also an excellent way for restaurants to reduce costs associated with hiring and training servers while at the same time improving customer service.

The Dinerbot series from Keenon Robotics is one of the most widely used systems. With five different versions of the robot available as of March 2023, restaurants can install the one that fits their needs best. These robots are designed to serve as waiters in restaurants, providing customers with a unique and efficient dining experience. The robots are equipped with three to four trays that can carry up to 40 kg, allowing them to serve multiple tables at once. The latest version of the Dinerbot, the T8, can only carry up to 20 kg but has a sleeker design that is more aesthetically pleasing to customers.

Figure 2.65: Restaurant/hotel delivery robot T9 with a payload of 40 kg or 10kg per layer from Keenon. Image credit: Keenon.

Pudu Technology Inc. is another company that specializes in developing service robots for the hospitality industry, focusing predominantly on restaurant robots. Their robots include the Pudubot, PuduBot2, Bellabot, Kettybot, and Swiftbot. The Bellabot robot differs from the traditional navigation technologies by additionally offering the possibility to place visual markers on the ceiling, which it can recognize with a ceiling-pointed camera. These markers help the robot to track its movement through the environment, ensuring stable localization even during very crowded times. The robots are equipped with three to four trays that can carry up to 30-40 kg, and all tray setups are customizable to fit the specific needs of the restaurant. Bellabot is designed to look like a cat to catch the 'customers' attention. Kettybot offers a display for advertisements, making it a valuable marketing tool for restaurants. Pudubot2 is water and dust-proof, making it suitable for outdoor use or in areas where spills and dust are common. Lastly, Swiftbot offers a more dexterous omnidirectional base with a projector to indicate where the robot is set to move, making it easier for customers to anticipate the robot's movements and avoid collisions.

Bear Robotics Inc., a US-based company, has also developed a range of service robots for restaurants - Servi, Servi Mini, and Servi+. They have a carrying capacity of 20-40 kg, making them suitable for carrying food and drinks. Servi and Servi Mini feature trays and a closable container, while Servi+ carries four containers instead of open trays, rendering it ideal for larger orders. The closed setup of these systems is aimed at more private transportation, in which the specific order of a customer is not as clearly visible as with a fully open setup. Servi and Servi Mini have round trays, while Servi+ has a rectangular loading space. In March 2024, LG announced a strategic investment of USD 60 million in the company.[218]

Beijing Orionstar Technology Co. Ltd has developed two service robots for restaurants - Lucki and Lucki Pro. With a carrying capacity of 40-60 kg, they are capable of carrying three to four trays. The robots have a modular design that enables tray orders to be changed. Additionally, microphones with a 5-meter range are installed for user interaction. Lucki Pro utilizes computer vision-based recognition of the food that is placed on the tray. The use of AI technology in these robots is an exciting development, and it will be interesting to see how this technology continues to evolve in the future.

The Plato server robot, developed by Aldebaran Robotics, a member of the United Robotics Group in France, is one of the latest products on the restaurant delivery market. The robot has a touchscreen display that allows customers to interact with the robot and place orders. The company adheres to all relevant European Union regulations and standards, ensuring that the robot is safe for use in a public environment. The Plato robot is compliant with the General Data Protection Regulation (GDPR) of the European Union, which mandates strict data protection and privacy regulations. This is especially important if these robots utilize vision sensors (e.g. color or depth cameras), as these images are protected under the GDPR. Ensuring that these critical data are not accessible from outside the robot is an important task to protect the data of everyone in the restaurant.

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218 https://www.bearrobotics.ai/blog/bear-robotics-secures-60m-series-c-funding-led-by-lg-electronics.

Figure 2.66: Plato helps staff to carry food and drinks to customers. Image credit: United Robotics Group GmbH.

The Cloi Servebot prototype from LG provides another solution for restaurant delivery. The robot has three trays with a carrying capacity of up to 30 kg and uses visual 3D obstacle detection and avoidance technology to navigate the environment.

The Amy Robot Waitress from the Pangolin Robot Corp. is another robot designed to serve customers in restaurants. The robot has a special design, making it appear more human-like than other service robots. It has one single tray for carrying food and drinks and a touchscreen integrated in its chest for customers to place their order.

Courier and luggage robots for hotels and airports

The Relay robots mentioned before in the context of hospital transport solutions have already commenced operation at numerous international hotels. They interface with elevators, doors, and communication systems in the building. The robots are about 92 cm tall, 51 cm wide, weigh 40.8 kg, and travel at 2.5 km/h. The robots deliver snacks and amenities to hotel guests, enabling hotel staff to focus on the other guests' needs. The users can interact with the robots by using the attached touchscreen, their smartphones, or voice.

The Jeeves hotel delivery robot, developed by Robotise, followed a similar development path. Originally designed for hotels and the hospitality industry, it is now also used in healthcare applications. Jeeves from Robotise has five closable shelves that can be adapted to the needs of the hotel, making it possible to deliver food, drinks, or other items to the guests' rooms. With cooling features and a maximum carrying capacity of 45 kg, Jeeves can cater to multiple guests at once. Additionally, the robot is equipped with a touchscreen on top for user interaction, allowing customers to place orders via a smartphone or app. Once the order has been placed, the robot navigates the hotel corridors using Lidar sensors and 3D sensors for collision avoidance. It can even use elevators to reach different floors. Upon arrival at the designated room, Jeeves sends a notification to the customer, who can then retrieve their ordered goods.

The Hyundai Motor Group presented its latest prototype of a hotel delivery robot at the CES 2022 conference. The robot has a futuristic design, resembling an egg-shaped figure, which makes it stand out from other delivery robots. The main goal of this robot is to relieve hotel workers during busy evening hours by delivering ordered food to the guests' rooms. The robot is equipped with four single-actuated wheels, which allow it to turn on the spot and move sideways, making it highly maneuverable in smaller spaces. Orders can be placed via an app, and the robot can use elevators as well. To recognize its environment, the robot utilizes visual sensors and deep learning, ensuring safe and efficient delivery services.

The Yobot, an automated luggage storage and retrieval system, is a central feature in the lobby of the Yotel hotel in New York. The theatrically illuminated arm of the concierge Yobot, which is housed behind a secure glass enclosure, picks up luggage that has been dropped off in the lobby and stores it in one of the 117 lockers for a small fee. The Yobot is based on a conventional industrial robot, specifically the ABB IRB 6640 articulated arm, which serves as an automated luggage storage and retrieval system. Guests can retrieve their bags by presenting their bar-coded receipt to the Yobot when they are ready to leave.

2.6.2.3. COST-BENEFIT CONSIDERATIONS AND MARKETING CHALLENGES

AMRs for transport tasks in public environments are of benefit to the operators of the individual institutions and therefore also to the provider's customers:

- Increased reliability and elimination of human errors
- Increased operational productivity
- Logistics network expansion and enhancement
- For the customer: Increased service availability and flexibility, reduced transport costs and time

Due to their novelty, some customers, such as hotels, might want to integrate the robots' services into their operations to demonstrate their receptivity toward innovation. In addition, the rising personnel costs in some sectors like healthcare imply that there is a need to automate certain transport tasks. Domain studies have indicated that nurses and other healthcare workers might spend as much as 20% of their workday performing transport tasks that could easily be automated. Not only the costs of labor, but also the low availability of workers in some sectors drive the need for automation to relieve the burden on the workforce. Helpmate, for example, makes schemes for cost calculations and cost models for courier robots available. With a simple tool, the profitability of the courier service can be determined by comparing the hourly rate.[219]

Transport robots in public buildings might require a significant infrastructure, such as door openers or radio-controlled escalators, to access different floors. The robots also need devices that enable them to communicate with automated doors and elevators to allow coverage of the entire building. These investments will pay off much faster if the robot is used 24/7. Particularly for repetitive and long missions, courier robots will certainly be a reliable and eventually a cost-effective investment. Aethon claims returns on investment (ROI) in the range of 20% to 50% for their hospital logistics robot system Tug. The company indicates that for a 300-bed facility, an estimated USD 4 million are spent annually on people pushing carts. Each day, more than 600 hours of staff time is dedicated to this task. One Tug working just two shifts seven days a week is claimed to save the labor costs of 2.8 full-time equivalent (FTE) employees, yet it costs less than one single FTE. A study on internal hospital supply chains emphasizes the importance of effective logistics practice and presents performance measurement techniques.[220]

A further benefit of using transport robots in hospital environments is the security of drug deliveries. The problem in this regard is the way medications are handled. Inventory management may be inefficient, drugs are misplaced too often, and narcotic medications are prone to theft. As reported by the Wall Street Journal, Aethon's Tug mobile robots have been introduced at the University of Maryland Medical Center to overcome these problems. Besides increased delivery reliability and predictability, "the per-trip cost using a robot is USD 2.40 on average, down from USD 5.50 for manual delivery, and in its first year the system freed up 6,123 hours that nurses previously spent tracking or retrieving medications."[221]

In the EFFIROB study[222], an economic profitability was concluded for the scenario "container transport in hospitals by autonomously guided service robots" if the number of containers to be transported per day is above 600. It should also be noted that the use of service robots has some additional benefits, such as documentation, hygiene, and workload reduction, that significantly contribute to an improved quality of the actual "service" provided by a hospital. Such additional benefits might, therefore, have a positive impact on a potential user's investment decision, particularly in cases where economic profitability is marginal. Against this background, a high market acceptance of

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[219] Andreasson, H. et al.: Autonomous transport vehicles: Where we are and what is missing, IEEE Robotics & Automation Magazine, March 2015, pp. 64-75; https://ieeexplore.ieee.org/abstract/document/7059356.

[220] Moons, K.; Waeyenbergh; G.; Pintelon, L.: Measuring the logistics performance of internal hospital supply chains – a literature study. Omega, January 21, 2018; http://iranarze.ir/wp-content/uploads/2018/02/E5866-IranArze.pdf.

[221] Landro, L.: Hospitals Address a Drug Problem: Software and Robots Help Secure and Monitor Medications, The Wall Street Journal, February 23, 2014;
https://www.wsj.com/articles/hospitals-address-a-drug-problem-1392762765.

[222] https://www.ipa.fraunhofer.de/en/reference_projects/EFFIROB.html (German content in the study).

the service robot solutions can be expected in medium-sized hospitals. It is assumed that the calculated market potential will be fully exploited in the long term and that conventional transportation systems (fixed installations) will be fully supplanted.

Restaurants that use mobile robots for serving food and drinks can additionally improve customer service. Especially the convenience of having their orders delivered quickly and accurately without having to wait for a server is something customers enjoy. One major issue currently challenging the restaurant sector is the unavailability of human workers. According to a recent report by the Washington Post[223], an all-time high of roughly 1.9 million jobs are currently on offer in the USA alone, representing the global trend in the hospitality sector. To still provide high-quality service to customers, restaurant owners are starting to look more and more into automation, for which service robots provide good flexibility and the possibility to operate in public spaces.

The DHL Logistics Trends Radar identifies the major innovation opportunities and challenges and concludes: “Today, we are seeing more and more applications for indoor mobile robots in logistics. Especially in markets with higher labor costs, indoor mobile robots are being used extensively in order fulfillment. […] As soon as indoor mobile robots can be deployed at scale, they have enormous potential to reduce cost and increase efficiency within operations. […] More steps are being taken toward full warehouse orchestration so, in the not-so-distant future, indoor mobile robot solutions together with stationary robotics will start to automate and support a large part of warehouse work.”[224]

In general, the service model of transport robots for operators in public spaces is crucial due to the many challenges they face. Many operators lack technical expertise and are often skeptical toward service robots. Therefore, Robots-as-a-Service (RaaS) is often a promising service model. RaaS includes on-site installation, as well as a repair and bug-fixing service to ensure 24/7 operation. This also includes remote inspection of the systems, enabling technical staff to simply log into the robot at any time. While stand-alone business models are also considered, they are currently not as attractive as RaaS. By implementing RaaS, operators can tackle technical challenges and ensure efficient operation of service robots in public spaces.

[223] Bhatarrai, A.; Penman, M.: Restaurants can’t find workers because they’ve found better jobs. The Washington Post, February 3, 2023; https://www.washingtonpost.com/business/2023/02/03/worker-shortage-restaurants-hotels-economy/.

[224] Logistics Trend Radar: Delivering insight today. Creating value tomorrow! Version 2022, DHL Customer Solutions & Innovation, 2022;
https://www.dhl.com/global-en/home/insights-and-innovation/insights/logistics-trend-radar.html.

2.6.2.4. EXPERT VIEW

The following interviews by Meanwhile from France, Swisslog from Switzerland, Keenon Robotics from China, and United Robotics Group from Germany were conducted in 2023 as part of the major focus chapter revision by Fraunhofer IPA.

Transportation in hospitals and care facilities

2.6.2.4.1. *INTERVIEW WITH MEANWHILE*

Company:	Meanwhile SAS, Villeurbanne, France
No. of employees:	11-50
Products:	Autonomous, mobile robots (XuP, Evy)
Interview partner:	Charlotte Herbillon (Marketing & Communication Manager)

Why did you choose to develop hospital logistics robots?

The choice to develop hospital logistics robots is linked to Meanwhile's raison d'être. Sacha Stojanovic, CEO of Meanwhile, is passionate about robotics and new technologies and was inspired by problems experienced by his wife, who is a nurse. He decided to draw on his 20 years of experience in robotics to design transport robots, helping staff to focus on their core tasks.

What was the most impactful decision for your product development?

One of Meanwhile's priorities was to create robots that are quickly and easily accepted by nursing staff in order to avoid any misunderstandings concerning their use: "It is not there to replace nursing staff, but to help them in their daily tasks." Meanwhile's robots are therefore designed in their entirety (design, human-machine interface, etc.) to ensure users feel safe and confident when they are close to the robot. Ergonomics and design play a major role in the ease of use, with, for example, a badge reader, a simple and intuitive screen interface, strategically placed emergency stop buttons, etc.

What are the biggest hurdles in terms of bringing your robots to the market?

An obstacle encountered in bringing our robots to the market is related to our technologies, as they were initially designed for industrial use. Working with hospital staff allows us to adapt our solutions to a non-expert public and to work on the ease of use, ergonomics, acceptability, etc. Another obstacle is the long and tedious purchasing process due to the fact that public markets in France must carry out calls for tender. However, to facilitate the purchase of our robots by public health establishments, our products are referenced in purchasing groups.

Looking into the future, what are the biggest challenges ahead for your customers?

In general, the biggest challenges for our customers are recruiting and retaining care staff, improving the quality of life at work by reducing musculoskeletal disorders and psychosocial risks, and boosting productivity by delivering the right service at the right time to the right place. In terms of mobile robotics, our customers will face new challenges, including how to make AMRs and AGVs cohabit.

How are you planning to further develop your products to tackle these challenges?

Robots are the tip of the iceberg. Meanwhile offers a complete solution based on a powerful software foundation. To meet the new challenges of our customers, we are working hard on improving this software, thereby making it more user friendly, and creating plug-and-play solutions. For example, for the XuP-Med, the security cabinet is fully configurable. To meet new needs, we plan to develop different secure access features at cabinet level.

Delivery robots for health care facilities

2.6.2.4.2. INTERVIEW WITH SWISSLOG HEALTHCARE

Company:	Swisslog Healthcare AG, Buchs, Switzerland
No. of employees:	501-1000
Products:	Hospital automation (e.g. transport robot Relay)
Interview partners:	Matthias Geier (Product Manager)

Why did you choose to develop hospital logistics robots?

Our company has a long history of providing hospital logistics services using robots to transport textiles or food. The key motivation behind our use of robots is the need to reduce labor costs and improve efficiency in the transportation of items within hospitals. However, we have recently re-evaluated our strategy and shifted our focus to the transportation of medication. In this new direction, we recognize the importance of finding a partner who can provide a hybrid solution that combines logistics with social capabilities. This is important since we believe in attributes that caregivers and patients like to interact with robots instead of being afraid of them. We started a collaboration with Relay Robotics, which offers robots that can operate in crowded front office environments, where navigation plays a major role due to patients, caregivers, and visitors being around.

What was the most impactful decision for your product development?

The most impactful decision was to go with a mobile robot partner that offers the potential of such a hybrid robot. Therefore, besides focusing on key logistics specifications, like volume, kilograms, payload, etc., we also placed the spotlight on social attributes, as this is very important in front office environments.

What are the biggest hurdles in terms of bringing your robots to the market?

One of the biggest hurdles we faced was deploying mobile robots that are capable of operating in various crowded environments. These robots require sophisticated sensors, good navigation software, and regular maintenance. Unfortunately, most hospitals do not have technicians capable of maintaining mobile robots. To address this problem, we developed a service business model to take care of everything for a hospital's technical department. However, not all hospitals were willing to accept this model, as some preferred to purchase the robot outright and handle maintenance themselves. Another challenge we underestimated was our own organizational readiness. Our sales, installation, and service teams needed to be trained to work with mobile robotics, which required significant time and resources. Additionally, hospitals were often hesitant to invest in large volumes of robots right away, preferring to start with smaller numbers and scale up gradually. This made it difficult to motivate our teams to work with the robots and to maintain a steady pace of growth. Building up our internal processes and teams to work with the robots was one of the biggest challenges we faced.

Looking into the future, what are the biggest challenges ahead for your customers?

One of the biggest challenges for our customers is the initial infrastructure integration project. It requires significant collaboration between our team and the customer's IT and technical departments. We must ensure that we always have mobile connectivity, interfaces into the building, and access to the user database, as well as elevator and door control systems. This can be a lot of work for hospitals, which is why we are constantly working to make it easier for them. As we develop new products, we aim to simplify the integration process by creating standard APIs that allow us to connect with building management systems more readily. This will reduce the need for individual wiring and make the process more efficient for our customers and us. While we believe that handling the service ourselves is the right approach, we acknowledge that the realization phase can still be challenging, particularly when it comes to integration. We are committed to continuing to improve and make this process as easy and as streamlined as possible for our customers.

How are you planning to further develop your products to tackle these challenges?

We are constantly exploring innovative solutions in collaboration with our partners to overcome the hurdles of building integration. For instance, we developed a prototype robot with a small arm. It basically looks like R2-D2 from the Star Wars movies and can push buttons, thus eliminating the need for elevator integration. Experimentation is one way to overcome these hurdles, but it is even more crucial to connect and collaborate with door and elevator companies to align with and agree on standards. We firmly believe that establishing common standards, such as BACNet, is the only way forward for the seamless integration of robots into buildings. Rather than wiring each elevator individually, we aim to establish software interfaces with elevator companies. To achieve this, we need to engage in conversations and partnerships with other mobile robot providers, elevator companies, and building infrastructure providers. This collaborative approach is a crucial aspect of product development.

Delivery robots for restaurants

2.6.2.4.3. INTERVIEW WITH KEENON ROBOTICS

Company:	Keenon Robotics Co. Ltd., Pudong, China
No. of employees:	101-250
Products:	Commercial service robots (e.g. Dinerbot, Guiderbot, Butlerbot)
Interview partners:	Alexander Gehb (D/A/CH Country Manager)

Why did you choose to develop delivery robots for restaurants?

Our mission is to help the service sector through the ongoing transformation of the labor market, to become more productive, and to focus on guest satisfaction and customer experiences. It is time to think work processes differently. By letting robots act as a productivity enhancer, we put the focus back on the sovereignty of humans, thus freeing up time to apply their creativity as well as their problem-solving skills and empathic abilities.

What was the most impactful decision for your product development?

Our vision is to automate operational processes and facilitate daily tasks for the global service workforce, moving toward a more guest and customer-focused environment. We want to offer a real solution that is different yet perfectly complements currently existing work processes by being implanted into them.

What are the biggest hurdles in terms of bringing your robots to the market?

The type of hurdle depends on the perspective you look at the current situation from: End users, e.g. restaurants, hotels or healthcare facilities, are still facing a lack of knowledge about what is currently available, how to integrate these robots into their work processes, and what future developments will offer. They also worry about the return of investment and acceptance. In contrast, distributors and resellers see a massive emerging market and along with it rising customer interest. There is, however, not enough end customer demand at the moment, since many of them are still working on establishing their own company strategy and are reluctant to invest and commit to larger numbers.

Looking into the future, what are the biggest challenges ahead for your customers?

To foster their own technology readiness, end customers as well as our distributors need to be adequately informed and trained for the abilities of the robots. They further need to be supported in planning investments by explaining the costs with the benefits and how to integrate the robots into existing processes to gain a good return and to alleviate staffing challenges. Last but not least, a suitable strategy for communication must be developed toward their colleagues and guests to ensure acceptance.

How are you planning to further develop your products to tackle these challenges?

It is important for us to stay closely connected with the end customers to understand their worries and challenges. Our distributors and local country management teams work together on this issue. We are also trying to anticipate future needs by listening to the market and enhancing the current functions of the robots. For example, as a next step, we are planning to integrate voice interaction between human operators and the robots, develop interfaces to communicate with other machinery, e.g. vending machines, and incorporate a “balancing mechanism” to allow for more stable deliveries.

Delivery robots for restaurants

2.6.2.4.4. INTERVIEW WITH UNITED ROBOTICS GROUP

Company: United Robotics Group, Bochum, Germany
No. of employees: 11-50
Products: Bundling hardware and software expertise for service robots (e.g. Plato, uMobile Lab, etc.)
Interview partners: Thomas Linkenheil (COO and CFO)

Why did you choose to develop delivery robots for restaurants?

As the world emerges from the COVID-19 crisis, expectations for experiences in the service industry are at an all-time high. Coupled with job shortages, particularly workers in the food sector are on the front line of offering these experiences of service and care. With Plato and, more generally, Cobiotx, the United Robotics Group is changing the way humans interact with robots and supports service industry workers with better working conditions and putting the emphasis on the value brought to the hospitality experience.

What was the most impactful decision for your product development?

Cobiotx robotic solutions mark the beginning of a new era and a turning point for the robotics market by putting humans at the center of the relationship between humans and robots, providing an accountable response to various challenges in multiple industries through versatile and adaptable solutions. In the first generation of robots, conventional large industrial robots were programmed to work independently of humans. With the second generation, small and lightweight cobots, collaboration with humans was possible. But with Cobiotx, we are completely revolutionizing the way humans interact with robots, allowing people to focus on high-value human interactions while ensuring a safe environment.

What are the biggest hurdles in terms of bringing your robots to the market?

The first issue was related to the ability of humans to interact easily and in real-time with the robot: This is essential to expand the footprint of automation tasks that are difficult to predict and anticipate. The main technical challenge of Plato's design was its architecture. It took two years of work by teams composed of 180 people to develop Plato. The project started in March 2020. After nine months of design work, the teams unveiled an initial prototype. Experiments were then conducted in restaurants not far from the premises in Paris to validate its functions. The feedback was very positive, showing an adoption of Plato by the waiters in just a few minutes. Initially announced in the summer of 2022, Plato's launch was delayed due to the component crisis, which led to adaptations being made and security being strengthened.

Looking into the future, what are the biggest challenges ahead for your customers?

Labor shortage: In 2030, talent shortages will result in EUR 8.5 trillion in unrealized annual revenues, plus 85.2 million job vacancies will be left unfilled. In the hospitality sector, stressful and unpleasant working conditions result in staff health issues, resignations, and employee turnover costs. In France, reported accidents at work in the service sector, i.e. sprains due to slipping and falling, musculoskeletal disorders due to repetitive movements, standing in the same place for long periods of time, or lifting heavy objects, account for almost two million missed working days per year and EUR 600 million in annual costs. Operational challenges include finding and retaining qualified staff, increasing business profitability and service efficiency, controlling operational costs, facing fierce direct and indirect competition, dealing with demanding customers, plus many more.

How are you planning to further develop your products to tackle these challenges?

Three patents have been filed. Plato, which runs on AWS's Greengrass software, is the first robot to benefit from a dedicated security architecture. The chosen sector – hospitality and catering – also represented a challenge for the teams. It is this sector that offers the most complexities, as the environment – chairs and tables for example – is extremely varied. Plato has three 3D sensors and Lidar to avoid obstacles and started with minimum requirements. Due to labor shortages, there is a need in the market, which we wanted to satisfy by introducing a robotic solution to the hospitality sector. We also have a roadmap of new features and accessories, which will be launched over the coming years and will allow partners, such as integrators, to participate with value added services.

2.6.2.5. PRODUCERS

Aeolus Robotics, Aethon, Aitheon, Alphadroid, Amyrobotics, Asimov, Bear Robotics, Beijing Yunji Technology, Canbot, Cartken, CloudMinds Technology, Coga Robotics, Continental, CtrlWorks, Cyberdyne, DF Automation & Robotics, Diligent Robots, Dynsoft, E-Novia, Fubao Intelligent Technology, Geek+, Guangdong Jaten Robot & Automation, HD Hyundai Robotics, HIT Robot Group, IdMind, Inbot Technology, Infocom, Invento Robotics, JD, Jungheinrich, Marses, Meanwhile, Milvus Robotics, Movvo, Mrobot, MT Robot, Muratec, Neura Robotics, Orionstar, Pal Robotics, Panasonic, pi4 Robotics, Pixel Robotics, Pudu Technology, Qenvi, Rainbow Robotics, Relay Robotics, Rice Robotics, Robotis, Robotise, Segway Robotics, Shanghai Keenon Intelligent Technology, Shenzhen Anseboo Technology, Shenzhen Guoli Intelligent Technology Co. LTD, Slamtec, Social Robotics, Soft Design RTS, Standard Robots, Suzhou Alpha Robot, Swift Robotics, Techmetics Robotics, Temi, Twinny, UBT Robot, Ugo, United Robotics Group, United Robots, Unlimited Robotics, Yuman Robots, ZMP

2.6.3 AP53: OUTDOOR ENVIRONMENTS WITHOUT PUBLIC TRAFFIC

While most AMRs operate in indoor environments, there is a growing number of use cases in outdoor environments. Many applications resemble their counterparts in indoor manufacturing environments but introduce more challenges for the sensors, robot localization, and robot control due to uneven static ground like levels or stairs, traversable obstacles like cable bridges, fewer landmarks, and a higher number of disturbances like sunlight, rain, or changing surface irregularities, e.g., gravel and potholes.

2.6.3.1. TYPES OF OPERATIONS CARRIED OUT BY THE ROBOT

Transport robots that can navigate in outdoor environments without public traffic have become more and more popular in intralogistics applications in recent years, thereby closing the gap to the well-evolved indoor automation. The robot types range from automated conventional vehicles, like forklifts or tugger trains, to custom solutions, which often feature a weatherproof housing for the transport goods. Some systems run Global Navigation Satellite System (GNSS) based navigation, but the need for independent solutions grows with the expectation of operating in both indoor and outdoor areas. Similar to indoor navigation, the evolution goes from external guidance like RFID or inductive guidance to solutions that do not require an external infrastructure like SLAM navigation.

Another type of operation is the transport of cargo containers to ISO standard in port environments. Basic requirements include the control of the large chassis, which is usually driven and steered by a diesel-hydraulic power set. The vehicle drives on pneumatic wheels over unprepared road surfaces at speeds of up to 6 m/s. Typically, a fleet of autonomous vehicles, particularly for standard missions, is controlled by a fleet management system for maximum throughput.

Other robotic outdoor logistics applications include the automatic control of trucks for Euro pallets, waste transportation, airport logistics, and agricultural logistics. There is also the application of robot-based truck loading and unloading. If this takes place via an opening on the side of the truck, it basically occurs in an outdoor environment. Typically, however, most applications relating to truck loading and unloading are indoor applications, which is why they are dealt with in the corresponding chapter 3.2.5.1.

2.6.3.2. LEVEL OF DISTRIBUTION

High-speed container transport between quay and stackyard is one of the pioneering applications of outdoor AMRs. In 2005, the Brisbane Autostrad terminal started introducing robotized Kalmar E-Drive straddle carriers, purpose-built for uncrewed operations.[225] A fleet of 27 free-ranging machines with 65 tons of safe working load (SWL) was fitted with motion control and navigation systems that allowed them to operate round the clock in practically all weather conditions.[226] Meanwhile, the installations have been expanded and include, among others, the Sydney Port Botany[227] and the Ports of Auckland (New Zealand) as well.[228] In 2019, Kalmar's manufacturer Cargotec started offering automated truck handling.[229]

Konecranes Gottwald Port Technologies reported the deployment of more than 84 electrically operated outdoor vehicles at the Hamburg Container Terminal Altenwerder (Germany). Navigation is based on 19,000 transponders that are installed in the ground. This greatly increases the speed and efficiency of container handling in comparison to traditional transport methods using trucks and cranes. The port has gradually replaced its diesel-electric AGVs with new ones powered by lithium-ion batteries, totaling 95 vehicles in 2023.[230] Konecranes Gottwald has expanded to ports around the world, including 72 AGVs in the Long Beach Container Terminal in Los Angeles County, with 30 additional vehicles ordered in 2020.[231] One step further is the use of automated container stacking cranes as the link between quayside and landside equipment, such as ship-to-shore cranes, transport vehicles, and trucks.

Companies specializing in logistics are seeking methods to decrease traffic and enhance safety in open spaces. As a result, autonomous vehicles might offer an excellent option by performing various on-site logistical tasks, such as moving and repositioning items for transport like pallets and interchangeable containers.

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[225] Automated straddle carrier facility wins Terminal of the Year Award, Cargotec, December 21, 2010;
https://www.cargotec.com/en/old-news/automated-straddle-carrier-facility-wins-terminal-of-the-year-award-/.

[226] Durrant-Whyte, H.; Pagac, D.; Rogers, B.; Stevens, M.; Nelmes, G.: Field and service applications - An autonomous straddle carrier for movement of shipping containers - From Research to Operational Autonomous Systems, IEEE Robotics & Automation Magazine, vol. 14, 2007, no. 3, pp. 14-23; and Hollamby, M.: The ease of automation. Automation is a key competitive advantage for Patrick's container terminal at the Port of Brisbane, Australia, Kalmar Global; https://www.kalmarglobal.com/globalassets/customer-cases/all-customer-cases/patrick-brisbane-australia/case_patrick_brisbane_autostrad_web.pdf.

[227] Saulwick, S.: Sydney's Patrick terminal goes automated, with fewer staff but dancing robots, The Sydney Morning Herald, June 18, 2015; https://www.smh.com.au/national/nsw/sydneys-patrick-terminal-goes-automated-with-fewer-staff-but-dancing-robots-20150617-ghqc24.html.

[228] Robot Port Cranes in Container Terminals Would See Stevedore Job Cuts, Handy Shipping Guide, February 23, 2016; http://www.handyshippingguide.com/shipping-news/robot-port-cranes-in-container-terminals-would-see-stevedore-job-cuts_6992.

[229] https://www.cargotec.com/en/nasdaq/trade-press-release-kalmar/2019/kalmar-adds-automated-truck-handling-to-its-autostrad-offering.

[230] Konecranes receives 6th order in 5 years for additional AGVs to CTA in Hamburg, December 22, 2021; https://www.konecranes.com/press/releases/2021/konecranes-receives-6th-order-in-5-years-for-additional-agvs-to-cta-in-hamburg/.

[231] Konecranes to provide 30 AGVs to Long Beach Container Terminal, May 19, 2020;
https://www.ship-technology.com/news/konecranes-agvs-long-beach-container-terminal/.

Figure 2.67: Autonomous mobile robots for outdoor logistics from Robotnik: RB-Vogui (left) and RB-Car (right). Image credit: Robotnik.

BASF has implemented an AMR system at its Swiss location, developed in collaboration with Stäubli WFT and Sick. The system allows for autonomous intralogistics, transporting products from the production hall to the warehouse. The vehicle is flexible in size and can be deployed at any BASF location. It is capable of safely operating both indoors and outdoors, with the help of outdoor certified LiDAR sensors that initiate an emergency stop when a person or object gets too close.[232]

Figure 2.68: The Stäubli PF10 moves up to 10 tons and automatically connects different manufacturing halls in the automotive industry. Image credit: Stäubli.

[232] Autonomous intralogistics from indoors to outdoors: SICK and Stäubli WFT provide a seamless logistics chain for BASF, SICK Sensor Intelligence, June 20, 2022; https://www.sick.com/cz/cs/sick-sensor-blog/autonomous-intralogistics-from-indoors-to-outdoors-sick-and-staeubli-wft-provide-a-seamless-logistics-chain-for-basf/w/blog-autonomous-intralogistics-indoors-outdoors/.

The French supply chain provider Idea has introduced the indoor/outdoor AMR L-S 1PT from Exail (formerly ECA Group) to accelerate logistics flows. The AMR, in operation since June 2021 at an Idea site in Nantes, aims to automate low value-added operations like transfers between production buildings and logistics buildings. The AMR operates on an open track, respects traffic rules, and guarantees safety for pedestrians and vehicles.[233]
In 2023, Exail announced the extension of their range of outdoor/indoor autonomous logistics solutions with the Alvin FT Forklift Truck. This modular forklift can handle loads up to 2.5 tons and up to six meters, with the ability to replace standard forks with customizable interfaces for increased versatility.

Ek Robotics has successfully implemented its Out Move platform at multiple production sites for production hall to warehouse transport, including the German companies JTI, Gerolsteiner, and Baxter. The system relies on RFID or inductive guidance and has a load capacity of up to 6 tons at a maximum speed of 1.2 m/s. The IP65 certified weatherproof housing for the transport goods has a customized interior finishing, for example with a cooling unit. The energy supply is achieved by contactless electromagnetic transmission or a fully automated battery changing system.

[233] IDEA and ECA GROUP present their first autonomous vehicle, IDEA group, September 30, 2021; https://www.groupe-idea.com/en/linfo-idea/idea-et-eca-group-presentent-leur-premier-vehicule-autonome.

Figure 2.69: The automated guided vehicles for combined indoor and outdoor operation from Ek Robotics continuously transport goods between production halls and warehouses and are equipped with weatherproof superstructures. Image credit: Ek Robotics GmbH.

4am Robotics offers the autonomous tugger train ATO-H for high payloads and long distances for both indoor and outdoor use. It can pull up to six trailers with a maximum total weight of eight tons at speeds of up to 10 km/h. The system is based on a Linde P60C or Still LTX-50 with an attached autonomy kit, consisting of safety laser scanners and additional sensors with processing hardware for SLAM navigation. It is in productive use at Evonik Industries and automotive production sites.

Innok Robotics offers the Induros transport robot for indoor and outdoor use especially suited for maneuvering in confined spaces thanks to its small footprint and tight turning radius. It can operate as a tugger train with automatic trailer coupling or with a roller conveyor to carry small load carrier containers directly on the robot. It has a towing capacity of 500 kg at speeds of up to 0.9 m/s and is powered by a lithium-ion battery running up to 16 hours and charging to 80% within 2 hours. The system has been installed at the flowers and plants producer cooperative Landgard and the tire manufacturer Rigdon.

Figure 2.70: The Innok Robotics AMR Induros autonomously moves tires from the outdoor storage to the production stations at the Innok customer Rigdon. Image credit: Innok Robotics.

Standing in-between indoor and outdoor delivery, AMRs for automatically parking cars in multi-story parking decks have been installed by Mhe-Demag. In contrast, Stanley Robotics (France) has designed a system for picking up and moving cars in large outdoor parking areas like factory compounds using 3D-LiDAR and Real-time kinematic (RTK)-GPS.

The 3E-D18 is Honda's (Japan) AI-equipped outdoor mobile platform. By replacing the upper attachment, the 3E-D18 can perform various tasks, such as firefighting, farm work, and sports training support. Its off-road capabilities allow for autonomous operation on rugged terrain, e.g. on farms and mountains.

Segway Loomo from Segway Robotics (China) is based on the former Segway Personal Transporter. Indoor and outdoor robots can be built on these platforms using its developer program. The Anymal C from Anybotics (Switzerland) is a multi-purpose, legged outdoor platform capable of moving and operating autonomously in challenging terrain while interacting safely with the environment.

Figure 2.71: The Warthog unmanned ground vehicle from Clearpath Robotics can transport 272 kg. Image credit: Clearpath Robotics Inc.

2.6.3.3. COST-BENEFIT CONSIDERATIONS AND MARKETING CHALLENGES

Due to the high complexity of outdoor robotic applications, these robots are mostly highly specialized in the tasks they perform and the environments they operate in. Therefore, it is still difficult to buy an outdoor robot off-the-shelf and to operate it in a variety of different environments. The need for specialization drives up the costs for the robot application. However, outdoor environments also provide advantages, as there is usually much more space to move around and less traffic.

The most sophisticated solutions have been presented for production sites to transport goods between production hall and warehouse. The primary driving factor for introducing these types of systems is labor shortage rather than return on investment, due to their high costs.

2.6.3.4. EXPERT VIEWS

Three interviews with the companies Capra Robotics from Denmark, 4am Robotics from Germany and DTA from Spain are presented below. The interviews are part of the major focus chapter revision in 2024 by Fraunhofer IPA.

2.6.3.4.1. INTERVIEW WITH CAPRA ROBOTICS

Company:	Capra Robotics, Denmark
No. of employees:	35
Products:	CAPRA CARRIER CART, CAPRA CARRIER LINK, CAPRA CARRIER BOXY
Interview partner:	Niels Jul Jacobsen, CEO

Why did you choose to develop robots for outdoor intralogistics?

We chose to develop robots for combined indoor-outdoor intralogistics, or interlogistics, because we identified a significant gap in the market where businesses struggle to efficiently manage logistics tasks that span both indoor and outdoor environments. Traditional logistics solutions often require a manual transfer of goods between these zones, leading to interrupted logistics flows and inefficiencies. We designed our mobile robots to seamlessly operate across diverse terrains and conditions, ensuring a continuous, automated flow of materials.

What was the most impactful decision for your product development?

The most impactful decision for our product development was the integration of advanced sensor fusion algorithms for our navigation systems. Our Fused Hybrid Localization and Navigation System uses the latest advances in AI-based mapping and satellite-based positioning to enable both indoor and outdoor navigation. The combination allows our robots to accurately perceive and adapt to complex and changing environments, ensuring reliable operation both indoors and outdoors.

What are the biggest hurdles in the development of robots for outdoor intralogistics?

The biggest hurdles in developing robots for outdoor intralogistics include navigating variable and unpredictable environmental conditions, ensuring robust communication and connectivity, and achieving high levels of reliability and safety. Outdoor environments pose challenges such as uneven terrain, weather conditions, and obstacles that can affect the robot's performance. Maintaining consistent and reliable communication in outdoor settings, especially over large areas, requires mixed networking solutions, which impose requirements, not only on the robot, but also on the entire ecosystem around it. Ensuring the safety of both the robots and their surroundings is paramount and requires extensive testing and compliance with regulatory standards. Overcoming these hurdles demands continuous innovation and a multidisciplinary approach to engineering.

Looking into the future, what are the biggest challenges ahead for your customers?

The biggest challenges for our customers will likely involve adapting to the rapid pace of technological change and integrating new systems into their existing operations. The ongoing digital transformation in logistics requires businesses to be agile and forward-thinking. The need for automated solutions is further worsened by global labor shortage trends that challenge process conformity and jeopardize growth plans. Customers will need to manage the transition to more automated and data-driven operations while ensuring that their workforce is trained to work alongside advanced robotic systems. Addressing these challenges will be key to maintaining a competitive edge in the market.

2.6.3.4.2. INTERVIEW WITH 4AM ROBOTICS

Company:	4am Robotics, Baden-Württemberg, Germany
No. of employees:	40
Products:	ATo-H, Autonomous Tugger Train Outdoor Heavy
Interview partner:	Sebastian Asbeck (Product Owner AMR)

Why did you choose to develop robots for outdoor intralogistics?

Usually, production plants are evolved facilities. This means that over the years production capacities and variety have been continuously expanded and increased. As a result, the company premises also become larger, with new halls being opened one after another. Consequently, there is a material flow between these halls because logistics and production are often separated. To facilitate these transport routes, our vehicle needs to move between the halls through the outdoor area.

What was the most impactful decision for your product development?

We initiated product development as part of a pilot project with a Bavarian automotive manufacturer, who presented their needs to us. In 2016, we had already developed an Autonomous Indoor Tugger Train for the same automotive OEM, as the solutions available on the market at the time did not meet the OEM's requirements. After numerous indoor projects, the logical next step was to automate material flow in outdoor areas as well.

What are the biggest hurdles in terms of bringing your robots to the market?

After achieving a positive ROI, which serves as the basis for any project, our primary focus, especially in outdoor settings with customers, is to instill confidence that our vehicles operate reliably not only in sunny conditions but also in adverse weather. To build this trust, we offer inexpensive trial installations in the customer's environment. "Inexpensive" means covering only the fixed costs for transport, insurance, etc. A trial installation involves conducting "small-scale commissioning". We map the surroundings, establish a virtual route, optimize it, and have the customer's future target process running autonomously after just one day. Ideally, the trial takes place in rainy weather, snow, cold, and various other adverse conditions to demonstrate the system's robustness and reliability to the customer.

Looking into the future, what are the biggest challenges ahead for your customers?

Excluding large corporations, most companies still have some homework to do before they can even consider efficient automation. This includes reviewing and revising processes and catching up on missed digitalization measures.

For example, Tugger Train drivers drive through the facility and gather materials because they happen to know what is needed in production. In order to be able to automate this process, the requirements in production must first be recorded digitally so that the autonomous system can be assigned appropriate transport tasks in the future.

How are you planning to further develop your products to tackle these challenges?

Increasing stability against weather influences to ensure a constant flow of goods. We continuously test the latest sensor components for outdoor operation from renowned manufacturers and rigorously evaluate them in practical use. If we find that a new sensor provides us with entirely new possibilities regarding safety, flexibility, or availability, then we integrate it into the next generation of vehicles.

2.6.3.4.3. INTERVIEW WITH DTA

Company:	DTA, Madrid, Spain
No. of employees:	70
Products:	Dolphin, Rhino, T-Rex, Tiger – heavy-duty outdoor transport
Interview partner:	Gonzalo de Sebastián (Sales)

Why did you choose to develop robots for outdoor intralogistics?

There is a big demand in the market, and only a few suppliers are capable of developing a reliable automated solution for outdoors that works in tough weather conditions. We have already developed different navigation solutions with SLAM and 3D LiDAR.

What was the most impactful decision for your product development?

DTA designs and manufactures tailor-made mobile robotic solutions for handling heavy and special loads, and we offer solutions for all kinds of heavy industries, such as aerospace, railroad, automotive, steel mill, nuclear, or windmill, so the most impactful decision was to replicate solutions that had already been tried and tested.

What are the biggest hurdles in terms of bringing your robots to the market?

We have not really encountered that many hurdles when bringing robots to the market, as DTA was formed in 1972 and we basically started off manufacturing heavy-duty diesel transporters for the shipbuilding industry, so we had managed to establish a "brand" throughout the 1970s, 1980s, and 1990s before designing the first AGV for Airbus in 2003. Our clients called the transporters supplied "DTAs". Therefore, it was easy for us to penetrate the robotic solution market due to our early background, and at that time we did not have many competitors in the market.

Looking into the future, what are the biggest challenges ahead for your customers?

We definitely want to develop detailed outdoor mobile robotic solutions, as there are not many competitors in the market and, for sure, whoever comes first will succeed. Also, it is important that safety devices and other navigation and location solutions improve their technology infrastructure. If they do, we will definitely succeed.

How are you planning to further develop your products to tackle these challenges?

We have to constantly innovate and check out new suppliers, new technologies, new software and hardware devices, etc.

2.6.3.5. PRODUCERS

4am Robotics, Agility Robotics, AGVE, Art Robot, Capra Robotics, Casun, Doog, Droneshub, Effidence, Esatroll, Exail, GAM Soluciones, Gaussin Macnica Mobility, Global Tech Co, Gridbots Technologies, Harvest Automation, Honda, Innok Robotics, Iplusmobot, Jaso Industrial, Kalmar, Kion, Konecranes, Mabo Engineering&Automation, Movvo, Neumaier Industry, Otsaw Digital, Qenvi, Rockwell Automation, SMP Robotics, Spijkstaal, Stanley Robotics, Stäubli, Twinny, Twinswheel

2.6.4 AP54: OUTDOOR ENVIRONMENTS WITH PUBLIC TRAFFIC

Robots operating in outdoor environments, using normal roads and reacting to other traffic participants, can be seen as the most prestigious robot application with a wide range of difficulties and many overlaps with the discipline of autonomous driving.

2.6.4.1. TYPES OF OPERATIONS CARRIED OUT BY THE ROBOT

The use of outdoor robots in the public traffic space is dominated by the "last mile" discipline that bridges the gap between restaurants or supermarkets and homes. To tackle this highly personalized delivery task, the focus lies on using robots with a relatively small payload.

Figure 2.72: The TwinswHeel droids are autonomous mobile robots for urban logistics. ciTHy S, ciTHy M, and ciTHy L can carry 50 kg, 150 kg, and 300 kg respectively. The droids are in operation in France, Switzerland, and Germany. Image credit: Twinswheel.

2.6.4.2. LEVEL OF DISTRIBUTION

Numerous logistics service providers and online retail companies are experimenting with robotic systems to stretch the last mile from delivery points to the customers' front doors. Robot solutions, both mobile (ground-based) and drone-based (aerial), seem to compete against each other to account for the costly last step in transporting goods.

Figure 2.73: Otsaw Digital's autonomous last mile delivery robot. Image credit: Otsaw Digital.

Numerous startups are developing and offering conceptually similar autonomous outdoor vehicles or drones to help reduce logistics costs for instant on-demand delivery.[234,235] Explored robots of this nature include Starship (created by the founding engineers of Skype), Teleretail, and Dispatch (a startup from the Massachusetts Institute of Technology and the University of Pennsylvania). The latter was acquired by Amazon and was subjected to extensive trial tests of ferrying goods to homes in four US locations in 2021. The delivery system called Scout typically drives on the sidewalk but can cross streets and avoid obstacles and other passersby. Amazon announced the establishment of a "Development Center" in Helsinki, Finland, to further develop 3D software for improved safety. [236] However, at the end of 2022, Amazon announced that it was scaling back the project. Based on customer feedback, the program did not meet all customer needs.[237] On the other hand, the Starship robot can carry a load of typically 10 kg and is mainly used to deliver food. It has completed more than one million deliveries in around 15-20 service areas globally. [238] During the COVID-19 lockdowns, there were quite a few

[234] Automating The Last Mile: Startups Chasing Robot Delivery By Land And Air, CB Insights, March 30, 2017; https://www.cbinsights.com/research/autonomous-drone-delivery-startups.

[235] 8 Delivery Robot Startups for Last Mile Delivery, Nanalyze, April 27, 2018, https://www.nanalyze.com/2018/04/8-delivery-robot-startups-last-mile-delivery.

[236] Amazon plans to build delivery robot tech in Finland, CNBC, July 1, 2021; https://www.cnbc.com/2021/07/01/amazon-plans-to-build-scout-delivery-robot-tech-in-finland.html.

[237] Amazon scales back Scout delivery robot program, TechCrunch October 7, 2022; https://techcrunch.com/2022/10/07/amazon-scales-back-scout-delivery-robot-program/.

[238] Starship Completes One Million Autonomous Deliveries, Medium, January 27, 2021; https://medium.com/starshiptechnologies/one-million-autonomous-deliveries-milestone-65fe56a41e4c.

startups that raised awareness by supporting medical and food supply. [239, 240] Examples include the California-based startup Nuro and the Chinese startup Neolix, which had reported a large increase in orders for their self-driving vehicles in the past and raised USD 29 million of funding in February 2020.

2.6.4.3. COST-BENEFIT CONSIDERATIONS AND MARKETING CHALLENGES

A 2016 McKinsey study sums up the situation of last mile delivery as a global growth sector, especially due to increased B2C deliveries driven by e-commerce. The last mile accounts for roughly 50% of the total transport costs. [241] The use of robots is supposed to cut these costs by half.

Last mile delivery robots are designed to primarily travel on sidewalks and bike lanes at low speeds of up to 6 km/h (walking speed). Delivery robots are typically intended for relatively affluent and uncrowded suburban areas, gated communities, and campuses. On bike lanes, sidewalks, etc., robots travel a short distance from a local hub or retail outlet to the recipient, typically within 5 to 30 minutes. Customers can schedule the delivery via an app.

The autonomous vehicles are designed for maximum safety and reliability and consequently reduce the risk of accidents, hence implicitly increasing operating time. Despite the relatively high cost of the installations, the profitability of the described applications results from the three-shift operation of the outdoor robots. Compared to the overall system costs, the autonomous navigation capability is a minor cost item which should pay off relatively quickly. Maintenance and surveillance by human workers are outweighed by the retrenchment of human drivers, thus effectively cutting payroll costs. A further benefit is the relief from boredom of the repetitive job as a driver. Additional benefits include energy efficiency and the quality of delivery. [242]

2.6.4.4. PRODUCERS

Academy of Robotics, Agility Robotics, Aitonomi (TeleRetail), Ant Robotics, Capra Robotics, Cartken, Chuangze Intelligent Robot, Doog, Easymile, Efy Technology, E-Novia, HL Mando, Honda, Hugo Delivery, Hyundai Motor Group, Invento Robotics, Kiwibot, Konecranes, Mabo Engineering&Automation, Marorobottech, Neolix, Neubility,

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[239] Nuro's self-driving vehicles to deliver prescriptions for CVS Pharmacy, May 28, 2020 https://techcrunch.com/2020/05/28/nuros-self-driving-vehicles-to-delivery-prescriptions-for-cvs-pharmacy/.

[240] Autonomous vehicles could be crucial in responding to future pandemics, March 26, 2020; https://www.therobotreport.com/autonomous-vehicles-vital-role-solving-future-pandemics/.

[241] Joerss, M.; Schröder, J.; Neuhaus, F.; Klink, C.; Mann F: Parcel delivery - the future of last mile, McKinsey & Company, September 2016;
https://bdkep.de/files/bdkep-dateien/pdf/2016_the_future_of_last_mile.pdf.

[242] Caccamo, S.: Last Mile Delivery Robots; https://univrses.com/case-study/last-mile-delivery-robots/.

Nuro, Otsaw Digital, Ottonomy, Panasonic, Qenvi, Refraction AI, Robotis, Segway Robotics, Starship Technologies, Twinswheel, Unmanned Solution, Vayu Robotics, White Rhino, ZMP

2.6.5 AP55: INVENTORY

A special example of an indoor use case is inventory robots that may operate in areas separated from non-instructed people. They have also already been installed in public warehouses or stores.

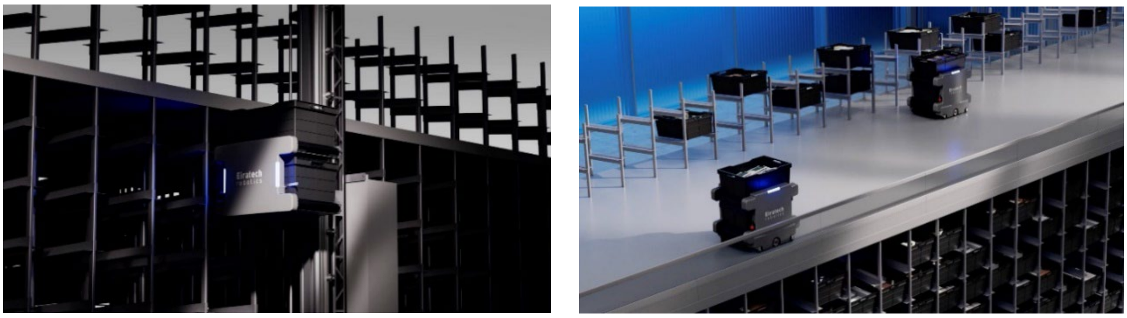

Figure 2.74: Eiratech has developed specialized e-grocery and dark store solutions involving different types of robot for the grocery industry. This facilitates order consolidation processes, such as picking, tote transport, storage and retrieval, sorting, buffering, and van loading. For the end user, this means significant increases in capacity, order fulfilment, and sales without the need to increase the store's available footprint. Image credit: Eiratech.

2.6.5.1. TYPES OF OPERATIONS CARRIED OUT BY THE ROBOT

Inventory robots are responsible for counting and refilling the stock and inventory. The environments are usually characterized by very few dynamics, and there is a wide range of autonomy, from line guided vehicles and optical markers to free navigation without any artificial markings. Apart from the localization and navigating tasks, key features of inventory robots are versatile grippers that can pick up a wide range of payloads as well as optical item detection to ensure a correct flow of material in a mixed product range.

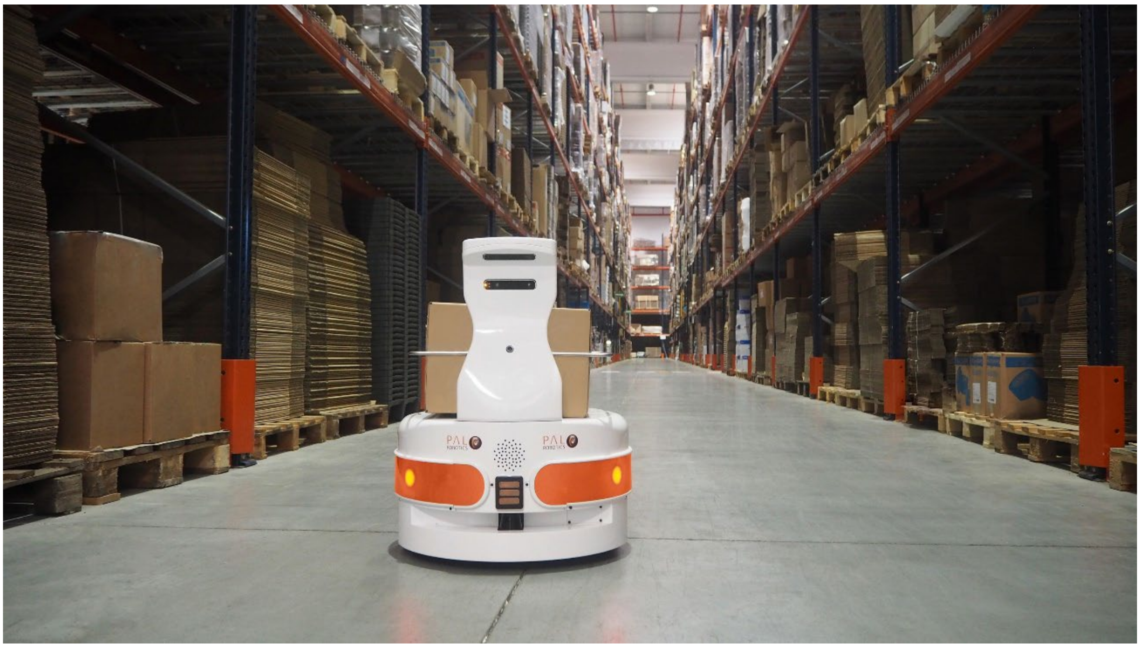

Figure 2.75: Tiago Base is the intralogistics indoor delivery solution from Pal Robotics. Image credit: Pal Robotics.

2.6.5.2. LEVEL OF DISTRIBUTION

Fetch Robotics, now Zebra Technologies[243], was one of the first companies to enter the market of mobile robotic commissioning systems (automated "milk runs"): After navigating to the proper inventory, Fetch can autonomously segment and detect items on the shelf, selecting the best item to fulfil the order. A similar system has been presented by Magazino. While its system Toru is an autonomous picking robot for shoeboxes, used at Zalando for example, SOTO is a solution for the automated feeding of manufacturing lines. Similar systems have been presented by Alibaba Quicktron, Greyorange, Gideon Brothers, Swisslog Carrypick, and Omron.

A further expansion of mobile robots is the addition of arms for picking and packaging. Mobile manipulators are offered by SEW Eurodrive and include, e.g., Toru from Magazino, KMR iiwa, KMR Quantec, and Flexfellow from Kuka, MP-400 from Neobotix, Fetch Mobile Manipulator, and many more.

To combine the advantages of mobile manipulators and traditional warehouse AMRs, Boston Dynamics and Otto Motors (a division of Clearpath Robotics) have presented trials of collaboration between the handle robot for picking up boxes and building pallets and the mobile robot platform Otto to show how heterogeneous robot teams can speed up warehouse processes.

Robotic solutions have also been used in public spaces, e.g. shops and stores, to facilitate the inventory process. For example, Tory RFID from Metralabs recognizes and

[243] Fetch Robotics was acquired by Zebra Technologies: Crowe, S.: Fetch Robotics acquired by Zebra Technologies for USD290M, The Robot Report, July 1, 2021; https://www.therobotreport.com/fetch-robotics-acquired-by-zebra-technologies-for-290m/.

captures 99% of all Radio Frequency Identification (RFID) tagged articles and counts inventory ten times faster than humans can, according to the company. The robot navigates completely autonomously and safely, even in dynamic environments. On top of its function as an inventory robot, Tory can also be used as a shopping assistant.

Figure 2.76: Tory RFID is an inventory robot that recognizes and captures RFID tagged articles in stores and warehouses. Image credit: Decathlon Germany.

Similar systems are offered by Pal Robotics (Stockbot) and Dexory (formerly Botsandus; with the latter having received new seed funding totaling nearly USD 13 million in June 2022).

Figure 2.77: Dexoryview is a warehouse intelligence platform that helps logistics providers to maximize visibility of daily inventory operations using autonomous robots to gather accurate, real-time data and generate actionable insights. Image credit: Dexory.

Built using Segway technology, Space Genius from 4D Retail Technology is a tall, thin robot that moves down aisles in stores, scanning items as it goes. Besides being able to log the number of items in place, the robot can also track the location and tag details to ensure everything in the store is in the right place. According to the developers, it can scan an entire supermarket in less than an hour. Space Genius also carries out 3D mapping and, as a result, can create a complete layout of stores, which can then be used by customers to find the goods they are looking for.[244] Ubica Robotics has developed a similar robot that creates digital twins of retail stores.[245]

2.6.5.3. COST-BENEFIT CONSIDERATIONS AND MARKETING CHALLENGES

The main benefits of robotic solutions for inventories include the reduction of required manual labor for tedious tasks and increased inventory accuracy. Additionally, the possibility of 24/7 operation allows for restructuring inventories overnight to ensure a more efficient flow of material during the day when human workers are present.

Mostly, the same considerations as in other indoor mobile robotic applications apply. In case of navigation without optical markers, no adaptions to the environment are required. Incremental installation without overly large initial investments is often possible.

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[244] This robot can scan the inventory of an entire supermarket in less than an hour, Bailiwick Express, April 2021; https://www.bailiwickexpress.com/jsy/life/technology/robot-can-inventory-entire-supermarket-less-hour/.

[245] What Happens In the Supermarket at Night, Bremeninvest, August 4, 2021; https://www.wfb-bremen.de/en/page/bremen-invest/robotics-in-retail-ubica.

2.6.5.4. PRODUCERS

Alstef Group, Corvus Robotics, Dexory, GAM Soluciones, Geek+, inVia Robotics, Jabil - Badger Technologies, JD, Jungheinrich, MetraLabs, Mrobot, MT Robot, Onward Robotics, Pal Robotics, Quicktron, Simbe Robotics, Soft Design RTS, Ubica Robotics, Zippedi

2.7 AP7: SEARCH, RESCUE AND SECURITY APPLICATIONS

Authors: Nikhil Srinath Betgov, M.Sc; Agha Ali Haider Qizilbash, M.Sc.

The firefighting, bomb fighting, surveillance, and (civil) security group refers to civilian robot applications. Many of those robots are tele-operated or semi-autonomous, thus robotic devices. This is due to the challenging environments in which the robotic devices are applied. A fully autonomous application is very difficult to realize. Therefore, this chapter considers actual robots as well as robotic devices which come with a limited level of autonomy.

IFR statistics

For the application group of **search and rescue and security** robots (AP7). 3,475 sold robots (+12%) were reported for 2023. Sales in this application group took mainly place in the Asia + Pacific region with close to 2,600 units sold and a growth rate of +14%.

The main application class within this group is **security services** (AP73) with a total of almost 68% of all sales and a growth rate of +17% in 2023. Demand for **firefighting and disaster relief** (AP71-72) remains on a comparable level as in the previous year with1,126 units sold and +3% growth. Note that numbers in AP7 also include robotic devices.

Table 2.10

Professional service robots for search and rescue, security (2022 and 2023)

	Application	Region	2022	2023	2023/2022	2022	2023	2023/2022
			units sold		growth rate	RaaS fleet (in units)		growth rate
AP7	Search and rescue, security	Total	3,095	3,475	+12%	**	**	-
		Europe+MENA	**	**	-	**	**	-
		The Americas	**	**	-	**	**	-
		Asia+Pacific	2,288	2,619	+14%	**	**	-
AP71-AP72	Firefighting and disaster relief	Total	1,095	1,126	+3%	**	**	-
		Europe+MENA	**	**	-	**	**	-
		The Americas	**	**	-	**	**	-
		Asia+Pacific	1,074	1,103	+3%	**	**	-
AP73	Security services	Total	2,000	2,349	+17%	**	**	-
		Europe+MENA	**	**	-	**	**	-
		The Americas	**	**	-	**	**	-
		Asia+Pacific	1,214	1,516	+25%	**	**	-

Source: World Robotics 2024
Results of IFR's annual survey and desktop research (26 robot companies for search and rescue)
*Regional breakdown cannot be revealed (minimum number of non-zero observations not reached).
**Results cannot be revealed (minimum number of non-zero observations not reached). Data included in application group total (AP1, AP2, etc.).

2.7.1 AP71: FIREFIGHTING

Several prototypes have been designed to locate and fight fires. However, very few designs have been commercialized and found their way into everyday use. Most of the designs are tele-operated vehicles equipped with various sensors and devices for fire extinguishing. Early on, the spectrum of tasks for robots in this class was expanded to include search and rescue in fires or hostile environments.

2.7.1.1. TYPES OF OPERATIONS CARRIED OUT BY THE ROBOT

Firefighting

The risk of an explosion as well as the extreme heat that develops during a fire, especially when oil is involved, forces firefighters to work from a distance. Consequently, positioning of the water jet is less precise and water pressure is lost over distance, resulting in decreased efficiency. The use of firefighting robots removes humans from dangerous environments, such as in or around houses that are likely to collapse.

Figure 2.78: Avenger Fire provides firefighting crews with the capability to remotely manage a fire or other hazardous threats with a reduced risk to first responders. Image credit: ICP NewTech.

Guided by remote control or moving autonomously, firefighting robots approach the fire and bring the mounted water or foam cannons into position. The extinguisher is either carried along or supplied through a hose, which is dragged behind and ensures a constant flow.

Alternatively, robots can be used to easily position separate, ordinary water cannons, and to return. The separate water cannons carry a detector to find and readjust the operating direction. The robot’s power, size, weight, and maneuverability vary according to the actual method of operation.

Despite numerous efforts, no firefighting robotic system has yet enjoyed wide market penetration. A good overview of the state-of-the-art in firefighting robots and a comparison of developed systems is given in the literature.[246, 247]

More recently, a few firefighting robots have gained attention. The LUF Nano firefighting robot can not only fight fires but can also provide life-saving support and can serve as an equipment carrier. The TAF60 and TAF60X firefighting robots using misting technology to get the most effective and efficient extinguishing and cooling capabilities of the turbine even with minimal use of water. A good survey of robotic solutions for forest firefighting is presented in the literature.[248]

Figure 2.79: The tele-operated firefighting robot with tracked undercarriage LUF 60 is a vehicle for operations under difficult conditions, which can produce a nebulized water jet of up to 2,400 liters of water per minute. Image credit: LUF GmbH.

[246] Tan, C. F.; Liew, S. M.: Firefighting Mobile Robot: State of the Art and Recent Development, Australian Journal of Basic and Applied Sciences, vol. 7, no. 10, 2013, pp. 220-230; https://rauterberg.employee.id.tue.nl/publications/AJBAS2013journal-a.pdf. (A more recent source does not seem to be available.)

[247] Firefighting robots: https://allonrobots.com/firefighting-robots/.

[248] Roldán-Gómez, J. J. et al.: A Survey on Robotic Technologies for Forest Firefighting: Applying Drone Swarms to Improve Firefighters' Efficiency and Safety. Applied Sciences, vol. 11, no. 1, Jan. 2021, https://doi.org/10.3390/app11010363.

2.7.1.2. LEVEL OF DISTRIBUTION

Most of the robots are tele-operated with relatively little autonomy. However, there is a clear path towards machine mission intelligence as technology develops and matures. Especially labs and first responders maintain a fleet of different robots.

Additional information in general on intelligent security/rescue robots and exemplary tasks they are used for are given in the listed literature.[249, 250, 251, 252]

MVF-5 from the privately-owned Croatian company Dok-Ing is a unique multifunctional robotic firefighting system developed to extinguish fires in life-threatening conditions and inaccessible areas. The robot system is operated from a safe distance by using tele-operated technology. MVF-5 extends the reach of firefighters to protect high-risk industrial facilities and other dangerous environments.

The original MVF-5 design is based on the proven technology used in the construction of demining systems that can survive mine detonations and other hazardous operations in the most demanding and destructive environments. The low center of gravity combined with a powerful engine and the compact original structure of MVF-5 allows for excellent maneuverability.

Equipped with the latest firefighting technologies, plus two storage containers for water and foam, MVF-5 can extinguish fires with minimal damage to itself and its operators, who remain outside the range of danger during operation. The components give the operators the capability to use water, foam, or a combination of both extinguishing liquids.[253]

Blade Formation, developed by the fire-extinguishing unit of remotely operated vehicles and uncrewed drones in Tongliao City in North China, is a robot unit consisting of seven reconnaissance and firefighting robots, two drones for fire detection, and one transport vehicle. However, there have not been any news whether these robots are being used since 2020.

This fire-extinguishing unit takes part in hazardous tasks that could seriously endanger the safety of human firefighters. The vehicles can be deployed for operations on industrial sites or in confined and closed spaces where visibility might be compromised,

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[249] Theodoridis, T.; Hu, H.: Toward Intelligent Security Robots: A Survey, IEEE Transactions on Systems, Man, and Cybernetics, vol. 42, 2012, no. 6, pp. 1219-1230; https://ieeexplore.ieee.org/abstract/document/6392475.

[250] Witwicki, S. J. et al.: A Testbed for Autonomous Robot Surveillance (Demonstration), Proceedings of the 2014 international conference on Autonomous agents and multi-agent systems (AAMAS '14), Paris, May 5-9, 2014, pp. 1635-1636. http://welcome.isr.tecnico.ulisboa.pt/wp-content/uploads/2015/05/3419_p1635.pdf.

[251] Sheh, R.; Schwertfeger, S.; Visser, A.: 16 Years of RoboCup Rescue, vol. 30, 2016, no. 3-4, pp. 267-77; https://link.springer.com/article/10.1007/s13218-016-0444-x.

[252] Chun, W. H.; Papanikolopoulos, N.: Robot Surveillance and Security. In: Siciliano, B. and Khatib, O. (eds.): Springer Handbook of Robotics, 2nd Edition. Berlin, Heidelberg: Springer, 2016, pp. 1605-1626.

[253] https://dok-ing.hr/products/mvf-5/.

such as in underground locations, deep tunnels, or large spaces in buildings. They can also be deployed for other missions, too. For example, an uncrewed "drone and robots equipped with water cannons were recently dispatched in an air-ground mission. These firefighting robots use 360-degree vision and an infrared thermal imaging system to detect the fire source and are directed to target it to control the fire. The robots feature multiple other functions, such as combustible gas detection and analysis, image and sound collection, autonomous obstacle avoidance, and on-site rescue."[254]

Another example is Colossus from Shark Robotics, which supports firefighters by extinguishing fires, transporting equipment, transporting wounded persons, and providing surveillance of the whole scene using optical recognition. Controlled by the Paris Firefighting Service, the 1,100-pound robot helped to save the Notre Dame cathedral when it caught fire in 2019.[255] The robot is specifically made to endure scorching fire conditions and perform several tasks. It can carry more than 1,200 pounds of payload.

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254 Yimei, L.: China's first firefighting robot unit now in service, May, 27, 2020; https://news.cgtn.com/news/2020-05-27/China-s-first-firefighting-robot-unit-now-in-service-QPjoan4UfK/index.html.

255 Hruska, J.: Colossal Achievement: Half-Ton Firefighting Robot Helps Save Notre Dame; ExtremeTech; April 17, 2019: https://www.extremetech.com/extreme/289693-colossal-achievement-half-ton-firefighting-robot-helps-save-notre-dame.

Figure 2.80: Shark Robotics offers the Colossus uncrewed system for extinguishing fires, transporting equipment or casualties, providing relevant information thanks to gas and temperature sensors, and enabling day/night and thermal vision to locate people even in smoke. Image credit: Shark Robotics.

Similarly, Thermite RS1-T3 from Howe & Howe Technologies was developed to provide safe access to fires of any magnitude or origin. Thermite gives firefighters and first responders instant insights into the circumstances surrounding a fire and the ability to attack the fire at its core. With the power to tow full hoses and dispense up to 1,250gpm (about 4,700l/min), Thermite's firefighting robot is able to take on firefighting to a new level.[256]

In 2020, firefighters in Los Angeles first introduced their newest member, Thermite RS3. Even before the formal introduction, the robotic device was called to an emergency to create a path for the firefighters in a fire in downtown L.A. To date, it is the first firefighting robot in the United States.[257] This was also the first domestic sale of Howe & Howe.[258]

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[256] Howe & Howe Technologies: Thermite, 2021; https://www.howeandhowe.com/civil/thermite.

[257] Giuliani-Hofmann, F.: The first firefighting robot in America is here – and it has already helped fight a major fire in Los Angeles; October 2020. https://edition.cnn.com/2020/10/21/business/first-firefighting-robot-in-america-lafd-trnd/index.html.

[258] https://www.textronsystems.com/our-company/news-events/articles/press-release/howe-howe-completes-first-domestic-sale-thermite-rs3.

Mitsubishi Heavy Industries, Ltd. has developed two firefighting robots: The Water Cannon Robot and the Hose Extension Robot. Combined, the two robots are expected to play an active role in situations that are too hazardous for firefighting crews. The Water Cannon Robot can extinguish and cool fires where human intervention is difficult while the Hose Extension Robot automatically lays out up to 300m of fire hose to supply water to the Water Cannon Robot.[259]

SmokeBot, an EU-funded research project, was driven by the demand for robots that operate in domains with restricted visibility. The focus was on civil robots supporting firefighting teams in search and rescue missions, e.g. during post-disaster management operations in response to tunnel fires.[260]

Milrem Robotics developed a Rescue Hose Cartridge which is a remotely operated mobile platform equipped with sensors and cameras for hose deployment in fire environments. Rescue Firefighter developed by the same company is equipped with a modular water monitor with a flowrate of 3,000l/min and is fully customizable. Multiscope Rescue Firefighter with Hydra is designed for warehouses, tunnels, and wildfire extinguishing activities. It has four pressurized water hose lines running behind it to ensure a sufficient supply of water. Finally, Multiscope Rescue Transport has been developed for the transport of critical supplies, equipment, and teams. It can be utilized to pack up gear quicker and with less people, thus enabling firefighters to be ready faster for upcoming challenges. All Multiscope Rescue Platform variants can be operated in different modes. Teleoperation and waypoint navigation already work for Hydra and Hose, whereas the functions where the robot follows a human firefighter or can collaborate with other robots in swarms are still under development. For Multiscope Rescue Transport, all different modes are still under development.

Firefighting involves a lot of investment, research, and talent. Only with the collaboration of institutions, universities research institutes, and companies on a global level, the problem of firefighting can be solved effectively. To this end, a lot of industries need to work together, more advanced materials to withstand fires and extinguishing them need to be researched, better components to help in traversing numerous types of terrain need to be developed. Even with such international cooperation, there is still the obvious financial limitation to develop a system for a disaster or catastrophe since the return on investment is not perceived to be high. However, with the numerous efforts that have been undertaken in the recent years, it is safe to say that in the coming years, the firefighting robots will have a significant impact. In fact, they have already started gaining widespread attention. There is an expectation of the compound annual growth rate of

[259] MHI Develops Autonomous ‘Water Cannon Robot’ and ‘Hose Extension Robot’ for Use in Firefighting. Expected to Play Active Role in Hazardous Situations Inaccessible to Firefighting Crews, press release by Mitsubishi Heavy Industries, March 25, 2019; https://www.mhi.com/news/story/190325.html.

[260] Mobile Robots with novel environmental sensor for inspection of disaster sites with low visibility; EU Project H2020 ICT-23-2014-Robotics; 2021; http://www.smokebot.eu.

the firefighting robot market to increase by 9.7% for the years 2023 - 2031.[261] Research is progressing at a fast pace. With the advancements in technology, there is lesser response time of firefighting agencies and better real-time monitoring and sensing of fires. It should not be long before firefighting robots have a firm position and recognition in the market.

2.7.1.3. COST-BENEFIT CONSIDERATIONS AND MARKETING CHALLENGES

The high costs of firefighting robots (starting at around €50,000) prevent firefighting services from keeping several systems, which could be utilized in large fires. Using only one robot to position several cheap, conventional extinguishers near the fire takes maximum advantage of the robot's features and reduces the risk of losing the expensive navigating robot in the event of an explosion or a collapsing structure. This, of course, requires the cannon equipment to be compatible with the robot. Getting out of a fire quickly is a major problem that these robots do not yet solve.

2.7.1.4. PRODUCERS

AiDrones, BIA5, Boston Dynamics, Citic HIC Kaicheng Intelligence Equipment Co., Ltd , Dok-Ing, Efy Technology, Fotokite, Groupe Intra, HIT Robot Group, Howe and Howe, International Robotics Solutions, LUF, Mitsubishi Heavy Industries, Qiteng Robot, ReconRobotics, Robotics Design, Servosila, Sevnce, Shandong Guo Xing Intelligent Technology, Shark Robotics, Suzhou Pangolin Robot, Yijiahe Technology

2.7.2 AP72: DISASTER RELIEF

Disaster-fighting robots consist of a mobile unit on which a manipulating arm is mounted, or, recently, of humanoids that can execute the task of dual arm manipulation, torso, and legged manipulation. The offered platforms are used across application domains, such as surveillance/security on both land and in water, or demining. Efforts are underway to add partial autonomy to the robots based on rich sensor information and rescue strategies.

2.7.2.1. TYPES OF OPERATIONS CARRIED OUT BY THE ROBOT

Robots for disaster relief are primarily deployed in environments that require immediate assistance for mitigating widespread damage. These robots are equipped with technology that enables them to enter and navigate through hazardous scenarios which

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[261] Robotic Firefighters Market Size is Expected to Reach US$ 2.9 Billion by 2031, 15 June 2023, https://www.globenewswire.com/en/news-release/2023/06/15/2689347/0/en/Robotic-Firefighters-Market-Size-is-Expected-to-Reach-US-2-9-Billion-by-2031-Rising-at-a-Market-Growth-of-9-7-CAGR-During-the-Forecast-Period-Transparency-Market-Research-Inc.html.

is sometimes not possible for humans. With the use of these robots, humans no longer have to put themselves in danger and intervene in order to minimize damage caused due to the disasters.

Disaster-fighting robots also help humans in search and rescue. They provide immediate help to people stuck in such dangerous environments and rescue them. The manipulating arms mounted on top of the robots enable them to quickly assist humans in difficult tasks such as picking up of heavy rocks and boulders. Humanoids or legged robots in general use these manipulation skills to work more efficiently and navigate faster in unfavorable conditions compared to wheeled robots. Their abilities to navigate through small enclosed and crowded areas, over uneven terrain, climbing stairs and ladders etc. make them the go-to robots for search, rescue and recovery operations.

2.7.2.2. LEVEL OF DISTRIBUTION

In general, the disaster relief robots are receiving a lot of attention and are slowly being integrated into search and rescue operations. The ease with which these robots aid humans has been demonstrated successfully and is now used by several organizations. With ongoing technological developments, more and more features to tackle complex scenarios are being added to these robots which make them favorable for deployment in life-threatening environments.

Atlas

Boston Dynamics' famous Atlas robot (a research platform) is the latest in a line of advanced humanoid robots the company is developing. 2024, the company introduced its latest innovation designed for practical real-world applications.[262] This new version of Atlas is a fully electric successor to its predecessor, which utilized hydraulic actuators. The transition to electric actuators enhances the robot's efficiency, precision of movements, and allows for quieter operations. One of the most striking features of the new Atlas is its agility. The robot boasts extended capabilities and greater freedom of motion, allowing it to perform movements that are impossible for humans, while also mimicking the grace of human movement. This agility enables Atlas to navigate complex environments effectively. In addition to its nimbleness, Atlas surpasses human capabilities in terms of strength and dexterity. Its control algorithms enable the robot to plan its movements strategically, taking into account the surrounding environment. The combination of advanced real-time perception, manipulation abilities, agility, and strength might position Atlas as one of the most dynamic humanoid robots available. However, the new platform still has to prove itself and it remains to be seen to what extent the promised features and possibilities will actually lead to concrete applications of the robot.

[262] Reid, C.: The Atlas Robot Is Dead. Long Live the Atlas Robot, Wired, April 7 2024; https://www.wired.com/story/the-atlas-robot-is-dead-long-live-the-atlas-robot.

MIT Cheetah

MIT's Cheetah was developed to run and jump across rough terrain; it can climb a staircase filled with obstacles and even regain its balance if shoved. It relies mainly on a technology called "blind locomotion" to navigate its surroundings. Blind locomotion does not rely on vision from cameras; instead, it uses tactile information. Sangbae Kim, an associate professor of mechanical engineering at MIT, who is also the robot's designer, claims: "Vision can be noisy, slightly inaccurate, and sometimes not available, and if you rely too much on vision, your robot has to be very accurate in position and eventually will be slow. So, we want the robot to rely more on tactile information. That way, it can handle unexpected obstacles while moving fast."[263]

Snakebot

Snakebot, also known as the snake robot, is a biomorphic hyper-redundant robot that resembles a biological snake.[264] It was developed at Carnegie Mellon University with more than twelve joints, allowing it to crawl and climb through debris that first responders cannot reach. A "head"-mounted camera, LED lights, and distance-measuring laser technology allow rescue personnel to shepherd the snake through rubble while it transmits video material back to a remote crew.[265] It was deployed, for example, during the Mexico earthquakes in 2017.[266]

A very active research community in robotics search and rescue drives the state-of-the-art through joint research and numerous competitions. Several publications describe these activities as well as provide an overview of advanced robot rescue scenarios.[267, 268]

The Fukushima accident as a large-scale disaster-relief robot operating scenario

The Great East Japan Earthquake was a dramatic event that struck Japan on March 11, 2011. The tsunami that followed caused extensive and severe damage to Tohoku (Northeast Japan). Unlimited efforts were taken to secure the Fukushima nuclear power plant. In desperate efforts, robots were introduced to the area, particularly to monitor the nuclear site, collect data, and to deploy sensors and other equipment. Several accounts reflect the use and operation of robots (e.g. from QinetiQ, iRobot, and other

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263 Chu, J.: "Blind" Cheetah 3 robot can climb stairs littered with obstacles, July 4, 2018; http://news.mit.edu/2018/blind-cheetah-robot-climb-stairs-obstacles-disaster-zones-0705.

264 Spice, B.: Carnegie Mellon Snake Robot Winds Its Way Through Pipes, Vessels of nuclear Power Plant, July 9, 2013; https://www.cmu.edu/news/stories/archives/2013/july/july9_snakerobot.html.

265 Gossett, S.: 12 ways rescue robots save the day during disasters and emergencies, Built In, June 25, 2019; https://builtin.com/robotics/rescue-robots.

266 Carnegie Mellon Snake Robot Used in Search for Mexico Quake Survivors, Carnegie Mellon University, September 27, 2017; https://www.cmu.edu/news/stories/archives/2017/september/snakebot-mexico.html.

267 RobocupRescue; 2021; https://www.robocup.org/domains/2.

268 NCCR Robotics, Rescue Robotics; 2021: https://nccr-robotics.ch/research/rescue-robotics/.

manufacturers).[269, 270] It was stated that "the Japanese government had spent USD 300m developing six prototype robots to assist in nuclear accidents, but the nuclear plant operators decided not to buy them. These robots were developed in the wake of a 1999 accident at another nuclear plant in Japan."[271] Robots can be used inside the disaster area for long-term clean-up operations; see chapter 2.5.2. An impression of the rescue activities and the used robots in these efforts (texts and pictures) are accessible on various websites.[272, 273] Of particular interest might be the overview of robots used at the disaster site and the ongoing clean-up and dismantling process since 2014.[274, 275] For surveillance purposes, the newest robotic technologies were also employed at the nuclear plant in Chernobyl to ensure a safe decommissioning process.[276]

In any case, the disaster has fueled efforts in creating reliable, high-performance robots through government programs or private initiatives. These robots typically show one or two armed configurations on a tracked mobile platform. Examples are:[277]

- Packbot from Flir, which is used for on-site inspection and data acquisition.
- Maintenance Equipment Integrated System of Telecontrol robot (MEISTer) from Mitsubishi Heavy Industries.
- A high-access survey robot to collect data on the first floor of the damaged reactor jointly developed by Honda and the National Institute of Advanced Industrial Science and Technology (AIST). Similar to this design is the Astaco-Sora robot (Hitachi) for the heavy-duty dismantling of contaminated structures.

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[269] Important Stories on Decommissioning 2018: Fukushima Daiichi Nuclear Power Station, now and in the future, Agency for Natural Resources and Energy, Ministry of Economy, Trade and Industry, March 2018 (updated in 2022); https://www.meti.go.jp/english/earthquake/nuclear/decommissioning/index.html.

[270] Murphy, R.: International Cooperation in Deploying Robots for Disasters: Lessons for the Future from the Great East Japan Earthquake, Journal of the Robotics Society of Japan, vol. 32, no. 2, April 15, 2014, pp. 104-109; https://doi.org/10.7210/jrsj.32.104.

[271] Gilhooly, R.: Robots go deep inside Fukushima nuclear plant to map radiation. New Scientist, April 15, 2015, https://www.newscientist.com/article/mg22630172-300-robots-go-deep-inside-fukushima-nuclear-plant-to-map-radiation.

[272] Photos and Videos Library: http://photo.tepco.co.jp/en/index-e.html. A continuous update of main Fukushima activities: http://www.tepco.co.jp/en/press/corp-com/release/index_ho-e.html.

[273] Vella, M.: Robots have failed Fukushima Daiichi and Japan, Fortune, March 20, 2013; https://fortune.com/2013/03/20/robots-have-failed-fukushima-daiichi-and-japan/.

[274] Strickland, E.: Meet the Robots of Fukushima Daiichi. A cleanup crew of automatons will go where humans fear to tread, IEEE Spectrum, February 28, 2014;

http://spectrum.ieee.org/slideshow/robotics/industrial-robots/meet-the-robots-of-fukushima-daiichi.

[275] R&D and Innovation Needs for Decommissioning Nuclear Facilities, OECD, 2014; https://www.oecd-nea.org/rwm/pubs/2014/7191-rd-innovation-needs.pdf.

[276] Ackerman, E.: Boston Dynamics' Spot Is Helping Chernobyl Move Towards Safe Decommissioning, November 2020, https://spectrum.ieee.org/boston-dynamics-spot-chernobyl.

[277] Robots enlisted to survey Fukushima World Nuclear News, June 24, 2013; http://www.world-nuclear-news.org/C-Robots_enlisted_to_survey_Fukushima-2406134.html.

- Arounder from Hitachi, which delivers a high-pressure water jet for decontaminating walls, infrastructure, or equipment by removing paint, outer layers, or concrete. The robot is designed to suck back the water it uses.
- A robot for negotiating difficult terrains (stairs, obstructions, etc.) is Quadruped from Toshiba. The four-legged walking machine is equipped with a smaller wheeled robot that can be deployed to navigate hard-to-reach areas.

In addition, the disaster has contributed to motivating the DARPA Robotics Challenge for initiating groundbreaking research and development to ensure that robotics can perform the most hazardous activities in future disaster response operations. The challenge aims at demonstrating the following capabilities:[278]

- Compatibility with environments engineered for humans (even if they are degraded)
- Ability to use a diverse assortment of tools engineered for humans (from screwdrivers to vehicles)
- Ability to be supervised by humans who have had little or no robotics training

The DARPA Robotics Challenge (Defense Advanced Research Projects Agency) consisted of three increasingly demanding competitions over two years in 2013 and 2015.

Similarly motivated, the EU-funded euRathlon initiative aimed at providing real-world robotics challenges that would test the intelligence and autonomy of outdoor/off-road robots in demanding mock disaster-response scenarios. Missions required autonomous flying, land-based, and underwater robots operating together to survey the disaster, to collect environmental data, and to identify critical hazards. A competition for land-based robots in 2013 was followed by the one for underwater robots in 2014; the final competition in 2015 required a team of terrestrial, marine, and aerial robots to work collaboratively to survey the scene, to collect environmental data, and to identify critical hazards.[279, 280]

Furthermore, the Disaster Robotics Competitions within the World Robot Summit 2021 infused the topic with new technologies and demonstrations of technical feasibility. The Disaster Robotics category considered problem solving in the areas of infrastructure, disaster prevention, and response and aimed to achieve particularly difficult tasks, such as plant disaster prevention and tunnel disaster response.

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[278] The DARPA Robotics Challenge, June 2015; https://www.darpa.mil/program/darpa-robotics-challenge.

[279] Schneider, F. E.; Wildermuth, D.; Wolf, H.-L.: ELROB and EURATHLON: Improving Search & Rescue Robotics through Real-World Robot Competitions, Proceedings of the 10th International Workshop on Robot Motion and Control, Poznan University of Technology, Poland, July 6-8, 2015.; https://www.researchgate.net/publication/286354629_ELROB_and_EURATHLON_Improving_search_rescue_robotics_through_real-world_robot_competitions.

[280] ELROB – The European Land Robot Trial; ELROB: http://www.elrob.org.

There were three challenges to obtain sufficient results:[281]

- Plant disaster prevention (in reference to the Fukushima disaster)
- The world's first tunnel disaster response and recovery
- Standard disaster robotics

2.7.2.3. COST-BENEFIT CONSIDERATIONS AND MARKETING CHALLENGES

Robin Murphy, professor at Texas A&M University and known as a founder of the fields of rescue robots, concluded some points in a 2019 interview (which unfortunately does not seem to be online available anymore). All ground, aerial, and marine robots have been tele-operated (like the Mars Rovers) rather than fully autonomous (like a Roomba), primarily because the robots allow the responders to look and act in real time; there is always something they need to see or do immediately. Robots have been present at at least 35 events and have actually been used at at least 29 of them (sometimes the robot is too big or not intrinsically safe). The biggest technical barrier is human-robot interaction. However, human error is also a considerable reason for failure. In general, robots are not immediately used following a disaster. On average, it takes 6.5 days before a robot is deployed to a disaster zone; either an agency has a robot and they use it within half a day, or they do not and it takes them several days to realize a robot would be of use and to get it over to the site.

In order to increase effectiveness of robotic use in responding to disasters, ergonomics and research in human factors have become a primary topic. Test methods have been developed to measure and optimize the baseline robot/operator capabilities necessary to perform operational tasks defined by emergency responders, soldiers, and their respective organizations. Over 100 robots have been tested to varying degrees of completeness across the roster of standard test methods. A detailed overview describes how to use appropriate test methods to evaluate robots, to specify and defend purchasing decisions, and to train operators with measures of proficiency.[282]

A wide range of bomb-disposal robots have been developed in the past. Today, these – usually tele-operated – robots play an increasing role in homeland security efforts. The typical bomb-disposal robot configuration is a mobile platform with a manipulator arm and gripper, a set of diagnostic instruments (camera, chemical detectors), bomb-disposal instruments, and a tele-operated unit (tethered or wireless). As the manipulating arm of bomb-disposal robots can carry weight, change tools, and pick up new ones,

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[281] World Robot Summit, Disaster Robotics Category, Tokyo, October 7-21, 2018. There are also some results from December 2021 (https://wrs.nedo.go.jp/en/news/) but unfortunately no more information available.

[282] Guide for Evaluating, Purchasing, and Training with Response Robots Using DHS-NIST-ASTM International Standard Test Methods, NIST, ASTM International Standards Committee on Homeland Security Applications; Operational Equipment; Robots (E54.08.01): Standard Test Methods For Response Robots; http://www.nist.gov/el/isd/ks/upload/DHS_NIST_ASTM_Robot_Test_Methods-2.pdf.

manual help is not needed. Additionally, bomb-disposal instruments, such as on-board freezing units or water guns, can deactivate explosive devices on-site, so that the operators can stay at a safe distance throughout the operation. From there, they rely on camera images, and thus good positioning is crucial in order to perform the required precision work. Of course, skilled operators who are capable of precise handling and have experience with such robots are another prerequisite for successful operation. Additional diagnostic instruments, such as X-ray photography, give precise information immediately and allow rapid and information-based decision-making.

2.7.2.4. PRODUCERS

AiDrones, Boston Dynamics, Dok-Ing, Fotokite, Groupe Intra, Howe and Howe, Kowa Tech, Lockheed Martin CDL Systems, LUF, Mitsubishi Heavy Industries, ReconRobotics, Robotics Design, Servosila, Suzhou Pangolin Robot, Yijiahe Technology

2.7.3 AP73: SECURITY SERVICES

Surveillance robots are used to assist human guards covering a large territory or to remain vigil in potentially dangerous areas. Typically, they are based on a mobile robot platform, on which a number of specialized instruments can be mounted so that they can be adapted to particular tasks in many applications.

Figure 2.81: E4 is an autonomous patrolling robot that acts like a watchdog to secure premises and protect employees. Image credit: A.I.Mergence.

2.7.3.1. TYPES OF OPERATIONS CARRIED OUT BY THE ROBOT

These mobile robots carry a variety of sensors, depending on their specific application or mission environment, such as camera equipment (including infrared) for tele-operation and telepresence, or microphones to help detect human presence, as well as chemical or smoke sensors.

Usually, the robots bear a high resemblance to or are in many cases technical derivatives of uncrewed ground, aerial, or underwater vehicles from defense applications.

Figure 2.82: The O-R3 robot operates 24/7, boosting the reliability and productivity of security operations. Image credit: Otsaw Digital.

Uncrewed ground vehicles (UGVs)

A typical surveillance/security robot with an outdoor-suitable mobile platform is equipped with a variety of sensors (microphones, radar, tele-operated pan-tilt camera, motion detector). Today, these robots are not just wheeled vehicles but also legged robots. Often, the robots can extend their missions by automatically recharging. In order to continuously cover large spaces, either several robots can be coordinated or – as an interesting option – one robot can automatically place active sensor probes on the ground to transmit information to the parent robot to form a sensor network. These sensor probes are lost when either their energy is used up or the robot collects them at the end of the mission to be re-used. Core security applications are listed as:

- Access control, e.g. for security sensitive locations (military bases, government units). Biomimetic sensors for detecting or even identifying persons are part of the system's external data acquisition.
- Anomaly detection and alarming. This comprises analyzing the person's behavior or environmental conditions (presence and state of objects, infrastructure, and atmosphere) through adequate sensor channels (sound, vision, radiation, etc.).
- Detection and inspection of objects. This involves the robot detecting and analyzing the presence, location, status, possible changes to the function of objects (facilities, transportation, everyday objects).

Often, these robots have been confined to environments where surveillance by personnel is tedious, costly, or hazardous and justifies the still relatively high costs of these systems. Costs typically range from USD 25,000 to about USD 150,000, depending on the robot's performance and sensor equipment. Mission environments are usually inside buildings (factories, museums, and corporate headquarters), chemical plants, military arsenals, nuclear power stations, etc. Other areas include inspections of the underfloor of cars or more complex kinematics for even inspecting the inside of suitcases, boxes, or containers through small holes.

Uncrewed ground vehicles (UGVs) for surveillance and disaster relief (e.g. reactor supervision and related accidents, bombs before or after an explosion, search of sources out of regulatory control, long-term measurements) are usually derived from defense-type mobile systems. Usually, these platforms are propelled by tracks and run on batteries. The vast majority of these systems have manipulators for handling the explosive device (mobile manipulator). The systems are usually not very fast and the stair-climbing capabilities require a skilled (tele-)operator. Typical UGV models for these jobs are, amongst others, Packbot from Flir, Cutlass or Wheelbarrow, TeleMax and Teodor, Talon, and Defender.

Figure 2.83: EOD (explosive ordnance) robot Telemax EVO and EOD robot Teodor EVO with Telerob service vehicles. Image credit: Telerob Gesellschaft für Fernhantierungstechnik mbH.

Figure 2.84: Avenger Lite is a compact mid-sized robot with the ability to access tight spaces while still deploying EOD render safe tools, equipment, and sensors common to the entire Avenger family of robots (left). Avenger 2.0 includes a manipulator arm with seven degrees of freedom, offering the necessary reach and lift for EOD operations (right). Image credit: Med-Eng.

Uncrewed aerial vehicles (UAVs)

UAVs are robots or categories of aircrafts/drones that are controlled remotely by remote control or even autonomously where possible. While the robots are able to perform certain tasks independently to a certain extent, the operator can always intervene via remote control. An example is Talon from QinetiQ, which claims to be the “easiest robot to operate”. Using a joystick-based remote control, similar to game controllers, makes it easier for the operator to feel familiar with the system after a short period of time. These robots have no human pilots and typically carry sensors, transmitters and other equipment that interact with the environment.

Typical ground and aerial supervisions are:

- 3D mapping of buildings, open mines, landscapes, etc. by uncrewed aerial systems
- Monitoring of radioactivity, gas concentrations, and atmospheric parameters
- Measuring and observing biological and zoological activity

UAVs for civil security and anti-terrorism are increasingly performing civilian tasks as the technology becomes more common. Examples for commercial applications can be found in the literature:[283]

Humanitarian organizations have started to use UAVs, e.g. in Haiti and the Philippines, for data collection and information tasks that include real-time information and situation

[283] Marzani, A.: 16 Drone Security Use Cases You’ve Never Thought Of, DARTdrones, April 4, 2017; https://www.dartdrones.com/blog/drone-security.

monitoring, public information and advocacy, search and rescue, as well as mapping. The most likely humanitarian application in the areas of delivery and logistics would be the delivery of small medical supplies, such as vaccines.

2.7.3.2. LEVEL OF DISTRIBUTION

Many suppliers provide platforms for various adjacent areas, from logistics, through inspection, to uncrewed ground vehicles for defense. The types of platforms are also often used for rescue purposes. Over the last few years, the application of robots and robotic devices in surveillance and security tasks, especially in dangerous and hazardous environments, has been continuously increasing due to the new capabilities of legged robotics and UAVs which are able to move in complex situations. Equipped with different types of sensors and with decreasing costs due to developments in autonomous driving, the robots and robotic devices are able to provide necessary information from these complex environments and situations. These new sensor technologies, new robotic capabilities, and challenges like DARPA or the World Robot Summit make robots and robotic devices for unstructured environments more reliable and economically successful and introduce higher autonomy into these applications.

Uncrewed ground vehicles (UGVs)

Security robots can also be encountered in industrial settings. SMP Robotics developed a security robot of its S5.2 series for autonomous patrolling in protected areas. It has been designed for intelligent video surveillance and offers 360-degree panoramic video surveillance, including human and face detection and audible warnings. Collaborative patrolling is enabled by using several robots evenly divided along the patrol route with communication between all the units.

Knightscope K5 is a 1.5m tall mobile robot. Predictive analytics and collaborative social engagements are utilized to predict and prevent crime. It features most of the above-listed sensors. Operation areas are listed as schools, hotels, car dealerships, stadiums, casinos, law enforcement agencies, seaports, and airports. Other categories exist for different styles of environments. Knightscope also provides three more types of security robots for indoor, outdoor, and static use. Similarly, EOS Innovation's security robot, e-vigilante, which moves at speeds of between 5 and 10km/h, follows pre-programmed routes, and identifies anomalies, break-ins, and movements. When it detects an incident, e-vigilante alerts an off-site security operator, sending real-time video feeds and information, which display on the site map. The security operator can then take control of e-vigilante remotely to assess the situation, categorize the level of alert, and take any necessary measures while staying out of physical danger.

Uncrewed aerial vehicles (UAVs)

With the availability of uncrewed vehicles (aerial, ground, or underwater) from defense-related applications, UAV systems have become available for surveillance, monitoring, and general data collection. In fact, there has been significant growth in recent years which has led to the establishment of a large supplier base. In UAV systems for civil/commercial applications, it is estimated that there are at least ten manufacturers for professional multi-rotor aircraft and fixed-wing aircraft which can be upgraded by sensors and adequate control interfaces for surveillance or environmental monitoring of any kind.[284] These UAVs are able to patrol autonomously and detect for example invaders or, if equipped with a thermal imaging camera, also fire.

Since 2004, the Wildlife Research and Application Partnership, a joint NASA and US Forest Service project, has demonstrated and transitioned innovative technologies for real-time information data delivery to incident management teams on wildland forests in the USA. The resources and capabilities included a NASA Ikhana fixed-wing UAV, multiple sensors, satellite support, and visualization.[285]

The Ebee fixed-wing UAV from Sensefly is a drone that can be operated in swarms to survey and map areas as large as 12km.[286]

2.7.3.3. COST-BENEFIT CONSIDERATIONS AND MARKETING CHALLENGES

Autonomous operation frees up security guards from regular patrols. They can stay at a central office and follow the robots via video transmission. Where several robots operate in this way, much larger areas can be covered with fewer personnel. Pricing may follow different ways, such as on an hourly basis. As an example, Knightscope advertises a rental price of USD 4 to 9 per hour.[287]

In some areas, such as chemical plants, nuclear storage facilities, offshore oilrigs, etc., a visit to various parts of the plant might be associated with considerable risk. Here, it is advantageous to deploy robot systems. Often, the cost is of secondary importance, which has resulted in relatively early adoption of the technology. Recent disasters certainly emphasize the justification for increased research and development and availability of these platforms.

Where appropriate sensor equipment is used, the robots can detect more than humans can. Their infrared sensors can reliably trace human beings through their body warmth

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[284] Small Unmanned Aircraft System industry news for professionals, business directory: http://www.suasnews.com/category/the-market.

[285] Conner, M.: NASA Armstrong Fact Sheet: Ikhana Predator B Unmanned Science and Research Aircraft System, NASA, April 23, 2019; https://www.nasa.gov/armstrong/meda-resources/fact-sheets/#aircraft.

[286] eBee X fixed-wing mapping drone, sensefly, 2021: https://www.sensefly.com/drone/ebee-x-fixed-wing-drone/.

[287] Knightscope Inc.: MaaS Subscription Price, 2021; https://www.knightscope.com/price/.

in dark rooms (at room temperature and distances of 20 - 50 meters) and microwave sensors detect even the smallest movements up to 20 meters away. Flame, heat, and smoke sensors assure fire prevention. Additional gas sensors, measuring the concentration of carbon monoxide, acetone vapor, or methane, can be added to monitor the surrounding air and to prevent accidents.

The different sensors are additional equipment, and the price of a security robot depends on the number and kind of sensors mounted. The cheapest and thus simplest versions do not have a quality advantage over humans and a human guard remains necessary to take action in case of an emergency.

More refined versions with good perception capabilities can work under inconvenient or even extreme conditions, such as in power plants or places where gas might escape. Their value thus lies mainly in improving safety.

2.7.3.4. PRODUCERS

Aerob, Aerocon, AI Mergence, AiDrones, Aizuk, Amyrobotics, Art Robot, Ascento, Ava Robotics, BIA5, Capra Robotics, Chuangze Intelligent Robot, Cobalt Robotics, CSG, Dalu Robotech, DFKI Industrials, Digger, Dogugonggan, Dok-Ing, Enova Robotics, Everis ADS, Flir, Four D Robotics, Future Robot, Gecko Systems, Ghost Robotics, Hello Nimbo, HL Mando, Hyundai Rotem, Inbot Technology, Independent Robotics, Innok Robotics, International Robotics Solutions, Jabil - Badger Technologies, JMU Defense Systems, Knightscope, Mine Kafon, Mitsubishi Heavy Industries, Neubility, NXT Robotics, Obodroid, Ocius, Ogawayuki, Otsaw Digital, pi4 Robotics, ReconRobotics, Rice Robotics, Roboteam, Robotics Design, Rockwell Automation, Running Brains, Saildrone, Secom, Seqsense, Shandong Guo Xing Intelligent Technology, Shark Robotics, Shin Kong Security, SMP Robotics, Sohgo Security Services, ST Engineering (incl. Aethon), Terminus, Transcend Tactical, Ugo, UniRing, Unmanned Solution, ZhenRobotics, ZMP

2.8 AP8: HOSPITALITY

Authors: Florenz Graf, M.Sc.; Florian Jordan, M.Sc.; Cagatay Odabasi, M.Sc.; Dr. Birgit Graf

Service robots in everyday environments or public settings have gained significant momentum. Typically, these applications must be well designed to surprise or impress the public to invite further interaction and consumption, or they have to solve a task very efficiently and reliably. As the sector is developing quickly, some major application areas have evolved, such as food or drink preparation, as well as guidance points and information outlets in public environments. Service robots are taking over small services or promoting sales in stores, shopping malls, or at front desks. These robots usually require some robot-human interaction.

IFR statistics

Hospitality robots (AP8) enjoy growing popularity: More than 54,000 units (+31%) were sold in 2023. RaaS options are available in this application group, too. Robots for **mobile guidance, information, and telepresence** (AP82) account for most of these robots. Antitrust compliance rules do not allow the display of the breakdown by application class. Almost all of the hospitality robots reported to the IFR originate in the Asia + pacific region.

Table 2.11

Professional service robots for hospitality (2022 and 2023)

	Application	Region	2022	2023	2023/2022	2022	2023	2023/2022
			units sold		growth rate	RaaS fleet (in units)		growth rate
AP8	Hospitality	Total	41,559	54,377	+31%	**	**	-
		Europe+MENA	113	169	+50%	**	**	-
		The Americas	317	361	+14%	**	**	-
		Asia+Pacific	41,129	53,847	+31%	**	**	-
AP81	Food and drink preparation		**	**	-	0	0	-
AP82	Mobile guidance, information, telepresence		**	**	-	**	**	-

Source: World Robotics 2024
Results of IFR's annual survey and desktop research (22 robot companies for hospitality)
*Regional breakdown cannot be revealed (minimum number of non-zero observations not reached).
**Results cannot be revealed (minimum number of non-zero observations not reached). Data included in application group total (AP1, AP2, etc.).

2.8.1 AP81: FOOD AND DRINK PREPARATION

2.8.1.1. TYPES OF OPERATIONS CARRIED OUT BY THE ROBOT

When catering to visitors in public environments, robots can already perform several tasks, for example during special events or if human contact should be avoided. In restaurants, they can be used to help with the preparation of food or mixing and serving different kinds of beverages. They are especially useful when it comes to good hygiene practices or if the amount of ingredients should be precisely defined. Currently, robots are mostly used as an attraction to prepare or serve food and drinks but in the future, they will most likely play a key role in everyday business.

2.8.1.2. LEVEL OF DISTRIBUTION

With the further development of technical systems, robots are more often used to serve drinks to customers. For example, Makr Shakr from Italy has already deployed several robotic bartender systems (e.g. Toni or Bruno). These systems consist of two robotic arms mounted in the middle of the bar and several headfirst mounted bottles on the ceiling. The arms will collect the ingredients directly from the bottles. Tablet computers are affixed at selected points for ordering predefined drinks or creating one. The systems can either be fixed at a location or brought temporarily to an event. In recent years, several bars, exhibitions, and other locations have started using these robotic bartenders to offer drinks to their guests automatically.[288,289] Examples of installations can be found on several large cruise ships of the Royal Caribbean group, which provide a "Bionic Bar" created by Makr Shakr[290] or other on-land installations like at the Changi Airport in Singapore, the "Robo Bar" in Amsterdam, the "Tipsy Robot" in Las Vegas and several more.

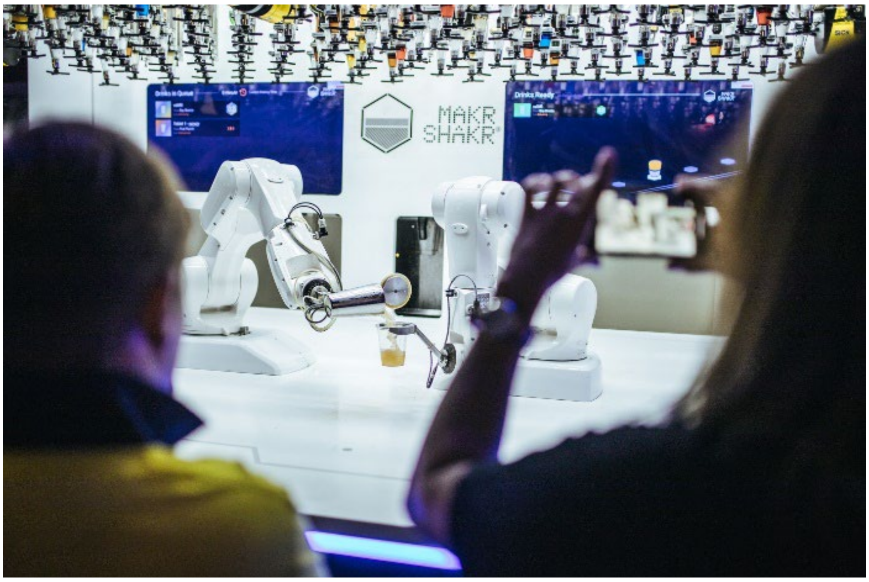

Figure 2.85: With "Toni", a fully automatic bar system from the Italian company Makr Shakr, a Kuka robot provides a taste of "la dolce vita". Image credit: Kuka.

Robots are also becoming more popular in coffee shops. For example, the robotic coffee bar from Café X has been deployed to several public environments, such as the airports

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[288] Baldwin, E.: Makr Shakr Opens Robotic Bars in Milan and London. ArchDaily, July 26, 2019; https://www.archdaily.com/921826/makr-shakr-opens-robotic-bars-in-milan-and-london.

[289] Miller, K.: This Icelandic Bar Is Utilizing Robot Bartenders For Its Reopening Plan. May 28, 2020; https://www.insidehook.com/daily_brief/restaurants-bars/iceland-robot-bartender-ice-fries.

[290] https://www.makrshakr.com/special-projects/royal-caribbean.

in San José and San Francisco (USA)[291], as well as the new Gigafactory of Tesla in Berlin.[292] This system is a standalone solution, featuring a single robotic arm in the center that handles the cups and a professional coffee machine and other barista equipment in the background. The arm is separated from the users by a window while they order different coffee specialties using the front-mounted tablet computers.

The Monty Cafe robot café from GBL Robotics from Estonia is also capable of making fresh coffee as a standalone kiosk. It consists of two robotic arms that are physically separated from the users. The robotic arms handle the cups filled with liquids and a coffee machine. They can also grab sweets or pastries, so it is possible to purchase small goods from the kiosk as well. This system offers a head-like display in between the two manipulators that has two eyes to make the robot look more anthropogenic. According to the manufacturer's website, Monty Cafe is in operation in several highly frequented public areas, such as shopping malls in Moscow and Ryazan (Russia) or Oakland (California).

Founded in 2019, the company My App Café has already deployed robot baristas in several public spaces in Germany (e.g. in Karlsruhe and Hamburg). Similar to other manufacturers, the standalone box consists of a physically separated single robotic arm, two coffee machines, and several cup dispensers for different-sized beverages. Ordering can be done via the provided smartphone app or the built-in touch screens. The kiosk can produce 80-120 drinks per hour, which can be a simple coffee, an espresso specialty, or a hot chocolate. The customer is also able to order a flavor syrup as an extra ingredient for all the offered products.

In 2021, the robot barista Ella made by Crown Digital has been deployed successfully in the Tokyo and Yokohama railway stations[293] and at a Bytes Station in Singapore[294]. The system consists of a single robotic arm made by Techman Robot, a cup dispenser, and several coffee machines. These parts are separated from the customers by a gorilla glass enclosure and the arm can drop off the ordered coffees in one of six handover boxes. Ordering can be done via the built-in touch screen or the available smartphone app. Additionally, several cameras have been mounted in the kiosk to observe every step of the process. By utilizing AI systems, errors like spillages can be detected and reported to a central supervision station, thereby allowing human workers to take care of these issues.

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[291] Mascarenhas, M.: Robotic Coffee Startup Cafe X Shutters Stores, Pivots To Airports. Crunchbase News, January 7, 2020; https://news.crunchbase.com/news/robotic-coffee-startup-cafe-x-shutters-stores-pivots-to-airports/.

[292] Wolf, M.: Cafe X's Robot Barista is Now Slinging Coffee in Tesla's Berlin Giga Factory. The Spoon, November 10, 2023; https://thespoon.tech/cafe-xs-robot-barista-is-now-slinging-coffee-in-teslas-berlin-giga-factory/.

[293] Sim, W.: Singapore-made robot Ella serves up coffee at Tokyo, Yokohama train stations. The Straits Times, December 8, 2021; https://www.straitstimes.com/asia/east-asia/ella-the-singapore-made-robot-serves-up-coffee-at-tokyo-yokohama-stations.

[294] Salim, Z.: S'pore robot barista ELLA now at Raffles Place, the first out of 30 MRT stations by end 2022. Vulcan Post, March 2, 2022; https://vulcanpost.com/780179/robot-barista-ella-raffles-place-mrt-singapore/.

Another example of a beverage robot is the standalone Robotic Bar developed by Smyze, which also has already been deployed in several public areas in Switzerland. [295] As with other solutions, this system offers a single robotic arm built by Franka Emika, a cup dispenser system, and a drop-off point, which are all separated from the customers by a window. In addition to offering coffee, this system can also hand out several beverages like mocktails or other specialties. For this, not only a coffee machine is mounted inside the operation area but also an ice cube dispenser and several faucets. As with other robotic bars, the customers can place an order via a built-in touch screen or a smartphone app. The robotic arm will then collect a suitable cup and all the necessary ingredients in a defined order and place the finished beverage at the drop-off point for collection.

Figure 2.86: Smyze serving drinks: At urban hotspots, during events, and wherever people feel like having a drink or coffee to go. Image credit: Smyze.

In April 2018, the U.S. startup 6d bytes launched a fully autonomous smoothie-making robot called Blendid. It has been successfully deployed to the campus of the University of San Francisco[296], to the campus of Sonoma State University[297], and more recently to

[295] Albrecht, C.: Switzerland: Smyze's Robot Barista Makes Coffee and Mocktail Drinks. The Spoon, June 17, 2021; https://thespoon.tech/switzerland-smyzes-robot-barista-makes-coffee-and-mocktail-drinks/.

[296] Albrecht, C.: Blendid's Smoothie Robot Heads Off to the University of San Francisco. The Spoon, March 26, 2019; https://thespoon.tech/blendids-smoothie-robot-heads-off-to-the-university-of-san-francisco/.

[297] Buzalka, M.: Blendid smoothie-making robot debuts at Sonoma State University dining services. Food Management, January 2, 2020; https://www.food-management.com/colleges-universities/blendid-smoothie-making-robot-debuts-sonoma-state-university-dining-services.

a Walmart store in Fremont.[298] The standalone system consists of a UR robotic arm in the middle that handles the cups, several containers with pre-cut fruit inside, an opening at the bottom, and a blender, which are all separated from the users by a window. The customers can order a predefined smoothie at the front-mounted touch screen or their own smartphone and change the amount of ingredients individually. Once a customer orders a product from the kiosk, Blendid's "food operating system" (foodOS™) handles that order by controlling the robotic arm and the built-in kitchen equipment.

Automating food preparation in catering services has increasingly become a topic for robot use. An example is the kitchen assistant "Flippy" from the startup Miso Robotics. This assistant consists of a robotic arm that is mounted in front of a grill or fryer and a 3D and a thermal camera. In an alternative version called "Flippy 2", the robotic arm is mounted headfirst on a linear axis under a kitchen hood to take up less space while still being able to operate several fryers.[299] It can autonomously handle 19 different food types, like flipping burger patties, burger buns, or chicken bits on the grill, and put food in or out of the fryer, controlled by the ChefUI software developed by Miso Robotics. It works together with humans in kitchens, where humans are making the burgers and taking care of other chores that the robot cannot do. In August 2018, the robot was used at the Dodger Stadium in Los Angeles[300], where it helped to serve over 50,000 customers a day. In 2020, a cooperation between Miso Robotics and the restaurant chain "White Castle" was announced to spread the use of food-preparing robots in the USA.[301] In another configuration called "Chippy", the robot is used at Chipotle restaurants to fry tortilla chips.

The company Ekim created a fully autonomous kitchen under the trademark Pazzi, in which three robotic arms bake pizzas depending on a customer's order. The kitchen is a room that is clearly separated from humans and uses highly specialized tools that take care of coating the dough and topping the pizza. The arms move the dough to the next station, spread sauce on it, and even cut it into slices after baking. It is possible to individualize the pizza with a touch screen installed in front of the kitchen.[302] In 2021,

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[298] Brown, L.: Blendid™ Opens Fourth Kiosk Location at Walmart in Bay Area. Cision PR Newswire, October 15, 2020; https://www.prnewswire.com/news-releases/blendid-opens-fourth-kiosk-location-at-walmart-in-bay-area-301152730.html.

[299] Meisenzahl, M.: Flippy, the USD 30,000 automated robot fast-food cook, is now for sale with 'demand through the roof' — see how it grills burgers and fries onion rings. Business Insider; October 18, 2020; https://www.businessinsider.com/miso-robotics-flippy-robot-on-sale-for-300000-2020-10?r=
DE&IR=T.

[300] Albrecht, C.: Flippy's Frying Pilot is a Hit at Dodger Stadium. The Spoon, September 24, 2018; https://thespoon.tech/flippys-frying-pilot-is-a-hit-at-dodger-stadium/.

[301] Tarantola, A.: Your next White Castle slider could be cooked by a robot. Miso Robotics' Flippy is part of an upcoming pilot program, July 14, 2020; https://www.engadget.com/your-next-white-castle-slider-could-be-cooked-by-a-robot-090012343.html.

[302] Huw, O.: France now has a robot-run pizza restaurant. Time Out, June 15, 2020; https://www.timeout.com/news/france-now-has-a-robot-run-pizza-restaurant-061520.

Ekim launched its first publicly accessible restaurant in Paris.[303] However, the restaurant had to close its doors in autumn 2022 since a French court liquidated its assets.[304] Other news with respect to the company were not available in Spring 2024 and it has to be seen to what extent the concept will remain in place in the longer term.

Another robot assisting in the topping process of pizzas is xPizza One, developed by xRobotics.[305] The process starts by placing a prepared pizza dough onto one of several autonomous carts. The cart then drives into a closed system in which optical markers for localization are printed onto the surface and then transports the pizza to the next station. At each station, a specific topping is added to the pizza from the ceiling of the system while the cart can move linearly and spin the plate to allow even distribution of the toppings. At the end, the cart moves out of the closed area and a human employee can put the garnished pizza into an oven. All the carts are synchronized by a main system, avoiding collisions and offering the flexibility of changing the recipe to arbitrary orders. The system was tested for one month in a Dodo Pizza outlet in Oxford, Mississippi, creating 100 pizzas per hour, 472 in total.[306]

In September 2019, the startup Niska opened an ice cream shop that is run mostly by robots.[307] The customers are greeted by Softbank’s Pepper robot and can order a predefined sundae or create their own by using the provided touch screen. After the order has been dispatched, a robotic arm starts to scoop the desired flavors out of the cooled containers and puts them into a mug. As soon as all the flavors are placed in the mug, the mug is transported to the next station at which a second two-armed robot puts different kinds of toppings (e.g. sprinkles or chocolate sauce) onto the ice cream. Lastly, the order is delivered onto a shelf that can be opened with a QR code printed on the customer’s receipt and out of which the customer can take their order safely. However, the store in Melbourne closed recently before being moved to the Middle East for further deployment.

In 2019, LG deployed its cooking robot in the Cloi-brand, called Cloi Chefbot, in a South Korean restaurant to help with preparing soup for the customers.[308] The robot receives a bowl with customer-picked ingredients and puts the ingredients into one of six water-boiling stations. After a certain amount of time, it takes them out again and puts them

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303 Albrecht, C.: Pazzi Opens Robotic Pizza Restaurant in Paris. The Spoon, July 7, 2021; https://thespoon.tech/pazzi-opens-robotic-pizza-restaurant-in-paris/.

304 Wolf, M.: French Robot Pizza Restaurant Startup Pazzi Shuts its Doors. The Spoon, October 7, 2022; https://thespoon.tech/french-robot-pizza-restaurant-startup-pazzi-shuts-its-doors.

305 Blake, R.: Age Of Robo-Pizza, Lukewarm On Arrival, Heats Up. Forbes, September 25, 2020; https://www.forbes.com/sites/richblake1/2020/09/25/age-of-robo-pizza-lukewarm-on-arrival-heats-up/?sh=530bca214a61.

306 Albrecht, C.: xRobotics’ Pizza Assembling Robot Concludes Test with Dodo Pizza. The Spoon, April 22, 2021; https://thespoon.tech/xrobotics-pizza-assembling-robot-concludes-test-with-dodo-pizza/.

307 Hogan, R.: Niska introduces robotic retail through ice cream. September 17, 2019; https://insidefmcg.com.au/2019/09/17/niska-introduces-robotic-retail-through-ice-cream/.

308 Mu-Yhun, C.: LG installs noodle making robot in restaurant. ZDNet, November 24, 2019; https://www.zdnet.com/article/lg-installs-noodle-making-robot-in-restaurant/.

together with hot gravy into a bowl and hands it back to the customer. The ultimate goal of LG is to deploy robots in kitchens so that they can take over repetitive or dangerous tasks to support the human staff.

Another general trend in automated food serving is fast assembly, which can be seen in operation in, e.g., the Semblr system from Karakuri.[309]

In these systems, a single robotic arm is placed in the middle of an inventory system in which different pre-chopped ingredients are placed by assisting workers. The customers can then order a defined meal or create their own compilation. After receiving an order, the arm moves dishes to each ingredient location, where an automatic dispersion module inserts the desired amount of ingredients into the dish. After completion of the order, the arm moves the finished dish to a separated hand-over station at which the customers can collect their orders. These types of system can handle multiple orders at once and offer a fast order fulfillment rate, making them suitable for crowded places like company canteens. In March 2024, the Germany based startup Goodbytz together with the food service company Sodexo put such a system prototype in operation at the university hospital in Tübingen.[310] According to Sodexo, operations in other locations are already in plan as well.

[309] Wolf, M.: Karakuri Semblr Food Robot To Feed Up to Four Thousand Employees at Ocado HQ. The Spoon, September 23, 2021; https://thespoon.tech/karakuri-semblr-food-robot-to-feed-up-to-four-thousand-employees-at-ocado-hq/.

[310] Hintersdorf, C.: Automatisierte Roboterküche kommt nach Tübingen. HOGAPAGE, March 14, 2024 https://www.hogapage.de/nachrichten/messeneuheiten/technik-software-messe/automatisierte-roboterk%C3%BCche-kommt-nach-t%C3%BCbingen/.

Figure 2.87: 17 ingredients, 2,700 combinations, and up to 110 meals per hour: The canteen robot Semblr tickles the tastebuds of Ocado employees with a Kuka KR Agilus. The brains behind Semblr can be found at the integrator Karakuri, a London-based startup. Image credit: Kuka Group.

2.8.1.3. COST-BENEFIT CONSIDERATIONS AND MARKETING CHALLENGES

Using robots in restaurants frees up human staff from routine tasks and ensures constant and good quality thanks to more precise planning and timing. Especially tiresome and repetitive tasks can be automated by robots, and by offering flexibility in programming and configuration, they can be adapted to other tasks. Nevertheless, acquiring a robot for these services is probably not very cost efficient as these services are entry-level tasks and as such not very expensive when fulfilled by humans. Moreover, customers often want to talk to a human worker in customer service scenarios. Still, with the ever-increasing lack of personnel, robots can provide assistance to many companies and take over selected tasks. Especially after restarting a business post COVID-19 lockdowns, hiring workers became even more difficult. Moreover, being able to automate even the simplest of daily tasks is highly valuable when it comes to keeping up with customer orders and quality requirements while also alleviating the load on human employees.

A major advantage might be leveraged through the high degree of attention that a robot tends to draw in public areas like restaurants and hotels, which is certain to have an advertising effect as long as the majority of the competitors do not make use of robotics, too.

2.8.1.4. PRODUCERS

Aeolus Robotics, Alkadur, Café X Technologies, Dexai Robotics, HD Hyundai Robotics, LG Electronics, Macco, Makr Shakr, Miso Robotics, Moley, Mrobot

2.8.2 AP82: MOBILE GUIDANCE, INFORMATION, TELEPRESENCE ROBOTS

2.8.2.1. TYPES OF OPERATIONS CARRIED OUT BY THE ROBOT

The robots covered in this chapter are used in public environments as attractions or in mobile information kiosks to promote goods and services (see chapter 2.6.2 for more information about delivery robots, for example in restaurants). Usually, they have a mobile platform with varying multimedia features on top. Environments for using these robots can be highly diverse, e.g. shopping malls, stores, trade fairs, sales and service centers, etc.

The operation modes can be fully or semi-autonomous or remote controlled, depending on the actual application. Most robots aim to reduce the workload on human staff. The autonomous navigation through the environment enables these robots to provide information to people at a desired place. For instance, they can guide people in museums or stores and provide them with information. Another typical field of application is the healthcare sector. Here, interaction robots, sometimes also referred to as "social robots", are used for a variety of purposes: They can address patients directly, activate them cognitively, enable interaction with family members or medical staff who are not on site, and can thus maintain or even improve the quality of stay in care and healthcare facilities despite financial or staffing bottlenecks. A few devices even offer medical functions, such as recording vital parameters. In this case, the products are listed as "medical robots" and presented in chapter 3.1.4.

Telepresence robots are typically tele-operated and allow a person to interact with the environment while not physically being there. According to the definition used in this publication, purely remote-controlled systems are not seen as robots but as robotic devices and are thus not covered in detail. However, autonomously navigating to pre-defined points is also offered by many manufacturers to ease the controllability of the robot.

As most of these robots are mobile robots and equipped with cameras, their duties can be shifted easily with small modifications. In 2020, due to the COVID-19 pandemic, numerous interaction robots were equipped with thermal cameras and used to measure the temperature of the people they were interacting with or to check whether masks were being worn properly.[311]

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[311] Meisenzahl, M.: An Indian hospital is using robots with thermal cameras to screen coronavirus patients – here's how they work. May 9, 2020; https://www.businessinsider.com/india-coronavirus-robot-uses-thermal-camera-to-take-temperature-2020-5?r=DE&IR=T.

2.8.2.2. LEVEL OF DISTRIBUTION

Mobile guidance and information robots

Robots with a screen

This robot design is very typical because it is comparatively easy to implement: Mobility is enabled by wheel-driven platforms, and the exchange between humans and robots, or humans and humans, takes place via a screen. To boost the level of hospitality with a human-like design, these robots can use a face on their screens. Inbot Technology offers a large variety of their Padbot robots. The Guide Robot X3 provides information on a large screen but also comes with abilities for ID card recognition and a thermal printer to support tasks in the administrative sector. It can also guide users to a designated window to handle their business.

Orionstar Robotics offers a set of service robots for informing customers in shopping malls, hotels, restaurants, and stores. The receptionist robot Greetbot Mini comes with a slim body and a screen on its head. It is capable of holding conversations with customers and accompanying them while they shop. Luckibot Plus is taller and equipped with a large screen for promotional and marketing content. Additionally, it can be used to guide people, e.g. to find a specific product in a shop or to take visitors to the meeting room.

Amy Robotics offers two similar types of robots. The AmyMY-A series robot is also of medium size and uses a screen as a head. The AmyMY-M1 series robots additionally have a large screen in front of their body for advanced interaction. The robots have already been used at various exhibitions and events.

LG has revealed a set of robots with the brand name CLOi, which are intended at to carry out various tasks, including information robotics. Particularly, LG’s Guidebot is designed to provide information to people in public spaces and guide them to where they want to go, if necessary. An example of the deployment of LG’s Guidebot can be seen in the collaboration with Hyundai Motor Company.[312] The robot employee is responsible for providing marketing materials, information to visitors, and guiding them around. Additionally, Hyundai launched its service robot DAL-e for car dealerships to welcome, interact with, and guide customers. It can analyze the emotions of customers and act accordingly. The company has already showcased a pilot robot at one of its showrooms in Seoul.[313]

[312] LG and Hyundai collaborate to bring robots and cars closer together. July 2, 2019; http://www.lgnewsroom.com/2019/07/beyond-news-lg-and-hyundai-collaborate-to-bring-robots-and-cars-closer-together/.

[313] Cha, J.: Hyundai Motor Group Introduces Advanced Humanoid Robot ‘DAL-e’ for Automated Customer Services. January 25, 2021; https://www.hyundainews.com/en-us/releases/3242.

At several Lowe retail stores, Lowebot has been introduced to guide customers to specific products autonomously and to inform them about current promotions.[314]

Ubtech Robotics deploys its robot, called Cruzr, in public places, such as retail stores, banks, and airports, for information and guidance purposes.

The Temi personal robot was launched in 2019 to support people by providing information via a screen and audio. The comparatively cheap robot (therefore also interesting for end users, see chapter AC 3.3.2.1) can navigate autonomously through its environment and combines speech recognition, face identification, and visual information to interact with humans. It is used in retail, healthcare, and hospitality applications. More than 7,000 robots are already in operation, primarily in the USA and Asia.

Robots with a screen and manipulator

The added value of interaction robots increases if they have arms for handling objects. However, there are still hardly any products on the market in this area. One reason for this is that manipulation capabilities are technically challenging to implement, thus augmenting the product costs. On the other hand, it is also a question of safety, as these arms must be able to operate safely in the entire usage space.

So far, there is only Pi4_robotics which offers different types of concierge robots that have manipulation capabilities thanks to an arm. Workerbot4 Concierge is a stationary robot for welcoming, registering, instructing, and informing visitors. The identity of the visitor can be verified by scanning their ID card and comparing it with the real camera image of the visitor. The visitor is informed about relevant guidelines on the touch screen and can confirm them by means of an on-screen signature. Workerbot9 Concierge comes with similar abilities but utilizes a mobile base, thus allowing it to move around autonomously.

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[314] Morgan, B.; The 3 Best In-Store Robots And Why They Work. May 13, 2020; https://www.forbes.com/sites/blakemorgan/2020/05/13/the-3-best-in-store-robots-and-why-they-work/#1adffc1137b2.

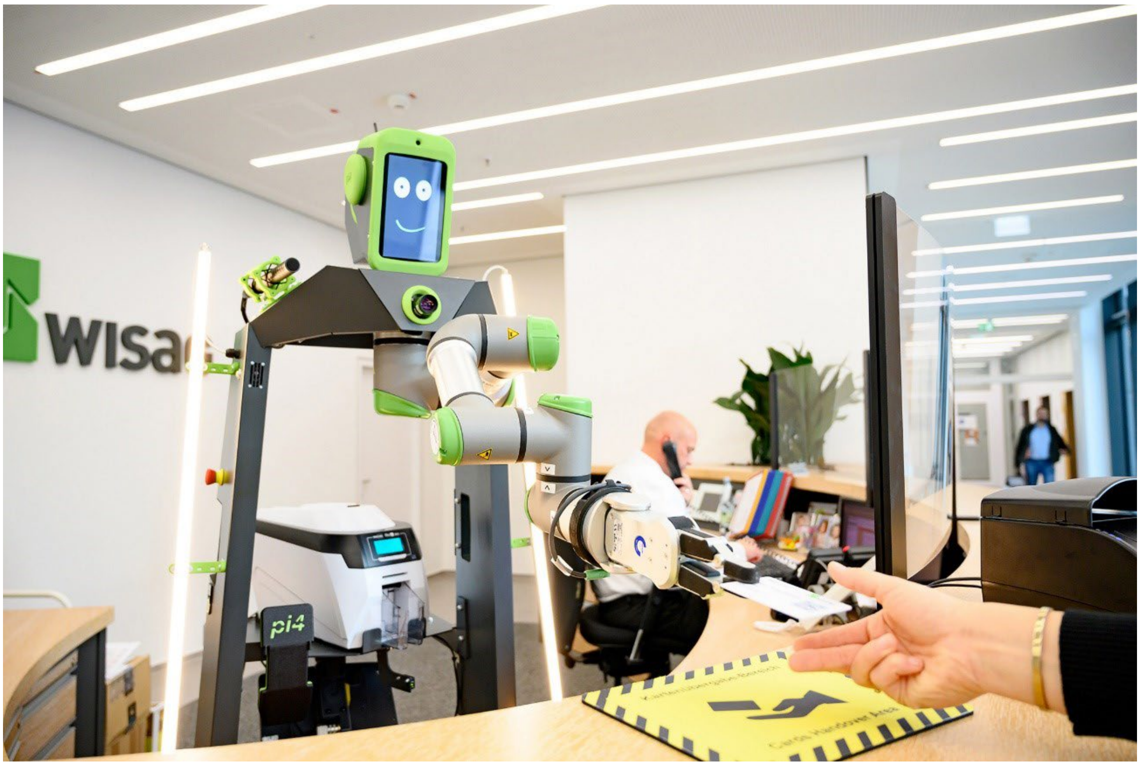

Figure 2.88: Check-in in under three minutes: The Workerbot4 Concierge robot from Pi4 at Wisag GmbH. Polite, reliable, fast, hygienic, and compliant with the General Data Protection Regulation (GDPR). Image credit: Wisag GmbH.

Tiago is the second, more prominent, product from Pal Robotics which can be equipped with different hardware components individually, e.g. a screen for interaction or a robotic arm. More than 200 units of the robot have already been sold. It is mostly used in research projects, e.g. for trials in healthcare institutions, but also for collaborative applications in industrial environments.

Figure 2.89: The Tiago platform interacting with an older individual through the touch screen. Image credit: Pal Robotics.

Robots with a human-inspired design

Another typical hardware structure is the humanoid design. This means that the robots are at least roughly modeled on humans in terms of size, structure, and appearance. However, too strong a resemblance is avoided here, as a machine design that is too human-like arouses fear. This is known as the "uncanny valley"[315]. However, if the machine is still easily recognizable as such and, for example, has arms like ours and a face like the one we know, this can strengthen our trust and sympathy, since such similarities promote a positive basic attitude. This can be explained by the "cuteness phenomena", which states that faces with large eyes usually appeal to us in a very positive way. In addition, a certain design raises people's expectations of the robot, which helps them to better assess the machine and thus have a positive attitude towards it. For example, a robot arm indicates that the robot also has gripping capabilities. Two legs, on the other hand, are still rare. However, many humanoids have platforms with wheels for locomotion. This is because they offer much more stability and require far less technical development than is necessary for two-legged humanoids.

One of the most popular robots for interaction, entertainment, and information exchange is Pepper from Aldebaran Robotics, which has been part of the German United Robotics Group since 2022. Pepper is an interactive and customizable humanoid robot designed for public environments to offer services, attract customer attention, and promote sales. Within the support of cloud computing (e.g. using the dialog services, the new popular

[315] Mori, M.: The Uncanny Valley. 2012; https://spectrum.ieee.org/the-uncanny-valley

tool ChatGPT, or other apps related to recognition tasks), there is a large potential to make this robot a versatile and customizable platform for human-machine interaction.[316] Pepper has since been introduced in numerous marketing and product promotion scenarios. It has made its debut both in the stores of major brand names (such as Nestlé, Nissan, and the telephone operator Softbank) and in over 1,000 independent retail outlets. Nao is the first robot originally created by Aldebaran. It is a small humanoid that can be used as a programming tool and is also typically used in education and research (see chapter AC 3.3.2.2). Companies and health care centers see it as an assistant for welcoming, informing, and entertaining visitors. Like humans, both robots are equipped with two arms. However, they have no or very limited manipulation capabilities, since their main task is to interact and communicate with people, something that does not require functional arms.

Ari from Pal Robotics has a humanoid head and arms for gesturing and pointing. It has been used as a receptionist, conference host, and info and attraction point, or to guide people, e.g., in stores or museums.

Promobot V.4 is a service robot that can serve people in public areas. Using a humanoid appearance, it can interact with people by performing some gestures or shaking hands. It is already used in several public buildings, airports, and amusement parts, as well as for medical applications.

Qihan Technology offers two versions of its Sanbot robot. Sanbot Elf only comes with abstract arms that cannot grasp anything but with a large screen for interaction. It is, on the one hand, used in education, e.g. for providing children puzzle game applications that are combined with the posture, language, and facial expressions of Sanbot. On the other hand, Sanbot Elf uses voice interaction to help users in a healthcare context to understand and deal with diseases, medications, daily life precautions, etc. Sanbot Max is able to carry and tow objects, autonomously map a room, avoid objects and people, translate, and answer the guests' questions.

A rather new development in this area is Navel from Navel Robotics. It is 72 cm high and comes with an expressive face. Its trademark is a knitted cap. Not only does it provide information, but it is also designed for bidirectional communication and to cognitively and emotionally stimulate users to help cope with loneliness and anxiety. Currently, it is used primarily in elderly care, but it could also provide support in childcare, psychotherapy, or care for people with disabilities. Also worth mentioning is a running field trial with Germany's two largest health care providers, who are testing Navel robots in several nursing homes.

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[316] Gardecki, A.; Podpora, M.: Experience from the operation of the Pepper humanoid robots. In Progress in Applied Electrical Engineering (PAEE), 2017, pp. 1-6; https://ieeexplore.ieee.org/document/8008994.

Figure 2.90: The robot Navel in a test scenario in a nursing home (Evangelische Heimstiftung Germany). Image credit: Navel robotics GmbH.

Alpha Mini from Ubtech Robotics is a small humanoid robot originally designed as a consumer product. However, it is also used in healthcare applications, e.g. it has been deployed in several nursing homes in Korea and Germany to provide emotional care, to remind the residents of appointments and to take their medication, or to dance with them.

Future Robot offers a versatile platform as a freely configurable information kiosk for visitor guidance. The robots can accommodate various business services (payment, printer, photo, etc.). They do not have arms but a head which moves and displays different emotional avatars.

Telepresence robots

Mobile telepresence robots are also in high demand because they allow people to attend meetings virtually with an embodied agent. During the COVID-19 pandemic, the interest in telepresence robots increased, as they provided a technical solution for human interaction despite social distancing, something that is very convenient for many but also particularly important for the elderly.[317]

Compared to tablets or smartphones, the mobile platform of the robots enables them to approach people actively, via remote control or semi-autonomous navigation (e.g. drive to a pre-defined location). For instance, telepresence robots made a remote graduation ceremony possible in 2020, despite the lockdown restrictions.[318]

Figure 2.91: With full autonomy, Ava telepresence robots empower and mobilize the hybrid workforce so that people can effectively – and safely – connect and collaborate as though they were actually in the same workspace. Image credit: Ava Robotics.

Double 3 from Double Robotics allows users to navigate the robot by using virtual markers visualized on the floor through augmented reality. Ohmnirobot from Ohmnilabs uses a similar concept with lightweight focus. An amazing variety of low-cost products

[317] Baptiste, I. et al.: Social Telepresence Robots: A Narrative Review of Experiments Involving Older Adults before and during the COVID-19 Pandemic, in: Int J Environ Res Public Health, April 2021; https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8037050/.

[318] Ingham, L.: Telepresence robots make lockdown graduation a reality for student. May 12, 2020; https://www.verdict.co.uk/telepresence-robots-graduation-students/.

for telepresence and autonomous navigation/interaction has appeared. Examples are Ava from Ava Robotics (which was used, in particular, during the pandemic[319]), Padbot (Inbot Technology), VGo (VGo Communications), Beam (now commercialized by GiBeRobots), and Anybots.[320]

The COVID-19 pandemic also forced museums to find innovative ways to let people visit their exhibitions. One example was the Hasting Contemporary Museum in the UK.[321] It hosted robot tours by using telepresence robots from Double Robotics, thereby allowing people to visit the museum with the aid of a robot from the comfort of their own home. The robot tours are still offered to groups and individuals in the local area who may be unable to travel to the museum due to a disability and/or long-term health conditions.

The COVID-19 pandemic also forced museums to find innovative ways to let people visit their exhibitions. One example was the Hasting Contemporary Museum in the UK.[322] It hosted robot tours by using telepresence robots from Double Robotics, thereby allowing people to visit the museum with the aid of a robot from the comfort of their own home. The robot tours are still offered to groups and individuals in the local area who may be unable to travel to the museum due to a disability and/or long-term health conditions.

To further extend the representation of the remote user in meetings, Microsoft is working on VR (Virtual Reality) and AR (Augmented Reality) technologies to show a virtual avatar of the remote user augmented on the telepresence robot.[323] An interesting event in this field is the Ana Avatar Xprize competition.[324] Its aim is to create robot avatars for merging the robot's body and the human's capabilities to ensure a human can be present via an avatar when needed.

Telenoid is a telepresence robot with a totally different appearance: It resembles a fetus. It transfers not only the voice but also the facial expressions of a person onto the face of the robot. Telenoid is being tested in various countries in different application scenarios; for example, in Japan with children and dementia patients, and in Denmark with people with disabilities, as well as in elderly care.

2.8.2.3. COST-BENEFIT CONSIDERATIONS AND MARKETING CHALLENGES

Public places, such as retail stores and museums, may benefit from interactive mobile robots. Experience shows that a creative installation may significantly contribute to the attractiveness of the environment, especially among children and teenage visitors. The

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319 Ackermann, E.: Telepresence Robots Are Helping Take Pressure Off Hospital Staff, IEEE Spectrum, April 15, 2020; https://spectrum.ieee.org/automaton/robotics/medical-robots/telepresence-robots-are-helping-take-pressure-off-hospital-staff.

320 Telepresence robots: https://www.pinterest.de/slanderretche/telepresence-robots.

321 https://www.hastingscontemporary.org/learning/#robot-tours.

322 https://www.hastingscontemporary.org/learning/#robot-tours.

323 Jones, B.: VROOM: Virtual Robot Overlay for Online Meetings; https://dl.acm.org/doi/fullHtml/10.1145/3334480.3382820.

324 https://www.xprize.org/prizes/avatar.

robots can focus the visitors' attention on the desired part of the location. Nevertheless, costs are still a restraint. In this respect, modular or multi-purpose robots can increase the benefits. For instance, a mobile robot can be a guide and an information desk at the same time.

One important aspect is voice recognition. Working closely with people requires robust, accurate algorithms, especially in speech recognition. If the customers were misunderstood, the interaction would be completely wrong and frustrating. Thus, the development of AI (and generative AI in particular) supports the deployment of service robots because the algorithms become more accurate and robust.[325]

Although telepresence robots can be beneficial for remote working, meetings, and remote visits, their costs start at around USD 1,000 to 1,500. The price range is still a significant constraint for the extensive adoption by end users. On the other hand, investment in telepresence robots could be profitable for companies because the robot can facilitate cooperation among multiple stakeholders and boost the companies' remote work practices and virtual meetings. As with all robots, telepresence robots also benefit from advancements in technology. With decreasing costs for the motor, sensor, and production, we will see more affordable products on the market.

[325] See for example: https://openai.com/research/whisper.

2.8.2.4. EXPERT VIEW

The following interviews with United Robotics Group from Germany, Pal Robotics from Spain, and Navel Robotics from Germany were conducted in 2024 as part of the major focus chapter revision by Fraunhofer IPA.

2.8.2.4.1. INTERVIEW WITH UNITED ROBOTICS GROUP

Company:	United Robotics Group, Germany
No. of employees:	> 450
Product:	Interaction robot Nao
Interview partner:	Tourcher Sandrine (Product Director)

Why did you choose to develop interaction robots?

At United Robotics Group, our mission is to create cobots that benefit society by improving quality of life, enhancing human-robot interaction, and offering educational or professional assistance to humans. We chose to develop Nao, one of our interaction robots, because we see them as powerful pedagogical tools to support education in diverse fields (technical and non-technical). For example, in the educational market, Nao can engage students in learning programming and technology, ensuring these subjects are more accessible and enjoyable. Our focus is on making technology approachable and beneficial for everyone, fostering a future where robots can empower humans in their missions.

What was the most impactful decision for your product development?

One of the most impactful decisions we made was to design a robot with several string interaction skills and an open platform. This decision has allowed us to collaborate with a wide range of developers and educators, who contribute their unique expertise to enhance our products. By making our robots highly customizable and adaptable, we have encouraged a community-driven approach to innovation, where users can develop new applications and functionalities. This collaborative ecosystem has significantly accelerated the development of our robots, ensuring they meet the diverse educational needs of our users and stay at the forefront of technological advancements.

What are the biggest hurdles in terms of bringing your robots to the market?

The biggest hurdles we face include ensuring affordability, achieving a user-friendly design, and overcoming societal acceptance. Developing advanced robotic technology is costly, and making these robots affordable for schools and businesses is an ongoing challenge. We also strive to design our robots to be cute, friendly, intuitive, and easy to use, minimizing the learning curve for new users. Additionally, there is a societal hurdle in terms of acceptance and trust in robotic technology. We work diligently to demonstrate the practical benefits and safety of our robots to build trust and encourage wider adoption.

Looking into the future, what are the biggest challenges ahead for your customers?

Our customers will face challenges related to integrating robotics into their daily activities and facilities. As robotic technology continues to evolve, ensuring that users can seamlessly incorporate these innovations into their existing systems will be crucial. Another challenge will be keeping up with the rapid pace of technological advancements. Educators, for instance, will need ongoing support and training to effectively use robots like Nao to enhance their teaching methods.

How are you planning to further develop your products to tackle these challenges?

To tackle these challenges, we are committed to continuous innovation and user support. We plan to enhance our products by incorporating more advanced AI capabilities, better vocal interactions, and making them more intuitive and responsive to user needs. We will also expand our educational programs and resources to ensure our users have access to comprehensive training and support. Additionally, we are investing in robust security measures to protect user data and to address privacy concerns. Our development roadmap includes regular updates and improvements based on user feedback, ensuring our robots remain relevant and valuable tools in their respective fields. By staying attuned to our customers' evolving needs, we aim to create a future where Nao can really change the way we learn, we teach, and we live with robots.

2.8.2.4.2. INTERVIEW WITH PAL ROBOTICS

Company: Pal Robotics, Spain
No. of employees: 100
Products: Interaction robot Ari, mobile manipulation robots Tiago and Tiago Pro
Interview partner: Narcís Miguel Baños, PhD (Head of Mobile Interaction)

Why did you choose to develop interaction robots?

We chose to develop interaction robots to meet the growing need for robots that can interact with and support people in various everyday applications. Our social robot Ari is designed for natural communication and social interaction, making it ideal for environments such as healthcare, education, and events. The robot facilitates natural language communication and provides valuable assistance in diverse settings. For instance, Ari has been successfully used in hospitals and educational projects, proving the platform's effectiveness in real-world scenarios.

Tiago offers robust manipulation and perception capabilities, making the robot versatile for tasks in healthcare, industry, and research. Moreover, Tiago is particularly effective in environments that require precise handling and complex task execution, such as industrial automation and assistive roles. Our latest platform, Tiago Pro, launched in May 2023, features advanced human-robot interaction capabilities and new arm technology, allowing the robot to safely share space with people and to handle complex tasks collaboratively. Tiago Pro combines all the strengths of its predecessors with enhanced usability and computational power, catering to a wide range of applications, from manufacturing to healthcare.

What was the most impactful decision for your product development?

A significant decision in our product development was prioritizing user-centric design and safety certification. For Ari, we focused on ensuring the robot could engage naturally with users, making Ari suitable for direct customer interaction in environments like hospitals, educational institutions and events. Tiago required the development of versatile manipulation capabilities to handle a wide range of service applications, from assisting in healthcare to performing industrial tasks. For Tiago Pro, the shift from research to practical applications involved co-designing the platform with a high degree of usability and obtaining comprehensive certifications to ensure safety in various environments. We aimed to create a product that maintained high usability while meeting rigorous safety standards.

What are the biggest hurdles in terms of bringing your robots to the market?

One of the primary hurdles in bringing PAL's robots to the market is ensuring seamless integration with diverse customer environments. Every industry and organization has its unique requirements, and customizing the robots to meet these specific needs can be challenging. However, our flexible design and robust support infrastructure are tailored to address these variations, ensuring that our robots can be adapted to a wide range of applications. Another significant challenge is achieving user acceptance and changing perceptions of robots in everyday life. Our robots are designed to assist and operate alongside people. Demonstrating the value of this collaboration and ensuring users feel comfortable interacting with our robots are crucial factors. We focus on intuitive design and user-friendly interfaces to make this transition as smooth as possible. Lastly, managing the rapid pace of technological advancements in AI and robotics is a constant challenge. To stay ahead, we invest heavily in research and development, ensuring that our platforms remain at the forefront of innovation and can incorporate the latest technological advancements.

What would you see as the biggest challenges ahead for your customers?

We understand that integrating robots like Ari and Tiago into existing systems might seem challenging. While the initial investment cost might be a concern, Ari and Tiago robots are an investment in future savings and efficiencies. Staying ahead in the rapidly evolving AI landscape is essential. We ensure that robots like Ari remain cutting-edge through continuous software updates and easy hardware upgrades, so you won't need frequent new investments and have sufficient computational power. Another challenge is the robot's operation in unstructured environments. Significant advantages of our robots are their advanced understanding of the semantics of a scene and their ability to manage unstructured environments effectively. Our robots can navigate and operate in dynamic and unpredictable settings, recognizing and adapting to various objects and scenarios. This capability ensures that the platforms can function seamlessly in real-world environments, providing reliable and efficient service.

How are you planning to further develop your products to tackle these challenges?

We continue to develop our products by engaging in collaborative projects and user feedback sessions. For Ari, we focus on enhancing communication and interaction capabilities, ensuring the robot meets the needs of end users in service roles. Projects like Pro-Cared, a Catalan language education initiative, and healthcare deployments in projects like Shapes and Spring, showcase Ari's adaptability and effectiveness in real scenarios. Tiago benefits from projects like Agimus and Pillar-Robots, which enhance decision-making and autonomy in manufacturing environments. These projects allow us to refine Tiago's capabilities to better serve industrial and healthcare applications. Tiago Pro is continuously refined through projects like Canopies, targeting outdoor applications with AI-driven vision tools, ensuring the robot remains at the forefront of interaction technology. By incorporating user feedback and conducting real-world trials, we optimize both hardware and software to meet diverse user needs.

2.8.2.4.3. INTERVIEW WITH NAVEL ROBOTICS

Company:	Navel Robotics GmbH, Munich, Germany
No. of employees:	2-10 employees
Products:	Social robot “Navel”
Interview partner:	Jakob Biesterfeldt (COO)

Why did you choose to develop social interaction robots?

The initial motivation was the shortage of nursing staff and the awareness that this is a trend that cannot be reversed in the near future. We have more and more people in need of care and fewer and fewer caregivers. This is a common issue in all industrialized countries around the world, and this gap can only be filled with technology. Robots are certainly an important part of that. Those in need of care, caregivers, and care providers can benefit from that. Our other motivation was a bit philosophical, so to speak. Our research field in the last years was human-machine interaction. Until now, the human always had to learn how to deal with the machine. We wanted to build a product where the machine has to learn how the human works, that was the original idea.

What was the most impactful decision for your product development?

Initially, the most important decision was to determine that the robot has to be able to recognize and process social signals and also give them back; that is the core challenge that we are trying to solve with our robot. A human constantly sends out social signals through facial expressions, via gestures, non-verbally, verbally in their speech, and through the pitch of their voice. There is contextual information that plays into it, i.e. what does the room look like, is the person sitting in a wheelchair, or how old is the person? All of these are social signals that we, as humans, intuitively perceive and incorporate into our conversations thereby creating a social resonance. We wanted to develop a robot that can understand such signals. On the output side, the robot should also be able to play these social signals back to the human. This means that the robot needs significant facial expressions and the ability to interact socially, also non-verbally, something which we are currently doing through eye contact. It was a very impactful decision that we put 3D lenses in front of the eyes of the robot, which simulate real eye contact. Very elementary for social interaction are also the robot’s head and eye movements. It has been thoroughly researched what people do, and we are trying to imitate that. The next important decision was the use of AI in the broadest sense and ultimately to work with GPT. And additionally, to integrate and use all the means of AI that are currently being developed.

What are the biggest hurdles in terms of bringing your robots to the market?

One thing is money. The development of hardware and software in this combination, where you serve absolute trend topics, i.e. autonomous driving, robotics, artificial intelligence, is obviously extremely expensive. Then, the people who can do something like that are in high demand and expensive. Finally, it is complex technology, whose development devours a lot of money. Robots and all the individual components have been around for a relatively long time. However, with the current possibilities, all this is very new in the overall package, and that means you cannot quickly design something at your desk and then bring it to market. You have to work in a very user-centered way and try out a lot, and, of course, that costs money. You have to build prototypes, then you have to do studies with them, you have to put yourself in the context of the customers, and then you have to collect feedback, and then you have to discard things and develop them again. It is also a challenge to find the real "killer" use cases. This is not only a question of money, but it is also a question of content: Where do you really find a solution to an existing problem of our customers? How can I refinance something like that? What do I get in return? There are legal hurdles or regulations that have to be taken into account. For example, there is the skilled worker quota on the wards, which cannot yet be dissolved or softened. Ultimately, there is the acceptance, impact, and benefit of understanding our customers and creating an awareness of the possibilities.

Looking into the future, what are the biggest challenges ahead for your customers?

It is difficult for healthcare facilities to understand which new technologies really make sense. And how can I try them out and what funding opportunities can I tap into for them? Many nursing homes do some kind of fundraising or must plan for the very long term. The regulatory environment is also difficult for them. The shortage of skilled workers is a big pain point for our customers, and I think it is also the biggest challenge of all. They cannot fill their beds to capacity and provide care the way they would like to; they are very inflexible. To bring in new ideas is hard and means a real commitment, and you have to have the people to put them into practice and to free up the necessary time. And then you need to know how to evaluate all this and say after a test phase, this works or doesn't work for us. Finding these criteria is really a challenge.

How are you planning to further develop your products to tackle these challenges?

One thing is pilot projects, which is the next thing we are doing very intensively. Their support is associated with a great deal of effort, which is certainly also a challenge. We are currently launching twelve more robots on the market, in various facilities, and it is very important that we collect feedback and then develop it further on this basis. Further development will be strongly related to efficiency-enhancing functions, i.e. the integration of the robot into existing systems. The robot must not only be understood as a standalone interaction machine but also counteract the shortage of skilled workers or the stress on the ward. For example, through integration with the documentation system, translators for foreign skilled workers or foreign residents, and fall detection. Also, the recognition of vital parameters that are not medical but that could be passed on, for example the speed of speech: Mr. Miller suddenly speaks much slower than usual on average, and then the robot informs the nurses. These are very specific use cases that go beyond pure social interaction. The further development of social skills is roughly on the same priority level, i.e. the additional integration of algorithms that process social signals, e.g. gestures. There are a lot of people who wave to the robot or say come here.

2.8.2.5. PRODUCERS

AkinRobotics, Amyrobotics, Asimov, Aubot, Ava Robotics, Avatar-In, Awabot, Axyn Robotique, Beijing Yunji Technology, Blue Ocean Robotics, Bot Eyes, Canbot, Chuangze Intelligent Robot, CloudMinds Technology, Co-Robotics, CT-Asia Robotics, Deduco, Devanthro, Double Robotics, Dynsoft, Elephant robotics, Fubao Intelligent Technology, Future Robot, HIT Robot Group, IdMind, Inbot Technology, Indy Associates, Infocom, InGen Dynamics, Invento Robotics, Keman Intelligent Technology, Kompaï Robotics, LG Electronics, Luvozo PBC, Marses, MetraLabs, Milagrow Humantech, Nanjing AvatarMind Robot Technology, Navel Robotics, Ohmnilabs, Orionstar, Pal Robotics, pi4 Robotics, Promobot, Pudu Technology, Quihan Technologies, Rice Robotics, Robotswim, Shanghai Keenon Intelligent Technology, Slamtec, Smart Robotics, Suzhou Pangolin Robot, Techmetics Robotics, Temi, Terminus, UBT Robot, Ugo, United Robotics Group, Unlimited Robotics, Zhejiang Buda Technology, Zorabots

2.9 AP99: OTHER PROFESSIONAL SERVICE ROBOTS

There are quite many other service robotics solutions that are not covered by the described application. Many of the units are powered exoskeletons intended to provide active support for workers, but there are also robots used in joyrides or simulators, professional lawn mowing robots used in sports and recreational facilities, robotic line painting solutions for sport fields, and robots in mining that are counted in this class. To give an impression about this variety, the following gallery presents some examples.

IFR statistics

Application class A9 contains robots for **other professional applications** that do not fit into any of the other classes. Here, growth in sales amount to +16% with 2,240 units sold in 2023.

Table 2.12

Other professional service robots (2022 and 2023)

Application		2022	2023	2023/2022	2022	2023	2023/2022
		units sold		growth rate	RaaS fleet (in units)		growth rate
AP99	Other professional service robots*	1,923	2,240	+16%	**	**	-

Source: World Robotics 2024
Results of IFR's annual survey and desktop research (22 other professional service robot companies)
*Regional breakdown cannot be revealed (minimum number of non-zero observations not reached).
**Results cannot be revealed (minimum number of non-zero observations not reached). Data included in application group total (AP1, AP2, etc.).

Figure 2.92: The Cray X power suit from German Bionic in operation at the Fiege Megacenter in Ibbenbüren, Germany, providing up to 30kg of active support per lifting movement Credit: German Bionic.

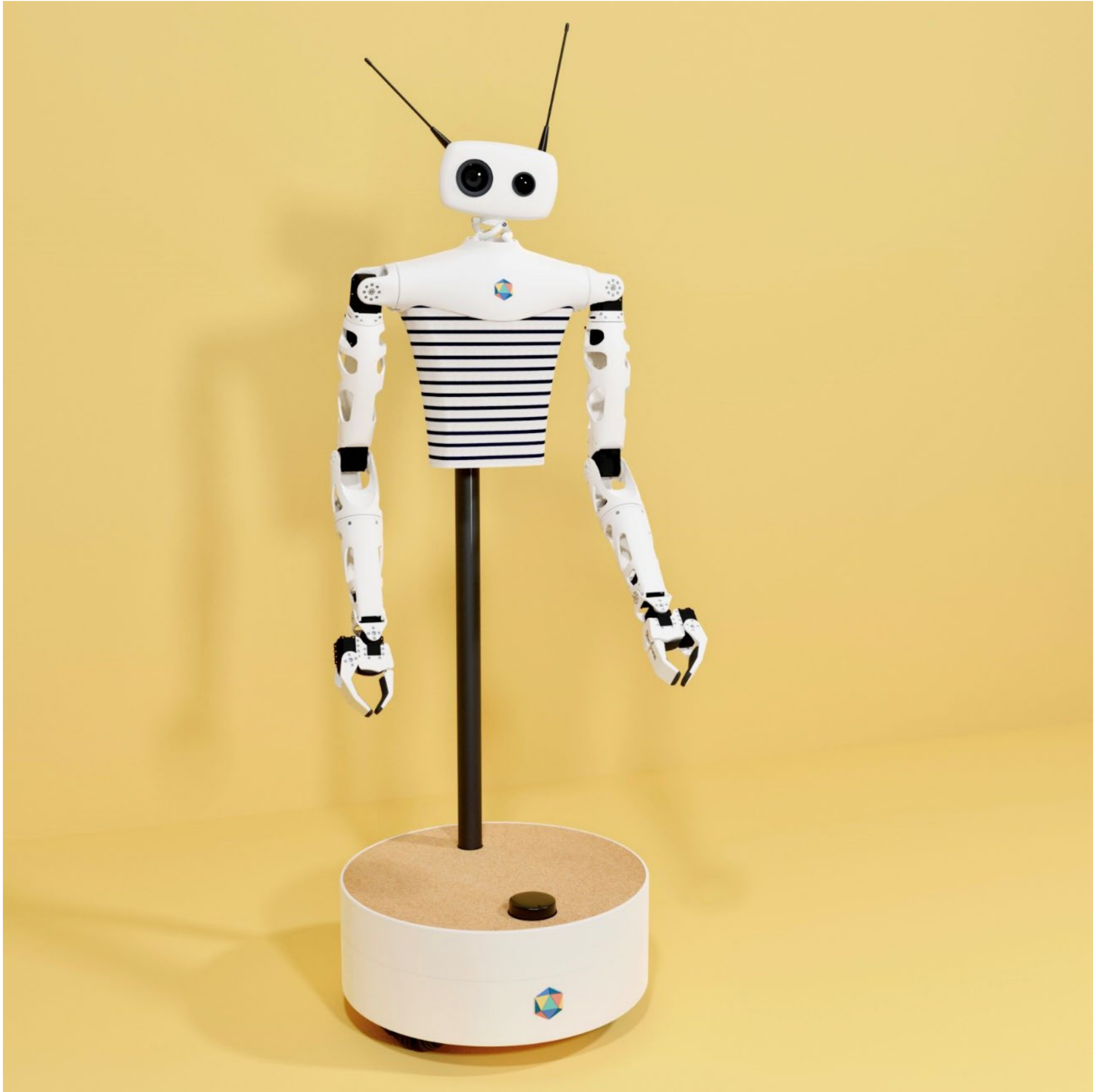

Figure 2.93: Reachy is an expressive open-source humanoid platform programmable with Python and ROS. It is particularly good at interacting with people and manipulating objects Image credit: Pollen Robotics SAS.

Figure 2.94: Exoback is useful for lifting heavy loads in professional works and jobs. Industry, construction, logistics are the main areas of interest for back support exoskeletons. Image credit: RB3D.

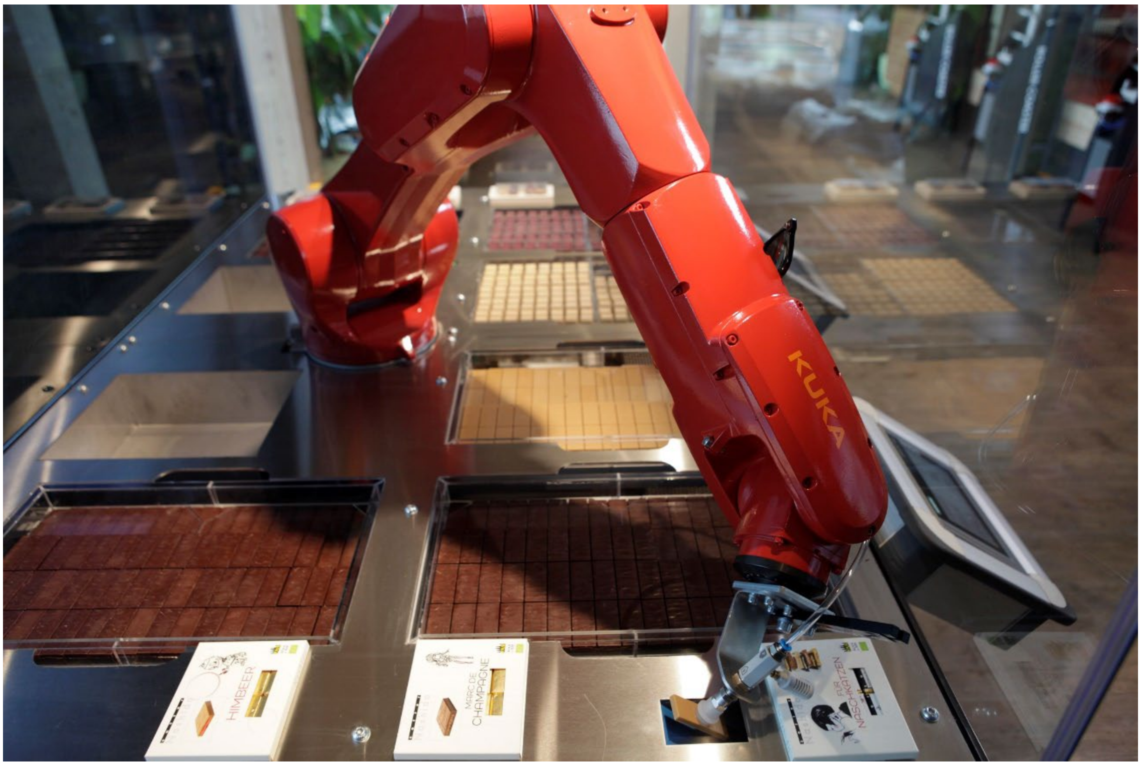

Figure 2.95: Traditional craftsmanship combines with state-of-the-art robotics: At the Zotter chocolate factory in Austria, a Kuka robot supplies visitors with the chocolate products. Using a touch panel, chocolate lovers can choose their favorites among the different chocolates or bars. Image credit: Kuka.

Figure 2.96: The 22-meter Saildrone Surveyor sails under the Golden Gate Bridge during sea trials in spring 2021. The Surveyor was first launched in January 2021 and is specially equipped with a suite of multi-beam sonars for deep-water ocean mapping, as well as fisheries sonars and an acoustic Doppler current profiler to measure ocean currents. Image credit: Saildrone.

2.9.1 PRODUCERS

1X, Aeolus Robotics, AkinRobotics, Apptronik, Astrobotic, BEC, BIA5, Bionic Power, Brain Navi Biotechnology, b-temia, Clearbot, Comau, Commonplace Robotics, Cyberdyne, Ekso Bionics, Engineered Arts, EV Safe Charge, Follow Inspiration, Furhat Robotics, German Bionic Systems, Gobio Robot, Hanson Robotics, Hefei Panshi Intelligent Technology, Hitachi, Hydronalix, Hyundai Rotem, Inovasyon Mühendislik, International Submarine Engineering, Ishikawa Iron Works, Jabil - Badger Technologies, Jigabot, JMU Defense Systems, Kawada Industries, KinderLab Robotics, Kokoro Robotics, Kongsberg Maritime, Korechi, Kuka, Laevo, MDA, Motiv space systems, Nabors, Nauticus Robotics, Neobotix, OceanAero, Oceanos, Pal Robotics, Pollen Robotics, PowerVision Robot Corporation, Rainbow Robotics, RB3D, Robomart, Rockwell Automation, Ronovatec, Rowbot Systems, Rubidium Light, Saildrone, Scythe Robotics, Shandong Guo Xing Intelligent Technology, Skeletonics, Skelex, Stähle Robot Systems, Stanley Robotics, Suzhou Pangolin Robot, SwarmFarm Robotics, TinyMobileRobots, Toyota, Turf Tank, Ugo, Unitree, Ursrobot, Xmachines, Yamabiko Europe

3 Medical Robots

Chapter 3 contains detailed information about the application areas of medical robots, including a selection of typical products and suppliers.

3 Medical robots

3.1 AP6: MEDICAL ROBOTS

Author: Simon Baumgarten, M.Sc.

Within 30 years, medical robotics has been transformed from a research field of robot technology into one of the most dynamic and interdisciplinary fields of modern robotics with strong commercial potential, innovation challenges, and high public visibility. The growth of this branch since the mid-1990s has been overwhelming, both as a field of innovation and research and as a market for new products and services. Today, medical robotics is considered one of the success stories in the field of service robotics.

Since 2021, however, there has been an update with regard to the classification of medical robots, which this yearbook now also takes up. In accordance with ISO standard 83731:2021, the yearbook follows the classification contained therein: "A medical robot is not regarded as an industrial robot (3.6) or a service robot (3.7)." Accordingly, medical robots are also considered a third robot category here.

Medical robots increasingly show their potential to revolutionize clinical practice by:[326, 327, 328]

- Facilitating medical processes by precisely guiding instruments, diagnostic equipment, and tools for any kind of diagnosis and therapy
- Improving safety, repeatability, and overall quality of medical surgery through interweaving and documenting diagnosis data and intervention procedures
- Enhancing the cost-effectiveness of patient care
- Improving the training and education of medical personnel through simulators
- Promoting the use of information in diagnosis and therapy

Most devices in medical robotics covered in this chapter are classified as robotic devices, not robots, due to their limited level of autonomy (see definition of a robot in chapter 1). They are employed for diagnosis, therapy, and patient care. The applications of these robotic devices vary from manually guided active kinematics for diagnosis to complex medical (possibly tele-operated, multi-manipulator) workstations. A distinction is made (and reflected in the statistical scheme) between:

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326 Taylor, R.; Menciassi, A.; Fichtinger, G.; Dario, P.: Medical Robotics and Computer-Integrated Surgery. In: Siciliano, B. and Khatib, O. (eds.): Springer Handbook of Robotics, 2nd edition. Berlin, Heidelberg: Springer, 2016, pp. 1657-1683; http://handbookofrobotics.org/.

327 ME 328: Medical Robotics: http://www.stanford.edu/class/me328/; particularly http://www.stanford.edu/class/me328/lectures/lecture1-intro.pdf.

328 Desai, J. P.; Patel, R. V., Ferreira, A.; Agrawal, S. K. (eds.): Encyclopedia of Medical Robotics. World Scientific, 2017; https://www.worldcat.org/de/title/encyclopedia-of-medical-robotics/oclc/1237230972.

- Diagnostics, chapter 3.1.1
- Robot-assisted surgery, chapter 3.1.2
- Rehabilitation, chapter 3.1.3
- Other medical robots (e.g. robots for telepresence, to support the care of patients, or for training of medical interventions), see chapter 3.1.4

The discussion of medical robotic systems in the subchapters will follow the listed scheme. Most of the robots and robotic devices surveyed, however, are used for surgery, especially for minimally invasive surgery.

In response to the Covid-19 pandemic, existing service robots have been adapted, or new service robots have emerged to assist medical staff in caring for patients or other care-related tasks. Some of these developments that often have to meet special requirements will be described in the following chapters as well as in chapters 2.3.5 (Professional cleaning, e.g., disinfection robots) and 2.6.2 (Transportation and logistics, e.g., mobile robots with a specialized cooling system for the transfer of medicines).[329]

For more details on current medical robotic research and development, market potentials, and overall challenges, please refer to the abundance of information presented in scientific, technical, and popular publications on the subject.[330, 331, 332, 333]

[329] Demaitre, E.: Coronavirus response growing from robotics companies, March 2, 2020; https://www.therobotreport.com/coronavirus-response-growing-robotics-companies/.

[330] Albala, D.; Patel, V. R. (eds): Journal of Robotic Surgery. Publisher: Springer; http://www.springer.com/medicine/surgery/journal/11701.

[331] Proceedings of the Hamlyn Symposium on Medical Robotics, Imperial College London, UK, June 24-27, 2018; https://www.imperial.ac.uk/hamlyn-centre/hamlyn-symposium/. The accompanying Surgical Robot Challenge: http://surgrob.blogspot.com/2018/02/hamlyn-challenge-2018.html.

[332] Medical Robots, IEEE Spectrum; https://spectrum.ieee.org/tag/medical-robots.

[333] Anvari, M.; Loughlin, C. (eds.): The International Journal of Medical Robotics and Computer Assisted Surgery; http://onlinelibrary.wiley.com/journal/10.1002/(ISSN)1478-596X.

IFR statistics

In 2023, sales of **medical** robots (AP6) were increasing by 36% to almost 6,200 units. RaaS business models are uncommon in this segment. Asia + Pacific and the Americas are the origin of the majority of sales and boast the highest growth rates: Asia + Pacific with close to 2,600 and the Americas with 2,900 units sold in 2023.

Diagnostics (AP61) increased to 222 units sold (+25%) in 2023. Close to 1,800 **surgery robots** (AP62; +14%) were sold, sales of robots **for rehabilitation and non-invasive therapy** (AP63) increased by 128% to almost 3,100 robots. Medical laboratory analysis (AP4) and **other medical robots** (AP69) reported close to 1,000 units sold, a decrease by 25%.

Table 3.1

Medical robots (2022 and 2023)

	Application	Region	2022	2023	2023/2022
			units sold		growth rate
AP6	Medical robots	Total	4,540	6,179	+36%
		Europe+MENA	593	628	+6%
		The Americas	1,959	2,908	+48%
		Asia+Pacific	1,988	2,643	+33%
AP61	Diagnostics		177	222	+25%
AP62	Surgery		1,609	1,842	+14%
		Europe+MENA	**	**	-
		The Americas	**	**	-
		Asia+Pacific	90	129	+43%
AP63	Rehabilitation and non-invasive therapy	Total	1,347	3,066	+128%
		Europe+MENA	**	**	-
		The Americas	**	**	-
		Asia+Pacific	766	1,684	+120%
AP64+AP69	Medical laboratory analysis and other medical robots		1,407	1,049	-25%

Source: World Robotics 2024
Results of IFR's annual survey and desktop research (35 medical robot companies)
No data on RaaS reported for this application group.
*Regional breakdown cannot be revealed (minimum number of non-zero observations not reached).
**Results cannot be revealed (minimum number of non-zero observations not reached). Data included in application group total (AP1, AP2, etc.).

3.1.1 AP61: DIAGNOSTICS

3.1.1.1. TYPES OF OPERATIONS CARRIED OUT BY THE ROBOT

Generally speaking, there are fewer robotic devices used in diagnostics than in surgery or rehabilitation. Diagnostic robotic devices may come in the form of robotic arms or manipulators that guide diagnostic equipment outside the human body, guide the body toward a diagnostic instrument, or carry diagnostic instruments inside the body. Two of the most established robotic guided procedures in this field are radiology and biopsy.

3.1.1.2. LEVEL OF DISTRIBUTION

In the mid-1990s, Zeiss launched MKM ("Mehrkoordinaten-Manipulator", "multi-coordinate manipulator") to enable motorized precision positioning of a microscope. The system consisted of a microscope fixed to a six-degrees-of-freedom and, for safety reasons, weight-balanced robotic arm. It was suited for open surgery, eye surgery, and neurosurgical procedures. Pioneering as it was, the system is no longer available on the market. Today, Zeiss offers new robotic microscopic systems, which assist doctors in surgery with advanced visualization functionalities, like Tivato 700 and Kinevo 900.

The Lucid Robotic System from Neural Analytics is a robot-guided neurovascular ultrasonic device. It non-invasively measures and displays brain blood flow and helps to assess the brain health of patients quickly. The system assists doctors in making clinical decisions in critical situations and is expected to improve patient outcomes, e.g. in the treatment of stroke patients.

In 2019, Intuitive Surgical Solutions' new Ion lung biopsy system won approval from the US Food and Drug Administration (FDA). The system is used for minimally invasive biopsies deep within the lung. The system consists of a catheter tube that can be navigated by the performing surgeon. The same year, Johnson & Johnson bought Auris Health for USD 3.4bn, and with it the Monarch™ robotic system. It is a robotic navigation system that enables clinicians to place mapping catheters in the lung for diagnosing and treating lung cancer.

Blood drawing, typically done by clinic personnel, is claimed to be carried out faster and more safely by using a robotic device. Veebot, an automatic phlebotomist, is based on an Epson industrial manipulator. It uses infrared light to illuminate the inner arm and a camera to pick the location of the veins. Once spotted, an ultrasound probe glides over a suitable vein before moving the needle into position to insert it. A similar robotic system, developed at Rutgers University, has successfully gone through first human trials. It showed better performance in drawing blood than clinical standards, with a higher success rate than using human staff, and has the potential to increase the speed of the blood drawing process.[334]

To help ramp up the testing capacities for Covid-19, Lifeline Robotics has set up a prototype system – Careebo – that can take throat swabs for virus testing. It features two arms from Universal Robots with a newly developed end tool and sensors that are able to autonomously take the swab from a person. The system is supposed to facilitate more testing, increase the quality, and reduce the number of personnel required for the testing process as well as the risk of infection for medical staff. Currently, the whole process takes about seven minutes. Tsinghua University[335], located in Beijing, China, and Brain Navi Technologies have developed similar systems.

An even more futuristic approach is capsule endoscopy through micro-robots, such as Pillcam™ (Medtronic), Endocapsule (Olympus), Mirocam (Intromedic), or Capsocam

[334] Leipheimer, J. M.; Balter, M. L.; Chen, A. I.; Pantin, E. J.; Davidovich, A. E.; Labazzo, K. S.; Yarmush, M. L.: First-in-human evaluation of a hand-held automated venipuncture device for rapid venous blood draws. In: Technology, vol. 7, 2019, no. 3-4, pp. 98-107. DOI: 10.1142/S2339547819500067; https://pubmed.ncbi.nlm.nih.gov/32292800/.

[335] https://www.straitstimes.com/asia/east-asia/coronavirus-china-develops-robot-for-throat-swab-sampling.

(Capsovision).[336] Micro-robots are inserted into the body and help determine the cause of gastrointestinal symptoms, such as abdominal pain, diarrhea, bleeding, or anemia.[337] A tiny camera contained in the capsule captures images of the gastrointestinal tract as it travels through the body and transmits the images to a computer, so that a physician can view them and make a diagnosis. Some capsules can be manipulated through external energy sources and current trends clearly point toward actuated and controlled systems in the future.[338] For example, the Sayaka Capsule Endoscope (RF System lab) does not need a motor to move but requires 50mW of power, which is drawn through induction charging, to run its camera, lights, and computer. A vest worn by the patient contains a coil that continuously transmits the required power.

Virob (Microbot Medical) follows the trend toward miniaturization as it is an autonomous crawling micro-robot which can be controlled remotely or within the body, e.g. for navigating and crawling in blood vessels, the digestive tract, or the respiratory system. Its unique structure gives it the ability to move in tight spaces and curved passages as well as the ability to remain within the human body for some time.

Further research is dedicated to equipping these micro-robots with mobility and navigation for on-site diagnosis and intervention, e.g. to precisely release drugs, detect tumors, or repair damaged human arteries or tissue.[339, 340] Also, the Max Planck Institute for Intelligent Systems is conducting the latest research in this field and has presented a novel approach to self-assembling mobile micro-machines.[341]

3.1.1.3. COST-BENEFIT CONSIDERATIONS AND MARKETING CHALLENGES

Broadly, the advantages offered by medical robotic devices in diagnostics are fourfold: They significantly improve the surgeon's technical ability to perform procedures by exploiting the complementary strengths of humans and robotics. Medical robotic devices can be constructed to be more precise and geometrically accurate than an unaided

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[336] Mapara, S. S.; Patravale, V. B.: Medical capsule robots: A renaissance for diagnostics, drug delivery and surgical treatment, Journal of Controlled Release, vol. 261, 2017, pp. 337-351; https://pubmed.ncbi.nlm.nih.gov/28694029/.

[337] Redondo-Cerezo, E.; Damián Sánchez-Capilla, E.; De La Torre-Rubio, P.; De Teresa, J.: Wireless capsule endoscopy: Perspectives beyond gastrointestinal bleeding, World Journal of Gastroenterology, vol. 20, 2014, no. 42, pp.15664–15673; https://pubmed.ncbi.nlm.nih.gov/25400450/.

[338] Koulaouzidis, A.; Iakovidis, D.; Karargyris, A.; Rondonotti, E.: Wireless endoscopy in 2020: Will it still be a capsule? World Journal of Gastroenterology, vol. 21, 2015, no. 17 pp. 5119–5130; https://www.wjgnet.com/1007-9327/full/v21/i17/5119.htm.

[339] Gauthier, M.; Andreff; N.; Dombre, E.: Intracorporeal Robotics: From Milliscale to Nanoscale, John Wiley & Sons, 2014.

[340] Singeap, A.; Stanciu, C.; Trifan, A.: Capsule endoscopy: The road ahead, World Journal of Gastroenterology, vol. 22, 2016, no. 1, pp. 369-378; https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4698499/.

[341] Novel approach to self-assembling mobile micromachines, Max Planck Institute for Intelligent Systems, June 25, 2019; https://is.mpg.de/news/novel-approach-to-self-assembling-mobile-micromachines.

human. The possibility of matching diagnostic data with precision procedures is of great value and has been widely acknowledged, particularly given the example of stereotactic brainstem tumors, which opens up new perspectives for the molecular characterization of these tumors as a crucial first step toward more individualized treatment concepts.[342]

Medical robotic devices can operate in environments that emit radiation, which may be hazardous for humans. They provide great dexterity for supporting minimally invasive procedures inside the body, thus reducing risks of infection or other threats of invasive surgery. They generate consistent, accurate information for further human or machine-based interpretation of patient data. This can help to make better clinical decisions and decrease the time in surgery, which can both be beneficial for the patient outcome.

Considering the shortage of qualified staff, autonomous or robot-assisted examinations relieve medical staff of the strenuous task of repositioning the patient during the diagnostic process and can speed up processes. Navigation of robot motion – the registration of the robotic device motions relative to (possibly moving) body parts of the patient – is generally less accurate than general positioning accuracies of robotic devices. In surgical navigation, the positions of instruments relative to the reference markers or natural features on the patient are tracked using specialized electromechanical, optical, electromagnetic, or sonic digitizers, or by more general computer vision techniques. Major research and development (R&D) efforts are dedicated to matching navigation and robotic device accuracy toward ranges of 0.1mm.

The capsule-based mini robots can revolutionize the current methods of diagnostics, drug delivery, and surgical treatment.[343, 344] As reflected in literature and startup activities, the results clearly point to providing these immersive robots with actuation and navigation inside the human body.[345] The next step in this field is predicted to be nanobots in cell size, considerably smaller than the capsule robots. They could be introduced to the human body in greater numbers and fulfil a variety of medical procedures or tasks of health maintenance. Expected functionalities are, e.g., cleaning arteries, taking biopsies, or fighting cancer cells.[346]

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[342] Kickingereder, P.; Willeit, P.; Simon, T.; Ruge, M. I.: Diagnostic Value and Safety of Stereotactic Biopsy for Brainstem Tumors: A Systematic Review and Meta-analysis of 1480 Cases, Neurosurgery, vol. 72, 2013, no. 6, pp. 873-882; https://pubmed.ncbi.nlm.nih.gov/23426149/.

[343] Palimaka, S.; Blackhouse, G.; Goeree, R.: Capsule endoscopy in the assessment of obscure gastrointestinal bleeding: an economic analysis, Ontario Health Technology Assessment Series, vol. 15, 2015, no. 2, pp. 1-32; https://www.ncbi.nlm.nih.gov/pubmed/26355732.

[344] Li, J.; de Ávila, B. E. F.; Gao, W.; Zhang, L.; Wang, J.: Micro/nanorobots for biomedicine: Delivery, surgery, sensing, and detoxification, Science Robotics, vol. 2, 2017, no. 4, eaam6431; https://pubmed.ncbi.nlm.nih.gov/31552379/.

[345] Ciuti, G.; Caliò, R., Camboni; D., Neri, L.; Bianchi, F.; Arezzo, A.; Magnani, B.: Frontiers of robotic endoscopic capsules: a review, Journal of micro-bio robotics, vol. 11, 2016, pp. 1-18; https://pubmed.ncbi.nlm.nih.gov/29082124/.

[346] https://www.therobotreport.com/nanobots-promise-change-medical-treatment/.

3.1.1.4. PRODUCERS

Bee Robotics, BizLink Robotic Solutions, Brainlab, CMR Surgical, Era Endoscopy, IntroMedic, Kuka, Medtronic, Siemens Healthineers, Stereotaxis, Veebot

3.1.2 AP62: SURGERY

Minimally invasive surgery (MIS) has made tremendous progress in the last 25 years, achieving improvements for both the patient and the surgeon. This has led to an increase in the use and development of robotic devices and platforms for general surgery. The benefits for patients are enormous: They generally experience less pain and faster postoperative convalescence. This is particularly important for elderly patients. Insurance costs are usually reduced because of shorter hospital stays. MIS is increasingly employed in almost all areas of modern surgery by general multipurpose surgical robot platforms or specialist designs.[347]

Figure 3.1: Dr. Guo performs neurosurgery using 20-30cc ICH and changes stroke treatment guidelines. Image credit: Brain Navi Technologies.

3.1.2.1. TYPES OF OPERATIONS CARRIED OUT BY THE ROBOT

The operational modes of robots can be quite different:

- Carriers for laparoscopic instruments in which one or more small incisions are used to access the surgical site with tools and a camera
- Steerable catheters which are actuated by servo-motors using typical robot

[347] Peters, B. S.; Armijo, P. R.; Krause, C.; Choudhury, S. A.; Oleynikov, D.: Review of emerging surgical robotic technology, Surgical Endoscopy, vol. 32, 2018, no. 4, pp. 1-20; https://www.semanticscholar.org/paper/Review-of-emerging-surgical-robotic-technology-Peters-Armijo/9945b4682a415fc3b678dee6ea15fae54b8a111e.

transmission, sensing, and control

- Guiding tools or instruments for specific surgical procedures, such as mill-cutting the inner part of a bone
- Percutaneous: Non-catheter percutaneous procedures employ needles, cannulas, and probes for drainage, drug delivery, and tumor destruction
- The robotic devices move the patient relative to a fixed or mobile target (such as an x-ray or ion source) during surgery

The main areas for surgical assistance are:

- Assistant functions (e.g. holding, placing, and guiding instruments and tools)
- Tele-surgical functions
- Execution of generated (partly) robot programs which are typical for radio, x-ray, or particle therapy (image-guided surgery)
- Activation of generated motions, such as the milling/drilling of bone material or transferring the surgeon's movements into the patient's body to move or cut tissue

Assistant functions are performed by one or more robotic arms, which typically hold an endoscopic camera. They can even be voice controlled or automatically follow the surgeon's head movements. Tele-surgical instruments allow surgeons to use the robotic device as an extension of their own direct manipulative capabilities. A navigation system provides accurate positional feedback on the location of a surgical instrument relative to the patient's anatomy so that a precise matching of diagnostic data and the physical intervention area can be secured; in advanced solutions, this is possible even when body parts or tissue are moving. They typically consist of a 3D localizing device and workstation to display positions relative to volumetric medical images. Some systems even integrate pre-surgical images and models in the operator/surgeon interface. The combination with preoperative imaging methods and 3D pre-surgical planning software can help the surgeons to prepare for the intervention.

In 2019, first remote procedures using 5G networks were successfully executed with surgeons operating from locations kilometers away from the operating table. Back-up surgeons were present at all times in case of an error. The new network technologies provide the necessary bandwidth and have low enough latencies for these kinds of procedures. The evolving field of remote surgery could prospectively lead to a better contribution of medical resources to remote areas or poor countries.

Surgical simulators and tele-robotic systems have become available in medical education and training, particularly in the fields of anesthesia, intensive care, flexible endoscopy, surgery, and interventional radiology.

One of the newest developments in robot-assisted treatments is supermicrosurgery. The surgeon’s hand movements are converted into smaller, more precise movements, which are then performed on the patient by a set of ‘robotic hands’. The device also stabilizes any tremor in the surgeon’s movements, which makes the procedure more controlled and thus easier to perform. In first clinical trials, the Musa system from Microsure, a TU Eindhoven spin-off, was used for suturing vessels of 0.3 to 0.8mm in patients’ arms to treat lymphedema. The study concluded an improved patient outcome after three months compared to conventional therapy.[348]

3.1.2.2. LEVEL OF DISTRIBUTION

Significant acquisitions of medical robotic device manufacturers have taken place in recent years and the trend is expected to continue, given a supplier group of currently almost 40 companies in this field.

Figure 3.2: Example for a surgery robot: The Hinotori™ was developed as a robotic-assisted surgery system based on Kawasaki Heavy Industries’ robot technology – cultivated over more than 50 years. Image credit: Kawasaki.

Manipulator-based surgical robots

[348] van Mulken, T. J. M.; Schols, R. M.; Scharmga, A. M. J.; Winkens, B.; Cau, R.; Schoenmakers, F. B. F. et al.: First-in-human robotic supermicrosurgery using a dedicated microsurgical robot for treating breast cancer-related lymphedema: a randomized pilot trial. In: Nat Commun vol. 11, 2020, no. 1. DOI: 10.1038/s41467-019-14188-w; https://www.nature.com/articles/s41467-019-14188-w/.

In some applications, conventional industrial robot systems (precise, heavy payloads, powerful controllers, mature technology) are being used for radiotherapy, especially in oncology, such as Cyberknife® from Accuray. Incorporating a compact linear accelerator mounted on a modified industrial robotic arm, the system provides the surgeon with unparalleled flexibility in terms of targeting. Advanced image guidance technology tracks the patient and target positions during treatment, ensuring accuracy without the use of an invasive head frame.

An example of modified Kuka industrial robots in synchronization has been installed at the Heidelberg Ion Beam Therapy Center (HIT), Germany. In each therapy room, a ceiling-mounted robot is used for imaging around the patient. The floor-mounted robot positions the patient relative to an ion source. The treatment tables are robot controlled to select the ideal entrance angle of the ion beam.[349]

The Robodoc® surgical system, now available in enhanced versions marketed by Curexo, was introduced in the late 1990s for assisting in hip arthroplasty procedures. Numerous operations have shown that the robot equipped with a high-speed milling tool is less traumatic for the patient and more precise than manual preparation techniques. Surgical procedures have been expanded into other typical orthopedic interventions and cover a large variety of clinical applications, ranging from ophthalmology to orthopedics.[350] The family of microsurgical systems has been growing in the past decade and some typical systems are listed below.

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[349] Sommer, A.: Industrial Robots for Patient Support. Ion Beam Therapy, Biological and Medical Physics, Biomedical Engineering, vol. 320, 2012, pp. 559-577; https://www.researchgate.net/publication/258733190_Industrial_Robots_for_Patient_Support .

[350] Díaz, C. E.; Fernández, R.; Armada, M.; García, F. X.: A research review on clinical needs, technical requirements, and normativity in the design of surgical robots, The International Journal of Medical Robotics and Computer Assisted Surgery, vol. 13, 2017, no. 4; https://pubmed.ncbi.nlm.nih.gov/28105687/.

Figure 3.3: Spine surgical robot. Image credit: Curexo Inc.

Davinci® from Intuitive Surgical Solutions is a versatile surgical robot system that follows the traditional master-slave operation principle: “Since the late 1990s, it has found worldwide acceptance through various system generations in advanced surgery, such as neurosurgery, microsurgery, orthopedics, ophthalmology, and cardiology.”[351] Davinci® is reported to have achieved an installation number of more than 5,500 globally (as of 2020) and more than seven million procedures have been performed with it.[352] Intuitive Surgical Solutions is dominating the market of surgical robotic devices due to revenue from dexterous fee models.

The new Mazor X Stealth robotic system for assisted spinal surgery from Medtronics was launched in 2019. It consists of software for planning the surgical procedure and a robotic arm that guides the spinal implants and instruments during the procedure.

Several surgical robot systems have been reported to be under development, like a four-armed system with the objective of enabling surgeons to remotely manipulate surgical instruments from Titan Medical or Mirosurge from DLR.

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[351] Cepolina, F.; Razzoli, R. P.: An introductory review of robotically assisted surgical systems. Int J Med Robot. August 2022 18(4).

[352] Q2 2020 Investor Presentation: https://isrg.intuitive.com/.

In the area of orthopedics, Mako System (Stryker) is a restorative surgical solution and a pioneer in the field. It can be used for total knee, hip, and partial knee replacement procedures. The knee procedure is reportedly difficult to do manually, but greatly facilitated in precision and operating times through the robotic arm platform.[353] More than 650 Mako robotic devices have been placed around the world, with more than 76,900 knee and hip replacement procedures performed in 2018.[354] A system for facilitating knee replacement by means of robot assistance has been introduced by Navio (Smith & Nephew). A robotic hand piece with integrated navigation capabilities assists in precise and repeatable bone preparation. In 2019, Tsolution One (Think Surgical) received FDA approval and joined the market of total knee replacement robotic systems.

Johnson & Johnson agreed to acquire the remaining stakes of Verb Surgical from Verily, Google Alphabet's research organization. Verb Surgical is as a joint venture between Google parent company Alphabet's Verily Life Sciences (formerly Google Life Sciences) and Johnson & Johnson's Ethicon (a medical devices subsidiary of Johnson & Johnson). The aim of the collaboration is the development of a digital surgery platform that brings together robotics, visualization, advanced instrumentation, connectivity, and data analytics. With this acquisition, Johnson & Johnson wants to move forward in the field of robot-assisted medical interventions. At the end of 2020, they unveiled their new Ottava surgical robot which can supposedly be deployed for treating a wide range of disease states. The six-armed robot was supposed to go into clinical trials in 2022, but the time plan has been delayed for about two years. The latest update states first clinical trials in the second half of 2024[355]

The Yomi robot from Neocis is the first FDA-approved system for full-arch dental implant surgeries. The system helps surgeons with planning surgeries and ensures a higher level of precision, which enables minimally invasive surgery. This leads to faster recovery and less pain for the patient.[356]

A robot system specialized for specific tasks is the Artas iX™ system from Restoration Robotics. This interactive, computer-assisted system utilizes image-guided technology to enhance the quality of hair follicle harvesting for the benefit of physicians and their patients. The system assists surgeons with harvesting follicles and planting the implants.

A modified industrial robot is used as part of a medical computer tomography and angiographic system (vascular imaging). The Artis pheno system produced by Siemens Healthineers increases the precision with which doctors can rotate and position a C-arm in surgery around a patient. This enables the surgeon to examine blood vessels and diseased areas in more detail than before, thus providing crucial information for making

353 Deirmengian, C. A.; Lonner, J. H.: What's New in Adult Reconstructive Knee Surgery, The Journal of Bone and Joint Surgery, vol. 90, 2008, pp. 2556-2565; https://pdfs.semanticscholar.org/d82b/865cbd68cd9526790614f1c76f74d21c7550.pdf.

354 https://www.therobotreport.com/stryker-leads-orthopedic-surgery-robots/.

355 https://www.jnj.com/media-center/press-releases/johnson-johnson-medtech-provides-details-and-timeline-for-general-surgery-robot.

356 https://www.therobotreport.com/yomi-robot-neocis-gets-fda-nod-full-arch-dental-implants/.

decisions on operations. Additionally, the patient does not have to be re-positioned for the scanning process.

Catheter-based robotic surgery

Instead of using larger robotic arms for manipulating and precisely guiding medical instruments, catheter-based robotic devices make use of catheters, which are introduced into body cavities, ducts, or vessels. Typical examples are listed below:

Viky from Endocontrol is a light endoscopic robotic device. Its role is to maintain and move the endoscope according to the surgeon's orders and is typically used by digestive, urological, and gynecological surgeons. It consists of several intuitive user control systems such as foot control, voice control, and an innovative instrument tracking system. The robotic device is attached to the operating table by a small passive arm. It guarantees endoscopic stability and precise endoscopic movements.

The Freehand system from Freehand 2010 allows surgeons to control the camera themselves when performing (micro-invasive) keyhole surgeries by using simple head movements. In skilled hands, using the robotic device saves time and money, as assistants are not required. Keyhole surgery is extending all the time to new areas and now covers general surgery, urological, and gynecological specialties.

Medrobotics reports on a kinetically most flexible system ("snake arm") to enable physicians to operate through non-linear circuitous paths through a single-site access into the body. One key benefit is that the robotic device avoids the use of heart-lung machines necessary for open-heart surgery (e.g. valve repair). The less invasive manner is claimed to improve patient recovery and decrease risks involved with the current procedures.

A similar system, Corpath developed by Corindus Vascular Robotics, enables the precise, robot-assisted control of coronary guidewires and balloon/stent devices from the safety of a radiation-protected, ergonomic interventional cockpit. Siemens Healthineers acquired the company in 2019. A recent system is Aeon Phocus from Aerne Engineering, a catheter steering system for treating cardiac arrhythmias. Instead of the constrained mechanical guidance of an actuated catheter, this system uses electromagnetic steering by an arrangement of actuated coils. The system can be operated from a separate control room to protect physicians from x-ray radiation. For example, the university medical center Freiburg started deploying one of these robots for intracardiac catheters in April 2021. The medical center appreciates the high precision of the system and the improved safety for employees who can now operate from outside the radiation area of imaging methods.[357]

[357] https://www.kma-online.de/aktuelles/medizintechnik/detail/neuer-herzkatheter-roboter-am-uniklinikum-freiburg-im-einsatz-a-45527.

Summary: Level of distribution

With the experience and knowledge gained from the systems already in use, acceptance of robot-assisted surgery is generally growing. The number of operations requiring technically advanced methods is increasing and, as a result, new methods are being sought. In addition, many more systems are being developed or are currently in their prototype phase and awaiting approval from medical authorities.

3.1.2.3. COST-BENEFIT CONSIDERATIONS AND MARKETING CHALLENGES

Active robotic surgery is precise and the systems used for orthopedic surgery, such as cement-less implantation, reduce gaps between implant and bone to less than 0.05mm compared to 1-4mm in the case of manual surgery. While a manual broach often leaves holes oversized by more than 30% and only 20% of the implant is in contact with the bone, robotic milling raises this level of contact to 96%. The tenability of the cement-less implants is reported to be 2.5 times higher. Since the postoperative complication rates associated with many orthopedic procedures are directly related to surgical accuracy, any measure that enhances surgical performance can lead to significant clinical and financial benefits. The costs of medical robotic devices, although still very high, can be compensated through:

- High system utilization, which means high throughputs
- Significant therapeutic advantages of robot-assisted intervention
- Less use of pain medications post-operatively
- Combination of the robot with high-tech diagnostic or therapeutic equipment for creating maximum benefits

Using a medical robotic device may be conveyed to the surgeon as a method of gaining experience with its use in a less technically demanding procedure, so that eventually the surgeon can apply the techniques of robotic surgery to more challenging operations.[358]

In recent years, robotic prostatectomy has become the most popular approach to this surgery in the United States and has boosted the prevalence and sale of robotics particularly across the USA. Over the past few years, a wealth of studies has been published on the cost-benefit performance and risk aspects of medical robotic devices (mostly compared to conventional surgery) for a large spectrum of interventions.

In general, studies critically assess the use of surgical robotic devices compared to other methods given specific national health systems and regulations (which vary considerably). However, the assessments draw increasingly positive conclusions as the

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[358] Angelos, P.: Can robotic approaches be justified for the benefit of surgeons? Surgery, vol. 161, 2017, no. 3, pp. 639-640; https://pubmed.ncbi.nlm.nih.gov/27913034/.

technology matures.[359] Still, they indicate further potentials in the design, operation of surgical robotic devices, and training for surgeons.[360] A widely discussed study covering 14 years of surgical robotics use concludes: "Despite widespread adoption of robotic systems for minimally invasive surgery, a non-negligible number of technical difficulties and complications are still being experienced during procedures. Adoption of advanced techniques in design and operation of robotic surgical systems may reduce these preventable incidents in the future."[361] The authors mention difficulties like events in complex surgical specialties of cardiothoracic and head and neck surgery or malfunctions of the devices.

Nonetheless, the FDA issued a warning against using surgical robotic devices in cancer treatment surgeries, especially breast cancer. This assessment is based on the lack of conclusive studies dealing with the benefits and risks of robot-assisted surgeries in this field.[362]

Still, the treating physician is in control of the medical procedures to a significant extent. The robotic devices are essentially doing what the physician commands, with varying levels of detail being left to the automated system. Aside from the evolving technology, the risk tolerance toward autonomous robots is expected to change.[363]

The regulatory, ethical, and legal barriers imposed on medical robotic devices necessitate careful consideration of different levels of autonomy, as well as the context of use.

3.1.2.4. PRODUCERS

Accuray, Aktormed, Asensus Surgical, BBZ, BEC, Beijing Tinavi Medical Technology, Brain Navi Biotechnology, Brainlab, Carl Zeiss Meditec, CMR Surgical, Connected Orthopadic Insight , Curexo, Endoquest, Era Endoscopy, Ergosurg, Free Hand Surgeon,

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[359] Turchetti, G.; Pierotti, F.; Palla, I.; Manetti, S.; Freschi, C.; Ferrari, V.; Cuschieri, A.: Comparative health technology assessment of robotic-assisted, direct manual laparoscopic and open surgery: a prospective study, Surgical Endoscopy, vol. 31, 2017, no. 2, pp. 543-551; https://link.springer.com/article/10.1007/s00464-016-4991-x.

[360] Kajiwara, N. et al.: Cost-Benefit Performance of Robotic Surgery Compared with Video-Assisted Thoracoscopic Surgery under the Japanese National Health Insurance System, Annals of Thoracic and Cardiovascular Surgery. May 16, 2014; https://www.jstage.jst.go.jp/article/atcs/advpub/0/advpub_oa.14-00076/_pdf.

[361] Alemzadeh, H.; Iyer, R.; Kalbarczyk, Z.; Leveson, N.; Raman, J.: Adverse Events in Robotic Surgery: A Retrospective Study of 14 Years of FDA Data, Presented as the J. Maxwell Chamberlain Memorial Paper for adult cardiac surgery at the 50th Annual Meeting of the Society of Thoracic Surgeons in January 2015; http://arxiv.org/ftp/arxiv/papers/1507/1507.03518.pdf.

[362] Crotti, N. : FDA warns about using surgical robots for cancer treatment, The Robot Report, March 2, 2019; https://www.therobotreport.com/surgical-robots-fda-warning-cancer/.

[363] Yang, G. Z.; Cambias, J.; Cleary, K.; Daimler, E.; Drake, J.; Dupont, P. E.; Santos, V. J.: Medical robotics – Regulatory, ethical, and legal considerations for increasing levels of autonomy, Science Robotics, vol. 2, 2017, eaam8638; https://www.science.org/doi/10.1126/scirobotics.aam8638.

Globus Medical, Intuitive Surgical, Johnson & Johnson, Kawasaki Heavy Industries, Kinova, Koh Young Technology, Kuka, Medical Microinstruments, Medicaroid, Medtronic, Meerecompany, Microsure, Momentis Surgical, Monteris Medical, Moon Surgical, Neocis, Procept Biorobotics, Renishaw, ROEN Surgical , Siemens Healthineers, Smith & Nephew, Stäubli, Stereotaxis, Stryker, Think Surgical, Vicarious Surgical, Virtual Incision, Zimmer Biomet

3.1.3 AP63: REHABILITATION AND NON-INVASIVE THERAPY

Rehabilitation robots and robotic devices assist people who have a disability with necessary activities, or they provide therapy to persons with the aim of improving their physical or cognitive functions. The main target here is increased training intensity for improved functional rehabilitation compared to the treatment provided by physiotherapists. Over the years, rehabilitation robotics has become a dynamic field of robotics research and development as well as a demanding and important field of commercial products and services.[364, 365] A variety of products has been launched.

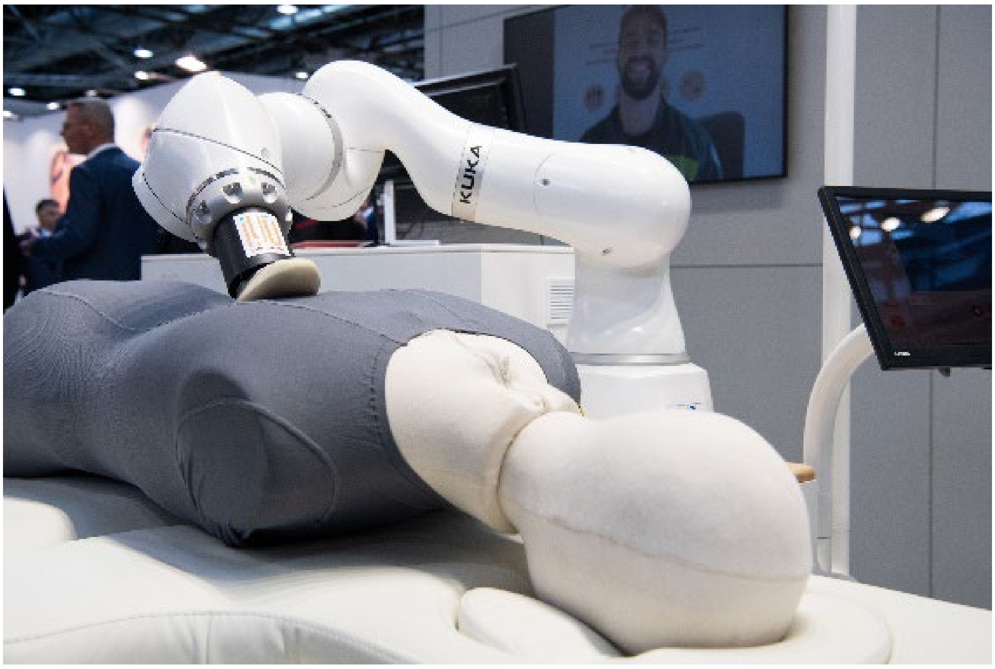

Figure 3.4: Back pain is a widespread health problem. The goal of the project of the developers at Capsix Robotics in Lyon is to perform an automatic and customized back massage using Kuka LBR Med. Image credit: Kuka.

3.1.3.1. TYPES OF OPERATIONS CARRIED OUT BY THE ROBOT

The field of rehabilitation robotics is generally divided into therapy and assistance robots and robotic devices. Additionally, rehabilitation robotic devices include artificial limbs (prosthetics), exoskeletons (for lower or upper limbs, as well as the whole body), neural stimulation, and devices for monitoring people during their daily activities. The following

[364] International Conference on Rehabilitation Robotics ICORR; https://icorr-c.org/.

[365] Colombo, R.; Sanguineti, V. (eds.): Rehabilitation Robotics, Academic Press, March 10, 2018; https://www.elsevier.com/books/rehabilitation-robotics/colombo/978-0-12-811995-2.

classification in rehabilitation robotics can be used according to Yakub et al. (simplified):[366, 367]

Physical therapy (through operational therapy robots), for example for the upper or lower extremities or the whole body. Robots or robot devices in this category are concerned with three areas: (1) neurological, which aims to help those patients with little or non-existent neurological control by training muscle control; (2) cardiopulmonary, for the treatment of breathing problems; and (3) for the musculoskeletal field which enables individuals to restore functionality in the muscle group and skeleton by improving coordination and strength.

In this field of applications, an abundance of current research and product development in exoskeletons is reported to be underway. These robotic systems can support rehabilitation in two ways: On the one hand, the exoskeleton can directly support and/or supervise the movement of the impaired patient, even for children, and, on the other hand, it can give extra strength to the nurse or therapist when mobilizing the patient. New research is dealing with soft exoskeletons that are lighter and more comfortable to wear. They can analyze the wearer's posture, gait, or movement when performing a task. This is relevant for physiotherapy or when performing strenuous movements in a more ergonomic way. Some can provide limited force support or correct the gait as well.

[366] Yakub, F.; Khudzairi, A. Z.; Mori, Y.: Recent trends for practical rehabilitation robotics, current challenges and the future, International Journal of Rehabilitation Research, vol. 37, 2014, no. 1, pp. 9-21; https://pubmed.ncbi.nlm.nih.gov/24126254/.

[367] Van der Loos, M. et al.: Rehabilitation and Health Care Robotics. In: Siciliano, B.; Khatib, O. (eds.): Springer Handbook of Robotics, 2nd Edition. Berlin, Heidelberg: Springer, 2016, pp. 1685-1728; http://http://handbookofrobotics.org.

Figure 3.5: Atlas 2030 pediatric gait exoskeleton from Marsi Bionics improves the quality of life of children affected by neurological diseases. Image credit: Marsi Bionics.

Emotional (social) therapy (through non-contact therapy robots – socially assistive robotics), for example for treating autism. In case of autism, patients typically respond better and are drawn to computers and robots because of the predictable behavior and reduced amount of external stimuli. Another application scenario is the use of a robot companion to support and motivate diabetic children to keep a diary.

3.1.3.2. LEVEL OF DISTRIBUTION

Physical therapy robots

The purpose of rehabilitation robotic devices is to stimulate sensory-motor movements of body parts and to learn to control mobility functions (gait and balance, arm and hand). Mobility training is based on controlled repetitive movements for neurological rehabilitation. Besides, mobility training is labor intensive and strenuous for therapists, so it is a prime target for automation. Several types of robotic systems for mobility training are already in use for therapy in several clinics worldwide:[368]

Gait and lower extremities training

Figure 3.6: Example of a gait rehabilitation robot. Image credit: Curexo Inc.

Gait Trainer GT II from Reha-Stim resembles a treadmill and interacts with the patient's lower limbs through two footplates while the body weight is unloaded as needed through an overhead harness. Four motorized joints (two per leg) move the hips and knees.

Lokomat® from Hocoma is an exoskeleton-like robotic device worn by the patient while walking on a treadmill. Motorized joints move the hips and knees while the patient's body weight is unloaded. During training, patients can move through various engaging virtual environments (produced by simulation on a screen), completing different exercises that encourage the patients' involvement in their therapy. Through the adjustment of intensity and level of difficulty for each task, exercises can be scaled to the cognitive and motor abilities and the needs of the patients, yielding personalized feedback.

Similarly, Robogait® from Bama Healthcare is a robot-assisted walking rehabilitation system used to regain and develop the ability to walk in situations where the loss of this

[368] Krebs, H. I.; Volpe, B. T.: Rehabilitation Robotics. In: Barnes, M. P.; Good, D. C. (eds.): Neurological rehabilitation. Handbook of clinical neurobiology, vol. 110, Edinburgh: Elsevier, 2013, pp. 283-294.

ability is the result of traumatic brain and spine injuries, strokes, or neurological or orthopedic causes.

Hunova from Movendo Technology uses a sensorized seat to actuate the patient’s leg/body motion, thus simulating different dynamics, such as elastic or fluid dynamic resistances. Biofeedback and gaming keep the subjects involved and motivated during the rehabilitation.

Based on divers research projects, the company Tediro is currently developing a commercial product for accompanied gait training on forearm supports. The robot is also capable of analyzing and documenting the patient's gait pattern and providing timely feedback via voice output.

Figure 3.7: Gait training support by the system Tediro. Image credit: Tediro.

Autoambulator, developed by Encompass Health (formerly Healthsouth Corporation), consists of two robotic arms that assist patients to step on a treadmill with their body weight supported as needed. The interface to the patient’s legs is realized through straps at the thigh and ankle.

First exoskeletons were introduced to the market once they received FDA approval (in the case of rehabilitation and handicap assistance), for example Ekso (Ekso Bionics), Indego (Parker Hannifin Corporation), and Rewalk (Lifeward, formerly Rewalk Robotics).[369]

Figure 3.8: EksoNR™ – exoskeleton for the lower extremities for neurorehabilitation. Image credit: Ekso Bionics.

Especially lower limb exoskeletons for supporting the upper leg or lifting strength in rehabilitation are being sold by various companies, e.g. Ekso Bionics, Indego (Parker Hannifin), Lifeward (Rewalk and Restore), Alterg (the Bionic Leg), Rex Bionics (Robotic Exoskeleton), or Honda in Japan (Stride Management System and Walking Assist Device with Bodyweight Support System). These systems are mainly aimed at supporting mobility-impaired persons and gait rehabilitation.[370]

[369] He, Y.; Eguren, D., Luu, T. P.; Contreras-Vidal, J. L.: Risk management and regulations for lower limb medical exoskeletons: a review. Medical devices (Auckland, NZ), vol. 10, 2017, pp. 89-107; https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5431736.

[370] Wolff, J.; Parker, C.; Borisoff, J.; Mortenson, W. B.; Mattie, H.: A survey of stakeholder perspectives on exoskeleton technology. Journal of Neuro Engineering and Rehabilitation, vol. 11, 2014; http://www.biomedcentral.com/content/pdf/1743-0003-11-169.pdf.

Figure 3.9: Angel Legs M is a gait-training robot for patients of any age with incomplete lower extremity paralysis. Image credit: Angel Robotics.

Alterg Bionic Leg is a wearable, battery-powered, robotic mobility assistance device and the only wearable robotic trainer that is activated by the patient's intent to move. It is used by physiotherapists for patients with impaired mobility and is designed to strengthen stance, improve gait, and enhance active motor learning while protecting its users.

Rewalk™ is a wearable, motorized quasi-robotic suit from Lifeward (formerly Rewalk Robotics).[371] The user walks with the assistance of crutches, controlling suit movement through subtle changes in the center of gravity and upper body movements. The exoskeleton offers an ambulation alternative to wheelchair users, enabling paralyzed people to stand, walk, and even climb stairs. The new Restore™ soft exoskeleton is used for the rehabilitation training of stroke patients with limited walking ability. Besides its light walking support for the patient, it offers real-time analyses of gait and overall progress to assist the physiotherapist in charge.

Similarly, Indego® from Parker Hannifin is a powered, light-weight lower limb exoskeleton that allows users to stand and walk on all surfaces, including stairs, and gain access to areas that are not wheelchair accessible.

Reactive Robotics' Vemo system helps care staff and therapists with the early mobilization of the most seriously affected patients (e.g. ventilated patients and/or patients in intensive care. The system is adapted to the patient's bed and enables a single person to carry out the whole mobilization process. In 2021, the developing team won the euRobotics Technology Transfer Award.

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[371] Strickland, E.: ReWalk Robotics' New Exoskeleton Lets Paraplegic Stroll the Streets of NYC, IEEE Spectrum, July 15, 2015; http://spectrum.ieee.org/automaton/robotics/medical-robots/rewalk-robotics-new-exoskeleton-lets-paraplegic-stroll-the-streets-of-nyc.

Figure 3.10: Reactive Robotics in the ICU: A robotics device equipped with artificial intelligence for the patient's individualized early mobilization therapy in the ICU. Image credit: Reactive Robotics.

The TEM LR2 leg rehabilitation robotic device from Yaskawa trains limbs after a cerebral stroke or bone fracture through generating diverse rehabilitation patterns. It consists of a robotic arm on a movable platform, making it easily transportable.

Robert from Life Science Robotics works similarly. The robotic arm helps the physiotherapist in mobilizing the patient. It has three modes: Active resistance (strength building), active assistance (guided exercise), and passive assistance (for immobile patients). Besides taking the strain off the therapist, the robot can reduce body contact, thus reducing the risk of transmitting Covid-19 and other transmittable diseases.

Figure 3.11: Robotic arm Robert. Image credit: Life Science Robotics.

Furthermore, robotic systems are used, for example, in movement therapy to improve trunk control and stability. As one example, the Hirob system from the Austrian company Intelligent Motion enables automated hippotherapy. Here, the patient must respond to the three-dimensional movement of the robot, which is modeled on a horse's back, and thus trains the trunk, pelvis and back.

Figure 3.12: The Hirob training device imitates the movements of the horse's back to strengthen the trunk muscles. Image credit: Intelligent Motion.

Upper extremities and arm/hand training

Armeo Power from Hocoma provides early rehabilitation for patients with severe neurological movement impairments. It is specifically designed for arm and hand therapy in the early stage of rehabilitation. It offers highly repetitive training for patients who have suffered strokes, traumatic brain injuries, or other neurological disorders resulting in severe arm and hand impairments.[372]

Toyota Motor Corporation has presented, within their Partner Robot Family, several rehabilitation robotic devices and robots (for physical therapy, mental therapy, and support), such as Welwalk WW-1000, Care Assist, and Robina; the latter is designed to provide medical and nursing care.[373] The company recently launched a trial rehabilitation robot rental service. Welwalk is made available to clients in Japan through Good Life

[372] Riener, R. et al.: Transferring ARMin to the Clinics and Industry, Topics in Spinal Cord Injury Rehabilitation, vol. 17, 2011, no. 1, pp. 54-59; https://meridian.allenpress.com/tscir/article/17/1/54/190916/Transferring-ARMin-to-the-Clinics-and-Industry.

[373] Toyota: Partner Robot Family; https://global.toyota/en/mobility/frontier-research/.

Design, a joint venture with Mitsubishi established in 2002 to support projects for medical, healthcare, and nursing facilities, as well as for companies.[374]

Figure 3.13: Myopro® is an adjustable orthosis that may help regain function in arms and hands paralyzed by a stroke, brachial plexus injury (BPI), cerebral palsy, or other neuromuscular disease or injury. Image credit: Myomo.

“Hand of Hope” from Rehab-Robotics is a therapeutic device that may help patients regain hand mobility through motor relearning. The patient self-initiates movements through often very weak voluntary EMG signals that indicate the intention to move. The system then filters and transmits data to a motor on the brace to enable the desired motion.

Amadeo from Tyromotion manipulates the individual fingers/thumb and the patient’s hand. Similarly, Myopro myoelectric upper limb orthosis from Myomo is a rigid brace used for supporting a patient’s weak or deformed arm to enable and train functional activities. The system is controlled by electromyographic signals which are detected on the user’s skin at the biceps and triceps muscles.

374 Toyota Launches Rental Service for the Welwalk WW-1000 Rehabilitation Assist Robot in Japan, press release by Toyota, April 12, 2017; http://newsroom.toyota.co.jp/en/detail/15989382.

Figure 3.14: Upper limb rehabilitation robotics that simulates a mechanical environment for the users through the force feedback algorithm and high-performance motor. Image credit: Fourier Intelligence International.

Emotional (social) therapy robots

The main function of these robots is to increase user interaction, which is why many of them simulate a pet or toy. Impressive results have been collected from using robots as part of specific therapies aimed at child autism, Alzheimer's disease, and mood or learning disorders. A major product in socially assistive robotics is Paro, an advanced interactive robot developed by Aist and licensed to the Intelligent System Co. for commercial distribution. This robot, resembling a baby seal, allows the documented benefits of animal therapy to be administered to patients in environments such as hospitals and extended care facilities where live animals are usually not allowed. Paro has five kinds of sensors: Tactile, light, audition, temperature, and posture sensors, with which it can perceive people and its environment. Paro has received wide recognition for its therapeutic benefit.[375] Another example is Telenoid™, an android robotic device developed at Osaka University together with the Advanced Telecommunications Research Institute International. The therapist can communicate with the patient from a remote location using the robotic device. Experiments are conducted for different

[375] Hung, L.: Liu, C., Woldum, E.; Au-Yeung, A.; Berndt, A.; Wallsworth, C. et al.: The benefits of and barriers to using a social robot PARO in care settings: a scoping review. In: BMC Geriatr, vol. 19, 2019, no.1, DOI: 10.1186/s12877-019-1244-6; https://pubmed.ncbi.nlm.nih.gov/31443636/.

application areas, e.g. in Japan, to interact with children and persons with dementia [376], or in Denmark to communicate with disabled persons or persons in elderly care. [377] The robot doll Kaspar from the University of Hertfordshire is used to encourage social interaction and communication in children with autism. Other well-known experimental robots in this field are Nao, Keepon, and Popchilla.[378, 379]

3.1.3.3. COST-BENEFIT CONSIDERATIONS AND MARKETING CHALLENGES

The development of rehabilitation robots and robotic devices is being promoted by the urgent needs of disabled users. Real innovation can only be attained if the results lead to a real benefit for the disabled. This is a very demanding goal as the kind of handicap, the person's economic situation, and often their cultural background must be considered.

In 2017, 2.1 million individuals in the USA were living with limb loss. The number is expected to double by 2050.[380] Considering these numbers, rehabilitation robotics should be used in therapeutic and rehabilitative procedures to achieve the best motor or cognitive functional recovery in daily life for disabled individuals with various diseases, such as a stroke, brain trauma, and neuro-motor disorders."

New findings show that robot-assisted devices can help patients regain limb movement years after suffering a stroke. There are about 6.4 million stroke patients in the USA (some 795,000 strokes every year; in Europe over 1.1m; worldwide some 16.9m first-ever strokes) with chronic deficits. In the USA alone, stroke-related medical costs are assumed to surpass USD 65.5bn every year (2010).[381]

Numerous studies have shown that robot-assisted therapy significantly improves controlled motions for everyday function and quality of life. Similarly, robotic devices could also help rehabilitate people injured in car accidents or disabled from arthritis, heart

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376 Yamazaki, R. et al.: Teleoperated Androids as an Embodied Communication Medium: A case study with demented elderlies in a care facility. In: 21st IEEE International Symposium on Robot and Human Interactive Communication, September 9-13, 2012, Paris, France 2012, pp. 1066-1071; https://pubmed.ncbi.nlm.nih.gov/3144/.

377 Leeson, C.: From an unfamiliar other to a cherished friend: The domestication of telenoid in the care of elderly and disabled people. Workshop on Portable Androids and their Applications. Aalborg. Presentation March 2, 2015; http://hil.atr.jp/projects/CREST/DenmarkSymposium/program.html.

378 Matarić, M. J.; Scassellati, B.: Socially assistive robotics. In: Siciliano, B. and Khatib, O. (eds.): Springer Handbook of Robotics, 2nd Edition. Berlin, Heidelberg: Springer, 2016, pp. 1973-1994.

379 Zheng, Z.; Bekele, E.; Swanson, A.; Weitlauf, A.; Warren, Z.; Sarkar, N.: The impact of robots on children with autism spectrum disorder. In: Casanova, M. et al. (eds.): Autism Imaging and Devices, CRC Press, pp. 397-415.

380 https://accessprosthetics.com/15-limb-loss-statistics-may-surprise/.

381 Stuntz, M.; Busko, K.; Irshad, S.; Paige, T.; Razhkova, V.; Coan, T.: Nationwide trends of clinical characteristics and economic burden of emergency department visits due to acute ischemic stroke, OAEM, vol. 9, 2018; https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5614785.

disease, and other conditions.[382, 383, 384] Challenges are seen in the long-term safety of rehabilitation robotic devices, the clinical effects, and the cost-benefit ratio of many of these interventions on functional recovery.

The potential of wearable technologies for rehabilitation is extremely promising. A highlight for promoting and making these technologies visible was the Cybathlon, a championship for athletes with disabilities using advanced assistive devices including robotic technologies. This event took place at the Swiss Arena, Kloten, Zurich, Switzerland, on October 8, 2016.[385] A global follow-up event was conducted virtually on November 13-14, 2020. A face-to-face meeting will take place again in October 2024.

3.1.3.4. PRODUCERS

Able Human Motion, Aitreat, Angel Robotics, Axiles Bionics, Bama Teknoloji, Barrett, BEC, Bionik Laboratories, Blue Ocean Robotics, Curexo, Cyberdyne, Egzotech, Ekso Bionics, ExoAtlet, Exomed, F&P Personal Robotics, Fourier Intelligence, GaitTronics, Gogoa, HealthSouth, Hocoma, Humanware, Intelligent Systems, KineteK, Lambda Health System, LAP, Life Science Robotics, Lifeward, Manntel, Marsi-bionics, Max Bionic, MediTouch, Movendo Technology, Myomo, MyoSwiss, Neofect, Neurobotics, P&S Mechanics, Panasonic, Pedasys, Reactive Robotics, Reha Technology, Reif, Rex Bionics, Safelog, Toyota, T-Robotics, TyroMotion, UBT Robot, Wandercraft

[382] Dohle, C. I. et al.: Pilot study of a robotic protocol to treat shoulder subluxation in patients with chronic stroke, Journal of NeuroEngineering and Rehabilitation, August 5, 2013; http://www.jneuroengrehab.com/content/pdf/1743-0003-10-88.pdf.

[383] Nef, T.; Guidali, M., Klamroth-Marganska, V.: Riener, R.: ARMin - Exoskeleton Robot for Stroke Rehabilitation, IFMBE Proceedings, vol. 25, 2009, no. 9, pp. 127-130; https://link.springer.com/content/pdf/10.1007/978-3-642-03889-1_35.pdf.

[384] Morone, G. et al.: Who May Have Durable Benefit From Robotic Gait Training? Stroke, vol. 43, 2012, no. 4, pp. 1140-1142;

http://stroke.ahajournals.org/content/43/4/1140.full.pdf?download=true.

[385] See more details on the competition and numerous accompanying events at http://www.cybathlon.ethz.ch.

3.1.4 AP69: OTHER MEDICAL ROBOTS

Over the last years, numerous robot developments, apart from diagnostic, surgical, and rehabilitation robots, have taken place and led to several innovations. Some of the most interesting product innovations are given in the following section to showcase the innovation potential of service robotics.

Robots for telepresence

Robots for remote presence can be thought of as a mobile platform equipped with a screen, video cameras, and user interfaces. They can be thought of as embodied video conferencing on wheels. These robots additionally enable healthcare providers (such as specialists or physicians) to instantly connect with a patient, either in a care unit or remotely, and to perform real-time attention, assessment, diagnosis, and patient management. In addition, the risk of an infection through personal contact is eliminated.

The shortage of staff in intensive care units increasingly poses problems. To extend the availability of physicians, intensive care institutions have started to adopt varying forms of remote presence technology, which is either used in hospitals or remote care facilities. A healthcare provider can connect to these devices from a control room or a remote location. A study on the users' experience with robotic remote presence technology praised the practical value of these robots. However, licensing, costs for technology, and reimbursement for robotic telepresence for the medical environment continue to impede progress.

Quite a few robots have already been introduced on the market with general abilities to interact with people and provide telepresence functions both for professional and consumer use (see chapters 3.2.8.2 and 3.3.2.1). Some of these robots are also used or have even been designed specifically for applications in healthcare environments. However, telepresence robots that count as a medical robot in the sense of the ISO definition (meaning that they provide medical functions) are quite rare.

One of the most prominent examples is InTouch Vita, a joint development of iRobot and InTouch Health, which has since been taken over by Teladoc Health. The robot hosts a panoramic visualization system and intuitive interfaces and allows the direct connection of medical devices, such as electronic stethoscopes, otoscopes, and ultrasound for transmitting data to the remote physician. It can be fully remote controlled but can also drive autonomously. As it cannot open doors to a patient's room by itself, it is primarily used in intensive care units where doors are typically left open.[386] As long as direct bedside care providers are available, non-robotic tele-medicine technology is preferred. While the maintenance of the robots currently operating in the field is still supported by

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[386] Garingo, A.; Friedlich, P.; Chavez, T.: "Tele-rounding" with a remotely controlled mobile robot in the neonatal intensive care unit. In: Journal of Telemedicine and Telecare, vol. 22, 2015, no. 2; https://www.researchgate.net/publication/279300194_Tele-rounding_with_a_remotely_controlled_mobile_robot_in_the_neonatal_intensive_care_unit.

Teladoc Health, the company is no longer producing and selling new Vita robots and has shifted its focus to non-robotic telehealth solutions.

Kompaï from Kompaï robotics is another example of this type of product. It can move around a facility by itself and is designed specifically to keep an eye on residents in elderly care facilities. The robot interacts with and guides the residents. It monitors health data, can send alerts, and is even able to call for emergency help.

Ohmnilabs has so far focused its developments on lightweight and low-cost general-purpose telepresence robots. Its latest development is the telehealth robot Ohmnicare. It can be used for telepresence (see chapter 3.2.8.2) but also comes with health monitoring and autonomous navigation functions. In order to enter a patient's room without having to ask a human to open the door for the robot, the company is currently developing a manipulator for it that can open doors.

Figure 3.15: Ohmnicare mobile telehealth robot in a hospital. Image credit: Ohmnilabs.

Another system for the aforesaid use cases is Vgo from Vecna. Apart from patient monitoring by medical and/or nursing professionals, another service offered by hospitals or care facilities is to enable virtual visits by relatives and friends or tele-exchange with medical and nursing staff. Severely ill children can participate in school lessons or other social activities, and healing processes at home can be monitored.

During the COVID-19 pandemic, telepresence robots offered great benefits for health professionals. These types of robots enabled them to quickly assess patients without personal contact and without the risk of contracting or transmitting the virus. This was, for example, helpful for doctors that were quarantined at home or for medical staff that could check on patients without the need for personal protective equipment.

Robots to support the care of patients

In this area, several solutions have been introduced lately to support the healthcare staff with their work in hospitals or in elderly care homes. Especially in Japan, where the ratio of the population older than 65 is predicted to increase to 38% by 2070[387], sales of nursing care robots is predicted to grow the fastest among service robots. Globally, especially in the most developed countries, the share of the population older than 65 is also predicted to increase significantly over the next decades according to the World Health Organization (WHO).[388] The impact of the lack of a sufficient workforce, especially in care-related jobs, is expected to be grave.

Positioning and bedding of patients or persons in need of care is a physically demanding task for care workers. Many of them must quit their job due to back problems caused by heavy lifting tasks. Various person lifters (mainly operated manually) are available on the market. However, to increase their usefulness and usability, companies and research institutes – mainly in Japan – are working on new solutions which integrate robotic technologies and (semi-) autonomous functions.

Toyota has introduced the Care Assist Robot[389], the prototype of a robot which also supports the transfer of persons in need of care. It helps them to get from a seated position to a standing position on the device, thus allowing them to be easily transported to a different location.

Other solutions consider the use of exoskeletons to support care staff during heavy lifting tasks. As mentioned in chapter 3.1.3, exoskeletons can be worn by medical staff to give them extra strength when executing strenuous tasks like lifting and repositioning patients or moving heavy objects. An example is HAL 3 (Hybrid Assistive Limb for Labor Support) from Cyberdyne, another example comes from the German company Hunic.

387 https://www.statista.com/statistics/606542/japan-age-distribution.

388 https://www.un.org/en/global-issues/ageing.

389 https://global.toyota/en/mobility/frontier-research/.

Further robots that support staff or patients with manipulation or handling tasks can also be found in the logistics chapter, if they are used in hospitals or nursery homes (see chapter 2.6.2) or in the chapter presenting solutions for care at home, if they are used by and sold to persons in their home (see chapter 4.4).

Figure 3.16: HAL Lumbar Type is an application designed to solve the physical burden in healthcare environment from two directions with a single unit: Supporting caregivers with heavy lifting and training the body core and lower limb functions of seniors. Image credit: Prof. Sankai, University of Tsukuba/Cyberdyne Inc.

Figure 3.17: The Softexo Lift is suitable for powerful and back-friendly lifting and moving of people or heavy items. Image credit: Hunic GmbH.

Another application area of robotic technologies designed to support healthcare staff is personal hygiene. This is an intimate procedure, which requires a certain level of trust between the patient and caregiver. For certain patients, an automated solution taking over this task may be preferred. Again, several solutions to support this task have been introduced by different companies; however, only a few are really used in practice.

In 1970, Sanyo from Japan already presented a Human Washing Machine[390], a washing cabin that you can be seated in and get washed. Similar functionality is offered by the robotic bath Santelubain 999 from Avant, also a Japanese company.[391] In addition to the cleaning process, it offers massage functions or the application of body lotion.

Another prototype introduced by Panasonic is a hair washing robot. It uses different sensors to detect the head of the user and cleans the hair using two robotic arms equipped with 16-fingered hands.

The European research project I-Support dealt with a solution better suited for the European market.[392] The robotic shower includes a robotic chair and showering arm as well as different interaction modalities.

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[390] https://www.nytimes.com/2004/03/05/world/machida-journal-japan-seeks-robotic-help-in-caring-for-the-aged.html.

[391] https://www.trendhunter.com/trends/human-washing-machine-avant-santelubain-999-applies-seaweed-packs-too.

[392] https://cordis.europa.eu/project/id/643666/factsheet.

Robots for training medical interventions

The use of simulation in healthcare education has become relevant to improve patient safety and quality of care. The adoption of more realistic simulation-based teaching methodologies serves as a bridge between the acquisition and application of clinical skills, knowledge, and attributes, and increasingly includes robotic simulators.

The birthing simulator Simone (developed by the Swiss Federal Institute of Technology ETH Zurich, the University Hospital Balgrist, Switzerland, and Klinikum rechts der Isar, TU München, Germany and sold by 3B Scientific GmbH) consists of a haptic, a graphical, and an acoustic user interface. The acoustic interface enables the user to hear the fetal heartbeat from the simulated cardiotocograph as well as the mother's (virtual) groaning and breathing. For a realistic simulation, the haptic impression is important for the learner. For that reason, applied forces are translated into real baby mannequin movements where the mannequin is connected to a Stäubli industrial robot. This realistic simulation results in a user-interactive mode, displaying the audio-visual and haptic reactions of the user actions on the physiology and biomechanics of the baby and the mother.

The company Gaumard Scientific has created a series of robotic mannequins which are used in the training of medical staff. The mannequins simulate vital functions and can be connected to actual medical equipment. Multiple injuries and medical interventions can be simulated with these systems, e.g. dislocated joints, childbirth, C-section, and intubation. The systems are robust and can be used regularly for training purposes over an extended period of time.[393]

Raven II from Applied Dexterity: Robotics experts at the University of California Santa Cruz and the University of Washington have completed a set of seven advanced robotic surgery systems to be used by major medical research laboratories throughout the United States. By making open-source platforms available to medical and engineering schools, advancement in research and innovation is promoted. Raven II resembles the Da Vinci system's robotic part and is equipped with two robotic arms, a camera for viewing the operational field, and a surgeon-interface system for remote operation of the robotic device.

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[393] https://www.therobotreport.com/gaumard-gives-simulated-patients-realistic-symptoms-medical-training/.

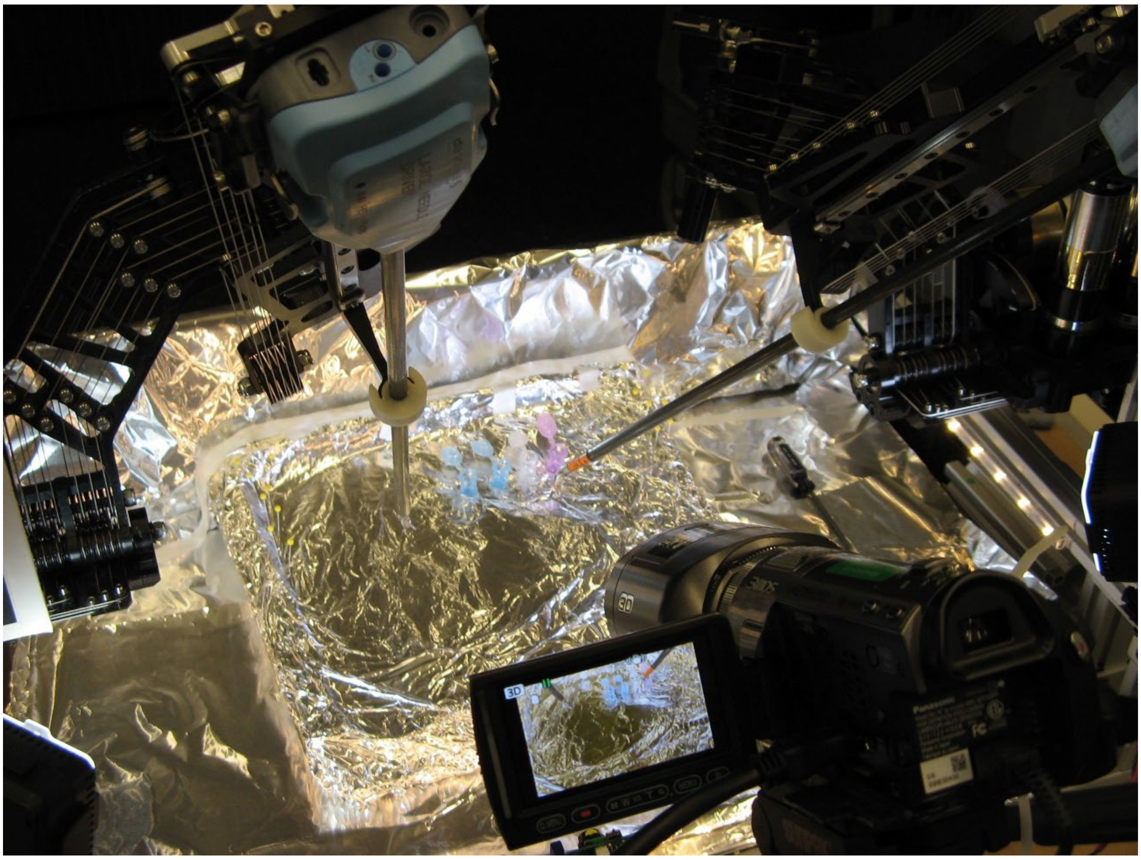

Figure 3.18: The Raven II system with simulated communication delay used to demonstrate the feasibility of tele-operated rodent dissection on the International Space Station from earth. Image credit: Applied Dexterity.

Robots for intra-corporal drug delivery

Similar to the previously mentioned intra-corporal diagnostic devices ("pill cams"), micro-robots may be used to precisely deliver drugs. Such robotic pills from Rani Therapeutics are currently undergoing preclinical studies and consist of an ingestible polymer and tiny hollow needles made of sugar that are designed to safely deliver drugs to the small intestine. These developments point to a completely new and fantastic product field of micro or even nano-scaled robots which are driven by bio-chemical sensory-motor principles.[394]

Laboratory robots

An additional application field in close connection to medical applications is service robots for providing support in laboratories. The shortage of staff and high costs of manually executed tasks together with many monotonous processes or working steps, which demand a very high level of accuracy, provide perfect conditions for the usage of

[394] Boffard, R.: Tiny bots to embark on fantastic voyage, Engineering & Technology, vol. 10, 2015, no. 5, pp. 34-36.

robotics. They cover stationary robots with different levels of sensor usage and data-based autonomy (sometimes on rails) as well as mobile robots with or without a manipulator on top.

However, the number of service robots for laboratory applications with the necessary degree of autonomy to fulfill the service robot definition criteria (see chapter 1 of this report) is rather small. Several companies offer stationary robotic devices dedicated to labs. Completely new service robots that assist, for example, in the transport of samples, are more likely to be assigned to the logistics application described in chapter AP 5. An exemplary development is the laboratory robot Kevin from Fraunhofer IPA, which executes fetch and delivery services autonomously. In 2023, the usage rights for Kevin were sold to the United Robotics Group.[395]

Several companies are acting as integrators for laboratory robots (e.g. LT Automation, Robominds, Unitelabs, and more). This means that they are using existing industrial manipulators, e.g. from Kuka or Universal Robots, together with mobile platforms, e.g. from Omron or MiR, and extend their capabilities for supporting tasks in laboratories. uMobilelab from United Robotics Group can drive autonomously to where it is needed and uses a UR manipulator, for example, to identify blood tubes in emergency laboratories. Another offering of the same company, “The Box”, uses a Sawyer robot from Rethink Robotics to support laboratory applications. An example of research activities for laboratory applications is the “Robotic Lab Assistant” presented by the University of Liverpool. It can move around a laboratory independently and conduct different scientific experiments.[396]

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[395] https://unitedrobotics.group/en/news-events-press/press-releases/kevin-laboratory-robot.

[396] https://www.theverge.com/21317052/mobile-autonomous-robot-lab-assistant-research-speed.

3.1.4.1. EXPERT VIEW

The following 2 interviews with Teledoc Health from Germany and Ohmnilabs from the US were conducted in 2024 as part of the major focus chapter revision by Fraunhofer IPA.

3.1.4.1.1. INTERVIEW WITH TELADOC HEALTH GERMANY

Company:	Teladoc Health Germany GmbH
No. of employees:	6 (Teladoc worldwide: >5,000)
Products:	Telepresence robots
Interview partner:	Sebastian von Lovenberg (Sales Director, HHS D-A-CH)

Why did you choose to develop telepresence robots?

Teladoc Health Germany decided to develop telemedicine robots in order to improve healthcare and facilitate access to specialists, especially in remote areas. The mission is to bridge the gap in medical care and to ensure that every patient actually receives the best possible treatment, regardless of their location, place of residence, or their current condition. The ability to use telemedicine to bring this expertise to any location was the main reason for developing these robots.

What was the most impactful decision for your product development?

One of the most important decisions was to focus on the integration of highly advanced technologies, such as AI-assisted navigation or high-resolution video communication. This is something we see time and time again with users who may also use other telemedicine solutions, some of which they have assembled themselves with quite simple means. They then realize that there is a controllable camera, a robot that I can control remotely, no matter where in the world I am, and which gives me so much more impact and opportunities to take care of the patient. This allows me to make a diagnosis better than someone holding a smartphone or tablet in their hand and who is unable to see what it conveys to me. Of course, this also requires the whole integration of AI, etc. to create a seamless, immersive experience for doctors and also for the patients with our robots, regardless of the distance that ultimately separates them.

What are the biggest hurdles in terms of bringing your robots to the market?

The biggest challenge is complying with the regulatory requirements in different countries while ensuring that our technology meets the high standards of medical practice. Sometimes, it is the case that you can technically do much more than is legally possible. This means that you are always a bit ahead of the actual time of usability. In addition, it is still the case that you also need to gain the trust of the medical community and clearly communicate the benefits of the solution for different medical specialties. We are not only concentrating on intensive care medicine, not only on telestroke, but have a broad product portfolio and thus also a wide range of possible specialties and application scenarios that we map. In the various disciplines, it is sometimes difficult to gain the required trust. Some have been doing this for 20 years, so I would say it's a “bread and butter business”, and for others it's actually still in its infancy.

In the future, what do you see as the biggest challenges for your customers?

One of the biggest challenges for our customers is certainly the increasing demand for healthcare services. This means that we have more and more older people with more complex diseases. On the one hand, fortunately, we are all getting a little older but usually have more aches and pains. This multi-morbidity, with the simultaneous increase in the number of patients, is a big challenge. At the same time, resources are becoming increasingly scarce because we have fewer and fewer skilled workers. Coping with these issues is a great challenge while also continuing to improve efficiency and maximizing patient satisfaction, which is also becoming increasingly important. We are not only talking about the treatment result but also about the patient's experiences during the process, something that is becoming more and more crucial. These are actually the main challenges, in addition to the challenges of financing, which we unfortunately encounter in many regions.

How are you planning to further develop your product to tackle these challenges?

We are committed to continuously developing and improving our products. We want to further increase their user-friendliness; we want to continue to integrate various data analyses and AI. We want to introduce new features that increase clinical efficiency so that the user does not have to somehow insert something extra or press a button somewhere. At some point, all this should no longer be necessary. We work closely with various medical professionals and continuously gather feedback from our users and customers, as we can ultimately only achieve a suitable solution together with them and meet the needs of the entire healthcare system. Of course, needs are also changing, especially since we do not even know what this technology can do today. For many people, it is the first time they have come into contact with it and they are completely overwhelmed; they did not even think it was possible. Then come the innovative ideas, we want to meet these needs and adapt our solution overall. I believe that in the end this will actually help to overcome the challenges I just mentioned, which lie in the future and are already present.

3.1.4.1.2. INTERVIEW WITH OHMNILABS

Company: OhmniLabs, Inc.
No. of employees: 56
Products: Telepresence robots (OhmniTelepresence, OhmniCare)
Interview partner: Tingxi Tan (Chief Product Officer)

Why did you choose to develop telepresence robots?

The inspiration for our telepresence robots came from a challenge my two co-founders and I faced – the desire to feel more connected to distant family members. The idea organically emerged, as we wanted more presence when communicating with them. We wanted a solution that could bridge that gap and make our virtual presence more tangible and immersive. While there were other telepresence robots on the market, the high cost kept them out of reach for most consumers. Driven by our engineering backgrounds, we decided to build our own.

What was the most impactful decision for your product development?

The most impactful decision was to do most of the manufacturing in-house using 3D printing, enabling us to iterate the product swiftly and go to market quickly. With a hardware product, especially in robotics, the traditional route is very challenging because it requires substantial capital commitment. Once you have created the injection molds, it takes about three years to recoup these upfront costs. Instead, we decided to 3D print, a main driver that allowed us to rapidly prototype, test, and iterate the hardware, enabling us to go to market quickly. While most hardware companies utilize 3D printing for prototyping, we specifically decided to 3D print production parts, a key decision that facilitated our agile development and swift market entry. Today, we use a combination of injection molding for external pieces and 3D printing for internal parts.

What are the biggest hurdles in terms of bringing your robots to the market?

There are various hurdles at every product stage. The biggest hurdle right now is navigating the complex healthcare system, especially the procurement process. You are not going to get anything deployed at scale until you have proven both financial ROI and clinical ROI in your pilots. This is truly difficult, as financial ROI can be proven relatively quickly in three to six-month pilots, but clinical ROI takes much longer to achieve. Only by having both can you deploy at scale.

In addition, being able to iterate on your product quickly enough to support the healthcare landscape, as well as having the experience, knowledge, and customer-driven mindset to identify the correct use case is extremely challenging.

In the future, what do you see as the biggest challenges for your customers?

In the future, I see staffing challenges and burnout as some of the biggest issues facing our customers in healthcare. There is immense pressure building up, particularly for healthcare providers across all roles – from nurses and clinicians to environmental services staff. The workload is taking a toll, leading to high levels of burnout and staffing shortages, as nurses and experienced professionals opt to quit their jobs or retire early.

Exacerbating this is the difficulty in effectively mentoring and onboarding new staff to fill vacancies, as seasoned employees do not want to take on additional training responsibilities. Coupled with rising costs, this creates a perfect storm that makes operations difficult to sustain.

In healthcare today, there are essentially three pillars to address cost and staffing challenges: 1) software solutions like EHR (electronic health record), telehealth, and AI-assisted services; 2) hardware innovations such as indoor delivery robots and sensor analytics; and 3) process improvements to streamline workflows and optimize employee scheduling. Our product, OhmniCare, can contribute to all three pillars – leveraging software for better scheduling, providing hardware robotic solutions for tasks like hospital deliveries, and enabling process enhancements that alleviate staff burdens through hybrid schedules and self-directed scheduling. This multifaceted approach is crucial for alleviating staffing strains while reducing costs in the healthcare environment.

How are you planning to further develop your product to tackle these challenges?

It is very important to spend time in the hospital to identify the actual problems our customers face rather than imagining what the problems are. This is a pitfall many robotics companies fall into – they find applications for their technology rather than truly understanding the problem first. Our success lies in spending time embedding our team members into hospitals to observe operations – from cleaning staff to nurses on their shifts. Instead of asking how we can apply our technology, we first seek to understand. Our company's product development mindset is solution focused, not feature focused. Immersing ourselves in the real problems before developing solutions is crucial.

3.1.4.2. PRODUCERS

Aeolus Robotics, Amyrobotics, Brain Navi Biotechnology, Curaco, Diligent Robots, Enova Robotics, Fuji Robotics, HIT Robot Group, Invento Robotics, Kawasaki Heavy Industries, Kinova, Kompaï Robotics, Muscle Corporation, Panasonic, Reif, Tmsuk, Toyota

4 Consumer Robots

Chapter 4 contains detailed information about the application areas of consumer robots, including a selection of typical products and suppliers.

4 Consumer robots

4.1 INTRODUCTION

Who would not want a robot at home taking care of tedious everyday chores, such as floor cleaning, watering plants, laying the table, or cleaning the kitchen? Given the huge number of potential customers and users, an increasing number of companies have ventured to develop and market robots for consumer use. The trend toward developing and using robots in domestic environments will certainly continue as is expressed by the large number of startups in this field. The development of such robots can be motivated by several strategies:

- Compelling application at a competitive price, such as robotic vacuum cleaners
- A fashion product that fascinates
- Fun, excitement, community experience (toy humanoids that can be programmed to perform tricks, exercises, fights, etc.)
- The product solves a practical problem (such as floor cleaning, entertainment, etc.)
- A new application or a new “robo gadget” is invented

In any case, the development and manufacture of consumer robots is marked by stressing their low cost, excitement, and even status.

Since the inception of the World Robotics survey, this field has experienced amazing market growth and its dynamism is unabated. Furthermore, it is expected that the cross-fertilization of home entertainment, smart phones, mobile computing, Internet, and robot technologies will continue in significant technology and product developments in the future. A clear sign in this direction is the entry of software companies and telecommunication into this domain to create an engineering environment for academic, hobbyist, and commercial developers for creating robotics applications across a wide variety of hardware.

Home robots will evolve from generation to generation in terms of appearance and functionality, opening up a broad commercial market. There will be fluid boundaries between home robots, intelligent home automation, and entertainment electronics.

4.1.1 IFR STATISTICS

Service robots for consumer use are recorded separately because quantities are much higher and thus the indicator “unit sales” is of different magnitude compared to service robots for professional use. Consumer service robots are also produced for a **mass market** with completely different pricing and marketing channels. So far, service robots for consumer use are mainly in the areas of domestic (household) robots, which include vacuuming and floor cleaning robots, gardening (mainly lawn-mowing) robots, outdoor cleaning (mainly pool cleaning) robots, and for social interaction and education.

Overall sales of robots for consumer use increased slightly by 1% to close to 4.1 million units in 2023. There are hardly any RaaS models offered in this category. The only small increase is due to the 3% decrease in sales for robots for **domestic tasks** (AC1) to below 3.8 million units sold. In contrast, the application groups for **social interaction and education** (AC2) and **care at home** robots (AC3) experience growth rates at much lower absolute numbers. Care at home robots (AC3) display a strong increase in unit sales by 195% up to 1,952 units sold in 2023. This remarkable growth is due to demographic change. As the population is aging further, the market for care at home robots is expected to grow in the long run. Social interaction and education robots (AC2) grew at 11% to almost 157,000 units in 2023. The steep increase in the application class **other consumer robots** (AC99) could in theory be attributed to two factors: The launch of new products for which the IFR statistics does not offer an appropriate classification scheme yet or service robot firms which are unable (for technical or other reasons) to disclose the proper classification of their product. Fortunately, the units reported in that category are below 0.5% of total robots for consumer use.

Units sold in RaaS decreased by 79% in 2023 worldwide, but RaaS is generally not a common business model in robots for consumer use.

Table 4.1

Service robots for consumer use in 2022 and 2023 by application group

	Application	2022	2023	2023/2022	2022	2023	2023/2022
		units sold		growth rate	RaaS fleet (in units)		growth rate
AC	**Consumer robots**	**4,094,778**	**4,128,141**	**+1%**	**11,365**	**2,377**	**-79%**
AC1	Robots for domestic tasks	3,880,259	3,780,573	-3%	**	**	-
AC2	Social interaction, education	141,185	156,625	+11%	**	**	-
AC3	Care at home	662	1,952	+195%	**	**	-
AC9	Other consumer robots	72,672	188,991	+160%	0	0	-

Source: World Robotics 2024
Results of IFR's annual survey and desktop research (49 companies for consumer use)
*Regional breakdown cannot be revealed (minimum number of non-zero observations not reached).
**Results cannot be revealed (minimum number of non-zero observations not reached).

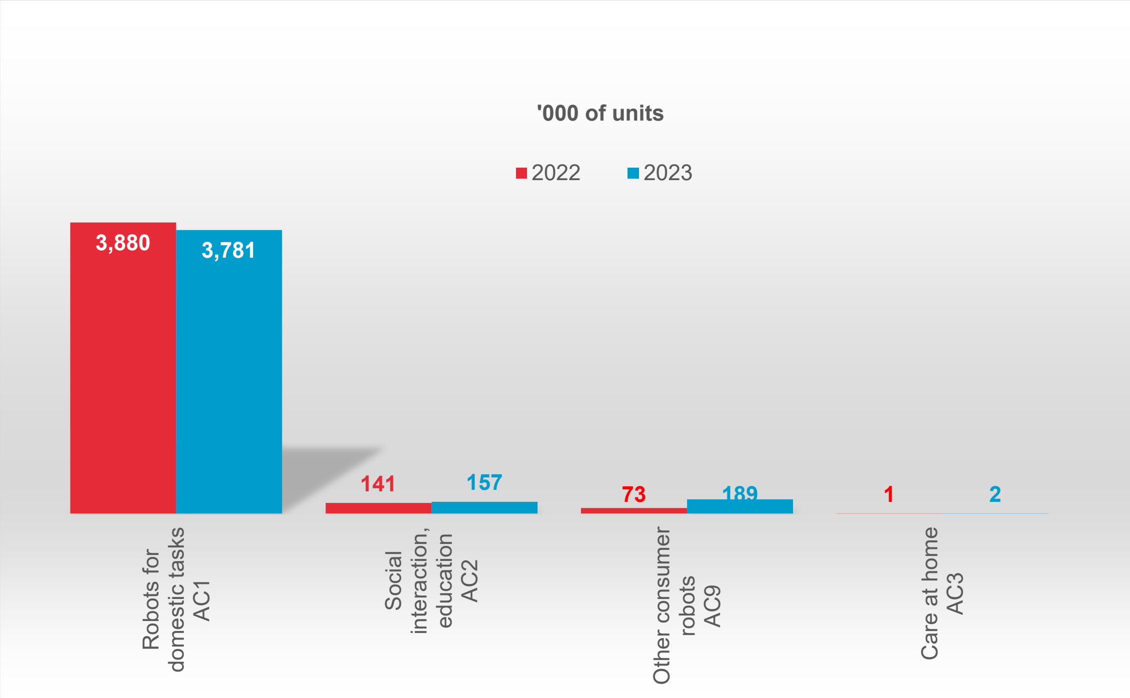

Figure 4.1: Service robots for consumer use. Unit sales 2022 and 2023

In 2023, almost 60% of total sales of robots for consumer use originated from Europe + MENA while 40% of sales originated from the Asia + Pacific region. Both regions display a similar growth rate around (+30%). The Americas display lower absolute numbers (almost 12,000 units in 2023) but a high growth rate (+103%). The low number of sales is most likely due to the underrepresentation of the Americas in the sample due to low participation rates in the IFR's annual survey. RaaS is not considered in the regional analysis because it is not a common business model in consumer use applications and the low number of non-zero observations (see table 4.1) prevent further regional breakdown.

Table 4.2

Service robots for consumer use by region of origin (2022 and 2023)

Application		Region	2022	2023	2023/2022
			units sold		growth rate
AP	consumer use service robots	Total	1,825,495	2,370,888	+30%
		Europe+MENA	1,061,294	1,395,134	+31%
		The Americas	5,830	11,835	+103%
		Asia+Pacific	758,371	963,919	+27%

Source: World Robotics 2024
Results of IFR's annual survey and desktop research (49 companies for consumer use)
*Regional breakdown cannot be revealed (minimum number of non-zero observations not reached).
**Results cannot be revealed (minimum number of non-zero observations not reached). Data included in application group total (AP1, AP2, etc.).

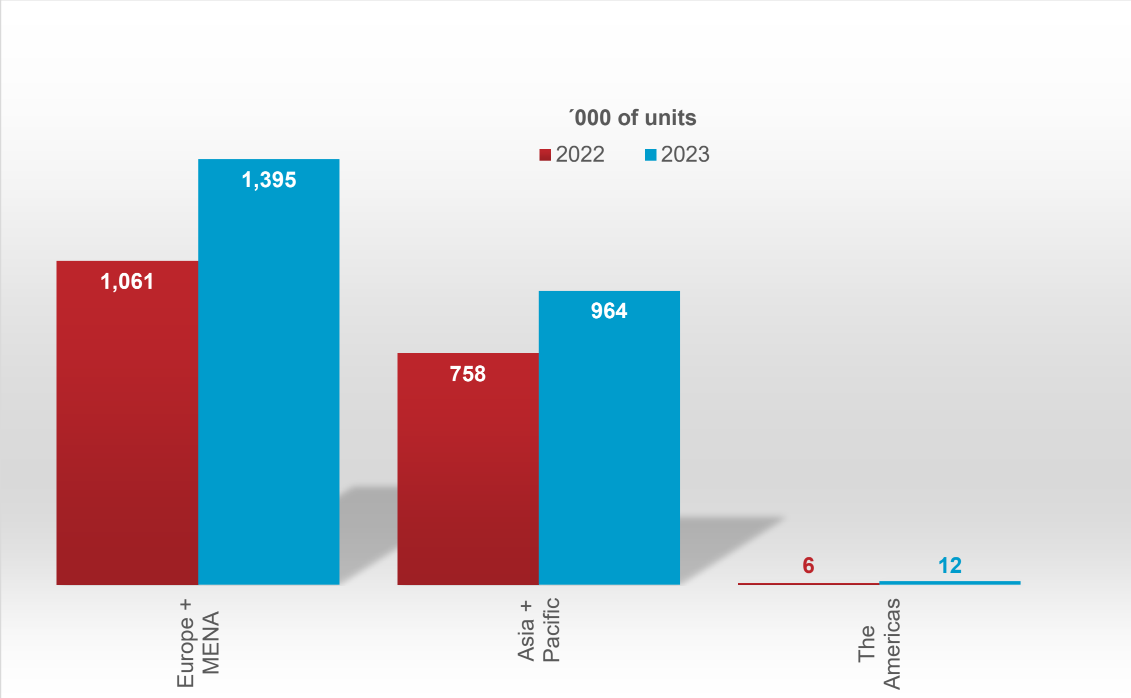

Figure 4.2: Service robots for consumer use. Unit sales by region of origin 2022 and 2023

The majority of service robots for consumer use are ground-based of which almost all are rolling and only a small fraction is fixed in place. This is because most robots for domestic tasks are floor cleaning or lawn mowing robots which are all type of movement ‘rolling’. Both aerials and wearables display negligible numbers. None of the robots for consumer use were reported swimming.

Table 4.3

Service robots for consumer use in 2022 and 2023 by type of movement

	Application	2022	2023	2023/2022	2022	2023	2023/2022
		units sold		growth rate	RaaS fleet (in units)		growth rate
A	Ground-based	4,086,452	4,120,225	+1%	**	**	-
A1	Rolling	3,725,205	3,643,199	-2%	**	**	-
A2	Walking	**	**	-	**	**	-
A3	Fixed in place	200,439	331,835	+66%	**	**	-
A4	Other ground-based	**	**	-	**	**	-
B	Water-based	0	0	-	0	0	-
B1	Swimming	0	0	-	0	0	-
B2	Diving	0	0	-	0	0	-
C	Aerial	164	289	+76%	**	**	-
C1	Fly	164	289	+76%	**	**	-
C2	Hover	0	0	-	**	**	-
D	Wearables	609	832	+37%	**	**	-
D1	Exoskeletons	**	**	-	**	**	-
D2	Other wearables	**	**	-	**	**	-
E	Others	0	0	-	0	0	-
E1	Other robots	0	0	-	0	0	-

Source: World Robotics 2024
Results of IFR's annual survey and desktop research (49 companies for consumer use)
*Results cannot be revealed (minimum number of non-zero observations not reached).
**Results cannot be revealed (minimum number of non-zero observations not reached). Data included in application group total (A, B, etc.).

4.2 AC1: ROBOTS FOR DOMESTIC TASKS

Author: Dipl.-Inf. Winfried Baum

IFR statistics

Robots for **domestic tasks** (AC1) are the largest group of consumer robots. Almost 3.8 million units were sold in 2023, marking a decrease by 3% During the COVID-19 pandemic, demand for robots for domestic tasks grew strongly due to lockdowns, travel restrictions, and other limited consumption opportunities. Since many households now own a robot for domestic tasks, replacement purchases are not yet needed. This and the overall economic downturn reduce the demand for such robots.

Demand for robot vacuums and other robots for **indoor domestic floor cleaning** (AC11) was down 18% to close to 2.1 million units. Nevertheless, this kind of service robot remains a pillar of consumer robotics. Robot vacuums are available in almost every convenience store, making it easily accessible for everyone. Numerous suppliers offer a huge portfolio covering different segments from low-priced to premium, addressing different consumer types**. Domestic window cleaning** (AC12), **gardening** (AC13), and **other domestic tasks** (AC19) increased by 40% to 700,000 units sold in 2023. Gardening robots (AC13) today usually comprise lawn mowing robots. Like robot vacuums, lawn mowing robots are nowadays available in most hardware and gardening stores, making them accessible to everyone. But the pricing remains somewhat higher compared to robot vacuums and the market potential is naturally lower because only homeowners with a garden are potential customers. The application class of **domestic cleaning outdoors** (AC14) mainly includes pool cleaning robots. In 2023, unit sales grew by 20% to almost 1 million units. Pool cleaning robots have a much smaller market potential than robot vacuums as only a small fraction of homes has a pool.

Table 4.4

Consumer service robots for domestic tasks (2022 and 2023)

	Application	Region	2022	2023	2023/2022	2022	2023	2023/2022
			units sold		growth rate	RaaS fleet (in units)		growth rate
AC1	Robots for domestic tasks		3,880,259	3,780,573	-3%	**	**	-
		Europe+MENA	**	**		0	0	
		The Americas	**	**		0	0	
		Asia+Pacific	624,910	695,655		**	**	
AC11	Domestic floor cleaning (indoor)		2,605,522	2,148,199	-18%	**	**	-
		Europe+MENA	**	**		0	0	
		The Americas	**	**		0	0	
		Asia+Pacific	616,910	589,803		**	**	
AC12, AC13, AC19	Domestic window cleaning, gardening, and other domestic tasks*		500,000	700,000	+40%	0	0	-
AC14	Domestic cleaning (outdoor)*		774,737	932,374	+20%	0	0	-

Source: World Robotics 2024
Results of IFR's annual survey and desktop research (18 companies for domestic tasks)
*Regional breakdown cannot be revealed (minimum number of non-zero observations not reached).
**Results cannot be revealed (minimum number of non-zero observations not reached). Data included in application group total (AC1, AC2, etc.).

4.2.1 AC11: DOMESTIC FLOOR CLEANING (INDOOR)

Domestic floor-cleaning robots have been available for more than two decades and are now a permanent fixture in many households.

Figure 4.3: Deebot T20 Omni from Ecovacs Robotics ensures fully automatic and overall floor cleaning tasks like vacuuming and mopping. Image credit: Ecovacs Robotics.

Their success is based, in particular, on the following trends:

- Decreasing prices for a given performance level
- Increasing performance
- Increasing openness of users to new technologies in general

The decreasing price is a consequence of the constantly increasing number of units produced and the use of electronic components (e.g. microprocessors, cameras, integrated circuits for wireless communication, etc.) adopted from other mass-market electronic products like smartphones, tablet PCs, or game consoles.

The performance has been greatly increased in recent years by advances in battery and navigation technology. Virtually all products from the mid-price segment upwards now use Li-Ion batteries and systematic navigation algorithms, resulting in higher available power for the cleaning unit combined with a more efficient and more complete coverage of the floor surface.

Mapping the environment in 2D (or even 3D with some models) is based on a laser scanner (Light Detection and Ranging, LiDAR), a 2D red green blue (RGB) camera (optionally combined with structured light for obtaining 3D information), a stereo camera, or a 3D time-of-flight camera mounted on the robot. While the laser scanners typically used in floor cleaning robots can detect obstacles and other objects only in the horizontal sensing plane of the sensor, 3D image capture also enables the detection of objects above and below this plane. Thus, detecting low obstacles (such as pedestals or cables) and overhanging objects (like bed frames) is also possible, where robots usually run the risk of getting stuck.

Most floor-cleaning robots provide wireless (Wi-Fi and/or Bluetooth) connectivity, which is used to control the robot (tele-operate and define areas to be excluded from cleaning) and to query its status and mapping progress via smartphone, tablet PC, or Internet.

An increasing number of vacuuming robots provide the possibility of automatically unloading the collected dust, which extends the operating time of the robot many times over. There is also progress in vacuuming technology. As an example, Samsung uses a multi-cyclone vacuuming unit in its newer robots.

4.2.1.1. TYPES OF OPERATIONS CARRIED OUT BY THE ROBOT

There are two types of cleaning performed by the robots: Vacuuming and wet mopping. While the former can be used on carpets and (with some restrictions) on hard floors, the latter is optimized for cleaning hard floors. An increasing number of robot models combine both cleaning methods in one unit.

The robots are simply put in their working area, where they operate by themselves. Manual intervention is thus only needed to empty the dust container at regular intervals and to change the overall operating area, e.g. when taking it to another floor of the house. Most of the robots can be used in special modes like spot cleaning or tele-operation and can be configured in various ways, e.g. by defining a time schedule or areas to be excluded from cleaning.

Some of the robot models also communicate via Internet with their manufacturer. Sending information about the environment, failures, and other details allows the manufacturer to continuously optimize the control software. However, this is also subject to privacy concerns.

Figure 4.4: Everybot Triple-Spin Floor Mopping Robot. Projecting mop pads clean up edges of the floor with less noise. Equipped with a sensor system and an electronic water supply system. Image credit: Everybot Inc.

Vacuum-cleaning robots are small enough to move under furniture and their round shape allows them to easily maneuver themselves out of impasses. Some of these robots are designed with a square front to reach deep into the corners for thorough cleaning. Most models are equipped with optical or acoustical sensors to detect the degree of soiling so that the robots can repeat the cleaning procedure on heavily soiled areas. The robots are able to automatically return to their charging station. Infrared sensors facing downward or light barriers protect them from falling downstairs.

4.2.1.2. LEVEL OF DISTRIBUTION

Due to their high benefit at a relatively low price, floor-cleaning robots are becoming increasingly popular. After years of many companies and research labs experimenting with prototypes of robotic vacuum cleaners, the first vacuum-cleaning robots entered the consumer market in 2001: Trilobite from AB Electrolux was initially only available on the Swedish market. In 2002, the distribution was extended to European countries. The price of Trilobite gradually decreased from some €1,500 to about €1,000.

Early in 2002, the American company iRobot released Roomba in the USA. The basic net price was just USD 199 and it was distributed through major chain stores and the web. The product had limited navigation sensors and operated by a random walk. Throughout the years, the product has been expanded into a continuously developing product family (vacuum, mops) and has made iRobot a market leader in this field. The robot has even created a large community, which explores their Roombas' use for tasks beyond standard vacuuming (i.e. "hacking" and functional product extensions

"Zoomba"). At about the same time, Samsung and LG Electronics announced small vacuum cleaners. Since then, several providers (particularly in Asia) have launched a wide range of vacuum cleaners onto the market. Most of these used the standard random walk navigation.

In 2009, SR-8855 from Samsung was introduced as the first robotic vacuum cleaner using a camera-based system for mapping the environment during cleaning for an efficient coverage of the room (method: ceiling visual SLAM (simultaneous localization and mapping)). Similarly, Neato XV-11 from Neato Robotics made its market appearance and introduced an infrared scanner for the same purpose (method: environmental laser SLAM). In 2014, Dyson has introduced an additional innovation with its fish-eye vision system, which lets the robot see the room before it begins cleaning. Since 2013, combined vacuum and wet cleaning robots (hybrid robots) have also been available, providing more customer benefits.

Some of the newer robot models can be used for other tasks in addition to the cleaning process. An example is Roxxter from Bosch introduced in 2017, whose on-board camera allows video streaming to a smartphone and therefore offers telepresence and home security.

For a few years now, artificial intelligence in the form of neural networks has been applied to some high-end floor cleaning robots, partly using dedicated computing hardware for this purpose. The following two examples give an impression of new features enabled by this technology.

In 2021, iRobot introduced Roomba j7+, which is able to distinguish between different types of objects in its vicinity by means of machine vision and Artificial Intelligence (AI). This enables the robot to identify furniture, cables, and even pet messes. By asking the user if an unknown object is permanent or temporary, the robot updates this information on its map and applies it to future cleaning processes in the same room.

Roborock S7 MaxV Ultra (early 2022) automatically empties and refills its water tank at the charging station, which has a water reservoir for this purpose. Furthermore, it uses a camera with structured light illumination of the environment, which allows for more precise 3D mapping of the environment. Similar to iRobot j7+, it uses AI methods for classifying the detected objects and showing them to the user on a map. In this way, the user can select a piece of furniture and ask the robot to clean just the area around this object.

Due to decreasing prices and increasing reliability, robot vacuum cleaners have become more common and almost every company producing household appliances now offers this type of product. In many cases, models are rebranded ("badge engineering"/white labeling). Some very low-priced robots with only an absolute minimum of mechanical and electrical components have disappeared from the market. An example of this was Robomop, which used only a single motor for performing a random movement and just a passive wiping cloth for collecting dust. There seems to be no demand for such cheap but also very "stupid" robots anymore.

4.2.1.3. COST-BENEFIT CONSIDERATIONS AND MARKETING CHALLENGES

While manual domestic appliances are noisy and require a guiding person to walk them up and down, vacuuming and floor-cleaning robots are designed to operate quietly and autonomously. This saves the owner time and liberates them from unpleasant and unrewarding tasks. The robots can be left in operation without supervision, so they are ideal for people who want their home to be cleaned while they are at work.

Due to the limited amount of energy available in battery-powered devices, the cleaning device of vacuum-cleaning robots is much less effective compared to manually operated vacuum cleaners. This disadvantage is partially compensated by more frequent usage and a longer, and therefore more thorough, cleaning procedure. Although the efficiency of today's floor-cleaning robots has increased considerably compared to their counterparts of the first generation due to systematic navigation, advanced battery technology, and optimized suction, the user is still required to perform basic cleaning from time to time.

Despite these shortcomings, floor-cleaning robots are the most sold robot types for domestic use. The reasons for this are still the acceptable benefit at a relatively low price (starting from around USD 50) and the ease of use (no installation and programming required).

4.2.1.4. PRODUCERS

Anker Innovations, Bissell, Blaupunkt, Bobsweep, Bosch, Cecotec, Dreame Technology, Dyson, Ecovacs, Electrolux Floorcare, Everybot, E-zicom, Hitachi, Hobot Technology, Hunan Grand-pro Robot Tech, iClean, iRobot, Kärcher, Kyvol, LG Electronics, Mamibot, Matsutek, Miele, Milagrow Humantech, Narwal, Osoji Robotics Corporation, PalNPaul, Panasonic, Philips, Proscenic, Roborock, Rowenta, Samsung, SharkNinja, Sharp, Shenzhen Anseboo Technology, Shenzhen Jisiwei Intelligent Technology, Suzhou Alpha Robot, Techtronic Industries, UBT Robot, Vorwerk, Xiaomi, Yujin Robot, Zaco / I Life

4.2.2 AC12: DOMESTIC WINDOW CLEANING

Professional window and solar panel-cleaning robots are discussed in chapter 2.3.2 and 2.3.6. Window and wall-cleaning robots for domestic use are available for only a fraction of the price of their professional counterparts and usually do not require any special infrastructure for operation (like rails or cable pulls). On the one hand, this gives them more flexibility but, on the other hand, their performance is very limited due to their highly cost-optimized design.

As window cleaning is one of the most unpopular household chores, one would expect such robots to be very widespread. But unlike floor-cleaning robots, their operation still requires a lot of support by the user, since even the latest models are not able to automatically switch between window casements and even less between separate windows. In addition, their water tank is very limited in size (due to weight limitations); it therefore has to be refilled quite often and there are also safety concerns such as the risk of falling devices in some environments.

Similar to floor-cleaning robots, many of the window-cleaning robots are rebranded models.

4.2.2.1. TYPES OF OPERATIONS CARRIED OUT BY THE ROBOT

These robots can climb on vertical windowpanes and clean them by applying a cleaning detergent dissolved in water and collecting the soiled liquid. The user must place them on the pane and remove them after the task has been completed. Currently available robots are not able to move between multiple window casements. Some of the robots can also be used for cleaning tiled walls in bathrooms (e.g. Winbot 880 from Ecovacs).

At present, virtually all window-cleaning robots can be classified into one of two main designs:

- An oval case equipped with two disc-shaped and rotating cleaning brushes. The brushes rotate alternately, which leads to a seal-like movement of the robot on the window.
- A rectangular case with a pair of wheels or caterpillars for moving and a cleaning cloth covering most of the bottom area of the robot. This design has the advantage of being able to clean all the way into the corners of the window.

Figure 4.5: Winbot W1 Pro from Ecovacs Robotics cleans large windows automatically due to innovative cross-spray technology. Image credit: Ecovacs Robotics.

There are three ways of holding the robot on the windowpane:

- Generating a vacuum between the robot and the pane by membrane pump or piston pump: This is more energy efficient than other vacuum-generating methods (see below) and is appropriate for battery-powered robots. However, since the achievable volume flow is very low, tight contact between the robot and the pane is essential. If this contact is disrupted for any reason, the robot will fall off.
- Generating a vacuum using a fan similar to the one in vacuum cleaners: This provides a much higher volume flow than the method mentioned above and makes additional benefit of the Bernoulli Effect. Thus, the robot can also be operated on surfaces that are not perfectly flat, e.g. on tiled bathroom walls. The drawback is considerably higher energy consumption, which is why most robots of this type require a power cable.
- Using two permanent magnets, one on the robot and one on the opposite side of the windowpane: This method works very reliably and safely on usual windowpanes, even in the event of power failure, but may fail on very thick panes. Furthermore, it is not applicable on tiled bathroom walls. Because of these disadvantages, this option is considered outdated and is no longer used in newly developed robots.

Most of the newer window-cleaning robots apply the second method (vacuum fan) in combination with a backup battery to overcome potential power failures and thus increase the level of safety. Some of them use the required power cable also as a securing means. State-of-the-art are also border detection sensors that work on both framed and frameless windows. While some of them (e.g. Hobot 298) use laser sensors measuring the distance to the glass surface for this purpose, others (e.g. Hobot 2S) use a vacuum leakage sensor at each corner instead.

Alfabot X7 was one of the first robots to use ultrasonic transducers for generating a fine mist of cleaning detergent. This leads to a more uniform distribution on the surface while requiring smaller amounts of detergent. Meanwhile, other manufactures have followed this example (e.g. Hobot 2S). Some manufacturers claim to use some kind of AI for planning the cleaning path (Hobot 298, Gladwell Gecko), but it is not specified which technology this AI is based on (e.g. neural networks or just one of the traditional coverage algorithms).

While with first generation models the user interaction was limited to switching the device on and off, many newer models provide remote control and display the status on a smartphone or tablet PC via Bluetooth or Wi-Fi. Like most of the floor-cleaning robots, many window cleaners now have a “spot cleaning” feature, which allows treating particularly soiled areas more intensively.

4.2.2.2. LEVEL OF DISTRIBUTION

The market for window-cleaning robots is growing, but they are much less widespread than robots for floor cleaning despite the growth of their application areas (not only windows, but also walls, frameless doors, etc.). The main reason for this is the lower autonomy, which requires the user to support the robot very often by placing it on the window and moving it between multiple windows. As mentioned above, there is a lot of support required from the user, and there are still safety concerns, both of which lead to a limited acceptance of this robot type.

4.2.2.3. COST-BENEFIT CONSIDERATIONS AND MARKETING CHALLENGES

Besides technical challenges regarding low cost and reliable adhesion to surfaces, including handling of different window sizes and forms (e.g. lattice windows), there is still the problem of securing the robot against unintended release from the window and possible harm to humans.

4.2.2.4. PRODUCERS

Ecovacs, Hobot Technology, Kärcher, Mamibot, Milagrow Humantech, Osoji Robotics Corporation, Shenzhen Anseboo Technology, Wexbi

4.2.3 AC13: GARDENING

The main task in which robots can help people in domestic gardens is still lawn mowing. Very much like vacuuming, many people consider lawn mowing to be one of the most boring and tiring tasks. However, it is also one of the most promising personal robot applications. Lawn-mowing robots are the modern replacement for sheep: They stay in the garden over the summer and ensure a neatly cut lawn.

Besides lawn mowing, there is also a weeding robot available (see below). Other tasks, such as fertilizing, have already been automatized in agriculture, but have not yet found their way into domestic gardens.

4.2.3.1. TYPES OF OPERATIONS CARRIED OUT BY THE ROBOT

The basic principle of robotic lawn mowers was pioneered by Husqvarna with its Solar Mower. Its Automower family, with more than one million robotic lawn mowers sold, is still considered a market leader.

It is recognized that robotic lawn mowers cut with precision and efficiency so that it is unnecessary to rake clippings afterwards. These clippings can even fertilize the soil. For larger lawns and fields, especially with steep slopes, lawn cutting may become tedious. In this respect, robotic lawn mowers can save time and money, giving the gardener more leisure time. Even 40% slopes can be negotiated.

As the advanced systematic motion coverage in robotic vacuum cleaners, the next generation of models introduces a similar capability based on the Global Positioning System (GPS). For example, the Husqvarna Automower X series uses GPS for mapping the lawn area and navigating. It also allows the user to define areas to be excluded from mowing. In 2021, Segway introduced their first family of lawn-mowing robots, which uses GPS navigation as well, making the boundary wire required for many other robots obsolete. In addition, the top model (H3000E) is equipped with ultrasonic sensors for contactless detection and obstacle avoidance. Thus, although GPS navigation is still a feature of high-end robots only, there is a constantly increasing number of models using this technology. Meanwhile, these robots address not only professionals but also private users who are interested in the latest technology.

Some cheaper models from Husqvarna (e.g. Automower 315 Mark II) are not equipped with GPS but are able to switch from random mode to a kind of semi-systematic navigation in narrow passages. However, the majority of lawn-mowing robots in the lower price range still applies variants of random walk strategies and requires a buried wire for detecting the boundaries of the area to be mown.

Most models still use tactile sensors for detecting collisions. Some of them have a floating shell that allows the robot to have a few centimeters of braking distance after a collision. Others do not have this option and therefore sometimes collide rather hard with objects. In general, tactile collision detection cannot reliably prevent the robot from knocking over flowerpots or harming wild animals, such as hedgehogs, which typically do not run away from a danger. Some newer ones (e.g. Worx Landroid S 300 and Segway Navimow H3000E mentioned above) use additional contactless (e.g. ultrasonic) sensors for this task, thereby avoiding collisions instead of just detecting them.

The operation of all of these robots can be scheduled, i.e. they start their work automatically on selected weekdays at predefined times. Most of the newer products can also be controlled by a smartphone or a tablet PC via Bluetooth or Wi-Fi, which simplifies the configuration considerably.

Some of the robots use GPS but still navigate in an unsystematic way (e.g. some Stihl Imow models). In these cases, GPS localization is just used for informing the user about the current robot position. This can be helpful for retrieving the robot when it is stuck under a bush in a large area or in case of theft.

A relatively rare feature is Internet connectivity, which is not only used for remote control but also for querying the weather forecast and scheduling mowing according to this information (e.g. Bosch Indego M+700).

Apart from this, the mowing power has increased as well, either by optimizing existing solutions or by adopting technologies from professional mowers. Some of the robots are now able to tackle grass heights of more than 10 centimeters. One of them is RMI 422 PC from Stihl, which uses a beam mower instead of the traditional rotary mower. It can even crush branches and fallen fruit.

There are also new approaches for the driving kinematics of the robot. Most models use a combination of two big driving wheels in a differential drive arrangement, supported by one or two passive castor wheels. In contrast to that, Automower 435X AWD from Husqvarna does not have castor wheels but two additional steerable driving wheels instead which enhance its maneuverability in uneven terrain.

In addition to lawn mowing, weeding is another tiring task in domestic gardens that many users would like to have automatized. Tertill from the Tertill Coperation (formerly Franklin Robotics) addresses this wish. It is solar powered and small enough to be able to move between crop plants. The weeding is performed by two means: A rotating nylon string cuts the weed and the four jagged driving wheels, which are tilted by 45 degrees, scrub the soil and prevent and eliminate weed plants before they can grow.

Figure 4.6: Tertill is a solar-powered, chemical-free, weather-proof robot that lives in domestic gardens. The robot measuring 21 centimeters in diameter eliminates the need for manual weeding. Image credit: Tertill Corporation.

4.2.3.2. LEVEL OF DISTRIBUTION

Since their first introduction around 1995, lawn-mowing robots have gained a positive reputation for their generally good mowing results. All major manufacturers of gardening equipment now provide a family of robotic lawn mowers, either as their own developments or as rebranded models. While their market penetration remained quite low for many years, mainly because of the relatively high price compared to other domestic robots like vacuum cleaners, this has changed significantly in the past few years.

4.2.3.3. COST-BENEFIT CONSIDERATIONS AND MARKETING CHALLENGES

The silent electric motors allow for round-the-clock operation without disturbing the neighborhood. In contrast to traditional gasoline-driven mowers, electric ones have no direct emissions. Some solar mowers have a solar panel to create their own energy: The internal computer decides whether to send the energy straight to the motor or to the batteries.

There are still safety concerns with respect to injuries at the mowing blade and the robot leaving the predefined mowing area. Meanwhile, the detection of the boundary wire works very reliable for the majority of the robot models; and the danger of injuries has been reduced considerably by optimizing the body shapes of the robots in this respect and by ensuring that the mowing blade stops instantly when the robot is lifted or turned over.

Most lawn-mowing robots are not able to cut grass measuring more than about eight centimeters in height. This requires the robot to be operated very frequently, typically two or three times a week during the summer.

4.2.3.4. PRODUCERS

Bosch, Einhell, E-zicom, Fuxtec, Honda, Husqvarna, Kärcher, Makita, Mammotion Tech, Milagrow Humantech, Mowbot, Ningbo Delin Machinery, PaINPaul, Positec, Segway Robotics, Stanley Black & Decker, Stiga, Stihl, Sveaverken, Tertill, Wonik Robotics, Yarbo, Zucchetti Centro Sistemi

4.2.4 AC14: DOMESTIC CLEANING (OUTDOOR)

4.2.4.1. TYPES OF OPERATIONS CARRIED OUT BY THE ROBOT

One typical task in this category is pool cleaning, a major problem associated with pools. Since manual cleaning is tedious and boring, there is an interest in automating this task. Robotic pool cleaners collect debris and sediment from swimming pools. Entry-level models (e.g. Aquabot FRC70, Maytronics Dolphin E10) only clean the floor of the pool and use random motion patterns hoping that that the entire floor surface will eventually be covered. Advanced ones (e.g. Aquabot UR300), on the other hand, also clean the walls and the waterline and use gyro-based navigation strategies for mapping the pool geometry and systematically cover all required surfaces. Robotic pool cleaners consist mainly of a drive unit, a pump, filters, and a control unit. The pump draws the water from the bottom of the robot, where the intake valves are located, through the filter and out to the top outlet of the cleaner. During this process, debris and dust on the pool surface are collected in a container.

Figure 4.7: Grillbot is a small fully automated device with replaceable brushes and a rechargeable battery. Image credit: Grillbot.

A different variant, such as Ariel from Solar-Breeze, swims on the surface and cleans it by removing leaves, debris, and pollen. Ariel is equipped with solar cells to collect the energy needed for operation. There are some other, less widespread cleaning robots for domestic outdoor use:

- Grillbot, as the name suggests, is a robot for automatically cleaning grills. It moves similarly to a vacuum robot and uses three rotating brushes made of nylon, brass, or stainless steel for scrubbing the grill.
- Kemaro 900 is a mid-sized outdoor sweeping robot. It uses a differential drive for moving and two rotating brushes for collecting dust. Although it is primarily designed for industrial use, it can be an aid for cleaning larger private premises. A new application not covered yet by any other domestic robot is snow blowing. The Snowbot was announced in 2021. In 2022, the Snowbot was rebranded “Yarbo” and came on the market. Yarbo is a multi-purpose yard care robot that can be equipped with interchangeable modules that enable snow removal, lawn mowing, and leaf blowing.

Besides the applications mentioned above, robots for domestic outdoor cleaning are very rare. Some years ago, Irobot produced a robot for cleaning gutters, but it was not very successful on the market (probably mainly due to technical problems) and was therefore discontinued soon after its launch.

4.2.4.2. LEVEL OF DISTRIBUTION

A large variety of pool-cleaning robot models have found their way into the market and have now become almost a standard device for any private and public pool. The mobility of pool-cleaning robots depends on wheels or tracks. Their motion control follows different and sometimes very interesting strategies for optimum coverage of both pool floors and walls. Domestic robots for all other outdoor cleaning applications are not very widespread.

4.2.4.3. COST-BENEFIT CONSIDERATIONS AND MARKETING CHALLENGES

The advantage of using a robotic pool cleaner is its ease of use and relatively good coverage of the pool. Some units are computer chip controlled and some even have remote controls, enabling the user to steer the unit. Since these robots are the only cleaners not attached in any way to the pool’s circulation system, they produce no resistance or backpressure during filtering. Their cost can be more than that of manual or electric suction or pressure side cleaners, which, however, is a fraction of the total cost of an entire pool.

4.2.4.4. PRODUCERS

Aiper, BWT, Fluidra, Grillbot, Hayward, KeelCrab, Kemaro, LF Intelligence, Maytronics, Milagrow Humantech, PalNPaul, Polaris, Snowbotix, Wybotics, Yarbo, Zucchetti Centro Sistemi

4.2.5 AC19: OTHER DOMESTIC TASKS

4.2.5.1. TYPES OF OPERATIONS CARRIED OUT BY THE ROBOT

A field of application for domestic robots that has not been covered very much yet is the kitchen. There are already many appliances for semi-automatic preparation of food, like baking bread, preparing pancakes, and the like. Moley Robotics intend to take food preparation one step further: Integrated into a modern, professional kitchen, their concept features two robotic arms with dexterous hands. It repeats the motions and actions of a master chef to prepare a meal. In 2020, Moley Robotics launched the first consumer version of this robot, at a price of USD 335,000 with possibly cheaper versions in the future. All the ingredients have to be prepared (e.g. vegetables have to be sliced or chopped) and put into boxes that are placed at predefined positions on the shelf. The robotic arms take out suitable cooking pots and the boxes with the prepared ingredients from the automatically opening drawers, put them all together according to a selected recipe, control the heat of the oven by using their touch controls, and stir the ingredients in the pots. Finally, the robot puts the meal on a plate and serves it to the user. As the system uses dexterous hands, it can use the same equipment as humans, avoiding the need for extra objects in the kitchen.

4.2.5.2. COST-BENEFIT CONSIDERATIONS AND MARKETING CHALLENGES

The Moley kitchens are very interesting products, but they are hardly affordable for the average user, and since they are pioneers in this area, they cannot be expected to be technically perfect just yet. Thus, their use is currently restricted to a small group of wealthy and tech-savvy persons. Nevertheless, this may change in the future.

4.2.5.3. PRODUCERS

Moley

4.3 AC2: SOCIAL INTERACTION, EDUCATION

Authors: Florenz Graf, M.Sc.; Cagatay Odabasi, M.Sc.; Dr. Birgit Graf

The domestic robots covered in the previous section come with clearly defined abilities to tackle specific household tasks – the applications targeted by the robots mentioned in this chapter are a bit harder to generalize. The social interaction and companion robots covered in 4.3.1 are primarily intended for fun and entertainment. Sometimes they also cover a more serious background, e.g. in elderly care or childcare and assistance. Some of them also come with educational abilities, whereas pure educational robots are covered in 4.3.2.

IFR statistics

Social interaction and education robots (AC2) are the second largest consumer application group. In 2023, 157,000 units (+11%) were sold. While sales of education robots (AC22) were up 15% to almost 65,000 units, sales of **social interaction and companion** robots (AC21) increased by 8% to more than 92,000 units. Most of these robots were reported from suppliers from Asia + Pacific but the number cannot be disclosed for compliance reasons.

Table 4.5

Consumer service robots for social interaction, education (2022 and 2023)

	Application	Region	2022	2023	2023/2022	2022	2023	2023/2022
			units sold		growth rate	RaaS fleet (in units)		growth rate
AC2	Social interaction, education*		141,185	156,640	+11%	**	**	-
AC21	Social interaction, companions*		85,078	92,121	+8%	0	0	-
AC22	Education		56,107	64,519	+15%	**	**	-
		Europe+MENA	16,810	16,751		**	**	
		The Americas	**	**		0	0	
		Asia+Pacific	**	**		0	0	

Source: World Robotics 2024
Results of IFR's annual survey and desktop research (19 companies for social interaction and education)
*Regional breakdown cannot be revealed (minimum number of non-zero observations not reached).
**Results cannot be revealed (minimum number of non-zero observations not reached). Data included in application group total (AC1, AC2, etc.).

4.3.1 AC21: SOCIAL INTERACTION, COMPANIONS

This chapter investigates social interaction and companion robots that operate in private homes. The core functionality of these robots is interaction with a human.[397] Characteristics of a social robot are autonomy, interaction, and communication with humans or other autonomous physical agents by following social behaviors and rules attached to its role. Like other robots, a social robot is physically embodied. Avatars or on-screen synthetic social characters are not embodied and therefore do not qualify as robots. This is an advantage compared to tablets or smartphones because the robot can move towards a person to interact with them or – in case of tabletop robots – move its

[397] Terntzer, D. N.: Rise of the Robots: The Future of Robotics is Social, Nasdaq, October 11, 2021; https://www.nasdaq.com/articles/rise-of-the-robots%3A-the-future-of-robotics-is-social-2021-10-11.

body to attract attention and react to the user input based on sensor data. Experiments for a puzzle game showed that people find tutoring embodied agents more helpful than on-screen agents.[398]

4.3.1.1. TYPES OF OPERATIONS CARRIED OUT BY THE ROBOT

Although they come in different shapes, most of the social robots tend to be small, sweet-looking, and talkative to ensure people socially accept them at home. Their mobility capabilities are generally limited compared to robots for professional use. They may not have any capabilities to navigate, as the operating environment is the home, which is a relatively small space, and because they can be easily carried thanks to their light weight. Furthermore, although they may have arms or hands, their manipulation capabilities are typically negligible. However, they are not only AI agents equipped with a microphone and a speaker like Amazon Alexa. To count an agent as a robot, it must be embodied and be able to react with its actuators; although for some robots, this reaction is still quite limited.

In general, the following categories can be distinguished and will be described in more detail in the following section:

- Small to medium-sized mobile robots
- Tabletop robots
- Animal-like robots

4.3.1.2. LEVEL OF DISTRIBUTION

Small to medium-sized mobile robots

The robots covered in this section are typically able to move around the home, detect a person, and interact with them by speech and/or touch screen. They come in different shapes, from abstract "screen-on-wheel" type systems to child-like robots, as well as humanoids with arms and legs. They often have some kind of "face", allowing them to react to user input and show emotions.

One of the most prominent robots in this category is Buddy from Blue Frog Robotics. It is a 0.6 m tall autonomous robot weighing 5 kg that moves from room to room. Outfitted with digital interfaces, Buddy can tackle all sorts of tasks: Keeping track of the family's agenda and acting as a tele-conferencing portal, a video and music-streaming device, and a home security sentry (via a built-in camera). It can also be (remote-)controlled with a smartphone, or via the Internet, and transfer camera images and sound.

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[398] Miller, B.; Feil-Seifer, D.: Embodiment, situatedness, and morphology for humanoid robots interacting with people. In: Goswami, A.; Vadakkepat, P. (eds): Humanoid Robotics: A Reference, 2017, pp. 1-23.

Figure 4.8: Buddy, the emotional robot. Image credit: Blue Frog Robotics.

Robocare offers different robots for the home that are built specifically to support elderly persons: Silbot is a medium-sized, wheel-based mobile robot with a screen as a face and arms for gesturing. It is designed for people who are at risk of dementia. It comes with a cognition training system that helps the activation of brain functions. The Bomi robot, which comes in a large and a small tabletop version, also provides cognitive training functions. The robots can additionally be used for emergency calls. The third robot type, Dori, is a small humanoid mounted on a mobile platform. It is designed for screening children for ADHD and providing behavioral development training and education.

iPal from Avatarmind is also a medium-sized humanoid robot that moves on a wheel-based platform. Possible application areas include elderly care, retail/hospitality, or child education. It can supplement personal care services, greet people, and provide information.

Palro from Fujisoft is a humanoid that actually moves with its feet and is able to identify the people it is interacting with. It has been developed and designed to communicate with people, as well as to learn and improve its assistance with time.

5e Nannybot is a flat, wheel-driven platform with a camera head designed as an assistant for parents. It can follow their children, or they can drive it to a specific location to watch over them. 5e VirtualRep can be used as a generic telepresence robot.

Miko is a similar small, wheel-based interaction robot with a round body and an expressive face that comes in different sizes, shapes, and colors. It provides learning games, educational videos, stories, puzzles, music, and more.

The aim of Lovot is to create a robot that supports the user's happiness. Lovot comes in an abstract, partly humanoid, shape and has a face with big eyes and a sensor to perceive the environment on top of its head. It can be dressed individually with clothes of various fabrics and can react to its user's mood.

Some larger size robots have also been designed to interact with and support users in the home. Most of them, however, are primarily used and tested in professional environments. One of them is Temi, a personal AI assistant robot for various application areas (see also application class AP82). One of the targeted fields is its use as an everyday digital assistant for senior citizens. The robot can navigate autonomously through its environment and combines speech recognition, people identification, and visual information support to interact with humans. Using its integrated screen and audio, it provides access to digital services. It also comes with an integrated emergency function.

Figure 4.9: Supporting care robot for in-patient care, health care, including reminder function and video consultation. Image credit: Medisana.

Mobika, the mobile communication assistant developed at Fraunhofer IPA, is another medium-sized system optimized for human-robot interaction. It comes with a functional design, which helps to illustrate that the robot's capabilities are far from that of a human, as it is not designed to replace human interaction. Its main feature is a height-adjustable tablet that allows interaction while standing, sitting, and lying down (e.g. in an emergency situation after a fall).

Figure 4.10: The mobile communication assistant Mobika supports telepresence, interaction, or reminder functions. Image credit: Fraunhofer IPA/Photo: Rainer Bez.

Tabletop robots

There are also tabletop robots without wheels. Their main purpose is to socially interact with people and to provide them with services such as online meetings with family and reminders, safety features for the home, games, and educational offerings, and some are even sensitive to touch and vibration. They generally have a static platform with a neck joint for the head. The head may include cameras, an animated face, or a screen so that people can interact with the robot. The functionalities and services offered by these robots are quite similar to the ones mentioned for mobile robots above.

The medium-sized Moxie from Embodied comes with an abstract humanoid form and simple arms and is designed for kids aged 5 to 10. It asks questions and is supposed to increase a child’s curiosity. Apart from focusing on education, Moxie also helps children have a playtime schedule and enhances physical strength by offering, e.g., breathing or meditation exercises.

Misa is also a medium-sized robot with a similar shape but uses a screen as a face. Its purpose is also to serve as an assistant at home. Misa can play with children, handle schedules, and keep the home safe. Misa robots are also being tested in different elderly care facilities to interact with and inform residents.

QTrobot from LuxAI is an expressive social robot designed to support a variety of use cases, including the education of children with autism, other special needs education, and human-robot interaction research and teaching. It also comes in a humanoid shape and with a screen as a face to express emotions.

ElliQ from Intuition Robotics has the shape of a bedside lamp. It is able to move its "head" and express itself through multiple modalities. It is described as an empathetic care companion for older adults that promotes a more active and connected lifestyle.

AV1 from No Isolation is a small stationary telepresence robot designed to reduce school absence. It can connect absent students, ensure learning and belonging, and support reintegration into the classroom.

Bocco emo is a communication robot with movable head and a round face able to show emotional expressions. It is designed to help people stay in touch and talk more. It helps with exchanging messages and provides weather alerts and schedule reminders.

Similar to it is the owl-shaped Zukku from HataPro, which is being used in a wide range of fields, from concierges in commercial stores to corporate receptions, and health management and monitoring for the elderly.

Eilik from Energize Lab is an even smaller robot very much like a pet that tells you how it feels emotionally and physically. It is sensitive to touch and vibration.

Emo from Living.ai is another small robot that stands and moves on two legs. It plays music, performs dance moves, and suggests online games. It can feel, hear, sense, touch, learn, think, and communicate with its user. The latest development of Living.ai is Aibi, a pocket pet robot to interact and provide information. Unibo from Unirobot is a similar system with a big head and humanoid shape.

Animal-like robots

Animal-like robots look and act like a pet dog or cat. Research has shown that robotic pets are useful to boost the mood of humans. For instance, Aibo from Sony is both an entertainment and a technical exploration platform with advanced sensors, cameras, and actuators to activate the puppy and to keep it interactive. It responds to voice and touch commands, and you can add tricks to its knowledge base through the Android/iOS app.

Loona from Keyi Tech is another dog-shaped robot, slightly smaller than Aibo. It comes with advanced agility using wheel-based movements. It can approach people or follow them. Loona also understands some hand gestures and voice commands and can assist with home security. Using the app, it can be sent to patrol various corners of the house, allowing you to see the real-time situation at home.

Marscat from Elephant Robotics is a bionic cat and quite a complex robot with abilities like walking, interacting, and playing with toys. It acts like a real cat and can automatically recharge itself. Additional products are Metacat and Metadog. Weilan has a similar product series called Alphadog.

Less complicated and hence cheaper robot pets are also available, such as the Top Race Robot Dog. It is a remote-controlled robotic device featuring complicated tricks. It is controlled and programmed with its remote controller but also accepts voice commands. There are many alternatives to these budget robots currently on the market. The company Ageless Innovation offers a touch-sensitive robot cat companion that makes sounds and vibrates upon contact.

The last two examples are Bittle and Nybble from Petoi. They are an open source, programmable robot dog and cat respectively. The customers must assemble the robot themselves and, as such, a certain amount of programming knowledge is required to fully benefit from these platforms as a learning and research platform.

4.3.1.3. COST-BENEFIT CONSIDERATIONS AND MARKETING CHALLENGES

The small robot companions are produced in relatively large numbers, which reduces their prices. However, reduced prices do not necessarily mean mass adoption. People still may not know what to expect from a robot companion, or they may not even be aware of them. That is why explanation and advertisement for end users are quite important for this field.

Even though some of the larger companion robots come with arms and grippers, it is important to mention that most of them are not able to carry out any “hard work”. Although it is not their primary task, this could also be a limiting factor hindering mass adoption. As the technology evolves, the abilities of the robots – especially cognition – are also improving; they can answer questions in a clever way, or they can recognize family members and personalize the experience. Therefore, people may accept them more easily in the future.

A lot of new robots in this category get introduced every year, often at the CES (Consumer Electronics Show) in Las Vegas. However, only a few of them manage to be successful on the market. Many of them are developed by crowd funding.

4.3.1.4. PRODUCERS

Aeolus Robotics, Ageless Innovations, Asimov, AvatarMind Robot Technology, Blue Frog Robotics, Canbot, Consequential Robotics, CT-Asia Robotics, Dereviaka, Elephant robotics, Embodied, EnergizeLab, Fujisoft, Furhat Robotics, Groove X, Hatapro Robotics, Hitachi, Honda, IdMind, Inbot Technology, InGen Dynamics, Innvo Labs, Jornco Info Tech, Keyi Technology, Kompaï Robotics, Lego, Lynxmotion, Miko, Misa Robotics LLC, Nanjing AvatarMind Robot Technology, Navel Robotics, OryLab, Quihan Technologies, Robocare, Shanghai PartnerX Robotics, SoftBank Robotics, Sony, Suzhou Alpha Robot, Tombot, Torooc, Toyota, UBT Robot, Unirobot, Vstone, Weilan, Yukai Engineering

4.3.2 AC22: EDUCATION

4.3.2.1. TYPES OF OPERATIONS CARRIED OUT BY THE ROBOT

The general idea of educational robots is to provide a platform for experimenting with robot technology without having to obtain a professional level of robot expertise first. Educational robots have proven successful in engaging people with programming and engineering, because they act as tools that enhance learning.[399, 400] A team of researchers at the Royal Institute of Technology in Stockholm studied the effectiveness of robots and found out that pointing the gaze of a robot toward the students can be used to balance the participation of students with different skill sets in the learning activity.[401, 402] In another study by the University of Twente, the Zeno robot was deployed for four months in an elementary school. Results showed that the robot can change the children's mindset in the learning process, because if the children made a mistake, the robot would motivate them.[403]

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399 Benitti, F.: Exploring the educational potential of robotics in schools: A systematic review. Computers & Education vol. 58, 2012, 3, pp. 978-988; https://www.sciencedirect.com/science/article/abs/pii/S0360131511002508.

400 See https://www.iberdrola.com/innovation/educational-robots for a nice overview about the topic.

401 Gillet, S. et al.: "Robot gaze can mediate participation imbalance in groups with different skill levels." Proceedings of the 2021 ACM/IEEE International Conference on Human-Robot Interaction. 2021; https://www.semanticscholar.org/paper/Learning-Gaze-Behaviors-for-Balancing-Participation-Gillet-Parreira/567d44c2a0c972ab9b39765f2802f85a2e73caa6.

402 Robots can use eye contact to draw out reluctant participants in groups, March 10, 2021, https://www.sciencedaily.com/releases/2021/03/210310122608.htm.

403 Hillegersberg, M.m.j. Van: Robots benefit special education students, April 21, 2021, https://techxplore.com/news/2021-04-robots-benefit-special-students.html.

Figure 4.11: Miro is a fully programmable autonomous robot for researchers, educators, developers, and healthcare professionals. Image credit: Consequential Robotics.

Usually, these robots consist of a programmable platform with basic functionalities that can be adapted to custom operations with a manageable amount of effort. Furthermore, numerous challenges and competitions are part of educational robotics. For example, the international FIRST Robotics Competition (FRC) is a robotics competition to foster science, technology, engineering, and mathematic (STEM) skills and to inspire innovation in people aged four to 18.[404] More professional robot platforms are also popular for education and research at universities. Mostly, students program these robots for their theses and for competitions at the university as well as at international level, e.g. in the RoboCup.[405]

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[404] FIRST (For Inspiration and Recognition of Science and Technology): https://www.firstinspires.org/about/vision-and-mission.

[405] https://www.robocup.org/.

Figure 3.12: Wonderworkshop offers educational robots for kids. Robot Dash brings coding to life. Kids can watch their virtual coding turn into tangible learning experiences in real time as Dash, with its performance and multiple sensors, interacts with and responds to its surroundings. Educators and parents can address and track tasks easily with the platform Make Wonder. Image credit: Wonderworkshop.

In 2020-2021, when the pandemic forced many people to stay at home and to isolate, remote learning gained a lot of attention because it offers a way to continue education despite social distancing. Although distance learning is mostly done with tablets or computers, robots offer a physical, hence more natural, interaction with the learner.[406] That is why another growing market seems to be robots engaging in interactive teaching. The idea is to utilize a robot as a practical method for education, e.g. to serve as a complement in remote areas.[407]

4.3.2.2. LEVEL OF DISTRIBUTION

Open-source platforms are also making an excellent contribution to this field because people can build their robot and upgrade it freely by referencing the schematics provided

[406] van den Berghe, R. et al.: Social robots for language learning: A review. Review of Educational Research vol. 89, 2019, 2, pp. 259-295; https://journals.sagepub.com/doi/pdf/10.3102/0034654318821286.

[407] Belpaeme, T.; Kennedy, J.; Ramachandran, A.; Scassellati, B.; Tanaka, F.: Social robots for education: A review. Science Robotics, vol. 3, 2018, 21, eaat5954; https://pubmed.ncbi.nlm.nih.gov/33141719/.

by the open-source project. Mona[408] is an example of such projects. It aims to be a platform for both research and education. It is a small mobile robot with a few sensors. Another project, Open-Source Rover [409] from NASA – Jet Propulsion Laboratory, enables everyone to build their own space rover.Leo Rover also has the same concept for outdoor robotics.[410] The software is open source, so everyone can check how the components are working. Poppy Project offers another open-source platform with a programming kit for education.[411] They have three different robots for different areas of robotics and for different budgets. A more academically oriented robot is Hoppy, which is a completely open-source robot for teaching dynamic legged robots.[412]

Lego and Makeblock have a wide range of modifiable robots, mostly for kids to boost their creativity. Children can build and program their own mobile robot using robotic kits. Different sensors or modules are available for upgrading the robots. Robo Wunderkind introduces a similar concept. Thanks to its different modules, children can create various robots that move, sense, and interact.

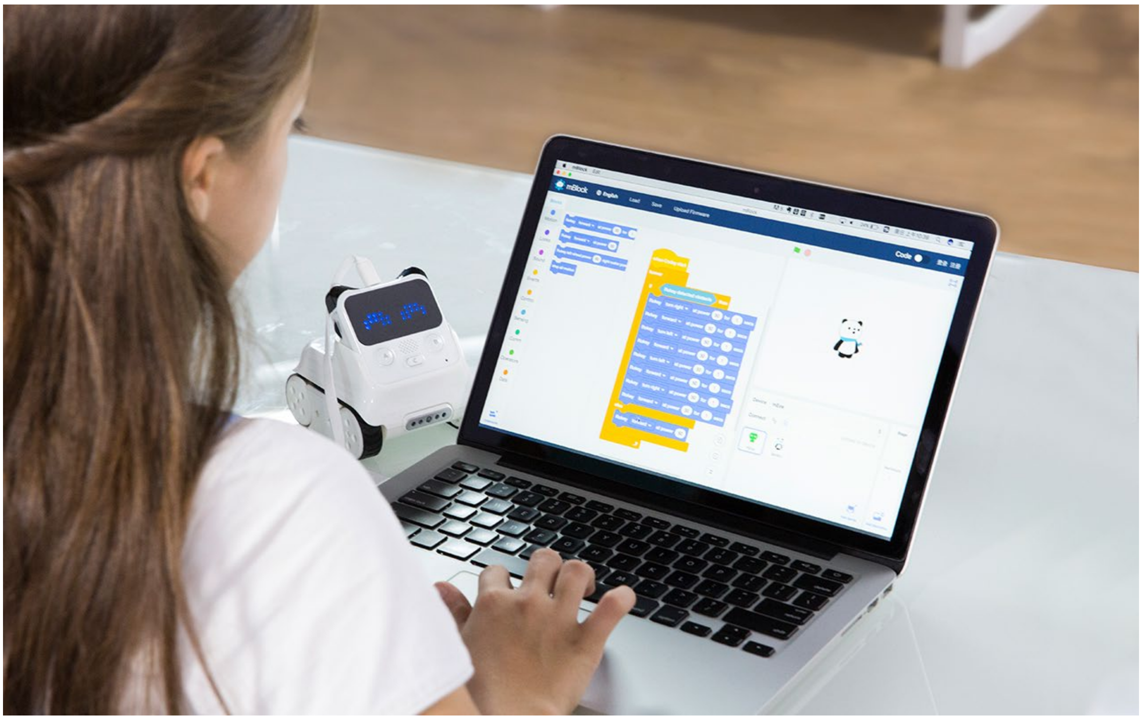

Figure 4.13: Makeblock Codey Rocky – the combination of robotics hardware with the visual programming software Mblock 5 enables students to enter the world of programming. Image credit: Solectric.

[408] Arvin, F. et al.: Mona: an affordable open-source mobile robot for education and research. Journal of Intelligent & Robotic Systems vol. 94, 2019, 3-4, pp. 761-775; https://dl.acm.org/doi/10.1007/s10846-018-0866-9.

[409] https://scienceandtechnology.jpl.nasa.gov/build-your-own-rover.

[410] https://www.leorover.tech/the-rover.

[411] https://www.poppy-education.org/.

[412] https://github.com/RoboDesignLab/HOPPY-Project.

Additionally, an abundance of robot kits is on sale. These kits serve as experimental platforms for education, leisure, and robot competitions. These robots are sold at relatively low prices, often through online shops, which also integrate platforms to enable them to connect to a user community in order to exchange software, designs, and general advice. Most of these platforms are mobile robots equipped with sensor components and sometimes with end effectors and arms. One of the most famous robots of this genre is Cosmo. It looks like a small truck with personality and AI capabilities and provides programming interfaces for different levels of complexity. A similar concept with a bigger screen is available from Miko.[413] Moreover, Dobot produces educative robotic arms for different age groups. With its camera, it aims to teach not only robot arm fundamentals but also AI fundamentals through playful examples. As the technology improves, new, smaller robots will be created. Scout from Moorebot is a small 4-wheel robot with mechanum wheels. It can autonomously navigate to fulfill different tasks like scouting. It also has a programming interface. Indi from Sphero is a tiny robot set to support STEM education with its small size, colorful tiles, and programming interface in addition to the other education robots in their portfolio such as RVR+, Bolt, Mini.

Figure 4.14: Scouting robot from Moorebot. Image credit: Moorebot.

iRobot has an online/offline learning platform called iRobot Education. This platform offers the robots Root and Create 3[414] and includes plenty of resources to program them. DJI also has a STEM education branch with several robots such as Robomaster EP Core, Robomaster S1, Robomaster TT, and Tello edu[415]. A concept similar to Robomaster, such as the RVR, has been introduced by Sphero. Furthermore, Turtlebot

[413] Demaitre, E.: Miko 2 educational robot coming to North America. October 29, 2019; https://www.therobotreport.com/miko-2-educational-robot-coming-north-america/.

[414] https://experience.irobot.com/achieving-diversity-equity-and-inclusion-through-stem-education-white-paper.

[415] Ridden P.: DJI sets up education branch, launches first product. August 5, 2020; https://newatlas.com/robotics/dji-education-robomaster-ep-core/.

is a popular research and education platform thanks to its modular architecture. It is used by numerous institutes all over the world for mobile robotics research.[416]

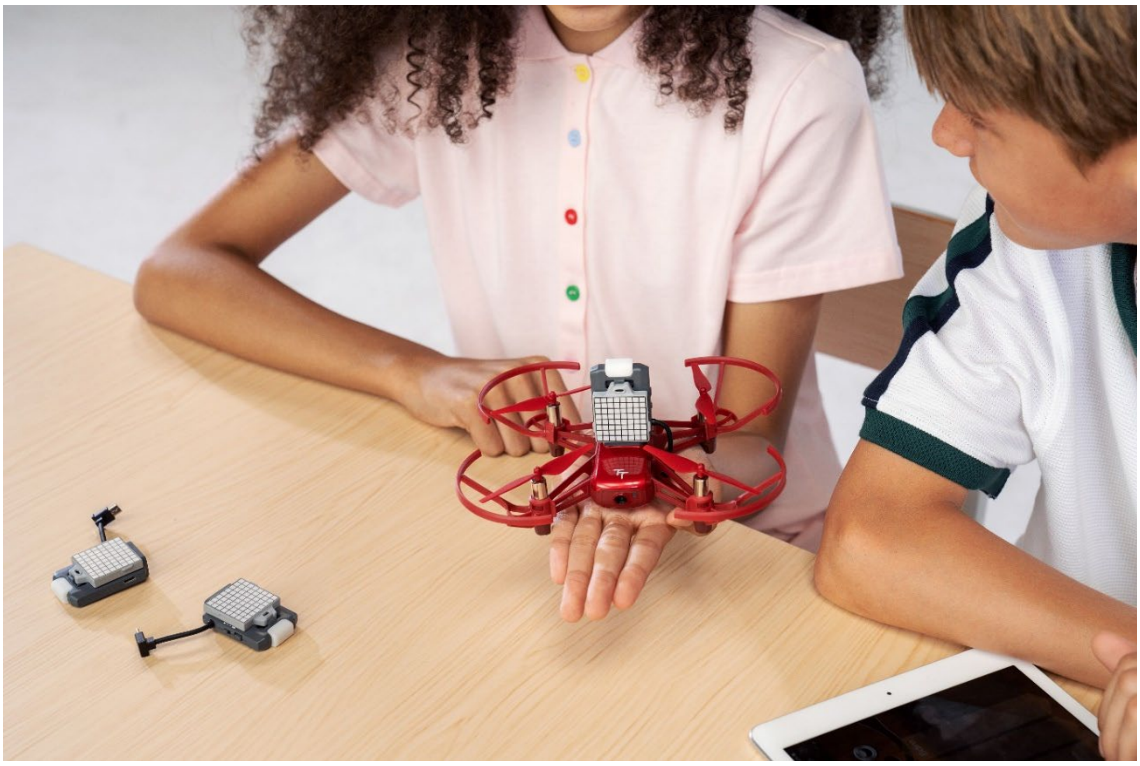

Figure 4.15: Developed by DJI Education as an educational drone, Robomaster TT fosters students' curiosity and confidence to help them get started in science and technology. Image credit: Solectric.

Softbank Robotics has Tethys, a visual programming tool for their Pepper robot.[417, 418] The tool simplifies programming and, hence, aims to teach students programming intuitively. Sphero has a similar concept with educational resources and education robots. Movia Robotics' robot-assisted instruction technology helps children with autism. They reference their software on different robots like Kebbi, Misty 2, Ipal, and Nao. Similarly, researchers from Interaction Lab, University of Southern California, let children with autism spectrum disorders play math games while their robot Kiwi gives them

416 https://www.google.com/maps/d/edit?mid=18St8TtmdVwpzZb9JVJI_XOOw3vE&ll=5.5652892073519595%2C0&z=2.

417 https://us.softbankrobotics.com/blog/meet-tethys.

418 Demaitre, E.: Tethys Enables Students to Code for SoftBank's Pepper Humanoid Robot. March 5, 2020; https://www.roboticsbusinessreview.com/news/tethys-enables-students-to-code-for-softbanks-pepper-humanoid-robot/.

feedback. As a result of this one-month-long study, the children's reasoning skills improved.[419, 420]

Robots that function as a tutor or peer learner to teach humans are a new field in educational robots. These robots make use of their skills using existing robot platforms besides offering software to transfer knowledge to people. In 2018, Finland tested the integration of robots in schools for a trial period of one year. They made use of Elias, a social robot based on Nao, for language teaching.[421] Moreover, they tested a math robot from Ovobot for preschool, first, and second grade children. In China, more than 600 kindergartens make use of the social robot Keeko from Zhitong Moment Technology for education. Keeko tells stories and challenges children with logical problems.[422] Moreover, Eagle 2.0 is a humanoid robot, which assists teachers and teaches students in classrooms. It is deployed at the Indus International School in India.[423] Abii is another robot tutor for children, which was reportedly tested with 4,000 students across 50 elementary schools between 2019 and 2021. The tests showed that the post-test scores of children tutored by Abii improved by 19%, compared to 8% with other solutions.[424] Additionally, Moxie is a companion robot aimed at children aged 5 to 10 to help them improve their emotional, social, and cognitive skills.

Miro-E is an animal-like shaped robot. It has many sensors, like camera, proximity, accelerometer, and touch, which allow students to create different social applications with the robot. Robosen offers quite interesting robots for learning how to program. Their robots can transform from vehicles to robots.

The free Robot Operating System (ROS) is an important part of robot programming and many robots utilize it. A great compilation of more ROS-enabled educational robots is listed on the ROS website.[425]

4.3.2.3. COST-BENEFIT CONSIDERATIONS AND MARKETING CHALLENGES

Small robots for basic concepts like introduction to programming/robotics/electronics are quite affordable. However, the basic kits only include the fundamental parts and if you want to upgrade it with sensors or motors, the costs are higher.

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[419] Dawson, C.: Children with autism could benefit from USC assistive robot. March 5, 2020; https://www.therobotreport.com/children-with-autism-could-benefit-from-usc-assistive-robot/.

[420] Jain, S. et al.: "Modeling engagement in long-term, in-home socially assistive robot interventions for children with autism spectrum disorders." Science Robotics 5, 39, 2020; DOI: https://doi.org/10.1126/scirobotics.aaz3791.

[421] https://nypost.com/2018/03/27/finland-schools-are-testing-out-robot-teachers/.

[422] https://phys.org/news/2018-08-robot-teachers-invade-chinese-kindergartens.html.

[423] Ullas, S.: this Bengaluru school, robots teach and teachers mentor (2019); https://timesofindia.indiatimes.com/city/bengaluru/at-this-bengaluru-school-robots-teach-and-teachers-mentor/articleshow/70867664.cms.

[424] https://www.smartrobottutor.com.

[425] https://robots.ros.org/tags/#education.

Monetary benefits are certainly not a main concern when considering the purchase of an educational robot. The utility of this kind of robot resides within the potential to impart knowledge and hands-on experience in a way other training methods lack. Possibly, these robots also reduce the resistance to accept robots as a part of everyday life and thus have a significant cultural impact.

4.3.2.4. PRODUCERS

AI Robots, Aka Intelligence, Barobo, Beijing BJ Robot Zhi Neng Jia Tech, BirdBrain Technologies, BiTronics, Brain Development, Cogibot, Comau, Consequential Robotics, CyberTech, Dereviaka, Dr Robot, Evollve, Evolvector, Evolver, Examen Technolab, EZ Robot, Festo Didactic, GCtronic, GeStream Technology, Hello Robot, Huawei, Innovation First, Jornco Info Tech, Kamibot, Keyi Technology, KinderLab Robotics, Kinova, K-Team, Kubo Robotics, Kuka, Lego, Lejurobot, Living Robot, LuxAI, Lynxmotion, Mekatronix, Milagrow Humantech, Minirobot, Mistyrobotics, Mobsya Association, Modular Robotics, Moorebot, Niryo, Pal Robotics, Parallax, Pasco, Robbo, Robix, Robobox, Robokind, Robo-Life, Robomation, Robot Ltd., Robotics Center, Robotis, Shanghai PartnerX Robotics, Shape Robotics, Shenzhen Anseboo Technology, Shenzhen Guoli Intelligent Technology Co. LTD, SK Telecom, Sphero, Suzhou Alpha Robot, Suzhou Pangolin Robot, UBT Robot, Zarnitza

4.4 AC3: CARE AT HOME

Author: Dr.-Ing. Birgit Graf

The aging society due to demographic change[426, 427, 428] and the transition from welfare-orientation to self-determination and social inclusion of people with disabilities[429] will result in a growing need for technical aids that contribute to achieving a level of independence to carry out daily activities. Even though many of the products available today are aimed at handicapped persons, they can also provide benefits to people with age-related impairments. Japan, due to its especially fast aging population, is particularly active in the research and development of personal aids and assistive devices. This is highlighted in the report of the Japanese Ministry of Economy, Trade and Industry (METI) on "The Four Priority Areas to Which Robot Technology Is to Be Introduced in Nursing Care of the Elderly". The critical scenarios to be supported by robot technologies (at home and in residential care facilities, see also chapter 3.1.4) are lifting aids, mobility aids, robotic toilets, monitoring systems for people with senile dementia, and bathing. Companies like Toyota are hoping that robots will be able to contribute to quality elderly care by proposing various robot types, such as walking assistants and personal handling and transfer assistants.

A relevant European initiative in this field was the SILVER project.[430] Its goal was to find new technologies to assist elderly people in their everyday lives. By using robotics or other related technologies, the elderly can continue to live independently at home even if they have physical or cognitive disabilities. In Germany, a special funding program, "Robotic Systems for Care", was issued with projects running from 2020 to 2023.[431]

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[426] Robinson, H.; MacDonald, B.; Broadbent, E.: The Role of Healthcare Robots for Older People at Home: A Review. International Journal of Social Robotics, July 2014, pp 575-591; https://link.springer.com/article/10.1007/s12369-014-0242-2.

[427] Gölder, M.; Herstatt, G.; Tietze, F.; Rehder S.: The Emergence of Care Robotics – A publication and patent analysis, March 2015, pp. 115-131; https://www.sciencedirect.com/science/article/pii/S0040162514002753.

[428] Johnson, D. O. et al.: Socially Assistive Robots: A Comprehensive Approach to Extending Independent Living. International Journal of Social Robotics, April 2014, Volume 6, Issue 2, pp. 195-211; https://link.springer.com/article/10.1007/s12369-013-0217-8.

[429] Codified, e.g. by the United Nations Convention on the Rights of Persons with Disabilities in 2008.

[430] SILVER: Supporting Independent Living for the Elderly through Robotics: https://cordis.europa.eu/project/id/287609.

[431] Robotics Systems for Care: https://www.pflege-und-robotik.de/en/start-page/.

IFR statistics

Care at home robots (AC3) experience high growth rates at low absolute numbers. Care at home robots (AC3) display a strong increase in unit sales by 195% up to 1,952 units sold in 2023. This remarkable growth is due to demographic change. As the population is aging further, the market for care at home robots is expected to grow in the long run.

The application classes **mobility assistants** (AC31), **manipulation aids** (AC32) and **other care robots** (AC39) enjoyed strong growth rates of 185% (AC31) and 281% (AP32 and AP39 combined), respectively.

Table 4.6

Consumer service robots for care at home (2022 and 2023)

	Application	Region	2022	2023	2023/2022	2022	2023	2023/2022
			units sold		growth rate	RaaS fleet (in units)		growth rate
AC3	Care at home		662	1,952	+195%	**	**	-
		Europe+MENA	86	119		**	**	
		The Americas	**	**		0	0	
		Asia+Pacific	**	**		0	0	
AC31	Mobility assistants*		593	1,689	+185%	**	**	-
		Europe+MENA	**	**		**	**	
		The Americas	**	**		0	0	
		Asia+Pacific	568	1,629		0	0	
AC32, AC39	Manipulation aids and other care robots*		69	263	+281%	**	**	-

Source: World Robotics 2024
Results of IFR's annual survey and desktop research (12 companies for care at home robots)
*Regional breakdown cannot be revealed (minimum number of non-zero observations not reached).
**Results cannot be revealed (minimum number of non-zero observations not reached). Data included in application group total (AC1, AC2, etc.).

Types of operations carried out by the robot

Robots in this application group aim to help people who have age-related constraints or disabilities. They can be used to assist with everyday activities and therefore support independent living. Typical robots supporting care-at-home tasks include:

- Robots for mobility assistance, such as robotized wheelchairs, walkers, or exoskeletons for everyday use.
- Robots for manipulation assistance, specifically eating aids and wheelchair-mounted manipulators.
- Interaction and communication robots. The latter will not be covered in this chapter. Most of these robots are not specifically designed for older or handicapped persons but for a more generic user group and are thus covered in chapter 4.3.1.
- Other care robots, specifically robots providing transport and mobile manipulation functions.

Cost-benefit considerations and marketing challenges

Assistive robots give disabled or elderly people the scope to participate, boosting their self-confidence. They can occupy themselves instead of being bored. The use of robots stimulates and, apparently, can improve coordination and physical condition. The implementation of an assistive system is a complex and demanding process; it must be adapted to the user's particular needs, staff have to be trained, and, after a trial period, the robot has to be re-adjusted. Once in use, there are no significant work reductions for the caregivers. Their tasks merely change, so that instead of feeding, they now prepare the tray and set up the machine.

Once installed, however, sophisticated assistive robotic devices can have a technical life span of up to 15 years. Prices vary widely between systems and degrees of specialization and can amount to USD 50,000, and even the cheapest system cannot be purchased for less than several thousand dollars. Health insurance funds will play a major role as they usually cover the complete or partial costs for health-related products if considered instrumental, i.e. they have a large say in which developments will be pursued and which abandoned. Judging from their present decision-making policies, these insurance funds are highly susceptible to innovations with a potential to cut care-giving expenses.

Although large-scale production will always be limited by the level of specialization, economies of scale in the production of the main components can be realized and will, together with the continuously improved cost effectiveness of robot technology in general, lower prices.

Whereas many specialized assistive robots are already available on the market, mobile manipulation robots designed as generalists still have to be seen as a vision or long-term development goal. The level of task fulfilment of these robots is not, and hardly ever will be, comparable to regular human task execution. The fascination of novel technologies may, in some cases, support the installation of such systems. Their low production volumes, complex technology, and complexity of installation result in high installation costs. However, economy-of-scale factors will be strong as most of the developing and engineering costs are bound by software.

Many of these robots have been made available to selected labs and pilot users as research platforms. The concept of focusing research and development on robust robotic assistants for everyday environments by using standard high-quality platforms has become the key to recent research initiatives worldwide. Examples are government-funded initiatives or private industry-led approaches toward building an ecosystem of technology and business partners to ignite this future market.[432, 433]

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[432] D'Onfro, J.: How a billionaire who wrote Google's original code created a robot revolution. February 13, 2016; https://www.businessinsider.in/How-a-billionaire-who-wrote-Googles-original-code-created-a-robot-revolution/articleshow/50988306.cms.

[433] Icub, an open source cognitive humanoid robotic platform; http://www.icub.org/.

4.4.1 AC31: MOBILITY ASSISTANTS

4.4.1.1. LEVEL OF DISTRIBUTION

Robot technology can improve the operation of electric wheelchairs, thus addressing and supporting new user groups. Other robotic technologies extend the operation of a wheelchair to areas which are difficult to access with standard wheelchairs.

Figure 4.16: Whill Autonomous Mobility Service in use. Image credit: Whill Europe B.V.

- Electric wheelchairs with an added obstacle avoidance system help people who have difficulties steering and maneuvering. They only have to signal the overall traveling direction and the system will find its way around fixed and unforeseen obstacles.
- Cyberworks offers an add-on module for standard electric wheelchairs that allows the wheelchair to navigate autonomously within a building.
- Alba Robot develops autonomously navigating wheelchairs with voice control. They are used at airports, hospitals, and museums.
- Another relevant product is offered by Whill. Their personal mobility devices have already been installed and tested at airports in Tokyo, Amsterdam, and Abu Dhabi. They assist all passengers, in particular those with walking difficulties. New implementations are planned for various North American airports.[434]

[434] Shieber, J.: WHILL brings its autonomous wheelchairs to North American airports: https://techcrunch.com/2019/11/20/whill-brings-its-autonomous-wheelchairs-to-north-american-airports/.

- Rakuro by ZMP is a new solution to support personal mobility in indoor and outdoor environments. It not only addresses wheelchair users but also elderly and frail persons who are unable to walk longer distances safely by themselves.
- Other robots for assisting the mobility of vision-impaired or blind persons are specialized in offering active guidance. Either a destination is specified or the person guides the robot, which safely overrides the user commands by guiding the person around obstacles.

Concerning enhanced mobility and flexibility for electric wheelchairs, manufacturers are investigating mechanisms that allow wheelchairs to climb stairs. Another goal is to raise wheelchair users from sitting level to eye-height, thereby enabling better interaction with people who are standing up.

- An interesting concept combining these functionalities was introduced as the iBot wheelchair robot back in 1999. This innovative wheelchair concept used two wheels positioned on top of each other to rise effectively to eye-level and climb stairways, thus adding a critical feature for making handicapped people's lives easier. Its development was discontinued in 2009, but the iBot has been available again from Mobius Mobility since 2019.[435]
- Bro from Scewo is also able to climb stairs. To solve this task, it uses chains in addition to two self-balancing driven wheels.
- As a combination of a lower extremity exoskeleton and a wheelchair, the Tek Robotic Mobilization Device from Matia Robotics is a mobility platform that supports individuals with paraplegia and other walking disabilities in their mobility needs. It also enables users to easily get from a seated to a standing position (on the wheelchair) and afterward move around with it freely.
- Upnride also provides upright and seated mobility for wheelchair users or other persons with standing or walking impediments. It uses a harness-based support system.
- Nino from Magic Mobility uses a self-balancing drive concept to improve the maneuverability of the electric wheelchair.
- Rodem from Tmsuk can be a robot, a vehicle, or a wheelchair. By adjusting the seat height and providing handles for support, it allows easy transfer onto the device and ensures comfortable positions for eating, washing, and other personal tasks.

Another approach to enhance the mobility of extremely frail elderly users is the use of robotic walkers, which extend manual solutions with additional safety and support functions.

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[435] The iBot is Back. Is the Second Time the Charm? https://www.newmobility.com/2019/07/the-ibot-is-back/.

Figure 4.17: Scewo power wheelchair easily overcomes various obstacles thanks to the built-in chains. Image credit: Scewo AG.

Figure 4.18: With its electric drive, the electric rollator beactive^{+e} supports people with limited mobility. Image credit: Bemotec.

- RT.2 from RT.works as well as the beactive^{+e} electric walker from Bemotec support users with force assist functions, e.g. when climbing up a slope, and use integrated brakes to reduce their speed when walking down a slope. They also provide stumble detection technologies and stop when users let go of the handles.
- The robotic assistant Kompaï from the company of the same name comes with different assistance functions, such as interaction, activation, and the delivery of different items. Being equipped with walking support handles, it can also be used as an intelligent, self-navigating walker.

Figure 4.19: The robotic assistant Kompaï offers functions like playing, cognitive exercises, maintaining social links, and can also be used as a walking aid. Image credit: Kompaï Robotics.

A third type of robots to support personal mobility on a daily basis are exoskeletons. Whereas for a long time, exoskeletons were mainly used for rehabilitation purposes (see chapter 3.1.3), several products are now available to also support people in their everyday lives. They are designed to compensate partial or full lower-limb paralysis by actively supporting motion of the knee and ankle joints. Some of them are used together with a walker or with crutches for better balance. Recent developments aim at reducing the size of the exoskeletons, e.g. with the smart knee orthosis from Ascend or "Powered Clothing" from Seismic. Current research is looking into increasing the "intelligence" of the exoskeletons, e.g. by adapting the support forces to varying real-world walking tasks and generating individualized assistance profiles.[436]

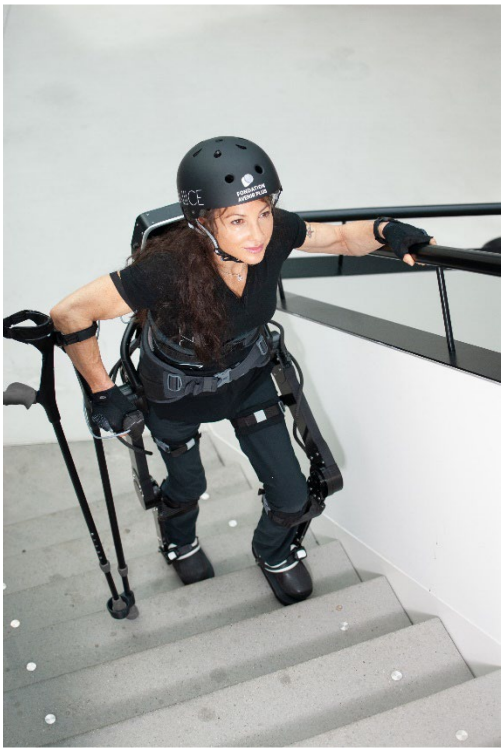

Figure 4.20: Silke Pan, a patient with motor-complete paraplegia, climbs stairs using Twiice One. Image credit: Twiice.

Several solutions to support individual mobility were presented and evaluated at Cybathlon 2020.[437] At this unique championship, people with physical disabilities competed against each other to complete everyday tasks using state-of-the-art technical assistance systems.

Generally, despite numerous research and development efforts, the diffusion of robotics into mobility for the disabled has been below expectation and technological possibilities.

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[436] Burrows, L./SEAS Communications: A personalized exosuit for real-world walking, November 10, 2021; https://wyss.harvard.edu/news/a-personalized-exosuit-for-real-world-walking/.

[437] Cybathlon – For a world without barriers. The next edition will take place end of October 2024; https://cybathlon.ethz.ch.

The reasons for this are mainly seen in the high extra costs for robotic assistive technology and the lagging industrial efforts in the face of difficult and fragmented regulations regarding financial support for assistive devices.

4.4.1.2. PRODUCERS

A&K Robotics, Aizuk, Angel Robotics, Ascend, b-temia, Cyberworks Robotics, Desin, Exomed, Free Bionics, Honda, Kompaï Robotics, Matia Robotics, Mobius Mobility, MyoSwiss, Panasonic, Pedasys, Roam Robotics, RT.works, Scewo, Techbionic, Tmsuk, Twiice, UPnRIDE Robotics, Whill, ZMP

4.4.2 AC32: MANIPULATION AIDS

4.4.2.1. LEVEL OF DISTRIBUTION

People with disabilities or elderly persons with little to no control over hand and arm functions, or limited strength or reach, rely heavily on caregivers for most of their daily activities, leaving them highly dependent and often creating an attitude of passivity and apathy. Assistive robot systems can help with eating and drinking or other manipulation tasks. Depending on the particular task, assistive robotic manipulators can be mounted directly on the user's wheelchair, on an autonomous powered base, or within a fixed workstation. They should be easy to operate for the user and adapted to their ability of manipulation.

- Jaco from Kinova Robotics and iArm from Assistive Innovations are robotic manipulators that can be mounted on a wheelchair. They come with different user interfaces providing multiple ways by which they can be controlled – depending on the user's current situation and abilities.
- Both manufacturers also offer arm support systems. They are used to hold the user's arm and reduce its weight, allowing them to perform manipulation tasks even if they do not have the required strength.
- Assistive Innovations also offers the iEat robot. It is an easy to operate assistive eating device designed for people with very little or no muscle strength or people with involuntary muscle contractions. It moves food to a predefined position in front of the person's mouth in autonomous or semi-autonomous mode.
- Bestic from Camanio Care is also designed to support individuals whose mobility is impaired in their arms or hands when eating on their own. The user controls both the settings and the operating cycle when using Bestic. First, the user chooses a piece of food, directs Bestic to pick it up, then leans forward, takes the food, and gives a new command, which lowers the spoon back down to the plate.
- Another solution is Obi from Desin. Obi is a robotic arm that selects virtually any properly sized food from one of four compartments. It then delivers the food to one of several thousand potential locations where the diner can eat from the spoon. This means Obi can accommodate nearly any age demographic and preferred position or orientation.

The aim of current research activities is to improve the ease of use of the feeding devices, e.g. by detecting individual food items as well as the mouth of the user with a camera and plan suitable movements automatically.[438]

[438] Houser, K.: This Autonomous Robot Arm Feeds People Who Can't Feed Themselves, March 14, 2019; https://futurism.com/autonomous-robot-arm-feeds-people.

Figure 4.21: Woman with upper body limitations in a motorized wheelchair applying makeup using the Kinova® Jaco® assistive robotic arm. Image credit: Kinova.

Figure 4.22: Obi is an eating assistive technology for individuals with upper extremity limitations. Obi allows users to eat with independence and enjoy a social eating experience. Image credit: Desin LLC, Obi Robot.

4.4.2.2. PRODUCERS

Assistive Innovation, Bioservo, Desin, Focal Meditech, Kinova, Mobius Bionics, Mobius Mobility, openbionics, Össur, Super Motorica, Techbionic, Tendo

4.4.3 AC39: OTHER CARE ROBOTS

4.4.3.1. LEVEL OF DISTRIBUTION

A new type of support robot introduced in 2021 is Labrador Retriever, a mobile robot that is able to navigate autonomously in the home. For people with limited mobility, the Labrador robot offers a place to store and transport heavy items that might be impossible for them to carry or move on their own. Special pallets can be attached to tables or countertops allowing the robot to independently retrieve trays with the required items.

A lot of research, and some industrial developments, are focusing on mobile manipulation robots which could - in the future - support elderly or handicapped users with a large variety of tasks in their homes. Due to their high costs compared to a limited range of functionalities, these robots are not yet sold to private end users. Many of them, however, are used by research institutes for technology and application developments and sometimes even practical trials in real-world environments.

A prominent development series for this type of application is Fraunhofer IPA's prototype of a robotic home assistant, Care-O-bot®, which is currently available in the fourth generation. Systematic analysis of different types of work identified a spectrum of household chores which could be mastered by the robot using today's technologies, including fetch-and-carry jobs, finding and lifting an object from the floor, cleaning up a table, or operating simple devices such as a microwave. The system follows a modular approach and consists of a mobile platform, one or two gripping arms, an expressive body for the positioning and orientation of sensors, and a movable head as an interaction surface. Alongside the cost factor, the key challenges include intuitive operation, reliable execution of tasks even in unstructured and changeable environments, as well as safe detection and gripping of numerous everyday objects.

Other robot assistants with manipulation abilities which are developed by companies and used for research in care and assistance applications are the Human Support Robot (HSR) from Toyota, Bot Handy from Samsung, Tiago from Pal Robotics, Mipa from Neura Robotics and Spotmini from Boston Dynamics. Toyota's HSRs helped disabled visitors at the 2020 Tokyo Olympic and Paralympic Games to find accessible seating and brought any refreshments they needed directly to their seats.[439]

Lio from F&P Robotics is a mobile manipulator designed to support staff in healthcare institutions, e.g. to perform fetch-and-carry tasks. It might also be used to assist individuals at home.

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[439] https://global.toyota/en/newsroom/corporate/28912712.html.

Figure 4.23: Mipa from Neura Robotics shall be able to help in various application scenarios, e.g. at home, in hospitals, laboratories, or public spaces like airports. Image credit: Neura Robotics.

Stretch RE1 from Hello Robot is also targeting manipulation assistance in the home. It can interact with people using a low-mass, contact-sensitive body. It can also work in cluttered spaces thanks to a compact footprint and a slender manipulator and is easy to transport due to its low weight of around 25kg. The robot is sold as a research platform. Subsequently, researchers have developed several autonomous support functions for the home.[440]

[440] Stretch RE1 Autonomy Demo: https://www.youtube.com/watch?v=QJxb89TMF68.

Figure 4.24: The Stretch RE1 mobile cobot from Hello Robot can provide assistance in the home and workplace. Image credit: Hello Robot.

Finally, yet importantly, there are quite many research activities going on in the field of humanoid robots. In 2021, at Tesla's AI day, Elon Musk introduced a concept for the Tesla Bot "Optimus", an autonomous bipedal "general purpose" humanoid robot. A first prototype was presented in autumn 2022 and shall be available for purchase in three to five years.[441] Other examples are the "Figure 01" from Open AI, "Apollo" from Apptronik, or "Cyberone" from Xiaomi just to mention a few of the initiatives. Very recently (spring 2024), Boston Dynamics announced the end of its old Atlas robot and in the same breath presented a new atlas, which for the first time uses electric actuators. However, none of the recent development is available for purchase for private use.

Several factors speak in favor of rapid longer-term growth in the market for robotic systems supporting care at home. The growing number of temporarily and permanently disabled persons as well as the rising share of older people in the age pyramid will increase the need for care. Considering the decline in the number of people of active age available to perform caregiver roles in the next years, there is a huge potential demand for assistive robotic devices. For this reason, many research institutions that work on service robots are developing a variety of new prototypes of assistive robots every year.

[441] Kolodny, L.: Elon Musk shows off humanoid robot prototype at Tesla AI Day. CNBC, September 30 2022; https://www.cnbc.com/2022/09/30/elon-musk-shows-off-humanoid-robot-prototype-at-tesla-ai-day.html.

4.4.3.2. PRODUCERS

Chuangze Intelligent Robot, Desin, F&P Personal Robotics, Gecko Systems, Group Salto, Hello Robot, Labrador Systems, Mobius Mobility, RT.works, Secom, Toyota

5 Industry structure

Chapter 5 contains an overview of the service and medical robotics industry and analyses of service and medical robotics industry structure

5 Service and medical robotics industry structure

The service and medical robot industry is developing at a high pace, attracting market players with different economic backgrounds. There are four main categories of service and medical robot manufacturers:

- **Industrial robotics manufacturers** explore options to use industrial robots in service or medical applications as part of their diversification strategies. They also use their knowledge from industrial robotics to expand their research and development activities or through mergers and acquisitions.
- **Startup companies** bring new and sometimes unconventional ideas and technological know-how, often from academic research, into industry. Many companies identify themselves as “deep tech”, meaning that they are willing to accept technological challenges during their product development phase to create technological advancement. This research and development driven approach of course includes the risk of failure and longer product development phases. Often, such companies are acquired by incumbents or by companies from other industries that want to expand into service or medical robotics.
- **Special machinery manufacturers** use motion control, navigation, machine vision, and other robot technology to develop autonomous or robotic versions of machines, vehicles, and handling devices that have hitherto been operated manually. These established companies are expanding their product portfolio to include service robots. Examples are professional cleaning, agricultural machines, diagnostics, surgery, or rehabilitation devices.
- **Consumer goods manufacturers** are similarly expanding their product portfolios to include autonomous solutions for traditional household products such as vacuum cleaners or lawn mowers. The price-to-volume ratio and product lifecycles in the consumer service robot segment are completely different from that in the professional segment.

The service and medical robotics industry is a young and growing industry with a rapidly developing technology. This chapter analyzes the list of all service and medical robot suppliers that are currently known to IFR (see table 5.2). The list is continuously updated and currently encompasses 943 companies. It is meant to include all businesses that produce marketable service or medical robots in the scope of this publication. Part and component suppliers, software developers, resellers and distributors without own robot production, and integrators that use third-party robots to build an own solution are not listed. Table 5.2 includes R&D companies that offer the development of prototypes but do not intend serial production. These companies engineer to order, sell licenses, or establish spin-off companies once they successfully developed a marketable robot. The industry structure analysis conducted in this chapter ignores R&D-only companies and focuses on the 921 companies that offer or intend to offer robots for consumer or professional service applications and medical applications.

5.1 SERVICE AND MEDICAL ROBOT SUPPLIERS BY REGION OF ORIGIN AND AGE

Europe is the home of most service and medical robot producers,[442] hosting 405 companies (44%). Asia (268 companies) holds a share of 29% and 233 companies (25%) are from the Americas (almost exclusively North America). There are 15 companies from Australia and 2 from Africa.

Although the service and medical robotics industry is a young and growing industry, 848 out of the 921 suppliers worldwide (92%) are considered incumbents that were established before 2019. This includes mature service and medical robot suppliers as well as companies from other industries that added service or medical robots to their portfolio. 73 companies (8%) were founded in 2019 or later and are thus considered as start-ups. The 2010s saw a wave of new service and medical robot manufacturers, peaking at 78 companies newly established in 2016 (see figure 5.1). The overall shape looks very similar for an isolated display of medical robot manufacturers and service robot manufacturers, indicating that there were related drivers -most likely the advancements in typical robotic technologies- that motivated startups in both industry segments.

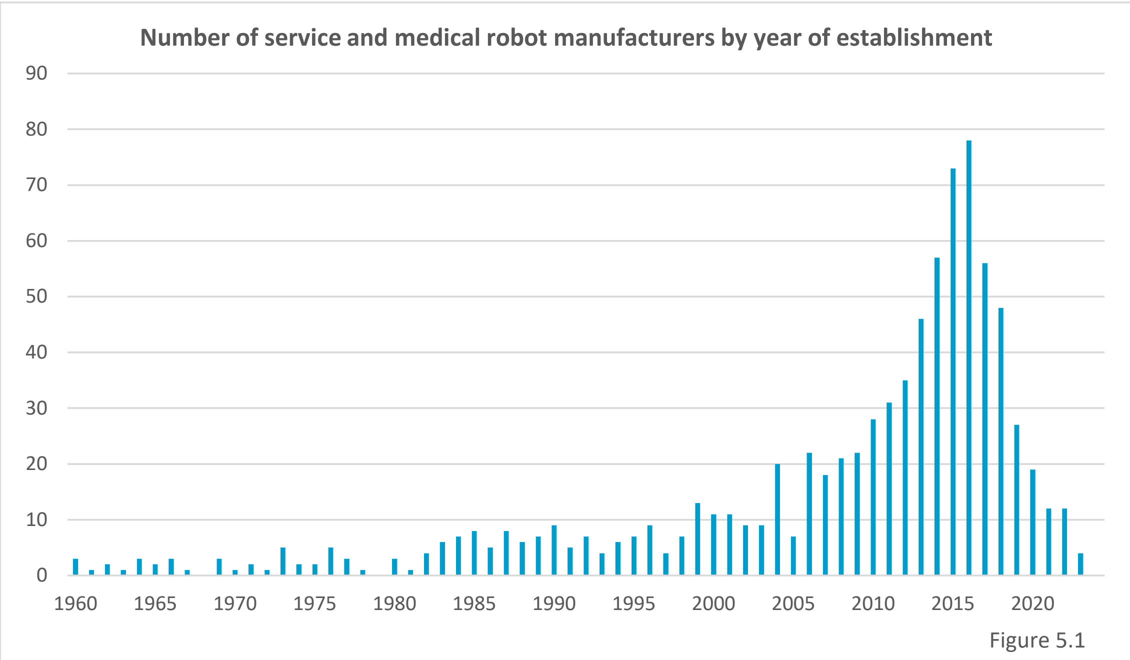


Figure 5.1

After 2016, the number of newly established companies steeply declined. Just four new establishment was registered for 2023 and none so far for the ongoing year. While this aspect might be due to the time lag between the establishment of a company and the diffusion of this information to the IFR, the general trend of a steep decline following the peak in 2016 seems robust. The share of start-ups used to be around 20% for many

[442] Attribution of the company to a country and continent is done according to the location of the headquarter.

years but has declined recently to just 8% by August 2024. IFR's market observation suggests three reasons for the decreasing share: Some market segments have already achieved a level of maturity that sees companies growing, for instance AMR for intralogistics. IFR is currently aware of 223 companies offering robots for indoor transportation and logistics in non-public environments (AP51). Thereof, 20 companies (9%) are start-ups. Sales of such AMRs have been growing strongly for many years now and companies matured and became incumbents. Second, founding activities shifted away from the development of robot hardware. Many service and medical applications are based on collaborative industrial robots, purchased from an industrial robot manufacturer. The service or medical robot supplier is therefore not considered a robot manufacturer as the robot itself is purchased from a third party. These companies act like a system integrator, combining different components and developing software to create a solution. Finally, the growing relevance of software, may it be traditional algorithms or artificial intelligence, has led to a shift in entrepreneurial activities towards this area, which does not appear in this statistic. The decreasing share of start-ups can be observed across all major regions: In Europe, the share of startups is down from 17% (90 out of 493 companies) in August 2021 to 9% (36 out of 405 companies) by August 2024. In (North) America it is 7% (17/233 companies), down from 17% (49/285 companies) in August 2021 and in Asia it is 7% (20/268 companies) down from 16% (42/259 companies) in August 2021.

677 companies (74%) are classified as producers of professional service robots.[443] Most of these companies, 312 (46%), are in Europe, followed by Asia (196 companies; 29%), and (North) America (155 companies; 23%).

218 companies (24%) are classified as consumer service robot producers. 39% are in Asia (84 companies), 33% are in Europe (72 companies), and 28% are in (North) America (62 companies).

109 companies (12%) are classified as medical robot producers. 44% are in Europe (48 companies), 28% are in Asia (31 companies), and 26% are in (North) America (28 companies).

[443] A company can supply all, professional service robots, consumer service robots, and medical robots. Hence, the sum of the sub-totals exceeds the grand total.

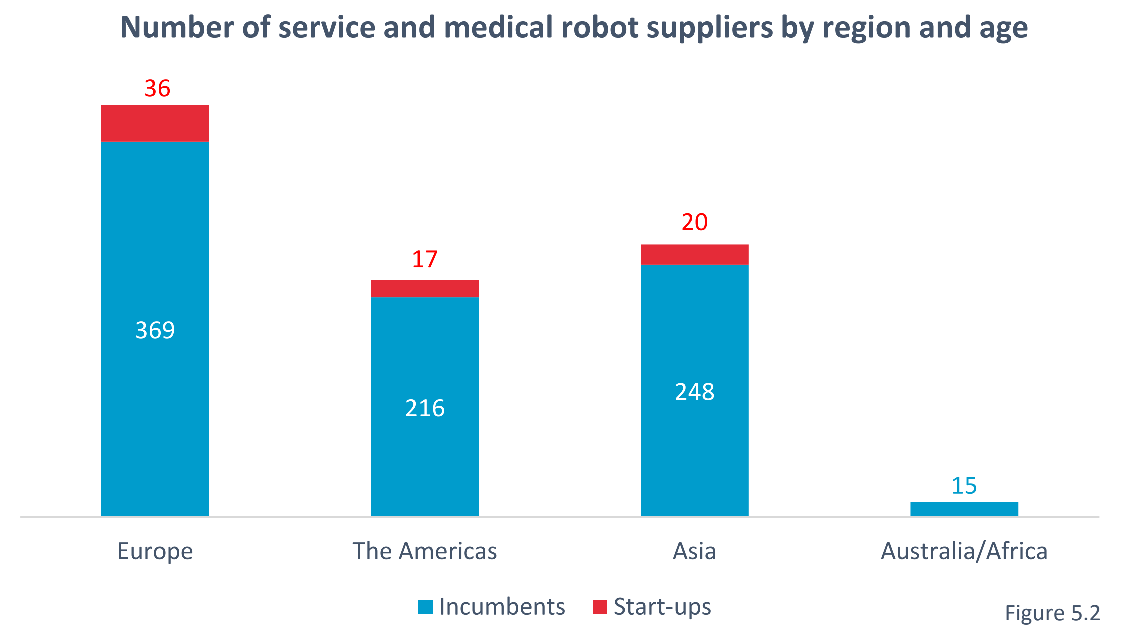


Figure 5.2

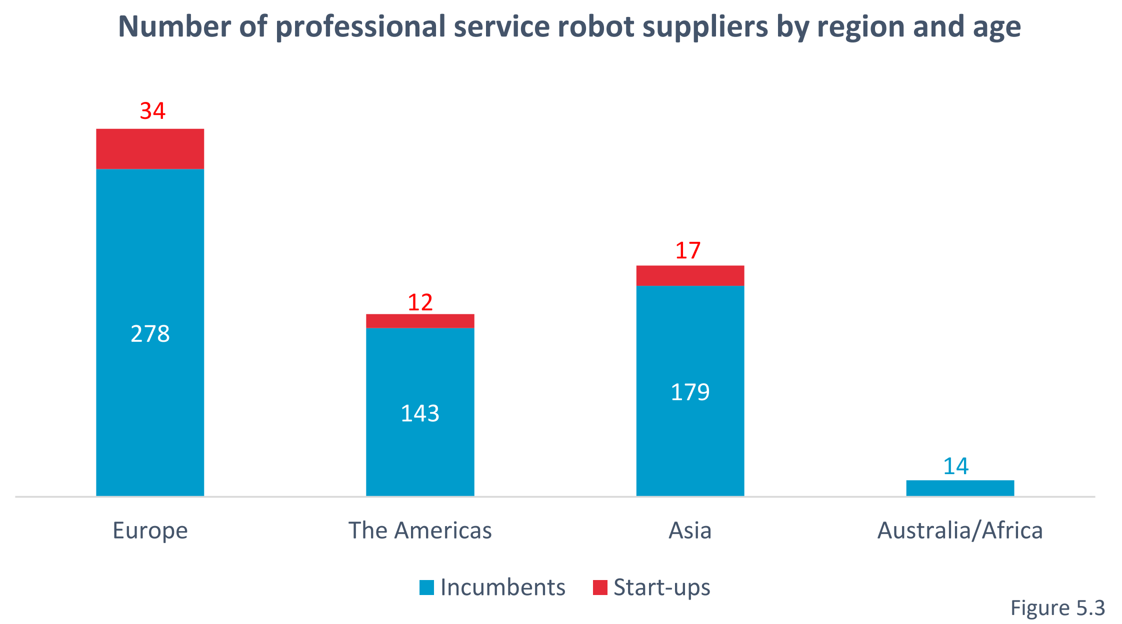


Figure 5.3

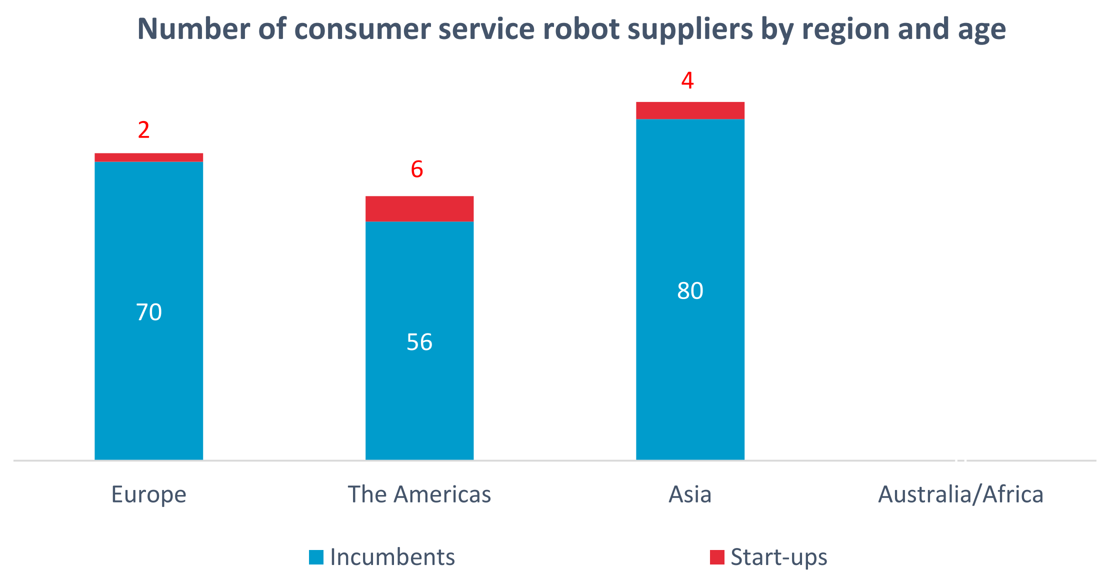


Figure 5.4

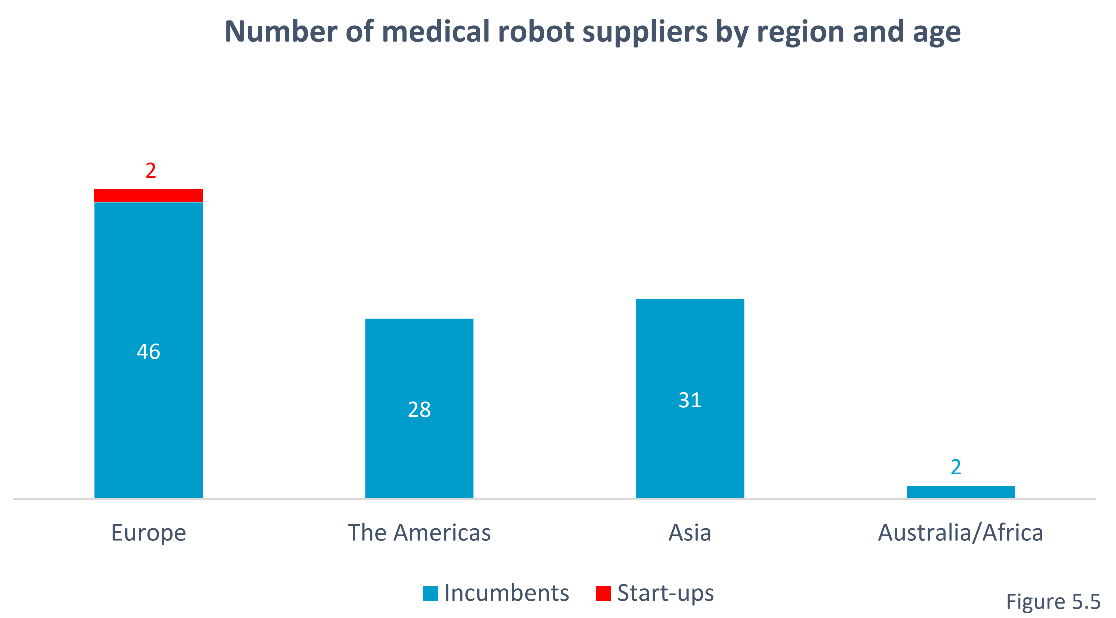


Figure 5.5

5.2 SERVICE AND MEDICAL ROBOT SUPPLIERS – TOP 10 COUNTRIES

The United States is home of most service and medical robot suppliers. 199 companies are located there. With 16 companies being founded in 2019 or later, the start-up ratio is 8% (-10 percentage points since August 2021). 131 companies (66%) produce professional service robots, while there are 54 suppliers of consumer service robots (27%) and 23 medical robot producers (12%).[444]

China has seen a huge number of start-ups in the first half of the 2010s. 53 out of the total of 107 companies (50%) were established in the years from 2011 to 2016. After 2018, just 9 companies were founded and are thus still considered as start-ups, yielding a start-up rate of 8%. 36 companies (34%) offer consumer robots. 86 companies (80%) offer professional service robots and 5 companies (5%) produce medical robots.

In Germany, 83 companies produce service robots. The startup-rate is above average: 13 companies were founded in 2019 or later (16%). Most companies offer professional service robots (68 companies, 79%), but there are also 14 companies (17%) that offer consumer applications and 10 companies that offer medical robots (12%).

Japan has 67 service robot suppliers, 97% of which (65 companies) are incumbents. 48 companies (72%) offer professional service robots, 21 companies (31%) offer consumer service robots, and 11 companies (16%) offer medical robots.

France has a lively service robot industry that has a focus on professional applications. 42 out of the 50 French service robot suppliers are active in this field (84%). There are also 6 suppliers of consumer service robots (12%) and 4 producers of medical robots.

The Republic of Korea has a mix of professional and consumer service robot and medical robot suppliers. 14 of the 47 service robot suppliers (40%) offer consumer robots, 26 companies offer professional service robots (55%), and 11 companies offer medical robots (23%). Many Korean suppliers were established in the first decade of the 2000s (19 companies, 37%). There are currently just 2 start-ups (4%). But there are also large consumer electronics suppliers that consider consumer robotics are natural expansion of their segment, and there are large players of the manufacturing industry that offer professional service robots.

Canada boasts 32 service and medical robot producers. There 23 suppliers of professional service robots (72%), 7 producers of consumer robots (22%), and 5 manufacturers of medical robots (16%).

Switzerland has 30 service and medical robot suppliers. Two thirds of the companies offer professional service robots (20 companies; 67%), 8 companies offer consumer service robots (27%), and 6 companies (20%) offer medical robots.

The Russian service robotics industry features 28 companies by August 2024, many of them located in the high technology business area of Skolkovo in Moscow. The Skolkovo Foundation was introduced in 2010, so those companies that received support and still

[444] Footnote 443 applies.

exist are now considered as incumbents. Currently, just one company is considered as a start-up. 13 companies (46%) produce professional service robots, another 13 companies (46%) are active in consumer robotics, and 3 companies (11%) produce medial robots. Russia used to rank among the top 10 countries in professional service robotics with 40 active companies in August 2022 but dropped down to eleventh in 2023. Some formerly Russian companies now operate from headquarters in other countries. Other companies ceased production, were dissolved, or disappeared without a trace. In consumer robotics, the country remains in sixth position.

The UK complete the top 10 with a population of 28 service and medical robot suppliers. There are 18 suppliers of professional service robots (64%), 6 suppliers of medical robots (21%), and 5 suppliers of consumer service robots (18%).

Other economies with a two-digit number of service and medical robot suppliers are the Netherlands (27), Italy (25), Denmark (20), India (18), Sweden (17), Spain (16), Israel (16), Türkiye (12), Austria (11), and Australia (10).

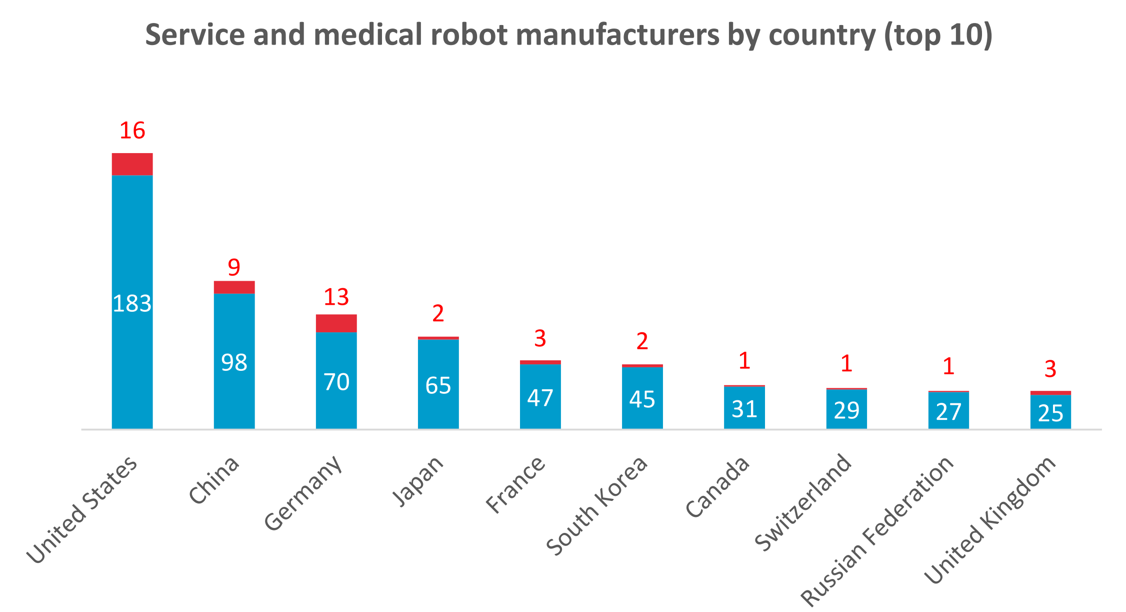


Figure 5.6

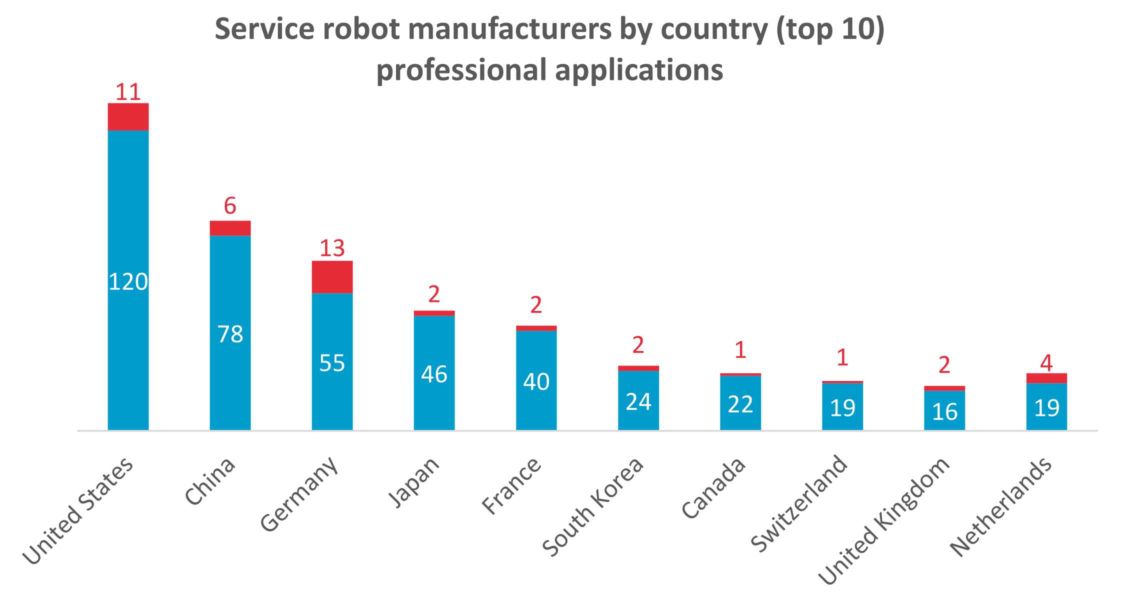


Figure 5.7

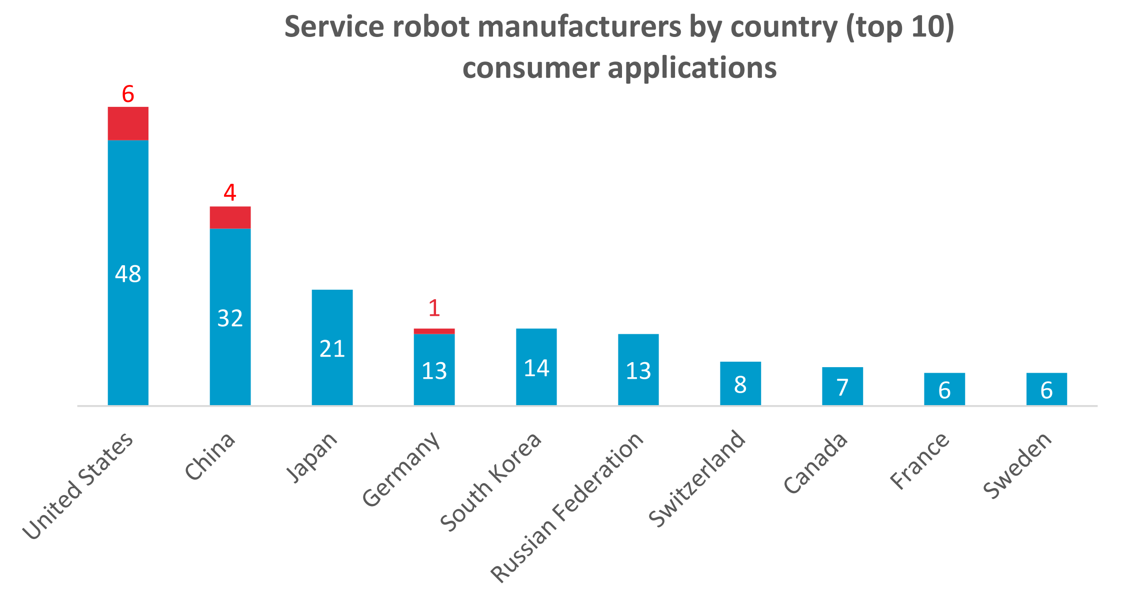
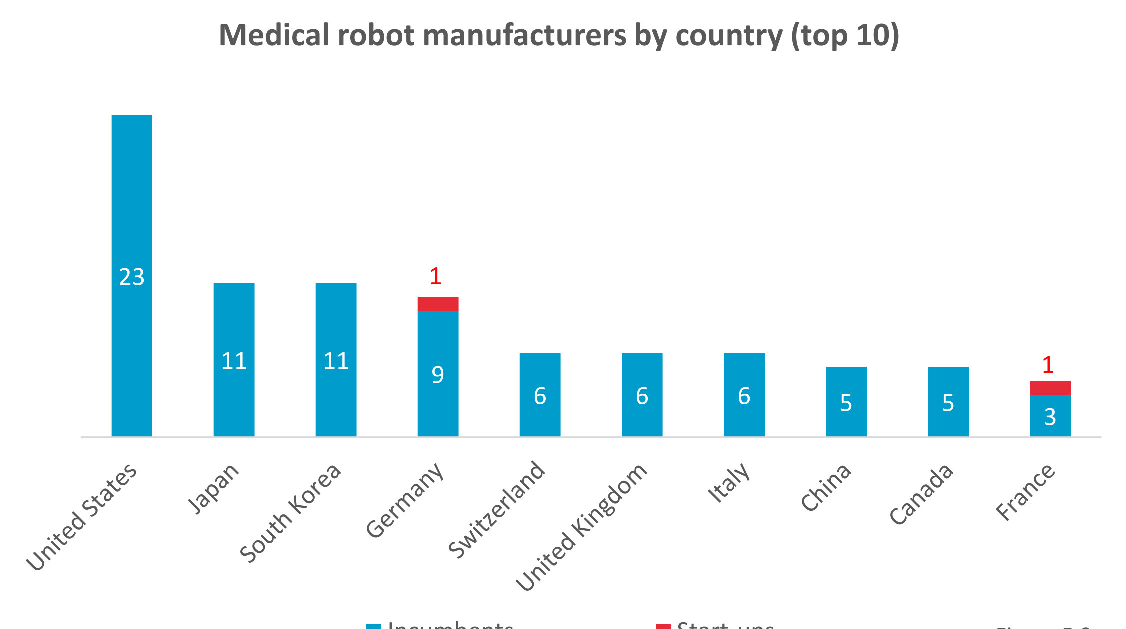


Figure 5.8


Medical robot manufacturers by country (top 10)
23
11
11
1
9
6
6
6
5
5
1
3
United States
Japan
South Korea
Germany
Switzerland
United Kingdom
Italy
China
Canada
France
Incumbents
Start-ups
Figure 5.9

5.3 SERVICE AND MEDICAL ROBOT SUPPLIERS BY BUSINESS SIZE

The service and medical robotics industry is a young and growing industry, which is also reflected by business size in terms of the number of employees. At global scale, 81%[445] of the companies are small or medium-sized enterprises (SME) with up to 500 employees. In fact, 50% of the companies do not have more than 50 employees and 17% of the companies have no more than 10 employees. Small companies have mostly been established as service or medical robot suppliers, while large companies are usually those market players that expanded from other industry segments or traditional medical equipment production and added service or medical robotics to their existing portfolio. Asian companies tend to be larger. The share of SMEs is just 71%, while it is 84% in Europe and 85% in (North) America. The share of very small companies (1-10 employees) is 7% in Asia, while it is 22% in Europe and 20% in (North) America.

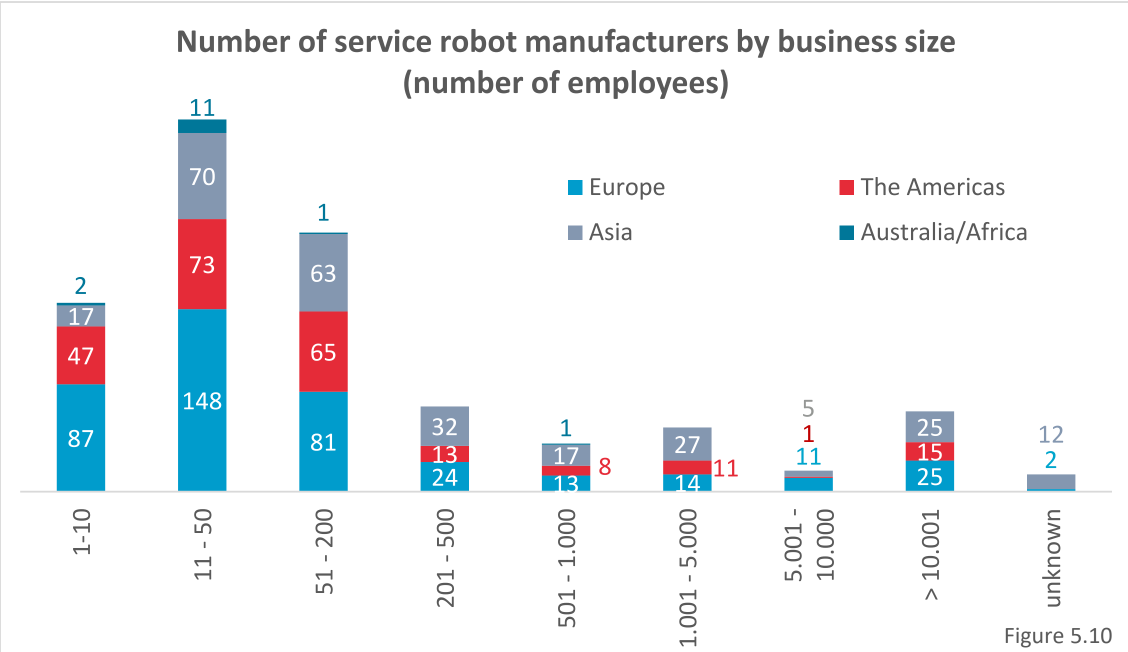


Figure 5.10

[445] Ignoring companies of unknown size.

5.4 CONSUMER SERVICE ROBOT SUPPLIERS BY APPLICATION

The consumer robot segment consists of 218 companies that produce robots for domestic tasks (IFR class AC1), robots for social interactions or education (AC2), and robots for elderly and handicap assistance (AC3) or other consumer applications (AC9).

IFR Statistical Department is currently aware of 76 suppliers[446] of service robots for domestic tasks worldwide, but white labeling is very common in this segment which makes it hard to distinguish genuine product manufacturers from companies offering white labeled products. Most of the companies active in the consumer segment are from Asia (33) and Europe (24). 19 companies are from the Americas – 18 from North America and one from South America. There are 44 suppliers of indoor floor cleaning robots for domestic use (AC11). These companies are usually located in Asia (25) or Europe (12). In the other applications classes the number of suppliers is lower: 23 companies offer robots for domestic gardening (AC13), mainly robotic lawn mowers, 16 companies offer domestic outdoor cleaning robots (AC14), mainly pool cleaners, and 8 companies offer robots for domestic window cleaning (AC12). One company invented a robot for a domestic task that does not fit into any of the above classes (AC19).

A total of 104 companies offers robots for social interaction or education purposes. Most companies are from Asia (45) and Europe (32), but (North) America also has a vivid population of 27 companies. Asian suppliers are more focused on social interaction robots (AC21; 29 companies), while European and (North) American suppliers emphasize educational robotics (AC22; 26 European companies and 20 American companies).

The elderly and handicap assistance segment is addressed by 42 service robot producers. The distribution of companies is well-balanced between the three main regions: Europe hosts 16 companies, (North) America is the home of 14 companies, and there are 12 Asian suppliers. The segment encompasses 25 producers of robotics mobility assistants (AC31), 12 producers of manipulation aids (AC32), and 11 producers of other kinds of care robots (AC39).

There are 10 suppliers that offer consumer service robots that do not fit into any of the above classes (AC99).

[446] A company can offer more than one type of consumer robot. Hence, the sum of suppliers by application exceeds the total.

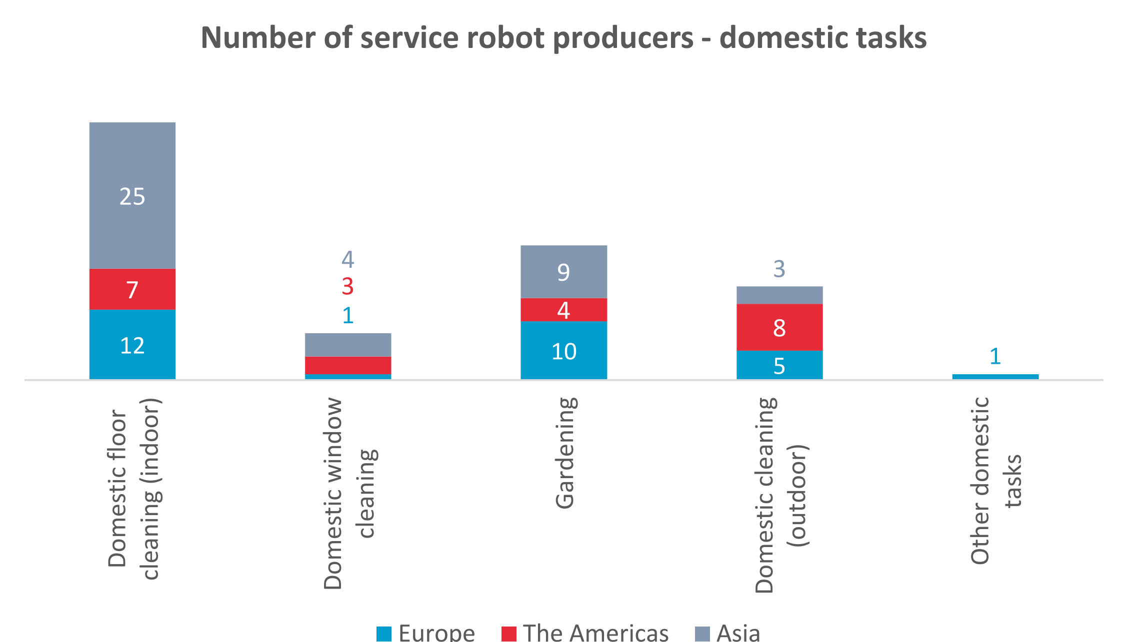


Figure 5.11

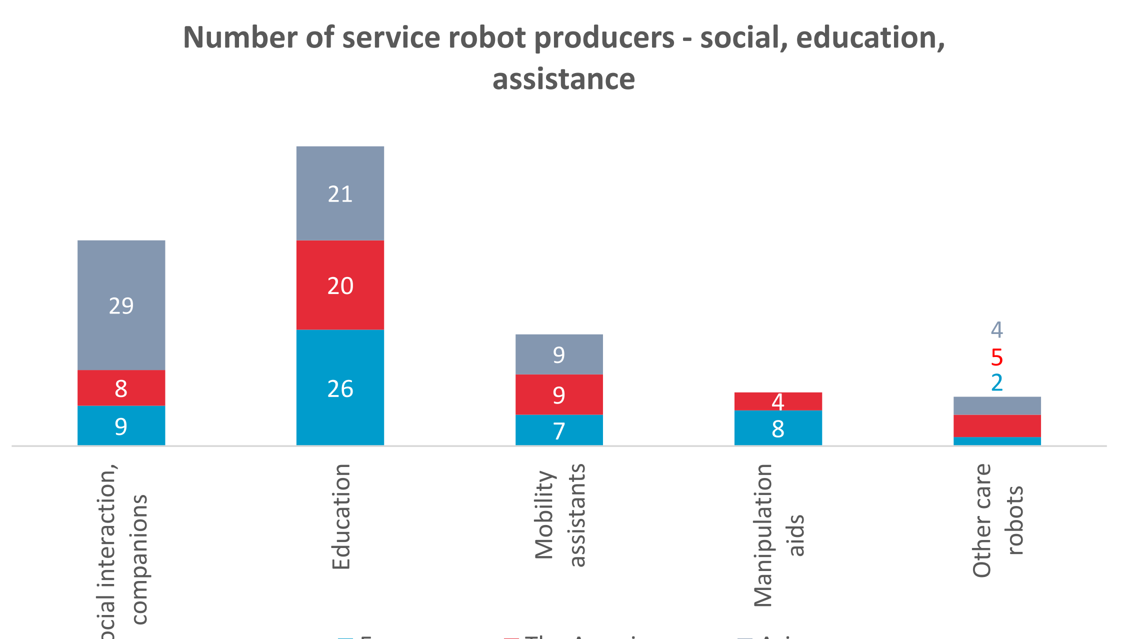


Figure 5.12

5.5 PROFESSIONAL SERVICE ROBOT SUPPLIERS BY APPLICATION

The professional service robotics segment consists of 7 major application areas plus one residual class (other professional service robots; AP9): Agriculture (AP1), professional cleaning (AP2), inspection & maintenance (AP3), construction & demolition (AP4), transportation & logistics (AP5), search & rescue, security (AP7), and hospitality (AP8).[447] IFR Statistical Department is aware of 677 professional service robot producers worldwide.

There are 83 suppliers of agricultural robots. Most of these companies are from Europe (50). There are 18 suppliers in (North) America and 12 suppliers in Asia. Most companies focus on cultivation tasks (AP11; 70 companies). 6 companies offer robots for milking (AP12) and 10 companies (all from Europe) produce robots for other livestock farming tasks (AP13). There are 3 suppliers of robots for other agricultural tasks (AP19) that do not fit into any of the above classes.

126 companies offer professional cleaning robots. The coronavirus pandemic has seen lots of companies quickly developing and supplying disinfection robots (AP25), leading to a total of 62 producers in August 2022. Meanwhile, 9 suppliers ceased production of such robots, giving a total of 53 suppliers in August 2024. Disinfection is nevertheless the application class with the largest number of suppliers within professional cleaning. Most companies are from Asia (22) and Europe (19). 11 companies are from (North) America. The second largest professional cleaning application is floor cleaning (AP21), addressed by 49 suppliers, thereof 25 Asian, 15 European, and 9 (North) American. 9 companies offer robots for hull cleaning (AP24), 6 companies offer robots for professional window and wall cleaning (AP22), and 4 suppliers offer robots for tank, tube and pipe cleaning (AP23). There are 24 suppliers that offer robots for other professional cleaning tasks (AP29).

There are 76 suppliers of inspection and maintenance robots. Most of these companies are from Europe (38), but there are also 18 (North) American and 18 Asian ones. 39 companies offer robots for the inspection of buildings and other construction (AP31). Robotic solutions for tank, tube, and pipe inspection (AP32) can be obtained from 31 suppliers. There are also robots for various other inspection and maintenance tasks (AP39) offered by 21 companies. Counting robot suppliers in this application group contains some uncertainty because there are many remote-controlled robotic devices offered and hardly any fully autonomous robot. The ISO 8373 definition of a robot requires “a degree of autonomy”, while devices that use robot technology but lack autonomy (e.g. remote-operated machines) are called robotic devices. The ISO definition remains vague about the exact delimitation of the functions that must be autonomous. Thus, the identification of a product as a robot (included in statistics) and a robotic device (excluded from statistics, except AP7 and medical robotics) remains arbitrary to some extent.

[447] Following the 2021 revision of ISO 8373, medical robots are now considered as an own category on the same hierarchy level as industrial robots and service robots (see chapter 1).

Compared to the size of the construction industry, the application of robots for construction and demolition is surprisingly low, but there is a larger number of suppliers that do not appear in this overview because they procure industrial robot arms of other (industrial) robot suppliers for their solution. There are 27 manufacturers of construction robots, mainly from Europe (14). The majority of 20 companies focuses on construction (AP41), while 7 companies offer robots for demolition (AP42).

In contrast, the boom of service robot use in logistics is continuing. IFR Statistical Department is currently aware of 316 companies that supply logistics robots of various kinds. This includes autonomous mobile robots but excludes autonomous guided vehicles that require physical manipulation of the environment, e.g. through markers or magnetic lines. Suppliers of self-driving cars and buses or other means of people transportation are excluded, too. There are 139 European, 114 Asian, and 61 (North) American suppliers of transportation and logistics robots. Most suppliers focus on logistics in indoor environments without public traffic (AP51; 223 companies). Several suppliers (70) offer robots for indoor logistics when public traffic may cross the robot's path (AP52). There are 36 producers of robots for outdoor environments with public traffic (AP54; mainly "last mile delivery"). Logistics robots for outdoor environments without public traffic (AP53) are offered by 35 companies. The segment of robots for inventory management (AP55) is served by 19 companies. There are 15 companies that offer transportation and logistics robots (AP59) other than the ones mentioned above.

The segment of search and rescue, security robots is served by 82 different suppliers, most of them are Asian (39 companies). There are 20 (North) American and 19 European manufacturers active in this field, too. Most companies offer robots or robotic devices for security services (AP73; 67 companies). 22 companies offer solutions for firefighting (AP71), and 15 ones address disaster relief (AP72).

Robots for hospitality tasks are offered by 71 companies worldwide, including 33 Asian, 25 European, and 11 (North) American companies. Most of these companies (61) offer robots for mobile guidance, information, or telepresence (AP82). Food and drink preparation robots are in the product portfolio of 11 companies. Food and drink preparation is another application that has many suppliers using third-party robots, i.e. these suppliers do not appear in this analysis.

There are 73 companies that offer robots for various other professional tasks that do not fit into any of the above classes (AP99).

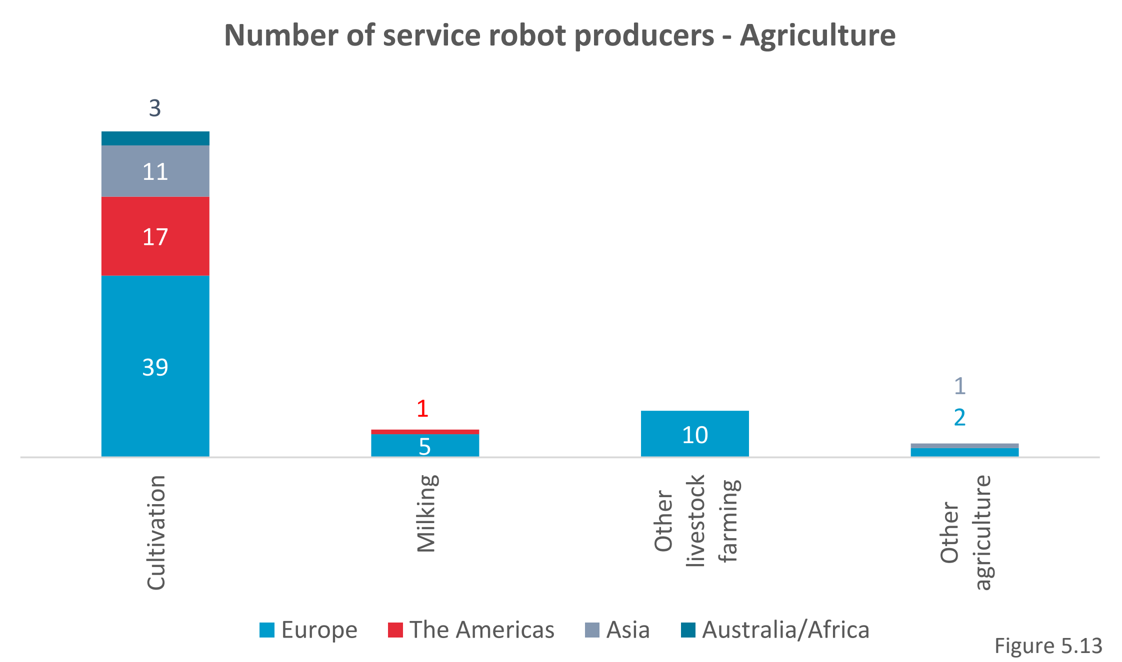


Figure 5.13

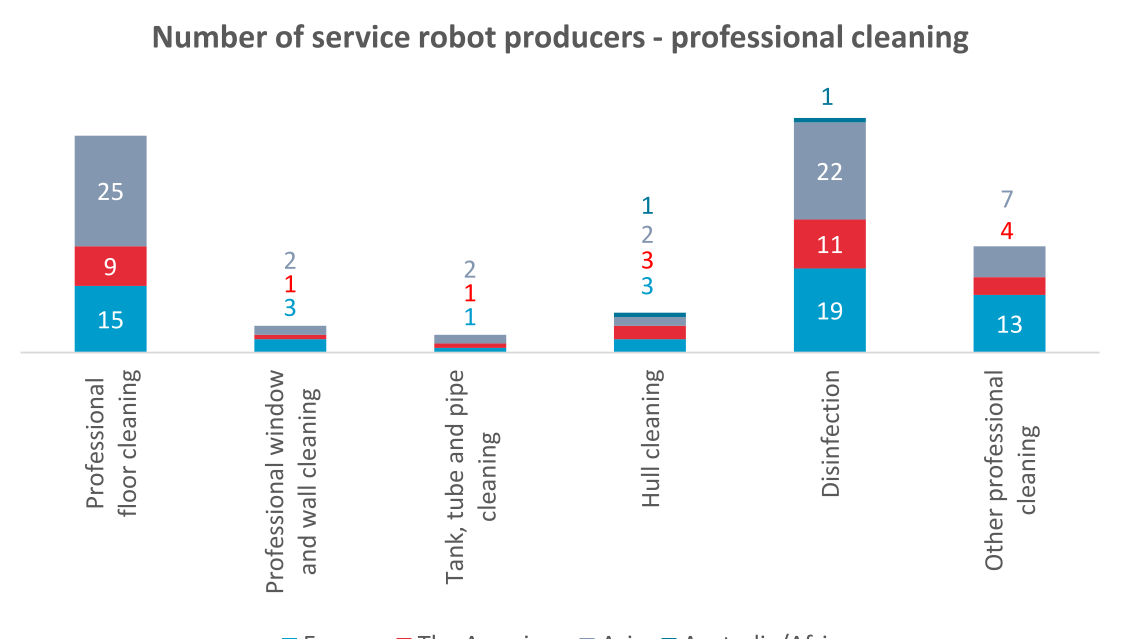


Figure 5.14

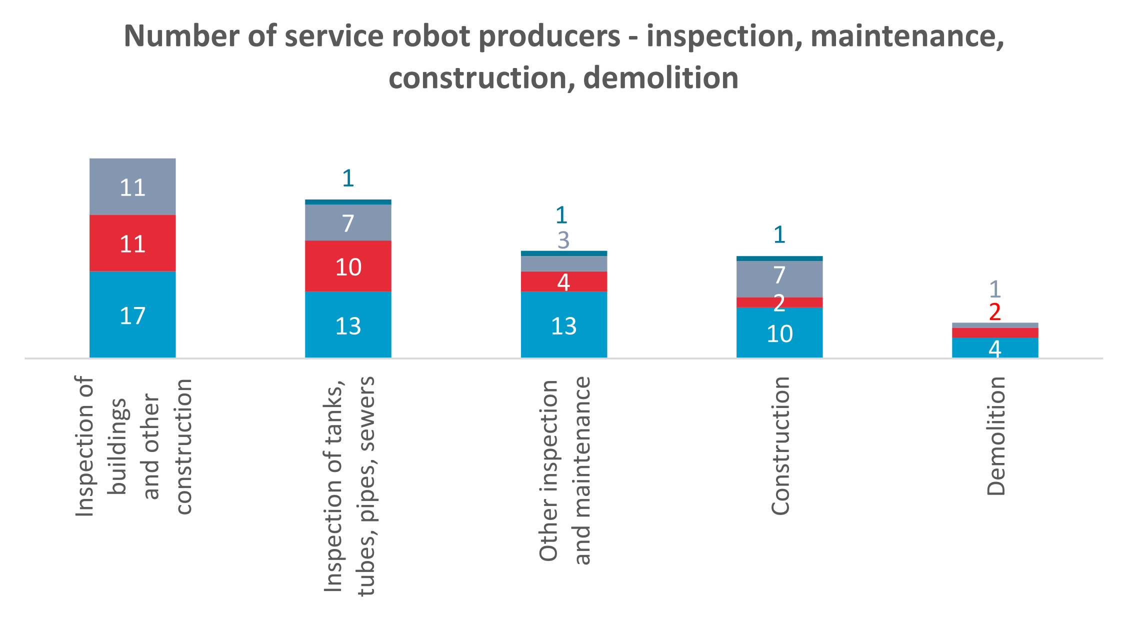


Figure 5.15

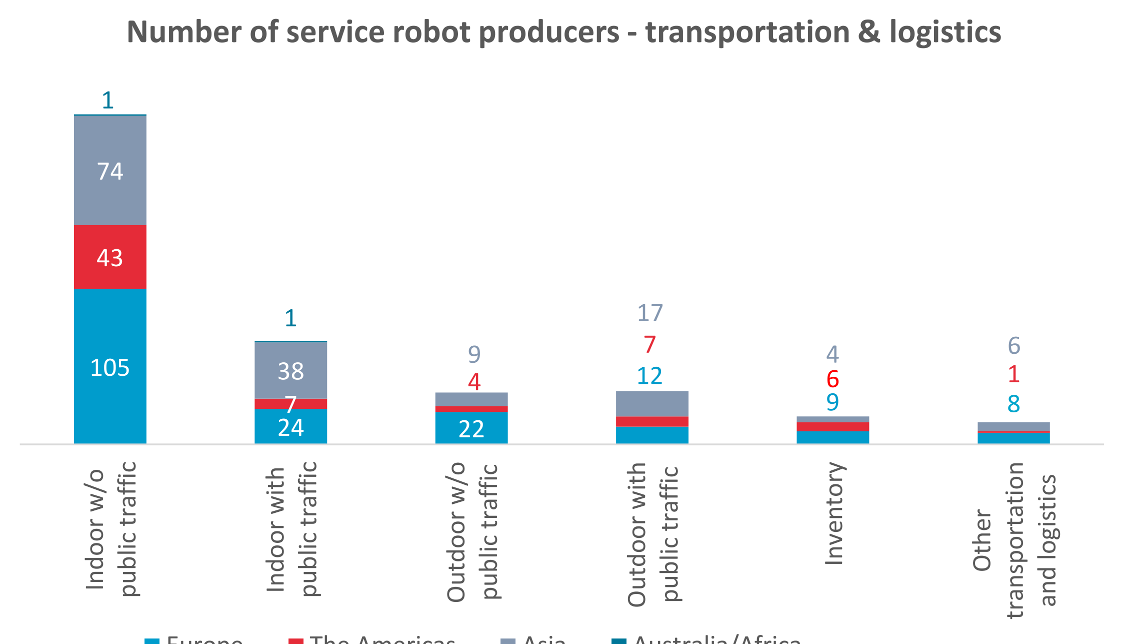
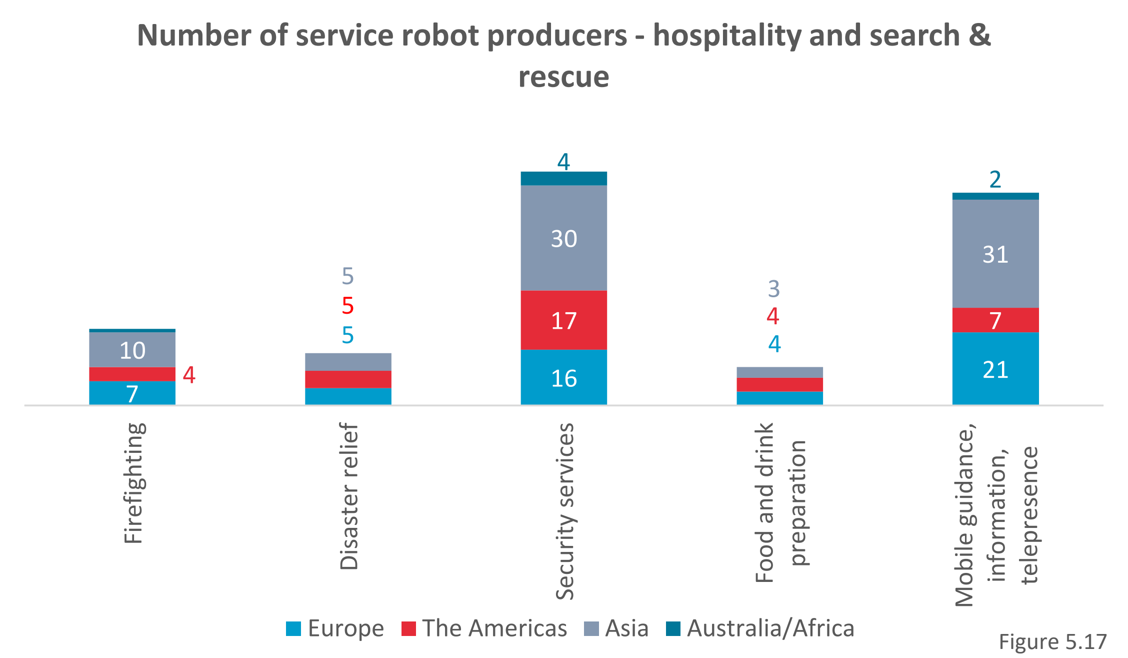


Figure 5.16



Number of service robot producers - hospitality and search & rescue
7
4
10
5
5
5
16
17
30
4
4
4
3
21
7
31
2
Firefighting
Disaster relief
Security services
Food and drink preparation
Mobile guidance, information, telepresence
Europe
The Americas
Asia
Australia/Africa

Figure 5.17

5.6 MEDICAL ROBOT SUPPLIERS BY APPLICATION

Medical robotics has attracted 109 suppliers worldwide, 48 of which are European, 31 are North American, and 28 are Asian. 50 companies offer robots for rehabilitation or non-invasive therapy (AP63). Most companies in this segment are European (26), but there are also 16 Asian and 7 North American companies, along with one Australian. The particularly delicate field of surgery robots is addressed by 44 companies. Thereof, 18 companies are from Europe and North America, each, and 8 companies are from Asia. There are 11 suppliers of robots for diagnostics (AP61), 7 of them are European. 17 companies offer robots for other medical purposes (AP69). Robotic solutions for laboratory analysis (AP64) are usually based on traditional industrial robots or collaborative industrial robots. Thus, most suppliers of such solutions do not appear here.

Note that AP61, AP63, and AP63 include suppliers of robotics devices.

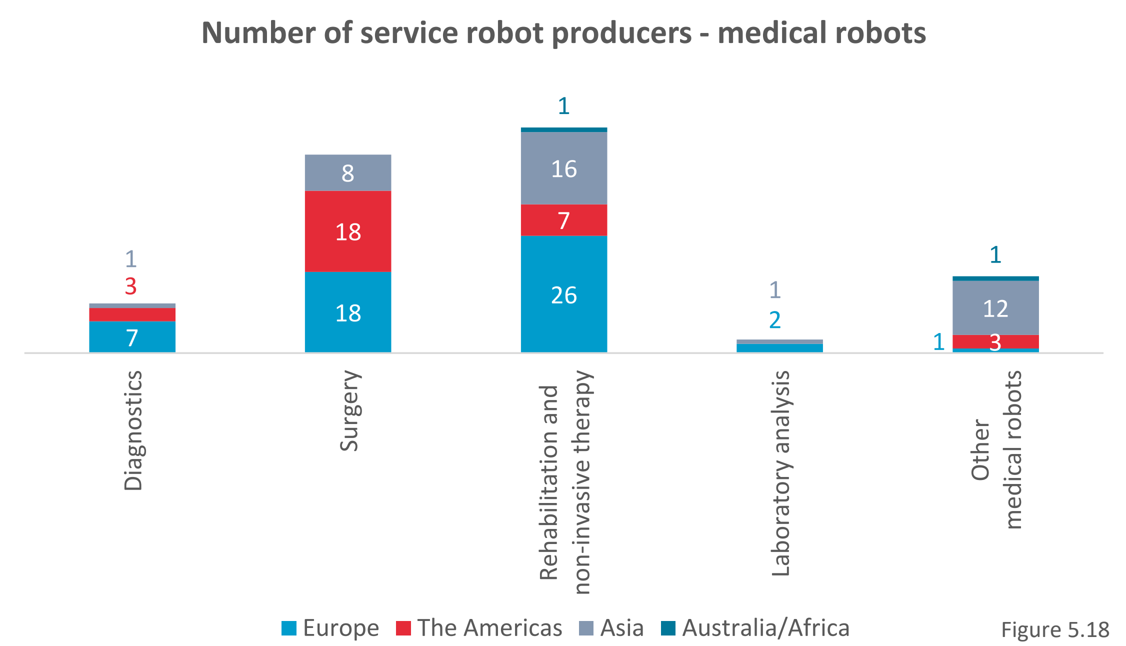


Figure 5.18

5.7 LIST OF SERVICE ROBOT SUPPLIERS WORLDWIDE

Class code	Number of employees
A	1 - 10
B	11 - 50
C	51 - 200
D	201 - 500
E	501 - 1.000
F	1.001 - 5.000
G	5.001 - 10.000
H	> 10.001

Table 5.1: Company size classification scheme

No.	Company name	Size	Est.	Loc.	Continent	Application classes
1	1X	C	2015	NO	Europe	Other professional service robots
2	4am Robotics	C	2015	DE	Europe	Logistics in indoor environments without public traffic, logistics in outdoor environments without public traffic
3	6 River Systems	C	2015	US	Americas	Logistics in indoor environments without public traffic
4	A&K Robotics	B	2015	CA	Europe	Mobility assistants
5	AAI Canada, Inc	A	1983	CA	Americas	Prototyping service
6	ABB Robotics	G	1998	CH	Europe	Other transportation and logistics
7	Able Human Motion	B	2018	ES	Europe	Rehabilitation and non-invasive therapy
8	Academy of Robotics	A	2016	UK	Europe	Logistics in outdoor environments with public traffic
9	Accuray	E	1987	US	Americas	Surgery
10	Addverb Technologies	E	2016	IN	Asia	Disinfection, logistics in indoor environments without public traffic
11	Adlatus Robotics	B	2015	DE	Europe	Professional floor cleaning
12	Advanced Intelligent Systems	B	2013	CA	Americas	Cultivation, disinfection
13	Advanced.farm	C	2018	US	Americas	Cultivation
14	Aeditive	B	2019	DE	Europe	Construction
15	Aeolus Robotics	C	2016	US	Americas	Social interaction, companions, disinfection, logistics in indoor

No.	Company name	Size	Est.	Loc.	Continent	Application classes
						environments with public traffic, other medical robots, food and drink preparation, other professional service robots
16	Aerob	B	2011	RU	Europe	Security services
17	Aerocon	B	1991	RU	Europe	Security services
18	Aethon	C	2004	US	Americas	Logistics in indoor environments with public traffic
19	Afara Agricultural Technologies	A	2023	TR	Europe	Cultivation
20	Ageless Innovations	B	2015	US	Americas	Social interaction, companions
21	Agility Robotics	A	2016	US	Americas	Logistics in outdoor environments without public traffic, logistics in outdoor environments with public traffic
22	Agilox	C	2017	AT	Europe	Logistics in indoor environments without public traffic
23	Agora Robotics	B	2018	RO	Europe	Professional floor cleaning, disinfection, logistics in indoor environments without public traffic
24	Agrobot	A	2009	US	Americas	Cultivation
25	Agrointelli	B	2015	DK	Europe	Cultivation
26	AGV International	A	2015	NL	Europe	Logistics in indoor environments without public traffic
27	AGVE	C	1985	SE	Europe	Logistics in indoor environments without public traffic, logistics in outdoor environments without public traffic, prototyping service
28	Agxeed	B	2018	NL	Europe	Cultivation
29	AI Mergence	A	2015	FR	Europe	Security services
30	AI Robots	A	2016	FI	Europe	Education
31	AiDrones	B	2011	DE	Europe	Other inspection and maintenance, firefighting, disaster relief, security services
32	Aiper	D	2021	US	Americas	Domestic cleaning (outdoor)
33	Aitheon	C	2017	UA	Europe	Disinfection, logistics in indoor

No.	Company name	Size	Est.	Loc.	Continent	Application classes
						environments with public traffic
34	Aitonomi (TeleRetail)	B	2014	CH	Europe	Logistics in outdoor environments with public traffic
35	Aitreat	B	2015	SG	Asia	Rehabilitation and non-invasive therapy
36	Aiut	E	1991	PL	Europe	Logistics in indoor environments without public traffic
37	Aizuk	B	2012	JP	Asia	Mobility assistants, security services
38	Aka Intelligence	E	2013	US	Americas	Education
39	Akara Robotics	A	2019	IE	Europe	Disinfection
40	AkinRobotics	C	1995	TR	Europe	Mobile guidance, information, telepresence, other professional service robots
41	Aktormed	B	2005	DE	Europe	Surgery
42	Alkadur	A	2011	DE	Europe	Food and drink preparation
43	Alog	A	2016	IN	Asia	Logistics in indoor environments without public traffic
44	Alphadroid	B	2022	IN	Asia	Logistics in indoor environments with public traffic
45	Alstef Group	D	1975	FR	Europe	Logistics in indoor environments without public traffic, inventory
46	Alta Material Handling	E	1984	US	Americas	Logistics in indoor environments without public traffic
47	Amano	G	1945	JP	Asia	Professional floor cleaning
48	Amazon Robotics	E	2003	US	Americas	Logistics in indoor environments without public traffic
49	Amazonen-Werke	F	1883	DE	Europe	Cultivation
50	Amerden Agvs	B	1988	US	Americas	Logistics in indoor environments without public traffic
51	American In Motion	B	2008	US	Americas	Logistics in indoor environments without public traffic
52	Amyrobotics	C	2015	CN	Asia	Disinfection, construction, logistics in indoor environments with public traffic, other medical robots, security services, mobile guidance,

No.	Company name	Size	Est.	Loc.	Continent	Application classes
						information, telepresence
53	Angel Robotics	C	2014	KR	Asia	Mobility assistants, rehabilitation and non-invasive therapy
54	Angsa Robotics	B	2019	DE	Europe	Other professional cleaning
55	Anker Innovations	F	2011	US	Americas	Domestic floor cleaning (indoor)
56	Anscer	A	2020	IN	Asia	Logistics in indoor environments without public traffic
57	Ant Robotics	A	2021	DE	Europe	Logistics in outdoor environments with public traffic
58	ANYbotics	B	2016	CH	Europe	Inspection of buildings and other construction
59	Anyware Robotics	B	2022	US	Americas	Logistics in indoor environments without public traffic
60	Apptronik	C	2016	US	Americas	Other professional service robots
61	Aquagenesis Intl	A	1985	US	Americas	Other professional cleaning
62	Art Robot	C	2015	CN	Asia	Cultivation, logistics in outdoor environments without public traffic, security services
63	ART Robotics	A	2018	BE	Europe	Other professional cleaning, inspection of buildings and other construction
64	ArvaTec	B	2002	IT	Europe	Cultivation
65	Ascend	D	2013	US	Americas	Mobility assistants
66	Ascento	B	2023	CH	Europe	Security services
67	Asensus Surgical	C	2006	US	Americas	Surgery
68	Asimov	C	2012	IN	Asia	Social interaction, companions, disinfection, logistics in indoor environments with public traffic, mobile guidance, information, telepresence
69	Asseco Ceit	D	2009	SK	Europe	Logistics in indoor environments without public traffic
70	Assistive Innovation	A	1989	NL	Europe	Manipulation aids
71	Astro	A	2021	US	Americas	Logistics in indoor environments without public traffic
72	Astrobotic	B	2008	US	Americas	Other professional service robots

No.	Company name	Size	Est.	Loc.	Continent	Application classes
73	ATC Autonomous Tractor Company	A	1983	US	Americas	Cultivation
74	Atlas Robotics	B	2017	US	Americas	Logistics in indoor environments without public traffic
75	Aubot	B	2013	AU	Australia	Mobile guidance, information, telepresence
76	Australian Droid + Robot	B	2010	AU	Australia	Other inspection and maintenance
77	Automata	B	2015	UK	Europe	Laboratory analysis
78	Autonomous Solutions	C	2000	US	Americas	Cultivation, demolition
79	Autonopia	A	2019	CA	Americas	Professional window and wall cleaning
80	Autopickr	A	2022	UK	Europe	Cultivation
81	Ava Robotics	B	2017	US	Americas	Disinfection, security services, mobile guidance, information, telepresence
82	Avatar-In	B	2020	JP	Asia	Mobile guidance, information, telepresence
83	AvatarMind Robot Technology	A	2022	GB	Europe	Social interaction, companions
84	Avenof	B	2003	TR	Europe	Logistics in indoor environments without public traffic
85	Aviator Robotics	A	2017	SE	Europe	Hull cleaning
86	Avidbots	C	2014	CA	Americas	Professional floor cleaning
87	Awabot	C	2010	FR	Europe	Mobile guidance, information, telepresence
88	Axiles Bionics	A	2018	BE	Europe	Rehabilitation and non-invasive therapy
89	Axyn Robotique	A	2014	FR	Europe	Mobile guidance, information, telepresence
90	BakerHughes (Waygate Technologies)	F	2006	DE	Europe	Inspection of tank, tubes, pipes, sewers
91	Baltrobotics	B	2014	PL	Europe	Inspection of buildings and other construction
92	Balyo	C	2006	FR	Europe	Logistics in indoor environments without public traffic
93	Bama Sistemas	C	1997	ES	Europe	Logistics in indoor environments without public traffic
94	Bama Teknoloji	B	2010	TR	Europe	Rehabilitation and non-invasive therapy
95	Bär Automation	C	1972	DE	Europe	Logistics in indoor environments without public traffic
96	Barobo	A	2010	US	Americas	Education

No.	Company name	Size	Est.	Loc.	Continent	Application classes
97	Barrett	B	1990	US	Americas	Rehabilitation and non-invasive therapy
98	BBZ	A	2013	IT	Europe	Construction, surgery
99	Bear Robotics	C	2017	US	Americas	Logistics in indoor environments with public traffic
100	BEC	C	2003	DE	Europe	Logistics in indoor environments without public traffic, surgery, rehabilitation and non-invasive therapy, other professional service robots
101	Bee Robotics	B	1999	UK	Europe	Diagnostics
102	Beijing BJ Robot Zhi Neng Jia Tech	B	2006	CN	Asia	Education
103	Beijing Multifit Electrical Technology	D	2009	CN	Asia	Other professional cleaning
104	Beijing Tinavi Medical Technology	C	2005	CN	Asia	Surgery
105	Beijing Yunji Technology	E	2014	CN	Asia	Professional floor cleaning, disinfection, logistics in indoor environments with public traffic, mobile guidance, information, telepresence
106	Berkeley Springs Instruments	B	2007	US	Americas	Inspection of tank, tubes, pipes, sewers
107	Besnovo	B	1989	CA	Americas	Hull cleaning
108	Bharati Robotic Systems	B	2013	IN	Asia	Professional floor cleaning
109	BIA5	B	2017	AU	Australia	Firefighting, security services, other professional service robots
110	Big Joe	C	1951	US	Americas	Logistics in indoor environments without public traffic
111	Bila	E	1988	DK	Europe	Logistics in indoor environments without public traffic
112	Biogriculture	A	2019	DE	Europe	Cultivation
113	Bionic Power	B	2007	CA	Americas	Other professional service robots
114	BionicHIVE	B	2014	IL	Europe	Logistics in indoor environments without public traffic
115	Bionik Laboratories	B	2010	CA	Americas	Rehabilitation and non-invasive therapy
116	Bioservo	B	2006	SE	Europe	Manipulation aids
117	BirdBrain Technologies	A	2010	US	Americas	Education
118	Bissell	F	1876	US	Americas	Domestic floor cleaning (indoor)

No.	Company name	Size	Est.	Loc.	Continent	Application classes
119	BiTronics	A	2015	RU	Europe	Education
120	BizLink Robotic Solutions	D	2013	FR	Europe	Diagnostics
121	BladeRanger	A	2016	IL	Europe	Other professional cleaning
122	BlastOne	D	1975	US	Americas	Hull cleaning
123	Blaupunkt	D	1924	DE	Europe	Domestic floor cleaning (indoor)
124	Blue Atlas Robotics	A	2018	DK	Europe	Other inspection and maintenance
125	Blue Frog Robotics	B	2014	FR	Europe	Social interaction, companions
126	Blue Ocean Robotics	C	2013	DK	Europe	Disinfection, rehabilitation and non-invasive therapy, mobile guidance, information, telepresence
127	Blue River Technologies	C	2011	US	Americas	Cultivation
128	BlueBotics	B	2001	CH	Europe	Logistics in indoor environments without public traffic
129	Bluepath Robotics	B	2016	TR	Europe	Logistics in indoor environments without public traffic
130	Bobsweep	C	2008	CA	Americas	Domestic floor cleaning (indoor)
131	Bosch	H	1886	DE	Europe	Domestic floor cleaning (indoor), gardening
132	Boston Dynamics	C	1992	US	Americas	Inspection of buildings and other construction, logistics in indoor environments without public traffic, firefighting, disaster relief
133	Bot Eyes	C	2002	RU	Europe	Mobile guidance, information, telepresence
134	Brain Development	A	2012	RU	Europe	Education
135	Brain Navi Biotechnology	B	2015	TW	Asia	Surgery, other medical robots, other professional service robots
136	Brainlab	F	1989	DE	Europe	Diagnostics, surgery
137	Brightpick	D	2020	US	Americas	Logistics in indoor environments without public traffic
138	Brokk	C	1976	SE	Europe	Demolition
139	Brüggli	D	2015	CH	Europe	Cultivation
140	b-temia	B	2010	CA	Americas	Mobility assistants, other professional service robots

No.	Company name	Size	Est.	Loc.	Continent	Application classes
141	Build with Robots	B	2017	US	Americas	Disinfection
142	Burro	B	2017	US	Americas	Cultivation
143	BWT	G	1990	AT	Europe	Domestic cleaning (outdoor)
144	Cablewalker	B	2013	RU	Europe	Inspection of buildings and other construction
145	Café X Technologies	A	2018	US	Americas	Food and drink preparation
146	Caja	B	2014	IL	Europe	Logistics in indoor environments without public traffic
147	Canbot	C	2008	CN	Asia	Social interaction, companions, logistics in indoor environments with public traffic, mobile guidance, information, telepresence
148	Candroid Robotics Corporation	A	2017	CA	Americas	Professional floor cleaning, disinfection
149	Canvas Construction	B	2017	US	Americas	Construction
150	Capra Robotics	B	2017	DK	Europe	Other inspection and maintenance, logistics in outdoor environments without public traffic, logistics in outdoor environments with public traffic, other transportation and logistics, security services
151	Carbon Robotics	C	2018	US	Americas	Cultivation
152	Carl Zeiss Meditec	G	1846	DE	Europe	Surgery
153	Carré	C	1938	FR	Europe	Cultivation
154	Cartken	B	2019	US	Americas	Logistics in indoor environments with public traffic, logistics in outdoor environments with public traffic
155	Cassioli	D	1943	IT	Europe	Logistics in indoor environments without public traffic
156	Casun	D	2007	CN	Asia	Disinfection, logistics in indoor environments without public traffic, logistics in outdoor environments without public traffic
157	Caterpillar	H	1925	US	Americas	Demolition
158	Cecotec	E	1995	ES	Europe	Domestic floor cleaning (indoor)

No.	Company name	Size	Est.	Loc.	Continent	Application classes
159	Chuangze Intelligent Robot	D	2010	CN	Asia	Other care robots, professional floor cleaning, disinfection, logistics in outdoor environments with public traffic, security services, mobile guidance, information, telepresence
160	Citic HIC Kaicheng Intelligence Equipment Co., Ltd	E	1991	CN	Asia	Firefighting
161	Clean Sea Solutions	A	2017	NO	Europe	Other professional cleaning
162	Cleanfix	C	1976	CH	Europe	Professional floor cleaning
163	Clearbot	B	2019	HK	Asia	Other professional service robots
164	CloudMinds Technology	E	2015	CN	Asia	Disinfection, logistics in indoor environments with public traffic, mobile guidance, information, telepresence
165	CMR Surgical	C	2014	UK	Europe	Diagnostics, surgery
166	Coalescent Mobile Robotics	A	2018	DK	Europe	Logistics in indoor environments without public traffic
167	Cobalt Robotics	B	2016	US	Americas	Security services
168	Coga Robotics	B	2017	KR	Asia	Logistics in indoor environments with public traffic
169	Cogibot		1920	FR	Europe	Education
170	Comau	H	1973	IT	Europe	Education, logistics in indoor environments without public traffic, other professional service robots
171	Commonplace Robotics	A	2011	DE	Europe	Other professional service robots
172	Conbotics	B	2021	DE	Europe	Construction
173	Conjet	B	1990	SE	Europe	Demolition
174	Connected Orthopadic Insight	E	1985	US	Americas	Surgery
175	Consequential Robotics	A	2016	UK	Europe	Social interaction, companions, education
176	Continental	H	1871	DE	Europe	Logistics in indoor environments with public traffic
177	Co-Robotics	A	2016	IT	Europe	Disinfection, logistics in indoor environments without public traffic, mobile

No.	Company name	Size	Est.	Loc.	Continent	Application classes
						guidance, information, telepresence
178	Corvus Robotics	B	2017	US	Americas	Inventory
179	CoTek	A	2016	CN	Asia	Logistics in indoor environments without public traffic
180	CSG	F	2002	CN	Asia	Logistics in indoor environments without public traffic, security services
181	CT-Asia Robotics	C	2009	TH	Asia	Social interaction, companions, mobile guidance, information, telepresence
182	CtrlWorks	B	2011	SG	Asia	Logistics in indoor environments without public traffic, logistics in indoor environments with public traffic
183	Curaco	B	2007	KR	Asia	Other medical robots
184	Curexo	C	1992	KR	Asia	Surgery, rehabilitation and non-invasive therapy
185	Cyberdyne	C	2004	JP	Asia	Professional floor cleaning, logistics in indoor environments with public traffic, rehabilitation and non-invasive therapy, other professional service robots
186	CyberTech	A	2012	RU	Europe	Education
187	Cyberworks Robotics	A	2008	CA	Americas	Mobility assistants, professional floor cleaning, logistics in indoor environments without public traffic
188	Dahlia Robotics	A	2018	DE	Europe	Cultivation
189	Dalu Robotech	B	2010	CN	Asia	Disinfection, security services
190	Dane Technologies	C	1996	US	Americas	Logistics in indoor environments without public traffic
191	Deduco	B	1987	BE	Europe	Mobile guidance, information, telepresence
192	Deep Robotics	C	2017	CN	Asia	Inspection of buildings and other construction
193	Deep Trekker	C	2010	CA	Americas	Inspection of tank, tubes, pipes, sewers
194	Delair Marine	B	2016	FR	Europe	Other inspection and maintenance

No.	Company name	Size	Est.	Loc.	Continent	Application classes
195	DeLaval International	F	1878	SE	Europe	Milking, other livestock farming
196	Dematic	H	1819	US	Americas	Logistics in indoor environments without public traffic
197	Demcon	E	1993	NL	Europe	Other inspection and maintenance
198	Dereviaka	A	2013	RU	Europe	Social interaction, companions, education
199	Desin	A	2010	US	Americas	Mobility assistants, manipulation aids, other care robots
200	Devanthro	A	2018	DE	Europe	Mobile guidance, information, telepresence
201	Dexai Robotics	A	2018	US	Americas	Food and drink preparation
202	Dexory	A	2015	UK	Europe	Inventory
203	Dexterity	D	2017	US	Americas	Logistics in indoor environments without public traffic
204	DF Automation & Robotics	C	2012	MY	Asia	Disinfection, logistics in indoor environments without public traffic, logistics in indoor environments with public traffic
205	DFKI Industrials	F	2012	DE	Europe	Security services
206	Diakont	E	1990	Ru	Europe	Inspection of buildings and other construction, inspection of tank, tubes, pipes, sewers
207	Digger	B	1998	CH	Europe	Security services
208	Diligent Robots	A	2015	US	Americas	Logistics in indoor environments with public traffic, other medical robots
209	Discovery Robotics	B	2014	US	Americas	Professional floor cleaning
210	DJI	H	2006	CN	Asia	Cultivation, inspection of buildings and other construction
211	Dogtooth Technologies	B	2014	UK	Europe	Cultivation
212	Dogugonggan	C	2017	KR	Asia	Security services
213	Dok-Ing	D	1991	CR	Europe	Firefighting, disaster relief, security services
214	Done Robotics	A	2020	FI	Europe	Disinfection
215	Doog		2012	JP	Asia	Logistics in indoor environments without public traffic, logistics

No.	Company name	Size	Est.	Loc.	Continent	Application classes
						in outdoor environments without public traffic, logistics in outdoor environments with public traffic
216	Double Robotics	B	2012	US	Americas	Mobile guidance, information, telepresence
217	Dr Robot	B	2001	CA	Americas	Education
218	Dreame Technology	E	2015	CN	Asia	Domestic floor cleaning (indoor)
219	Droneshub	A	2018	RU	Europe	Logistics in outdoor environments without public traffic
220	DS Automotion	C	1984	AT	Europe	Logistics in indoor environments without public traffic
221	Dusty Robotics	A	2015	US	Americas	Construction
222	Dynsoft	A	2016	RU	Europe	Logistics in indoor environments with public traffic, mobile guidance, information, telepresence
223	Dyson	G	1993	UK	Europe	Domestic floor cleaning (indoor)
224	Earth Rover	A	2017	UK	Europe	Cultivation
225	Earth Sense	A	2016	US	Americas	Cultivation
226	Easy Floor Robotics	A	2018	IL	Europe	Construction
227	Easymile	D	2014	FR	Europe	Logistics in outdoor environments with public traffic
228	Eceon	B	2022	DE	Europe	Logistics in indoor environments without public traffic
229	Ecoppia	B	2013	IL	Europe	Other professional cleaning
230	EcoRobotix	B	2011	CH	Europe	Cultivation
231	Ecovacs	G	1998	CN	Asia	Domestic floor cleaning (indoor), domestic window cleaning
232	Eddyfi Technologies	D	1989	CA	Americas	Inspection of buildings and other construction, inspection of tank, tubes, pipes, sewers, other inspection and maintenance
233	Eelume	A	2015	NO	Europe	Other inspection and maintenance
234	Effidence	B	2009	FR	Europe	Construction, logistics in indoor environments without

No.	Company name	Size	Est.	Loc.	Continent	Application classes
						public traffic, logistics in outdoor environments without public traffic
235	Efy Technology	C	2015	CN	Asia	Inspection of buildings and other construction, logistics in outdoor environments with public traffic, firefighting
236	Egzotech	B	2013	PL	Europe	Rehabilitation and non-invasive therapy
237	Einhell	F	1964	DE	Europe	Gardening
238	Eiratech Robotics	B	2014	IE	Europe	Logistics in indoor environments without public traffic
239	Ek Robotics	C	1963	DE	Europe	Logistics in indoor environments without public traffic
240	Ekobot	A	2016	SE	Europe	Cultivation
241	Ekso Bionics	C	2005	US	Americas	Rehabilitation and non-invasive therapy, other professional service robots
242	Elatec	B	2011	FR	Europe	Cultivation
243	Electrolux Floorcare	H	1919	SE	Europe	Domestic floor cleaning (indoor)
244	Elephant robotics	A	2016	CN	Asia	Social interaction, companions, mobile guidance, information, telepresence
245	Elettric80	E	1980	IT	Europe	Logistics in indoor environments without public traffic
246	Emayor Synersight Technologies	C	2017	ES	Europe	Logistics in indoor environments without public traffic
247	Embodied	B	2015	US	Americas	Social interaction, companions
248	Empire Unmanned	A	2014	US	Americas	Inspection of buildings and other construction, other inspection and maintenance
249	Endoquest	C	2017	US	Americas	Surgery
250	EnergizeLab	C	2019	CN	Asia	Social interaction, companions
251	Energy Robotics	B	2018	DE	Europe	Inspection of buildings and other construction, inspection of tank, tubes, pipes, sewers

No.	Company name	Size	Est.	Loc.	Continent	Application classes
252	Engineered Arts	B	2004	UK	Europe	Other professional service robots
253	Enova Robotics	B	2014	TN	Africa	Other medical robots, security services
254	E-Novia	A	2012	IT	Europe	Logistics in indoor environments with public traffic, logistics in outdoor environments with public traffic
255	Enway	B	2007	DE	Europe	Professional floor cleaning
256	Epiroc	H	1873	SE	Europe	Demolition
257	Era Endoscopy	A	2004	IT	Europe	Diagnostics, surgery
258	Ergosurg	A	2006	DE	Europe	Surgery
259	Esatroll	B	1995	CH	Europe	Logistics in indoor environments without public traffic, logistics in outdoor environments without public traffic
260	EV Safe Charge	A	2016	US	Americas	Other professional service robots
261	EV Soosung	C	1973	KR	Asia	Logistics in indoor environments without public traffic
262	Everis ADS	C	1999	ES	Europe	Security services
263	Everybot	B	2015	KR	Asia	Domestic floor cleaning (indoor)
264	Evollve	B	2012	US	Americas	Education
265	Evolvector	A	2015	RU	Europe	Education
266	Evolver	B	2015	CN	Asia	Education
267	Ex Robotics	B	2017	NL	Europe	Inspection of buildings and other construction
268	Exail	F	1990	FR	Europe	Logistics in outdoor environments without public traffic
269	Examen Technolab	B	2011	RU	Europe	Education
270	ExoAtlet	C	2014	LU	Europe	Rehabilitation and non-invasive therapy
271	Exomed	A	2016	RU	Europe	Mobility assistants, rehabilitation and non-invasive therapy
272	Exotec	C	2015	FR	Europe	Logistics in indoor environments without public traffic
273	EZ Robot	B	2011	CA	Americas	Education
274	E-zicom	B	2009	FR	Europe	Domestic floor cleaning (indoor), gardening
275	F Poulsen Engineering	A	2006	DK	Europe	Cultivation
276	F&P Personal Robotics	A	1996	CH	Europe	Other care robots, rehabilitation and non-invasive therapy

No.	Company name	Size	Est.	Loc.	Continent	Application classes
277	Fabric	C	2015	IL	Europe	Logistics in indoor environments without public traffic
278	Farmdroid	C	2018	DK	Europe	Cultivation
279	Farming Revolution	A	2009	DE	Europe	Cultivation
280	FarmWise	C	2016	US	Americas	Cultivation
281	FastBrick Robotics	B	2015	AU	Australia	Construction
282	Ferrari Costruzioni	C	1961	IT	Europe	Cultivation
283	Festo Didactic	E	1925	DE	Europe	Education
284	FF Robotics	A	2014	IL	Europe	Cultivation
285	Fleet Cleaner	B	2011	NL	Europe	Hull cleaning
286	Flir	C	2016	US	Americas	Security services
287	Floatic	A	2021	KR	Asia	Logistics in indoor environments without public traffic
288	Fluidra	C	1982	US	Americas	Domestic cleaning (outdoor)
289	Flyability	C	2014	CH	Europe	Other inspection and maintenance
290	Focal Meditech	B	1992	NL	Europe	Manipulation aids
291	Follow Inspiration	B	2012	PT	Europe	Logistics in indoor environments without public traffic, other professional service robots
292	Forssea Robotics	B	2016	FR	Europe	Other inspection and maintenance
293	ForwardX Robotics	C	2016	CN	Asia	Logistics in indoor environments without public traffic, other transportation and logistics
294	Fotokite	B	2014	CH	Europe	Firefighting, disaster relief
295	Four D Robotics	B	2009	CA	Americas	Security services
296	Fourier Intelligence	B	2015	CN	Asia	Rehabilitation and non-invasive therapy
297	Fox Robotics	B	2018	US	Americas	Logistics in indoor environments without public traffic
298	Fraunhofer IPA	E	1959	DE	Europe	Prototyping service
299	Free Bionics	B	2017	TW	Asia	Mobility assistants
300	Free Hand Surgeon	B	2011	UK	Europe	Surgery
301	Fubao Intelligent Technology	A	2016	CN	Asia	Disinfection, logistics in indoor environments with public traffic, mobile guidance, information, telepresence
302	Fuji Robotics	D	1944	JP	Asia	Other medical robots
303	Fujisoft	H	1970	JP	Asia	Social interaction, companions
304	Fujita Corporation	F	1910	JP	Asia	Construction

No.	Company name	Size	Est.	Loc.	Continent	Application classes
305	Furhat Robotics	B	2014	SE	Europe	Social interaction, companions, other professional service robots
306	Future Robot	B	2009	KR	Asia	Security services, mobile guidance, information, telepresence
307	Fuxtec	C	2008	DE	Europe	Gardening
308	Fybots	B	2002	FR	Europe	Professional floor cleaning, disinfection
309	GaitTronics	A	2012	CA	Americas	Rehabilitation and non-invasive therapy
310	GAM Soluciones	F	2003	ES	Europe	Logistics in indoor environments without public traffic, logistics in outdoor environments without public traffic, inventory, other transportation and logistics
311	Garford Farm Machinery	A	1986	UK	Europe	Cultivation
312	Gausium	F	2013	CN	Asia	Professional floor cleaning
313	Gaussin Macnica Mobility	D	2014	FR	Europe	Logistics in outdoor environments without public traffic
314	GCtronic	A	2005	CH	Europe	Education
315	GE Hitachi Nuclear Energy	F	2007	JP	Asia	Inspection of tank, tubes, pipes, sewers
316	GEA Farm Technologies	H	1881	DE	Europe	Milking, other livestock farming
317	Gebhardt	E	1952	DE	Europe	Logistics in indoor environments without public traffic
318	Gecko Robotics	D	2013	US	Americas	Inspection of buildings and other construction, inspection of tank, tubes, pipes, sewers, other inspection and maintenance
319	Gecko Systems	A	1997	US	Americas	Other care robots, security services
320	Geek+	E	2015	CN	Asia	Logistics in indoor environments without public traffic, logistics in indoor environments with public traffic, inventory
321	Ger4tech	C	2008	AT	Europe	Logistics in indoor environments without public traffic

No.	Company name	Size	Est.	Loc.	Continent	Application classes
322	German Bionic Systems	C	2016	DE	Europe	Other professional service robots
323	Gerotto Federico	C	1966	IT	Europe	Inspection of tank, tubes, pipes, sewers
324	Gessmann	E	1942	DE	Europe	Logistics in indoor environments without public traffic
325	GeStream Technology	B	2006	TW	Asia	Education
326	Ghost Robotics	B	2015	US	Americas	Inspection of buildings and other construction, security services
327	Gideon Brothers	C	2017	CR	Europe	Logistics in indoor environments without public traffic
328	Gieicom	C	1985	MX	Americas	Logistics in indoor environments without public traffic, other transportation and logistics
329	Global Tech Co	C	1998	KR	Asia	Logistics in indoor environments without public traffic, logistics in outdoor environments without public traffic
330	Globus Medical	F	2003	US	Americas	Surgery
331	Gobio Robot	B	2012	FR	Europe	Other professional service robots
332	Gogoa	B	2015	ES	Europe	Rehabilitation and non-invasive therapy
333	Graal Tech	B	1998	IT	Europe	Prototyping service
334	Grenzebach	F	1960	DE	Europe	Logistics in indoor environments without public traffic
335	GreyOrange	E	2011	SG	Asia	Logistics in indoor environments without public traffic
336	Gridbots Technologies	B	2007	IN	Asia	Inspection of tank, tubes, pipes, sewers, logistics in indoor environments without public traffic, logistics in outdoor environments without public traffic
337	Grillbot	A	2014	US	Americas	Domestic cleaning (outdoor)
338	Groove X	C	2015	JP	Asia	Social interaction, companions
339	Ground	B	2015	JP	Asia	Logistics in indoor environments without public traffic
340	Group Salto	D	1994	ES	Europe	Other care robots

No.	Company name	Size	Est.	Loc.	Continent	Application classes
341	Groupe Intra	B	1988	FR	Europe	Inspection of buildings and other construction, firefighting, disaster relief
342	Guandong Unipin Medical Technology	C	2020	CN	Asia	Professional floor cleaning, disinfection, other professional cleaning
343	Guangdong Jaten Robot & Automation	D	2002	CN	Asia	Disinfection, logistics in indoor environments without public traffic, logistics in indoor environments with public traffic
344	Gumich Robotics		2018	RU	Europe	Prototyping service
345	Guozi	E	2010	CN	Asia	Logistics in indoor environments without public traffic
346	Hai Robotics	D	2016	CN	Asia	Logistics in indoor environments without public traffic
347	Hako	F	1948	DE	Europe	Professional floor cleaning
348	Hangcha Forklift	F	1956	CN	Asia	Logistics in indoor environments without public traffic
349	Hanson Robotics	C	2013	CN	Asia	Other professional service robots
350	Harvest Automation	B	2008	US	Americas	Cultivation, logistics in outdoor environments without public traffic
351	Harvest Croo	B	2013	US	Americas	Cultivation
352	Hatapro Robotics	B	2017	JP	Asia	Social interaction, companions
353	Hausbots	A	2018	UK	Europe	Inspection of buildings and other construction
354	Hayward	F	1923	US	Americas	Domestic cleaning (outdoor)
355	HD Hyundai Robotics	H	1977	KR	Asia	Disinfection, logistics in indoor environments with public traffic, food and drink preparation
356	HealthSouth	H	1984	US	Americas	Rehabilitation and non-invasive therapy
357	Heemskerk Innovative Technology	B	2007	NL	Europe	Prototyping service
358	Hefei Panshi Intelligent Technology	D	2012	CN	Asia	Other professional service robots
359	Hefter Cleantech (Vermop Gruppe)	D	1993	DE	Europe	Professional floor cleaning
360	Hello Nimbo	B	2018	AU	Australia	Security services

No.	Company name	Size	Est.	Loc.	Continent	Application classes
361	Hello Robot	A	2017	US	Americas	Education, other care robots
362	Hetwin Automation Systems	B	2004	AT	Europe	Other livestock farming
363	Hexagone Manufacture	C	1995	FR	Europe	Other professional cleaning
364	HiBot	B	2004	JP	Asia	Inspection of tank, tubes, pipes, sewers
365	Hikrobot	F	2014	CN	Asia	Logistics in indoor environments without public traffic
366	HIT Robot Group	E	2014	CN	Asia	Other professional cleaning, logistics in indoor environments without public traffic, logistics in indoor environments with public traffic, other medical robots, firefighting, mobile guidance, information, telepresence
367	Hitachi	H	1920	JP	Asia	Domestic floor cleaning (indoor), social interaction, companions, other professional service robots
368	HL Mando	F	2014	KR	Asia	Logistics in outdoor environments with public traffic, security services
369	Hobot Technology	B	2010	TW	Asia	Domestic floor cleaning (indoor), domestic window cleaning
370	Hocoma	C	1996	CH	Europe	Rehabilitation and non-invasive therapy
371	Honda	H	1948	JP	Asia	Gardening, social interaction, companions, mobility assistants, logistics in outdoor environments without public traffic, logistics in outdoor environments with public traffic
372	Honeybee Robotics	C	1983	US	Americas	Inspection of tank, tubes, pipes, sewers
373	Honeywell International	H	1885	US	Americas	Logistics in indoor environments without public traffic
374	Howe and Howe	B	2006	US	Americas	Firefighting, disaster relief

No.	Company name	Size	Est.	Loc.	Continent	Application classes
375	Huawei	H	1987	CN	Asia	Education
376	Hugo Delivery	A	2018	SE	Europe	Logistics in outdoor environments with public traffic
377	Hullbot	A	2015	AU	Australia	Hull cleaning
378	Humanware	C	1994	IT	Europe	Rehabilitation and non-invasive therapy
379	Hunan Grand-pro Robot Tech	D	2012	CN	Asia	Domestic floor cleaning (indoor)
380	Husqvarna	H	1689	SE	Europe	Gardening, demolition
381	HyCleaner	B	2008	DE	Europe	Professional window and wall cleaning, other professional cleaning
382	Hydronalix	B	2009	US	Americas	Other professional service robots
383	Hydro-Quebec	H	1944	CA	Americas	Inspection of buildings and other construction
384	Hyster-Yale	G	1989	US	Americas	Logistics in indoor environments without public traffic
385	Hyundai Motor Group	H	1976	KR	Asia	Logistics in outdoor environments with public traffic
386	Hyundai Rotem	F	1977	KR	Asia	Cultivation, security services, other professional service robots
387	Hyundai-wia	F	1976	KR	Asia	Logistics in indoor environments without public traffic
388	IBAK	B	1945	DE	Europe	Inspection of tank, tubes, pipes, sewers
389	IBG Automation	D	1982	DE	Europe	Logistics in indoor environments without public traffic
390	ICA	C	1986	DE	Europe	Disinfection
391	ICE Cobotics	D	2019	HK	Asia	Professional floor cleaning
392	iClean	C	2013	IN	Asia	Domestic floor cleaning (indoor)
393	Idealworks	B	2020	DE	Europe	Logistics in indoor environments without public traffic
394	IdMind	A	2000	PT	Europe	Social interaction, companions, inspection of tank, tubes, pipes, sewers, logistics in indoor environments with public traffic, mobile guidance, information, telepresence

No.	Company name	Size	Est.	Loc.	Continent	Application classes
395	IMS Robotics	C	1992	DE	Europe	Inspection of tank, tubes, pipes, sewers
396	Inbot Technology	A	2013	CN	Asia	Social interaction, companions, disinfection, logistics in indoor environments with public traffic, security services, mobile guidance, information, telepresence
397	Independent Robotics	A	2009	CA	Americas	Other inspection and maintenance, security services
398	Industrial Research and Technology Institute	G	1973	TW	Asia	Prototyping service
399	Indy Associates	C	1994	JP	Asia	Mobile guidance, information, telepresence
400	Infocom	C	1996	UA	Europe	Disinfection, logistics in indoor environments without public traffic, logistics in indoor environments with public traffic, mobile guidance, information, telepresence
401	InGen Dynamics	C	2015	US	Americas	Social interaction, companions, mobile guidance, information, telepresence
402	Innok Robotics	A	2012	DE	Europe	Cultivation, other agriculture, other inspection and maintenance, logistics in indoor environments without public traffic, logistics in outdoor environments without public traffic, security services
403	InnoTechnix	A	2011	CA	Americas	Prototyping service
404	Innovation First	C	1996	US	Americas	Education
405	Innvo Labs	A	2009	US	Americas	Social interaction, companions
406	Inovasyon Mühendislik	B	2010	TR	Europe	Disinfection, logistics in indoor environments without public traffic, other professional service robots

No.	Company name	Size	Est.	Loc.	Continent	Application classes
407	Inspector Systems	B	1983	DE	Europe	Inspection of buildings and other construction, inspection of tank, tubes, pipes, sewers
408	Intelligent Systems	C	2004	JP	Asia	Rehabilitation and non-invasive therapy
409	International Robotics Solutions	B	2016	CH	Europe	Inspection of buildings and other construction, firefighting, security services
410	International Submarine Engineering	C	1974	CA	Americas	Other professional service robots
411	IntroMedic	C	2004	KR	Asia	Diagnostics
412	IntroScan Technology	A	2013	RU	Europe	Inspection of tank, tubes, pipes, sewers
413	Intuitive Surgical	F	1999	US	Americas	Surgery
414	Invata	C	2010	US	Americas	Logistics in indoor environments without public traffic
415	Invento Robotics	B	2016	IN	Asia	Logistics in indoor environments with public traffic, logistics in outdoor environments with public traffic, other medical robots, mobile guidance, information, telepresence
416	Invert Robotics	B	2011	IE	Europe	Inspection of buildings and other construction
417	inVia Robotics	B	2015	US	Americas	Logistics in indoor environments without public traffic, inventory
418	Invio Automation	D	1974	US	Americas	Logistics in indoor environments without public traffic
419	Iplusmobot	D	2016	CN	Asia	Logistics in indoor environments without public traffic, logistics in outdoor environments without public traffic
420	IQ Robotics	C	2018	UAE	Asia	Logistics in indoor environments without public traffic
421	iRob	A	2008	TR	Europe	Logistics in indoor environments without public traffic
422	iRobot	E	1990	US	Americas	Domestic floor cleaning (indoor)
423	Iseki	G	1936	JP	Asia	Cultivation

No.	Company name	Size	Est.	Loc.	Continent	Application classes
424	Ishikawa Iron Works	B	1935	JP	Asia	Inspection of tank, tubes, pipes, sewers, other professional service robots
425	Isybot	A	2015	FR	Europe	Construction
426	IUVO	A	2015	IT	Europe	Prototyping service
427	iXblue Robopec	B	2008	FR	Europe	Prototyping service
428	Jabil - Badger Technologies	H	1966	US	Americas	Inventory, security services, other professional service robots
429	Janyu Technologies	B	2016	IN	Asia	Professional floor cleaning, professional window and wall cleaning, disinfection
430	Jaso Industrial	D	1965	ES	Europe	Logistics in indoor environments without public traffic, logistics in outdoor environments without public traffic
431	JBT	F	1894	US	Americas	Logistics in indoor environments without public traffic
432	JD	H	1998	CN	Asia	Logistics in indoor environments without public traffic, logistics in indoor environments with public traffic, inventory, other transportation and logistics
433	Jigabot	A	2012	US	Americas	Other professional service robots
434	Jinn-Bot Robotics & Design	A	2012	CH	Europe	Prototyping service
435	JMU Defense Systems	C	2009	JP	Asia	Construction, security services, other professional service robots
436	JNOV Tech	B	2018	FR	Europe	Logistics in indoor environments without public traffic
437	John Deere	H	1837	US	Americas	Cultivation
438	Johnson & Johnson	H	1886	US	Americas	Surgery
439	Joloda	D	1962	UK	Europe	Logistics in indoor environments without public traffic
440	Jornco Info Tech	B	2015	CN	Asia	Social interaction, companions, education
441	Joz	C	1950	NL	Europe	Milking, other livestock farming

No.	Company name	Size	Est.	Loc.	Continent	Application classes
442	Jungheinrich	H	1953	DE	Europe	Logistics in indoor environments without public traffic, logistics in indoor environments with public traffic, inventory
443	Kajima	G	1930	JP	Asia	Construction
444	Kalmar	H	1940	FI	Europe	Logistics in outdoor environments without public traffic
445	Kamibot	A	2014	KR	Asia	Education
446	Kärcher	H	1935	DE	Europe	Domestic floor cleaning (indoor), domestic window cleaning, gardening, professional floor cleaning
447	Kawada Industries	F	1922	JP	Asia	Other professional service robots
448	Kawasaki Heavy Industries	H	1896	JP	Asia	Surgery, laboratory analysis, other medical robots
449	KeelCrab	A	2012	IT	Europe	Domestic cleaning (outdoor), hull cleaning, other professional cleaning
450	Kelo Robotics	B	2021	DE	Europe	Disinfection, logistics in indoor environments without public traffic
451	Keman Intelligent Technology	C	2018	CN	Asia	Mobile guidance, information, telepresence
452	Kemaro	A	2016	CH	Europe	Domestic cleaning (outdoor), inspection of buildings and other construction
453	Keyi Technology	A	2014	CN	Asia	Social interaction, companions, education
454	KinderLab Robotics	A	2013	US	Americas	Education, other professional service robots
455	KineteK	A	2014	IT	Europe	Rehabilitation and non-invasive therapy
456	Kinova	D	2006	CA	Americas	Education, manipulation aids, surgery, other medical robots
457	Kion	H	2006	DE	Europe	Logistics in indoor environments without public traffic, logistics in outdoor

No.	Company name	Size	Est.	Loc.	Continent	Application classes
						environments without public traffic
458	Kite Robotics	A	2014	NL	Europe	Professional window and wall cleaning
459	Kivnon	C	2007	ES	Europe	Logistics in indoor environments without public traffic
460	Kiwibot	B	2016	CA	Americas	Logistics in outdoor environments with public traffic
461	Knapp	G	1952	AT	Europe	Logistics in indoor environments without public traffic
462	Knightscope	C	2013	US	Americas	Security services
463	Kobots	B	2018	DK	Europe	Construction
464	Koh Young Technology	E	2002	KR	Asia	Surgery
465	Kokoro Robotics	B	1984	JP	Asia	Other professional service robots
466	Koks Robotics	B	2011	NL	Europe	Tank, tube and pipe cleaning
467	Kompaï Robotics	A	2016	FR	Europe	Social interaction, companions, mobility assistants, disinfection, other medical robots, mobile guidance, information, telepresence
468	Konecranes	H	1933	FI	Europe	Logistics in outdoor environments without public traffic, logistics in outdoor environments with public traffic
469	Kongsberg Maritime	G	1997	NO	Europe	Other inspection and maintenance, other professional service robots
470	Korechi	A	2016	CA	Americas	Other professional service robots
471	Kowa Tech		2001	JP	Asia	Demolition, disaster relief
472	K-Team	B	1995	CH	Europe	Education
473	Kubo Robotics	B	2016	DK	Europe	Education
474	Kuka	H	1898	DE	Europe	Education, diagnostics, surgery, other professional service robots
475	Kyvol	E	2019	CN	Asia	Domestic floor cleaning (indoor)
476	Labrador Systems	A	2017	US	Americas	Other care robots
477	Laevo	B	2013	NL	Europe	Other professional service robots
478	Lambda Health System	A	2015	CH	Europe	Rehabilitation and non-invasive therapy

No.	Company name	Size	Est.	Loc.	Continent	Application classes
479	LAP		2013	JP	Asia	Rehabilitation and non-invasive therapy
480	Lego	H	1932	DK	Europe	Social interaction, companions, education
481	Lejurobot	B	2016	CN	Asia	Education
482	Lely	F	1948	NL	Europe	Milking, other livestock farming
483	Lemmer Fullwood	D	1785	UK	Europe	Milking, other livestock farming
484	LexxPluss	B	2020	JP	Asia	Logistics in indoor environments without public traffic
485	LF Intelligence	B	2020	US	Americas	Domestic cleaning (outdoor)
486	LG Electronics	H	1958	KR	Asia	Domestic floor cleaning (indoor), logistics in indoor environments without public traffic, food and drink preparation, mobile guidance, information, telepresence
487	Libiao	C	2016	CN	Asia	Logistics in indoor environments without public traffic
488	Life Science Robotics	A	2013	DK	Europe	Rehabilitation and non-invasive therapy
489	Lifeward	C	2001	US	Americas	Rehabilitation and non-invasive therapy
490	LionsBot	B	2018	SG	Asia	Professional floor cleaning
491	Living Robot	B	2018	JP	Asia	Education
492	Lockheed Martin CDL Systems	C	1992	US	Americas	Disaster relief
493	Locus Robotics	C	2014	US	Americas	Logistics in indoor environments without public traffic
494	Lodamaster	C	2011	TR	Europe	Logistics in indoor environments without public traffic
495	Lödige Industries	F	1948	DE	Europe	Logistics in indoor environments without public traffic
496	Loop Robots	B	2020	NL	Europe	Disinfection
497	Lowpad	C	2017	NL	Europe	Logistics in indoor environments without public traffic
498	LUF	B	1896	AT	Europe	Firefighting, disaster relief
499	Luvozo PBC	A	2013	US	Americas	Disinfection, mobile guidance, information, telepresence

No.	Company name	Size	Est.	Loc.	Continent	Application classes
500	LuxAI	B	2016	LU	Europe	Education
501	Lynxmotion	A	1995	US	Americas	Social interaction, companions, education
502	Mabi Robotics	C	1969	CH	Europe	Logistics in indoor environments without public traffic
503	Mabo Engineering&Automation	B	2010	BE	Europe	Logistics in indoor environments without public traffic, logistics in outdoor environments without public traffic, logistics in outdoor environments with public traffic
504	Macco	B	2013	ES	Europe	Food and drink preparation
505	Machinery Technology Development	D	2002	CN	Asia	Logistics in indoor environments without public traffic
506	Mad Automation	C	2007	IT	Europe	Logistics in indoor environments without public traffic
507	Makita	H	1915	JP	Asia	Gardening, professional floor cleaning
508	Makr Shakr	C	2017	IT	Europe	Food and drink preparation
509	Mamibot	E	2013	US	Americas	Domestic floor cleaning (indoor), domestic window cleaning
510	Mammotion Tech	D	2022	CN	Asia	Gardening, other professional cleaning
511	Manntel	B	2000	KR	Asia	Rehabilitation and non-invasive therapy
512	Mariner 3S	C	1945	CH	Europe	Other professional cleaning
513	Marorobottech	A	2008	KR	Asia	Logistics in indoor environments without public traffic, logistics in outdoor environments with public traffic, other transportation and logistics
514	Marses	B	2015	EG	Africa	Disinfection, logistics in indoor environments with public traffic, mobile guidance, information, telepresence

No.	Company name	Size	Est.	Loc.	Continent	Application classes
515	Marsi-bionics	B	2013	ES	Europe	Rehabilitation and non-invasive therapy
516	Matia Robotics	C	2006	US	Americas	Mobility assistants
517	Matsutek	B	1990	TW	Asia	Domestic floor cleaning (indoor)
518	Max AGV	C	1980	SE	Europe	Logistics in indoor environments without public traffic
519	Max Bionic	B	2016	RU	Europe	Rehabilitation and non-invasive therapy
520	Maytronics	E	1983	IL	Europe	Domestic cleaning (outdoor), other professional cleaning
521	MDA	F	1969	CA	Americas	Other professional service robots
522	Meanwhile	B	2017	FR	Europe	Logistics in indoor environments without public traffic, logistics in indoor environments with public traffic
523	Medical Microinstruments	C	2015	IT	Europe	Surgery
524	Medicaroid	C	2013	JP	Asia	Surgery
525	MediTouch	B	2004	IL	Europe	Rehabilitation and non-invasive therapy
526	Medtronic	H	1949	US	Americas	Diagnostics, surgery
527	Meerecompany	D	1984	KR	Asia	Surgery
528	Megvii	F	2011	CN	Asia	Logistics in indoor environments without public traffic
529	Mekatronix	A	1996	US	Americas	Education
530	Meropy	A	2018	FR	Europe	Cultivation
531	Metomotion	B	2017	IL	Europe	Cultivation
532	MetraLabs	B	2001	DE	Europe	Disinfection, logistics in indoor environments without public traffic, inventory, mobile guidance, information, telepresence
533	MG Tech	D	2004	FR	Europe	Logistics in indoor environments without public traffic
534	MHS	F	1999	US	Americas	Logistics in indoor environments without public traffic
535	Microsure	B	2016	NL	Europe	Surgery
536	Miele	H	1899	DE	Europe	Domestic floor cleaning (indoor)
537	Miko	D	2015	IN	Asia	Social interaction, companions
538	Milagrow Humantech	B	2007	IN	Asia	Domestic floor cleaning (indoor), domestic window

No.	Company name	Size	Est.	Loc.	Continent	Application classes
						cleaning, gardening, domestic cleaning (outdoor), education, other consumer robots, mobile guidance, information, telepresence
539	Milvus Robotics	B	2011	TR	Europe	Disinfection, logistics in indoor environments without public traffic, logistics in indoor environments with public traffic
540	Mine Kafon	B	2011	NL	Europe	Security services
541	Minirobot	B	2000	KR	Asia	Education
542	Minuteman International	F	1948	US	Americas	Professional floor cleaning
543	MIR Mobile Industrial Robots	C	2013	DK	Europe	Logistics in indoor environments without public traffic
544	Miraikikai	B	2004	JP	Asia	Other professional cleaning
545	Mircolomay	B	2009	CN	Asia	Logistics in indoor environments without public traffic
546	Misa Robotics LLC	C	2018	US	Americas	Social interaction, companions
547	Miso Robotics	B	2016	US	Americas	Food and drink preparation
548	Mistyrobotics	B	2017	US	Americas	Education
549	Mitsubishi Heavy Industries	H	1950	JP	Asia	Firefighting, disaster relief, security services
550	Mobius Bionics	C	2016	US	Americas	Manipulation aids
551	Mobius Mobility	A	1990	US	Americas	Mobility assistants, manipulation aids, other care robots
552	Mobsya Association	A	2010	CH	Europe	Education
553	Modoya	B	2015	TR	Europe	Logistics in indoor environments without public traffic
554	Modular Robotics	B	2008	US	Americas	Education
555	Moley	B	2014	UK	Europe	Other domestic tasks, food and drink preparation
556	Momentis Surgical	C	2013	IL	Europe	Surgery
557	Monteris Medical	C	1999	CA	Americas	Surgery
558	Moon Surgical	B	2020	FR	Europe	Surgery
559	Moorebot	B	2014	US	Americas	Education, other consumer robots
560	Morello	B	1946	IT	Europe	Logistics in indoor environments without public traffic

No.	Company name	Size	Est.	Loc.	Continent	Application classes
561	Motiv space systems	B	2014	US	Americas	Other professional service robots
562	Movendo Technology	B	2016	IT	Europe	Rehabilitation and non-invasive therapy
563	MoviĜo	B	2018	NL	Europe	Logistics in indoor environments without public traffic
564	Movu Robotics	D	2023	BE	Europe	Logistics in indoor environments without public traffic
565	Movvo	C	2018	ES	Europe	Logistics in indoor environments without public traffic, logistics in indoor environments with public traffic, logistics in outdoor environments without public traffic, other transportation and logistics
566	Mowbot	A	2017	US	Americas	Gardening
567	Mrobot	D	2014	CN	Asia	Inspection of buildings and other construction, logistics in indoor environments without public traffic, logistics in indoor environments with public traffic, inventory, food and drink preparation
568	MSI International	F	1986	TW	Asia	Logistics in indoor environments without public traffic
569	MT Robot	B	2008	CH	Europe	Logistics in indoor environments without public traffic, logistics in indoor environments with public traffic, inventory
570	Mujin Corp.	D	2011	JP	Asia	Logistics in indoor environments without public traffic
571	Mul Technology	B	2018	US	Asia	Logistics in indoor environments without public traffic
572	Multiway Robotics	C	2019	CN	Asia	Logistics in indoor environments without public traffic
573	Muratec	F	1935	JP	Asia	Logistics in indoor environments without public traffic, logistics

No.	Company name	Size	Est.	Loc.	Continent	Application classes
						in indoor environments with public traffic
574	Muscle Corporation		1988	JP	Asia	Other medical robots
575	Mushiny	C	2016	CN	Asia	Logistics in indoor environments without public traffic
576	MyBull			CN	Asia	Logistics in indoor environments without public traffic
577	Myomo	B	2004	US	Americas	Rehabilitation and non-invasive therapy
578	MyoSwiss	A	2017	CH	Europe	Mobility assistants, rehabilitation and non-invasive therapy
579	Nabors	H	1952	NO	Europe	Other professional service robots
580	Naio Technologies	C	2011	FR	Europe	Cultivation
581	Nakanishi Metal Works	F	1941	JP	Asia	Logistics in indoor environments without public traffic
582	Nanjing AvatarMind Robot Technology	C	2014	CN	Asia	Social interaction, companions, mobile guidance, information, telepresence
583	Narwal	F	2016	HK	Asia	Domestic floor cleaning (indoor)
584	Nauticus Robotics	C	2014	US	Americas	Other professional service robots
585	Navel Robotics	A	2017	DE	Europe	Social interaction, companions, mobile guidance, information, telepresence
586	Naver Labs	C	2017	KR	Asia	Prototyping service
587	Navflex	A	2020	US	Americas	Logistics in indoor environments without public traffic
588	NDT Global	H	2000	DE	Europe	Inspection of tank, tubes, pipes, sewers
589	Neobotix	A	2017	DE	Europe	Logistics in indoor environments without public traffic, other professional service robots
590	Neocis	C	2009	US	Americas	Surgery
591	Neofect	C	2010	KR	Asia	Rehabilitation and non-invasive therapy
592	Neolix	B	2015	CN	Asia	Logistics in outdoor environments with public traffic
593	Neubility	C	2017	KR	Asia	Logistics in outdoor environments with public traffic, security services

No.	Company name	Size	Est.	Loc.	Continent	Application classes
594	Neumaier Industry	C	1982	DE	Europe	Logistics in indoor environments without public traffic, logistics in outdoor environments without public traffic
595	Neura Robotics	C	2019	DE	Europe	Other consumer robots, logistics in indoor environments without public traffic, logistics in indoor environments with public traffic
596	Neurobotics	B	2004	RU	Europe	Rehabilitation and non-invasive therapy
597	Nevoa	B	2009	US	Americas	Disinfection
598	New Kinpo Group	H	1973	TW	Asia	Logistics in indoor environments without public traffic
599	Nexus Robotics	B	2017	CA	Americas	Cultivation
600	Nilfisk-Advance	G	1906	DK	Europe	Professional floor cleaning
601	Nimbl'bot	A	2019	FR	Europe	Inspection of buildings and other construction, inspection of tank, tubes, pipes, sewers
602	Ningbo Delin Machinery		2007	CN	Asia	Gardening
603	Nipper production logistics	B	2013	NL	Europe	Logistics in indoor environments without public traffic
604	Nippon Signal	F	1928	JP	Asia	Professional floor cleaning
605	Niqo Robotics	C	2015	IN	Asia	Cultivation
606	Niryo	B	2017	FR	Europe	Education
607	Nobleo Technology	C	2011	NL	Europe	Prototyping service
608	Nomadd	A	2013	SA	Asia	Other professional cleaning
609	Nordic Unmanned	B	2004	NO	Europe	Other inspection and maintenance
610	Novus Hitech	E	2004	IN	Asia	Logistics in indoor environments without public traffic
611	NPO Androidnaya Tekhnika	C	2009	RU	Europe	Prototyping service
612	NREC	C	1996	US	Americas	Prototyping service
613	Nuro	D	2016	US	Americas	Logistics in outdoor environments with public traffic
614	Nuzoo Robotics	B	2006	IT	Europe	Prototyping service
615	NXT Robotics	A	2012	US	Americas	Security services
616	Obodroid	B	2016	TH	Asia	Other consumer robots, security services

No.	Company name	Size	Est.	Loc.	Continent	Application classes
617	OceanAero	B	2012	US	Americas	Other professional service robots
618	Oceaneering	H	1964	US	Americas	Logistics in indoor environments without public traffic
619	Oceanos	B	2003	RU	Europe	Other professional service robots
620	Ocius	B	1999	AU	Australia	Inspection of tank, tubes, pipes, sewers, security services
621	Ocme	E	1954	IT	Europe	Logistics in indoor environments without public traffic
622	Octiva	C	2022	BE	Europe	Cultivation
623	Octopus Biosafety	B	1987	FR	Europe	Other livestock farming
624	Odd.Bot	B	2018	NL	Europe	Cultivation
625	Ogawayuki	B	1960	JP	Asia	Inspection of buildings and other construction, other inspection and maintenance, construction, security services
626	Ohmnilabs	C	2015	US	Americas	Disinfection, mobile guidance, information, telepresence
627	Okagv	C	2013	CN	Asia	Logistics in indoor environments without public traffic
628	Okibo	B	2018	IL	Europe	Construction
629	Omron	H	1948	JP	Asia	Logistics in indoor environments without public traffic
630	Onward Robotics	B	2012	US	Americas	Logistics in indoor environments without public traffic, inventory
631	openbionics	B	2014	UK	Europe	Manipulation aids
632	Oppent	C	1960	IT	Europe	Logistics in indoor environments without public traffic
633	Orano	H	2001	FR	Europe	Inspection of buildings and other construction
634	Organifarms	B	2021	DE	Europe	Cultivation
635	Orionstar	D	2016	CN	Asia	Logistics in indoor environments with public traffic, mobile guidance, information, telepresence
636	OryLab	B	2012	JP	Asia	Social interaction, companions
637	Osoji Robotics Corporation	B	2018	CL	Americas	Domestic floor cleaning (indoor),

No.	Company name	Size	Est.	Loc.	Continent	Application classes
						domestic window cleaning
638	Össur	F	1971	IS	Europe	Manipulation aids
639	Otsaw Digital	B	2015	SG	Asia	Professional floor cleaning, disinfection, logistics in indoor environments without public traffic, logistics in outdoor environments without public traffic, logistics in outdoor environments with public traffic, security services
640	Ottonomy	C	2020	US	Americas	Other consumer robots, logistics in outdoor environments with public traffic
641	P&S Mechanics	B	2004	KR	Asia	Rehabilitation and non-invasive therapy
642	Pal Robotics	C	2008	ES	Europe	Education, logistics in indoor environments with public traffic, inventory, other transportation and logistics, mobile guidance, information, telepresence, other professional service robots
643	PalNPaul	B	2010	IN	Asia	Domestic floor cleaning (indoor), gardening, domestic cleaning (outdoor), professional floor cleaning, professional window and wall cleaning, tank, tube and pipe cleaning, disinfection
644	Panasonic	H	1935	JP	Asia	Domestic floor cleaning (indoor), mobility assistants, cultivation, professional floor cleaning, construction, logistics in indoor environments with public traffic, logistics in outdoor environments with public traffic, rehabilitation and non-

No.	Company name	Size	Est.	Loc.	Continent	Application classes
						invasive therapy, other medical robots
645	Parallax	B	1987	US	Americas	Education
646	Pasco	C	1964	US	Americas	Education
647	Patika Robotics	B	2018	TR	Europe	Logistics in indoor environments without public traffic
648	PBA	E	1987	SG	Asia	Logistics in indoor environments without public traffic
649	Peanut Robotics	A	2017	US	Americas	Other professional cleaning
650	Pedasys	B	2014	IR	Asia	Mobility assistants, rehabilitation and non-invasive therapy
651	Peer Robotics	A	2019	IN	Asia	Logistics in indoor environments without public traffic
652	Pek Automotive	C	2019	SL	Europe	Cultivation
653	Peppermint Robotics	C	2019	IN	Asia	Professional floor cleaning, logistics in indoor environments without public traffic
654	Perceptual Robotics	B	2016	UK	Europe	Other inspection and maintenance
655	Philips	H	1891	NL	Europe	Domestic floor cleaning (indoor)
656	pi4 Robotics	C	1994	DE	Europe	Logistics in indoor environments with public traffic, other transportation and logistics, security services, mobile guidance, information, telepresence
657	Piaggio fast forward	C	2015	US	Americas	Other consumer robots, logistics in indoor environments without public traffic
658	Pixel Robotics	A	2020	DE	Europe	Logistics in indoor environments with public traffic
659	Pixelfarming Robotics	B	2019	NL	Europe	Cultivation
660	Pneumax (Automationware)	C	2002	IT	Europe	Logistics in indoor environments without public traffic
661	Polaris	H	1954	US	Americas	Domestic cleaning (outdoor)
662	Pollen Robotics	B	2016	FR	Europe	Other professional service robots
663	Positec	F	1994	CN	Asia	Gardening
664	Potenit	B	2010	KR	Asia	Other agriculture, logistics in indoor

No.	Company name	Size	Est.	Loc.	Continent	Application classes
						environments without public traffic
665	PowerVision Robot Corporation	E	2009	CN	Asia	Other professional service robots
666	PreNav	B	2013	US	Americas	Inspection of buildings and other construction
667	Prime Robotics	C	2018	US	Americas	Logistics in indoor environments without public traffic
668	Prinzing Maschinenbau	C	1981	DE	Europe	Other livestock farming
669	Procept Biorobotics	C	2009	CA	Americas	Surgery
670	Promobot	C	2015	US	Americas	Mobile guidance, information, telepresence
671	Proscenic	D	1993	CN	Asia	Domestic floor cleaning (indoor)
672	PTTEP	F	1985	TH	Asia	Inspection of tank, tubes, pipes, sewers
673	Pudu Technology	D	2016	CN	Asia	Logistics in indoor environments with public traffic, mobile guidance, information, telepresence
674	Q-bot	B	2012	UK	Europe	Construction
675	Qenvi	B	2008	FR	Europe	Logistics in indoor environments without public traffic, logistics in indoor environments with public traffic, logistics in outdoor environments without public traffic, logistics in outdoor environments with public traffic
676	QI	B	1971	JP	Asia	Inspection of buildings and other construction, other inspection and maintenance
677	Qingdao Kingerobot	B	2013	CN	Asia	Logistics in indoor environments without public traffic
678	Qiteng Robot		2022	CN	Asia	Inspection of tank, tubes, pipes, sewers, other inspection and maintenance, firefighting
679	Quantum Signal AI	B	2000	US	Americas	Prototyping service
680	Quasi Robotics	A	2017	US	Americas	Logistics in indoor environments without public traffic

No.	Company name	Size	Est.	Loc.	Continent	Application classes
681	Quest	C	2001	US	Americas	Logistics in indoor environments without public traffic
682	Quicktron	F	2014	CN	Asia	Logistics in indoor environments without public traffic, inventory
683	Quihan Technologies	D	2006	CN	Asia	Social interaction, companions, mobile guidance, information, telepresence
684	Rainbow Robot	F	2006	KR	Asia	Logistics in indoor environments without public traffic
685	Rainbow Robotics	C	2011	KR	Asia	Logistics in indoor environments with public traffic, other professional service robots
686	RanMarine Technology	B	2016	NL	Europe	Other professional cleaning
687	Rapyuta Robotics	D	2014	JP	Asia	Logistics in indoor environments without public traffic
688	RB3D	B	2001	FR	Europe	Other professional service robots
689	Reactive Robotics	B	2015	DE	Europe	Rehabilitation and non-invasive therapy
690	ReconRobotics	B	2005	US	Americas	Firefighting, disaster relief, security services
691	RedZone Robotics	C	1987	US	Americas	Inspection of tank, tubes, pipes, sewers
692	Refraction AI	B	2017	US	Americas	Logistics in outdoor environments with public traffic
693	Reha Technology	A	2011	CH	Europe	Rehabilitation and non-invasive therapy
694	Reif		2008	JP	Asia	Rehabilitation and non-invasive therapy, other medical robots, prototyping service
695	Relay Robotics	C	2013	US	Americas	Logistics in indoor environments with public traffic
696	Renishaw	G	1973	UK	Europe	Surgery
697	Rex Bionics	B	2007	NZ	Australia	Rehabilitation and non-invasive therapy
698	Rexroth	H	1795	DE	Europe	Logistics in indoor environments without public traffic
699	Rice Robotics	B	2019	HK	Asia	Disinfection, logistics in indoor environments with public traffic, security

No.	Company name	Size	Est.	Loc.	Continent	Application classes
						services, mobile guidance, information, telepresence
700	Rightbot	A	2020	US	Americas	Logistics in indoor environments without public traffic
701	Ripe Robotics	A	2018	AU	Australia	Cultivation
702	Roam Robotics	B	2012	US	Americas	Mobility assistants
703	Robbo	B	2016	RU	Europe	Education
704	Robix	B	1989	US	Americas	Education
705	Robobox	A	2016	FR	Europe	Education
706	Robocare	B	2014	KR	Asia	Social interaction, companions
707	RoboCV	B	2012	RU	Europe	Logistics in indoor environments without public traffic
708	Robokind	B	2011	US	Americas	Education
709	Robo-Life		2007	KR	Asia	Education
710	Robomart	B	2017	US	Americas	Other professional service robots
711	Robomation	A	1995	KR	Asia	Education
712	Roborock	D	2014	CN	Asia	Domestic floor cleaning (indoor)
713	Robosea	B	2015	CN	Asia	Other consumer robots, other professional cleaning, inspection of buildings and other construction
714	Robot Ltd.		2016	RU	Europe	Education
715	Robot++	C	2015	CN	Asia	Tank, tube and pipe cleaning, hull cleaning, inspection of tank, tubes, pipes, sewers
716	Roboteam	C	2009	US	Americas	Security services
717	Robotech	A	2004	IT	Europe	Prototyping service
718	Robotics Center	A		RU	Europe	Education
719	Robotics Design	A	1997	CA	Americas	Tank, tube and pipe cleaning, inspection of tank, tubes, pipes, sewers, firefighting, disaster relief, security services
720	Robotics Technology Leaders	B	2005	DE	Europe	Prototyping service
721	RoboticsPlus	C	2000	NZ	Australia	Cultivation
722	Robotis	C	1999	KR	Asia	Education, logistics in indoor environments with public traffic, logistics in outdoor environments with public traffic
723	Robotise	B	2017	DE	Europe	Disinfection, logistics in indoor

No.	Company name	Size	Est.	Loc.	Continent	Application classes
						environments with public traffic
724	Robotize	B	2016	DK	Europe	Logistics in indoor environments without public traffic
725	Robotswim	A	2009	FR	Europe	Mobile guidance, information, telepresence
726	Rocad	B	1998	RU	Europe	Prototyping service
727	Rockwell Automation	H	1903	US	Americas	Logistics in indoor environments without public traffic, logistics in outdoor environments without public traffic, security services, other professional service robots
728	Rocla	D	1983	FI	Europe	Logistics in indoor environments without public traffic
729	ROEN Surgical	C	2018	KR	Asia	Surgery
730	Ronavi Robotics	B	2014	RU	Europe	Other transportation and logistics
731	Ronovatec	B	2017	CH	Europe	Other professional service robots
732	Ross Robotics	B	2015	UK	Europe	Inspection of buildings and other construction
733	Rowbot Systems	A	2012	US	Americas	Cultivation, other professional service robots
734	Rowenta	E	1909	DE	Europe	Domestic floor cleaning (indoor)
735	RT.works	B	2014	JP	Asia	Mobility assistants, other care robots
736	Rubidium Light	B	2011	AU	Australia	Other professional service robots
737	Running Brains	B	2021	FR	Europe	Other inspection and maintenance, security services
738	Russell Robotics		2012	KR	Asia	Logistics in indoor environments without public traffic
739	SAC (BouMatic)	C	1938	US	Americas	Milking
740	Safelog	C	1996	DE	Europe	Logistics in indoor environments without public traffic, other transportation and logistics, rehabilitation and non-invasive therapy
741	Saildrone	C	2014	US	Americas	Security services, other professional service robots

No.	Company name	Size	Est.	Loc.	Continent	Application classes
742	Samsung	H	1969	KR	Asia	Domestic floor cleaning (indoor)
743	Scewo	B	2017	CH	Europe	Mobility assistants
744	Schauer Agrotronic	D	1949	AT	Europe	Other livestock farming
745	Schmiede.one	B	2017	DE	Europe	Cultivation
746	Scott	E	1913	NZ	Australia	Logistics in indoor environments without public traffic
747	Scythe Robotics	C	2018	US	Americas	Other professional service robots
748	SeaRobotics	B	1999	US	Americas	Hull cleaning, inspection of buildings and other construction
749	Seasony	B	2018	DK	Europe	Logistics in indoor environments without public traffic
750	Secom	H	1962	JP	Asia	Other care robots, security services
751	Seegrid	C	2003	US	Americas	Logistics in indoor environments without public traffic
752	Seer Robotics	D	2015	CN	Asia	Logistics in indoor environments without public traffic
753	Seerstems Robótica y Sistemas	A	2019	ES	Europe	Prototyping service
754	Segway Robotics	C	1999	CN	Asia	Gardening, logistics in indoor environments with public traffic, logistics in outdoor environments with public traffic
755	Seismic	B	2021	US	Americas	Other consumer robots
756	Seqsense	B	2016	JP	Asia	Security services
757	Serbot	A	2009	CH	Europe	Professional window and wall cleaning
758	Servosila	C	2013	UAE	Asia	Firefighting, disaster relief
759	Servus Robotics	C	1988	AT	Europe	Logistics in indoor environments without public traffic
760	Sesto	B	2006	SG	Asia	Disinfection, logistics in indoor environments without public traffic
761	Sevnce	C	2008	CN	Asia	Inspection of buildings and other construction, firefighting
762	SEW Eurodrive	H	1931	DE	Europe	Logistics in indoor environments without public traffic

No.	Company name	Size	Est.	Loc.	Continent	Application classes
763	SewerVUE technology	A	2007	CA	Americas	Inspection of tank, tubes, pipes, sewers
764	Shandong Guo Xing Intelligent Technology	C	2004	CN	Asia	Inspection of buildings and other construction, firefighting, security services, other professional service robots
765	Shanghai Keenon Intelligent Technology	C	2010	CN	Asia	Professional floor cleaning, logistics in indoor environments with public traffic, mobile guidance, information, telepresence
766	Shanghai PartnerX Robotics	F	1996	CN	Asia	Social interaction, companions, education
767	Shanghai Triowin Intelligent Machinery	D	1999	CN	Asia	Logistics in indoor environments without public traffic
768	Shape Robotics	B	2015	DK	Europe	Education
769	Shark Robotics	C	2016	FR	Europe	Disinfection, firefighting, security services
770	SharkNinja	F	1994	US	Americas	Domestic floor cleaning (indoor)
771	Sharp	H	1935	JP	Asia	Domestic floor cleaning (indoor)
772	Shenzhen Anseboo Technology	C	2016	CN	Asia	Domestic floor cleaning (indoor), domestic window cleaning, education, logistics in indoor environments with public traffic
773	Shenzhen Guoli Intelligent Technology Co. LTD		2017	CN	Asia	Education, disinfection, logistics in indoor environments with public traffic
774	Shenzhen Jisiwei Intelligent Technology	D	2013	CN	Asia	Domestic floor cleaning (indoor)
775	ShenZhen Wellwit Robotics	B	2015	CN	Asia	Logistics in indoor environments without public traffic
776	Sherpa Mobile Robotics	B	2016	FR	Europe	Logistics in indoor environments without public traffic
777	Shin Kong Security	F	1980	TW	Asia	Security services
778	Shintec Hozumi	D	1992	JP	Asia	Logistics in indoor environments without public traffic

No.	Company name	Size	Est.	Loc.	Continent	Application classes
779	Siasun Robot & Automation	D	2000	CN	Asia	Logistics in indoor environments without public traffic
780	Siemens Healthineers	H	1847	DE	Europe	Diagnostics, surgery
781	Simbe Robotics	B	2014	US	Americas	Inventory
782	Sitia	B	1986	FR	Europe	Cultivation
783	SK Telecom	F	1984	KR	Asia	Education
784	Skeletonics	A	2013	JP	Asia	Other professional service robots
785	Skelex	B	2013	NL	Europe	Other professional service robots
786	SkySpecs	C	2012	US	Americas	Inspection of buildings and other construction
787	Slamtec	C	2013	CN	Asia	Logistics in indoor environments with public traffic, mobile guidance, information, telepresence
788	Slip Robotics	B	2019	US	Americas	Logistics in indoor environments without public traffic
789	Smart Robotics	B	2016	JP	Asia	Disinfection, logistics in indoor environments without public traffic, mobile guidance, information, telepresence
790	Smart Technology SA (Smarlogy)	B	2003	ES	Europe	Logistics in indoor environments without public traffic
791	Smith & Nephew	H	1856	UK	Europe	Surgery
792	SMP Robotics	C	2010	US	Americas	Inspection of buildings and other construction, inspection of tank, tubes, pipes, sewers, logistics in outdoor environments without public traffic, security services
793	Snowbotix	A	2023	US	Americas	Domestic cleaning (outdoor)
794	Social Robotics		2015	JP	Asia	Logistics in indoor environments with public traffic
795	Soft Design RTS	B	1987	SE	Europe	Logistics in indoor environments without public traffic, logistics in indoor environments with public traffic, inventory
796	SoftBank Robotics	C	1986	JP	Asia	Social interaction, companions,

No.	Company name	Size	Est.	Loc.	Continent	Application classes
						professional floor cleaning
797	Sohgo Security Services	H	1965	JP	Asia	Security services
798	SolarACM	B	2016	CA	Americas	Other professional cleaning
799	Solaris Robots	B	2016	CA	Americas	Disinfection
800	Solenis	B	1985	US	Americas	Professional floor cleaning
801	Solving Oy	C	1977	FI	Europe	Logistics in indoor environments without public traffic
802	Somatic	B	2018	US	Americas	Other professional cleaning
803	Sony	H	1946	JP	Asia	Social interaction, companions
804	Sparkoz	C	2020	US	Americas	Professional floor cleaning
805	Sphero	C	2010	US	Americas	Education
806	Spijkstaal	B	1938	NL	Europe	Logistics in outdoor environments without public traffic
807	SSI Schäfer	G	1937	DE	Europe	Logistics in indoor environments without public traffic
808	ST Engineering (incl. Aethon)	H	1967	SG	Asia	Security services
809	Stähle Robot Systems	A	1984	DE	Europe	Other professional service robots
810	Standard Robots	D	2016	CN	Asia	Logistics in indoor environments with public traffic
811	Stanley Black & Decker	H	1843	US	Americas	Gardening
812	Stanley Robotics	C	2015	FR	Europe	Logistics in outdoor environments without public traffic, other professional service robots
813	Starship Technologies	D	2014	UK	Europe	Logistics in outdoor environments with public traffic
814	Stäubli	G	1892	CH	Europe	Logistics in indoor environments without public traffic, logistics in outdoor environments without public traffic, surgery
815	Steering Machines	A	2018	ES	Europe	Logistics in indoor environments without public traffic
816	Stereotaxis	D	1990	US	Americas	Diagnostics, surgery
817	Stiga	F	1934	IT	Europe	Gardening
818	Stihl	D	1926	DE	Europe	Gardening

No.	Company name	Size	Est.	Loc.	Continent	Application classes
819	Storojet	C	1982	DE	Europe	Logistics in indoor environments without public traffic
820	Stryker	H	1941	US	Americas	Surgery
821	Studio 3S	C	2017	KR	Asia	Logistics in indoor environments without public traffic, other transportation and logistics
822	Super Motorica	C	2015	RU	Europe	Manipulation aids
823	Suzhou Alpha Robot	C	2006	CN	Asia	Domestic floor cleaning (indoor), social interaction, companions, education, logistics in indoor environments with public traffic
824	Suzhou i-Cow	C	2015	CN	Asia	Logistics in indoor environments without public traffic
825	Suzhou Pangolin Robot	C	2006	CN	Asia	Education, firefighting, disaster relief, mobile guidance, information, telepresence, other professional service robots
826	Sveaverken	D	1911	SE	Europe	Gardening, other livestock farming, professional floor cleaning
827	SwarmFarm Robotics	B	2015	AU	Australia	Cultivation, other professional service robots
828	Swift Robotics	B	2020	UK	Europe	Logistics in indoor environments with public traffic
829	Syrius	C	2018	CN	Asia	Professional floor cleaning, logistics in indoor environments without public traffic
830	Syscon Robotics	C	2013	KR	Asia	Logistics in indoor environments without public traffic
831	System Logistics	C	1976	IT	Europe	Logistics in indoor environments without public traffic
832	Tailos	B	2015	US	Americas	Professional floor cleaning
833	Taisei	G	1873	JP	Asia	Construction
834	Taris	B	1992	RU	Europe	Inspection of tank, tubes, pipes, sewers, prototyping service

No.	Company name	Size	Est.	Loc.	Continent	Application classes
835	Tarqan	B		TR	Europe	Logistics in indoor environments without public traffic
836	TAS Global	A	2014	KR	Asia	Hull cleaning
837	Taurob	C	2010	AT	Europe	Inspection of buildings and other construction, inspection of tank, tubes, pipes, sewers
838	Techbionic	A	2013	RU	Europe	Mobility assistants, manipulation aids
839	Techmetics Robotics	B	2012	US	Americas	Disinfection, logistics in indoor environments without public traffic, logistics in indoor environments with public traffic, mobile guidance, information, telepresence
840	Techtronic Industries	H	1985	DE	Europe	Domestic floor cleaning (indoor)
841	Tecnoferrari	D	1966	IT	Europe	Logistics in indoor environments without public traffic
842	Tective Robotics	A	2019	NL	Europe	Other agriculture
843	Temi	C	2016	IL	Europe	Logistics in indoor environments with public traffic, mobile guidance, information, telepresence
844	Tendo	A	2016	SE	Europe	Manipulation aids
845	Tennant	F	1870	US	Americas	Professional floor cleaning
846	Tennibot	B	2016	US	Americas	Other consumer robots
847	Tensorfield Agriculture	A	2018	US	Americas	Cultivation
848	Terminus	F	2015	CN	Asia	Security services, mobile guidance, information, telepresence
849	Tertill	A	2015	US	Americas	Gardening
850	Tevel Aerobotics Technologies	C	2017	IL	Europe	Cultivation
851	The robot studio	A	2006	FR	Europe	Prototyping service
852	Think Surgical	C	2014	US	Americas	Surgery
853	Thira Robotics	C	2022	KR	Asia	Logistics in indoor environments without public traffic
854	TinyMobileRobots	B	2015	DK	Europe	Construction, other professional service robots
855	Tmsuk	B	2000	JP	Asia	Mobility assistants, other medical robots

No.	Company name	Size	Est.	Loc.	Continent	Application classes
856	Tombot	A	2017	US	Americas	Social interaction, companions
857	Tompkins Robotics	C	2017	US	Americas	Logistics in indoor environments without public traffic
858	Topy Industries	F	1921	JP	Asia	Inspection of buildings and other construction
859	Torooc	B	2012	KR	Asia	Social interaction, companions
860	Toyota	H	1937	JP	Asia	Social interaction, companions, other care robots, rehabilitation and non-invasive therapy, other medical robots, other professional service robots
861	Tractonomy	A	2019	BE	Europe	Logistics in indoor environments without public traffic
862	Transcend Tactical	B	2015	US	Americas	Security services
863	Trapo	C	1957	DE	Europe	Logistics in indoor environments without public traffic
864	Trimble	B	2016	FR	Europe	Cultivation
865	Triooo	B	2016	CN	Asia	Professional floor cleaning
866	T-Robotics	C	2004	KR	Asia	Rehabilitation and non-invasive therapy
867	Trombia Technologies	B	2011	FI	Europe	Other professional cleaning
868	Tru-D	C	2001	US	Americas	Disinfection
869	Turf Tank	C	2014	DK	Europe	Other professional service robots
870	Twiice	A	2015	CH	Europe	Mobility assistants
871	Twinny	C	2015	KR	Asia	Logistics in indoor environments without public traffic, logistics in indoor environments with public traffic, logistics in outdoor environments without public traffic
872	Twinswheel	B	2015	FR	Europe	Logistics in outdoor environments without public traffic, logistics in outdoor environments with public traffic
873	TyroMotion	C	2007	AT	Europe	Rehabilitation and non-invasive therapy
874	Ubica Robotics	C	2020	DE	Europe	Inventory

No.	Company name	Size	Est.	Loc.	Continent	Application classes
875	Ubiquity Robotics	A	2010	US	Americas	Logistics in indoor environments without public traffic
876	UBT Robot	E	2012	CN	Asia	Domestic floor cleaning (indoor), social interaction, companions, education, professional floor cleaning, logistics in indoor environments without public traffic, logistics in indoor environments with public traffic, rehabilitation and non-invasive therapy, mobile guidance, information, telepresence
877	Ugo	B	2018	JP	Asia	Logistics in indoor environments with public traffic, security services, mobile guidance, information, telepresence, other professional service robots
878	ULC Robotics	B	2001	US	Americas	Inspection of buildings and other construction, inspection of tank, tubes, pipes, sewers
879	UniRing	B	2011	TW	Asia	Professional floor cleaning, security services
880	Unirobot	B	2014	JP	Asia	Social interaction, companions
881	United Robotics Group	D	2021	DE	Europe	Logistics in indoor environments with public traffic, laboratory analysis, mobile guidance, information, telepresence
882	United Robots	B	2016	UK	Europe	Professional floor cleaning, disinfection, logistics in indoor environments with public traffic
883	Unitree	D	2014	CN	Asia	Other professional service robots
884	Unlimited Robotics	B	2021	IL	Europe	Logistics in indoor environments with

No.	Company name	Size	Est.	Loc.	Continent	Application classes
						public traffic, mobile guidance, information, telepresence
885	Unmanned Solution	B	2008	KR	Asia	Logistics in outdoor environments with public traffic, security services
886	UPnRIDE Robotics	B	2013	IL	Europe	Mobility assistants
887	Urakami		1978	JP	Asia	Prototyping service
888	Ursrobot	B	2019	US	Americas	Other professional service robots
889	Vayu Robotics	B	2022	US	Americas	Logistics in outdoor environments with public traffic
890	Vecna Robotics	D	1999	US	Americas	Logistics in indoor environments without public traffic
891	Veebot	A	2010	US	Americas	Diagnostics
892	Versa Box	C	2013	PL	Europe	Logistics in indoor environments without public traffic
893	Vicarious Surgical	C	2014	US	Americas	Surgery
894	Vincross	B	2014	CN	Asia	Other consumer robots
895	Virtual Incision	C	2006	US	Americas	Surgery
896	Vision Robotics	B	1999	US	Americas	Cultivation
897	Visionnav Robotics	E	2016	US	Americas	Logistics in indoor environments without public traffic
898	Vitibot	C	2016	FR	Europe	Cultivation
899	Vitirover	B	2011	FR	Europe	Cultivation
900	Volume Lagersysteme	B	2017	DE	Europe	Logistics in indoor environments without public traffic
901	Vorwerk	H	1883	DE	Europe	Domestic floor cleaning (indoor), professional floor cleaning
902	Vstone	B	2000	JP	Asia	Social interaction, companions
903	Wado Sangyo	D	1941	JP	Asia	Cultivation
904	Wall-ye	A	2008	FR	Europe	Cultivation
905	Wandercraft	C	2012	FR	Europe	Rehabilitation and non-invasive therapy
906	WayBot Robotics	A	2019	RU	Europe	Professional floor cleaning
907	Weda	B	1919	SE	Europe	Other professional cleaning
908	Weilan	B	2019	CN	Asia	Social interaction, companions
909	Wewo Techmotion	B	2006	NL	Europe	Logistics in indoor environments without public traffic

No.	Company name	Size	Est.	Loc.	Continent	Application classes
910	Wexbi	C	2019	US	Americas	Domestic window cleaning
911	Whill	D	2012	US	Americas	Mobility assistants
912	White Rhino	C	2019	CN	Asia	Logistics in outdoor environments with public traffic
913	Wobit	C	1991	PL	Europe	Logistics in indoor environments without public traffic
914	Wolf-e Robotics	A	2020	RO	Europe	Professional floor cleaning, disinfection
915	Wonik Robotics	B	2004	KR	Asia	Gardening
916	Wybotics	D	2005	CN	Asia	Domestic cleaning (outdoor)
917	XAG	F	2007	CN	Asia	Cultivation
918	Xiaomi	H	2010	CN	Asia	Domestic floor cleaning (indoor)
919	Xihelm	B	2016	UK	Europe	Cultivation
920	Xmachines	A	2017	IN	Asia	Cultivation, other professional service robots
921	Yamabiko Europe	C	2002	BE	Europe	Other professional service robots
922	Yamaha	H	1955	JP	Asia	Cultivation
923	Yanmar	H	1912	JP	Asia	Cultivation
924	Yarbo	C	2016	US	Americas	Gardening, domestic cleaning (outdoor)
925	Yeefung	F	1989	CN	Asia	Logistics in indoor environments without public traffic
926	Yijiahe Technology	D	1999	CN	Asia	Firefighting, disaster relief
927	Youibot	E	2017	CN	Asia	Inspection of buildings and other construction, logistics in indoor environments without public traffic
928	Yujin Robot	C	1988	KR	Asia	Domestic floor cleaning (indoor), logistics in indoor environments without public traffic
929	Yukai Engineering	B	2007	JP	Asia	Social interaction, companions
930	Yuman Robots	A	2022	DK	Europe	Logistics in indoor environments with public traffic
931	Zaco / I Life	E	2010	CN	Asia	Domestic floor cleaning (indoor), professional floor cleaning
932	Zarnitza	E	2003	RU	Europe	Education

No.	Company name	Size	Est.	Loc.	Continent	Application classes
933	Zauberzeug	B	2012	DE	Europe	Cultivation, professional floor cleaning
934	Zebra Technologies	C	2014	US	Americas	Logistics in indoor environments without public traffic
935	Zhejiang Blue Point Robotics	B	2020	CN	Asia	Disinfection
936	Zhejiang Buda Technology	A	2014	CN	Asia	Other transportation and logistics, mobile guidance, information, telepresence
937	Zhejiang Libiao Robot	C	2000	CN	Asia	Logistics in indoor environments without public traffic
938	ZhenRobotics	C	2016	CN	Asia	Professional floor cleaning, other transportation and logistics, security services
939	Zimmer Biomet	H	1927	US	Americas	Surgery
940	Zippedi	C	2018	CA	Americas	Inventory
941	ZMP	C	2001	JP	Asia	Mobility assistants, logistics in indoor environments with public traffic, logistics in outdoor environments with public traffic, security services
942	Zorabots	A	2021	NL	Europe	Mobile guidance, information, telepresence
943	Zucchetti Centro Sistemi	G	1985	IT	Europe	Gardening, domestic cleaning (outdoor)

Table 4.2: List of Service Robot Suppliers

6 Case Studies

Chapter 6 contains case studies on robots in service applications and use cases for mobile and medical robots.

6 Case studies

6.1 INTRODUCTION

Detailed information on the broad range of application areas of service mobile and medical robots including a collection of typical products, prototypes, and suppliers are provided in Chapters 2, 3 and 4. The brief examples of real-world applications provided in those chapters are complemented by more detailed case studies on the use those service robots out in the field. More case studies can be found on the IFR website at https://ifr.org/case-studies/service-robots.

Robot investments are becoming more and more profitable and hence become increasingly widespread within industry and professional application, also beyond manufacturing, and in many service sectors. In this chapter, a selection of case studies serves as an indication of what types of benefits and profitability are possible to obtain from robot investment and of the constantly increasing diversity of the use of robots.

Artificial intelligence extending the capabilities of robots

Artificial Intelligence (AI) holds great potential for robotics, enabling a range of benefits in sectors as diverse as customer care and healthcare. Though AI is already making its mark on robotics, it is at a much slower pace and in a far narrower field of application than is commonly assumed.

The main aim of using AI in robotics is to better manage variability and unpredictability in the external environment, either in real-time, or off-line. This offers benefits for manufacturers, logistics providers and retailers dealing with frequently changing products, orders and stock in so-called ‘high mix/low-volume’ environments, and it also helps robots to function in public environments – from supermarkets to hospitals - which are inherently unpredictable.

AI is not necessarily a prerequisite for dealing with variability and unpredictability. For example, simple pick and place applications with variance in product placement, but not in the product itself, can be achieved without AI. Also, robot mobility does not require AI. However, the greater the variability and unpredictability of the environment, the more likely it is that AI algorithms will provide a cost-effective and fast solution – for example for manufacturers or wholesalers dealing with millions of different products that change on a regular basis. AI is also useful in environments in which mobile robots need to distinguish between the objects or people they encounter and respond differently.

AI has considerable potential to speed up design and programming of robotic solutions, though this is still in early stages of development. AI could help significantly lower the overall cost of the deployment of a robotic application. This helps to customize service robots to a specific use case and set-up robotic solutions in individual environments. The use of AI in design and programming of robot applications is still at a very early stage, however.

Case studies on sample applications

Case studies have been regularly presented and analyzed in the World Robotics. In the present issue, we focus on case studies featuring robot solutions for green and new energy related industries as well as the energy saving potential of robots.

Each case study contains a short outline of the initial problem or task to be accomplished and the customer (industry, company size, country, other relevant information) for which the solution is developed.

The chosen solution is then described, highlighting the specific aspects of why this solution best matches the given problem and covering the following main questions:

- What was installed (machine, layout)?
- Why was this particular solution preferred to alternatives?
- How quickly could the solution be implemented?

Each case study closes by evaluating the main benefits provided by the specific solution.

This chapter only features solutions using service, mobile or medical robots. Any case studies involving industrial robots in manufacturing settings are covered in a respective chapter of World Robotics Industrial Robots

6.2 CASE STUDY 1 - ROBOTIC PARKING SYSTEMS RELIEVE CONGESTION IN SMART CITIES

By: Rachel Rayner, BlueBotics, Switzerland

The problem with car parking

Most private cars are parked 95% of the time. Car owners need a secure place to store their vehicles, and it benefits the owners of parking lots to ensure as many vehicles as possible are parked in the limited space available.

Robotic parking systems such as those created by Xjfam can help solve this problem.

Scaling up with vehicle options

Xjfam, a manufacturing and engineering company passed in Shenzhen, China, offers a massive range of smart parking options. Xjfam's six different types of car parking AGV all rely on ANT navigation technology by BlueBotics.

Because garages are by definition a dynamic environment, natural navigation with ANT is a logical choice. ANT driven vehicles need to recognize as little as 5% of the environment in order to navigate accurately, so they work well even when their view is blocked by an ever-changing array of cars. “The AGV’s flat body means the sensor is mounted just 50 mm from the ground, while the light is at 150 mm. We were concerned that this may have affected data acquisition, but BlueBotics ANT navigation is stable which improves equipment reliability,” confirms a Xjfam representative.

Scaling up the range of vehicles offered allows Xjfam to find success with the demanding Chinese market. The car parking robots offered by Xjfam differ more in form than functionality. For example, the same garage may be equipped with two or three different sizes of traverse handling systems to carry sports cars, sedans and SUVs. They all work in the same way and are built on the same technology stack, but are different sizes to deal with the different size of the vehicles they carry.

Example Project: Robotic parking system at Dalian Runde Plaza

The Dalian Runde Plaza is located in a trendy part of the central city, and space for both parking and people is at a premium.

A conventional carpark was not possible at the fashionable Runde Plaza.

A Xjfam representative explained: “Due to space limitations, it was not possible to construct a conventional car park. Car parks have strict requirements for access ramps, lanes, and parking spaces. The project’s underground garage just could not accommodate a conventional car park.”

A robotic parking system was the only solution to the issue.

Figure 6.1: A conventional carpark was not possible at the fashionable Runde Plaza. Image credit: BlueBotics.

Project details: Dalian Runde Plaza Parking Project

Location	Dalian Runde Plaza, Liaoning Province, China
Robots	2 carrier robots by Xjfam
Parking spaces	124
Number of floors	6 underground floors
Operation	24/7
Cars moved per day	140
Parking space size	560 x 220 cm (A standard US parking space measures 550 x 270 cm)
Vehicle weight	2.5 tons unloaded
Average access time	90 seconds

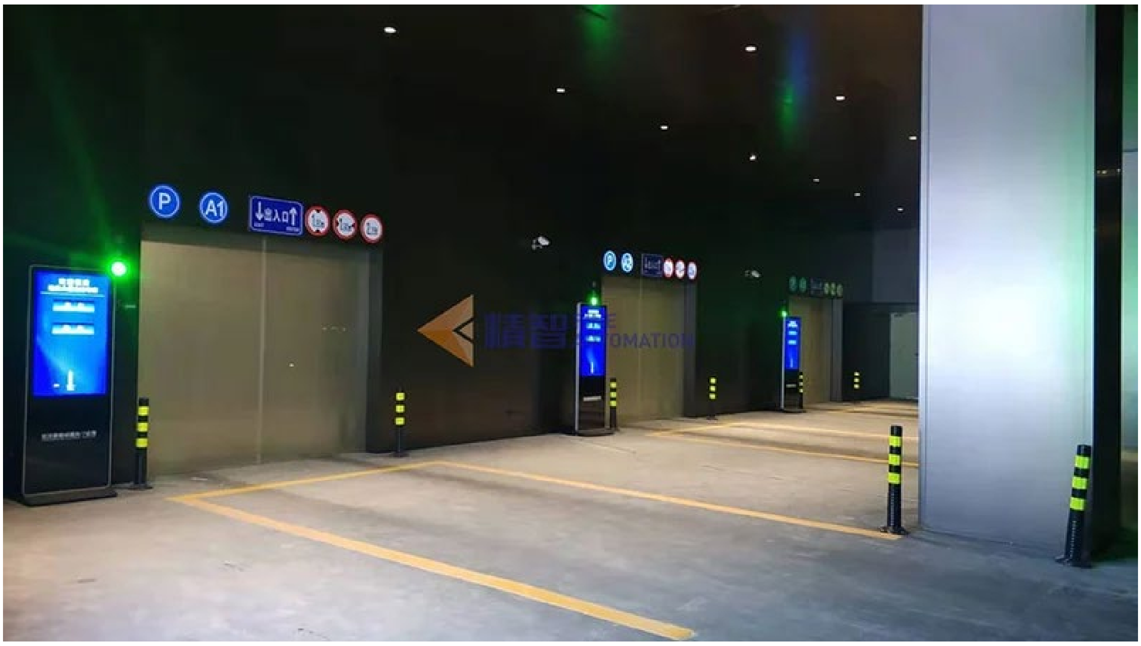


Figure 6.2: The entrance of a similar parking building. Note the touch screens which allow users to summon their vehicles. Image credit: BlueBotics.

The nearest available carrier AGV receives a summons, and slides under the car. If necessary, it performs a series of micro-adjustments to ensure the vehicle is centered before lifting it. A carrier AGV can lift up to 2.5 tons.

Figure 6.3: An example of the robotic parking system user control terminal, from a project in Shenzhen. Image credit: BlueBotics.

The AGV then moves the vehicle into the nearest available space. These spaces are situated closer together than in a typical parking garage, as there is no need to leave room for a door to be opened. There is also the possibility to park cars three or four deep, although in practice, this does not increase efficiency or even save space, due to the extra maneuvering required to extract a car parked behind several others.

Once the driver returns, they summon their car by entering the license plate number on a terminal, and the process is completed in reverse.

10 advantages of a robotic parking system

Advantages for the building owner

1. Overhead lights can be dimmed or even turned off, saving power.
2. Staffing needs are greatly reduced, or even eliminated.
3. Amenities for human visitors (such as rubbish bins, bathrooms and signage) are not needed, saving both set up and ongoing costs.
4. Parking bays can be much more closely packed, meaning more cars can fit in the same space.

Advantages for the user

5. Dropping off a car is faster than finding a parking space – and the return trip can be scheduled electronically, so your ride is ready when you are.
6. There's no risk of your car being scratched or dinged in the parking lot.
7. Cars can be parked and retrieved at any time of day or night.
8. There is no need to walk through the parking building which cars and exhaust may make unpleasant.

Advantages for the wider community

9. Automated parking buildings are more secure, deterring crime.
10. Automated parking buildings take a lot less space than conventional parking buildings.

The ROI of a robotic parking system

The project has been popular with the community as it relieves traffic jams – and with the developer, as it is cost effective.

A Xjfam representative explains: "If we take into account the price of land when calculating the cost of a conventional parking building, we will find that its cost is often higher than the construction of a "smart parking lot" with a robotic parking system. Because a conventional parking building needs an average of 25-35 square meters per parking space with lanes, the total cost of construction and land is about 260,000 - 300,000 yuan [$37,000 - 43,000 USD] per space. By comparison, constructing a smart parking building, including the parking equipment and AGVs costs around 180,000 yuan [$26,000 USD] per space."

The Xjfam representative continues: "A conventional above-ground parking lot in the same area covers 7,500 square meters while providing 291 parking spaces. By comparison, the smart parking lot has 308 parking spaces over 12 floors with a total height of 32 meters. It occupies 750 square meters - it only uses 10% of the land of the conventional parking lot. The smart parking lot saves land while increasing the owner's revenue."

Figure 6.4: As well as the upfront costs being lower per space, the ongoing returns are likely to be higher, as more cars can be parked in the same space. Image credit: Bluebotics.

Smart car parks for smart cities

In major cities across China, smart car parking solutions are increasingly becoming standard technology. By offering a wide range of solutions, powered by a robust navigation technology, Xjfam will continue to be a technology and innovation leader in China's parking industry.

6.3 CASE STUDY 2 - IMPLEMENTING INTELLIGENT ROBOTICS IN GERIATRIC REHABILITATION AT SINGAPORE UNITED MEDICARE CENTRE

By: Zen Koh, Fourier Rehab, China

Introduction

Globally, the WHO has estimated that over 1 billion people are affected by disabilities that impact their mobility and independence. Taking into perspective, this is equivalent to the entire population of Germany. In addition, by the year 2050, the global population of individuals aged 60 years and above is projected to reach 2.1 billion. Seeing the need to combat this rising need, the Singapore United Medicare Centre (UMC), Toa Payoh, a purpose-built nursing home opened in 2003 by then Minister for Health, Mr Khaw Boon Wan, embarked on integrating intelligent robotics and AI into its rehabilitation services. This initiative aimed to address the growing demand for quality nursing care outlined by the Ministry of Health (MOH), marking a significant step towards innovative elderly care. With the rapid increase of the global ageing population, prone to diseases and injuries, the intervention of rehabilitation robots in the clinical environment can assist by addressing the global insufficiency of clinical therapists.

Figure 6.5: The RehabHub™ aims to create a diversified and inclusive ecosystem, enabling greater patient recovery through robotics. Allowing for personalised rehabilitation solutions to cater for different needs. Image credit: Fourier Rehab.

Initial Problem/Task

Customer Profile:

- **Industry:** Healthcare (Geriatric Rehabilitation)
- **Company Size:** Medium-sized Nursing Home with Rehabilitation Centre
- **Country:** Singapore

- **Challenge:** Providing continuous, personalised, and intensive rehabilitation for an increasing number of elderly patients, many of whom suffered from stroke, musculoskeletal conditions, or cognitive impairments, was becoming increasingly challenging. The centre aimed to improve rehabilitation outcomes, enhance patient engagement, and alleviate the physical strain on therapists and caregivers.

Solution

What Was Installed:

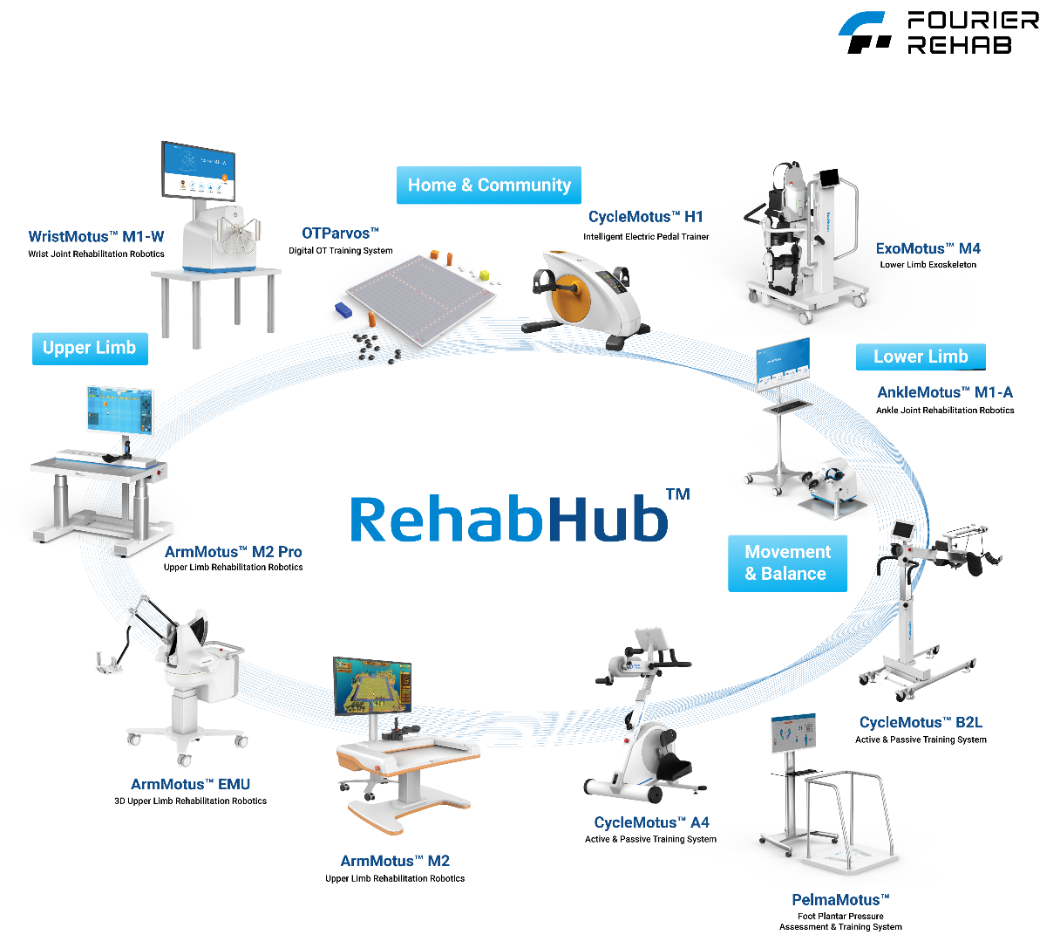


Figure 6.6: The RehabHub™ features a wide range of devices for upper and lower limbs, balance, and movement. Image credit: Fourier Rehab.

- **Machine/Layout:** The "RehabHub™", a suite of intelligent robotics explicitly designed for geriatric and neurorehabilitation, was introduced. It consists of upper, lower, balance and movement solutions from Fourier Rehab's inventory of robotic devices. These solutions allow therapists to utilise advanced sensors, AI algorithms for personalised therapy, and an engaging interface for individual and group therapy sessions. In addition, the system supports ongoing research and development in rehabilitative technology. With its ability to collect and analyse large volumes of data, the RehabHub™ provides valuable insights that can be used to refine existing therapies and develop new ones.

- **Why This Solution:** The RehabHub™ was chosen for its ability to adapt exercises in real-time based on patient performance, provide motivational feedback, and support a wide range of rehabilitation activities. It is a versatile tool that allows healthcare providers to cater to different patient needs, allowing for effective and comprehensive rehabilitative care and making it a one-stop solution for patients. Catering for upper, lower, movement and balance, patients who require attention in different areas can entirely focus on their recovery journey without being required to travel to multiple locations to receive various treatments. Whether a patient is recovering from a neurological event, such as a stroke, or managing age-related physical decline, it provides a unified platform that accommodates an expansive array of therapeutic exercises.
- **Implementation Timeline:** The solution was implemented within three months, including setup, clinical staff training, and full integration into the daily rehabilitation programs.

Evaluation

Benefits:

- **Enhanced Rehabilitation Outcomes:** The introduction of the RehabHub™ has marked a transformative shift in the landscape of rehabilitative care, particularly in enhancing patient outcomes across several crucial domains: mobility, balance, and cognitive functions. The improvements observed in these areas can be attributed mainly to the system's AI-driven, personalised, and adaptive approach to therapy, providing therapists with crucial information on the patient's mobility and range of motion, which allows for highly adaptable rehab protocols and treatments for different needs.
- **Increased Patient Engagement:** The devices within the hub significantly boosted patient motivation and satisfaction, making the rehabilitation process more appealing. Implementing gamified therapy allows patients to be highly engaged throughout their sessions. As traditional therapy methods involve patients doing repetitive and non-engaging tasks, gamified therapy, incorporated into each device within the hub, gives patients motivation and satisfaction during and after individual sessions. The system helps sustain patient interest and enthusiasm throughout recovery by transforming rehabilitation exercises into engaging challenges. This increased engagement is crucial as it makes patients look forward to their therapy sessions and deeply involves them in the activities. As a result, they are more likely to adhere to their therapy regimen and less likely to abandon it.

- **Reduced Physical Strain on Therapists and Caregivers:** By automating many of the repetitive and labour-intensive tasks associated with rehabilitation, RehabHub™ has revolutionised the role of healthcare professionals, enabling them to focus on more complex and nuanced aspects of patient care. These tasks, such as assisting patients with exercises or manually recording patient movements, can lead to physical strain and fatigue among healthcare workers. With the burden of repetitive tasks lifted, therapists and caregivers can redirect their energies towards more complex elements of rehabilitation care. This includes developing personalised care plans, monitoring patient progress with greater detail, and engaging in direct patient interaction focusing on psychological and emotional support. The ability to concentrate on these areas enhances the quality of care provided and allows for a more holistic approach to patient rehabilitation.

Contribution of AI and Digitalisation:

- **AI Algorithms:** AI algorithms serve as the backbone of the RehabHub™, playing an indispensable role in revolutionising rehabilitation care. These advanced algorithms are essential to deeply analysing patient data, allowing for customised therapy sessions tailored to each patient's needs and response patterns. This capability of making real-time adjustments based on patient responses enhances the efficacy of treatments and significantly improves patient outcomes. Designed to process a vast array of data points collected during therapy sessions, including movement precision and patient feedback, the AI can analyse these data and identify patterns and nuances in a patient's progress and struggles, which might be overlooked in a less sophisticated setup.
- **Digitalisation:** The digitalisation features of the hub play a pivotal role in modernising rehabilitation practices. A vital aspect of this technology is its ability to facilitate seamless patient data integration with a centre's Electronic Health Records (EHR). Through InfinityNet™, a cloud-based system that links all devices within the RehabHub™, this capability promotes a holistic approach to patient care and significantly enhances the rehabilitation process's efficiency and effectiveness. Automating the data entry process reduces the likelihood of manual errors and increases data management efficiency in rehabilitation settings. Minimising the need for handwritten notes and manual record-keeping saves time and reduces the potential for errors in the transcription and handling of physical documents. This leads to a more reliable and streamlined process, allowing therapists to spend more time with patients rather than on administrative tasks.

Conclusion

The successful integration of intelligent robotics and AI at the Singapore United Medicare Centre's rehabilitation facility demonstrates the transformative potential of these technologies in the geriatric healthcare sector. The RehabHub™ effectively addressed the specific challenges of geriatric care, offering a scalable, efficient, and engaging rehabilitation solution. This case study serves as a model for how innovative approaches can fulfil the needs of an ageing population, ensuring high-quality care and boosting the capabilities of healthcare providers in an increasingly digital world. Robot-assisted therapy has freed up the labour-intensive, repetitive work from the therapist, allowing them to focus on work that requires their professional knowledge, like therapy planning, prescription, and dexterous manual therapy that a robot cannot replicate. By doing that, a therapist's work efficiency has been maximised, offering more treatment sessions to the continually increasing patient populations.

6.4 CASE STUDY 3 - INNOK ROBOTICS AND RIGDON: A SUCCESS STORY THANKS TO AUTONOMOUS MOBILE ROBOTS AND THEIR OFF-ROAD AND OUTDOOR CAPABILITIES.

By: Daniel Brandt, Innok Robotics GmbH, Germany

The original problem/task and the customer:

Rigdon, a leading tyre reconditioning company based in Günzburg (Germany), was facing major challenges in its internal logistics. As a medium-sized company that transports a large volume of tyres between various production stations and the warehouse on a daily basis, Rigdon needed a solution that offered both efficiency and flexibility. The previous manual transport solutions were inefficient and required significant human resources. In addition, the floor conditions in the production halls and outside areas were so poor that conventional robotic solutions were out of the question.

Figure 6.7: The Innok Robotics Induros AMR autonomously moves tyres between the production stations at the Innok customer Rigdon. Image credit: Innok Robotics.

The following possible applications were evaluated:

- Transport vehicle for pallet trolleys, mesh boxes, CC containers, scrap/chip containers and much more.
- Replacement of a tugger train with several trailers

- With the "roller conveyor" option as an all-terrain transport solution for KLT containers and parcels

Rigdon decided to autonomise the following process first: The robot moves the tyre trolleys between the production stations and the warehouse, coupling and uncoupling them autonomously in each case

The solution:

a. What was installed (machine, layout)?

Innok Robotics installed the INDUROS, an autonomous mobile robot (AMR) specially developed for use in demanding conditions. The INDUROS was equipped with the ability to work fully autonomously both indoors and outdoors, namely multiterrain. Innok multiterrain means that the robots drive fully autonomously and in combination both indoors and outdoors - on good and bad floors, over obstacles such as speed bumps or gravel and also in wind and weather from hall to hall.

The layout involved integrating the INDUROS into the existing production process, with the robot driving the tyre trolleys between the production stations and the warehouse and coupling and uncoupling them autonomously.

Figure 6.8: The Innok Robotics AMR Induros autonomously moves tyres from outdoor storage to the production stations at the Innok customer Rigdon.Image credit: Innok Robotics.

b. Why was this particular solution chosen over the alternatives?

The INDUROS was chosen because of its unique ability to work in extreme conditions - Innok multiterrain. In addition, thanks to Innok Hybrid Navigation, no structural changes to the existing buildings or terrain were required, allowing for a cost-effective and quick implementation. INDUROS' safety standards, including certified laser scanners and outdoor-approved safety scanners, ensured that the robot could work safely in a crowded environment.

c. How quickly could the solution be implemented?

The INDUROS was implemented at Rigdon in a very short time. Thanks to the intuitive Innok Cockpit software, navigation and order management could be set up quickly and easily. The integration of the INDUROS into Rigdon's production process was completed within a few days, meaning that the robot could be integrated into daily operations immediately.

The evaluation:

What were the benefits? How did AI and/or digitalisation contribute to the success of the solution?

The introduction of INDUROS at Rigdon brought significant benefits. The autonomous coupling and uncoupling of the tyre trolleys and the reliable transport between the production stations and the warehouse led to a significant increase in efficiency. The INDUROS could work for up to 24 hours at a time and recharge itself fully autonomously and inductively during inactive periods, maximising uptime. This was particularly important as it was becoming increasingly difficult for Rigdon to find staff for the night shift.

The digitalisation and AI-based navigation of the INDUROS enabled precise and safe control of the robot, even in a difficult environment. This led to a reduction in operating costs and better utilisation of personnel, as key skilled workers could be deployed for more qualified activities.

Compared to human-operated vehicles, Rigdon achieves an ROI within 1.0 - 2.5 years, depending on the number of work shifts. Overall, Rigdon saves up to €40,000 per shift and year by using the INDUROS, depending on the utilisation of the robot in the order backlog. The Innok Hybrid Navigation and the robust design of the INDUROS made it the ideal solution for Rigdon. The continuous improvement of the technology ensures that Rigdon will continue to benefit from autonomous mobility in the future and that the acquisition of further robots in the fleet will be mapped via the Innok Cockpit or industry standards such as VDA5050.

6.5 CASE STUDY 4 - APPLICATION OF AUTONOMOUS MOBILE ROBOTS (AMRS) IN THE FRONT SECTION OF LITHIUM BATTERY FACTORIES

By: Paul Sun, IPLUSMOBOT, China

IPLUSMOBOT, a global leader in the innovative revolution of intelligent manufacturing automation, recently collaborated with a leading company in the lithium battery industry. IPLUSMOBOT deployed an integrated hardware and software solution in the production workshop. This project helps operators handle repetitive tasks, ensures clean internal environments, significantly enhances factory automation, and meets the client's input-to-output ratio requirements.

The client is one of the new energy industry giants, previously relied heavily on manual labor for material transfer and loading/unloading between various processes. As we know, high precision is required for AMR operations. Additionally, the factory logistics involves high-frequency handling, mixed human and vehicle traffic, narrow spaces, and frequent interactions with air showers and lifts, which demand high safety and stability performance from the AMRs.

Based on the actual layout and process requirements of the user's factory, IPLUSMOBOT developed a flexible, highly efficient intelligent manufacturing logistics solution. This solution includes multiple types of AMR carrying different materials in the battery production process, and with CLOUDIA Fleet Management System achieving On-Demand delivery, auto-charge and storage buffer management.

The CLOUDIA Fleet Management System seamlessly integrates with the user's WMS and MES systems, automatically receiving and dispatching task information. Different types of AMRs operate efficiently in a mixed tasks without human intervention, achieving digital, automated, and intelligent logistics throughout the handling process.

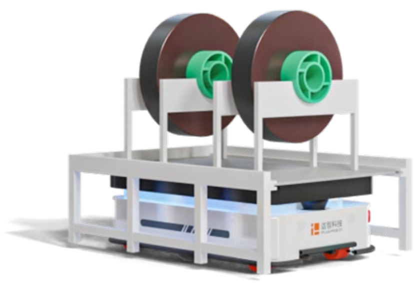


Figure 6.9: IPLUSMOBOT Standard AMR. Image credit: IPUSMOBOT.

In the factory's rolling and cutting workshop, after material processing, the materials are placed on turnover racks. The CLOUDIA system issues task information, calling the standard AMR to receive the materials. The AMR autonomously positions the empty rack, docks and turnovers the full rack through roller shutters, air showers, and corridors to the first floor. It places the full rack at the designated receiving location and updates task execution status to the MES system in real time. The AMR then returns to receive the next task or follows the setting for charging, standby, or waiting for the next task.

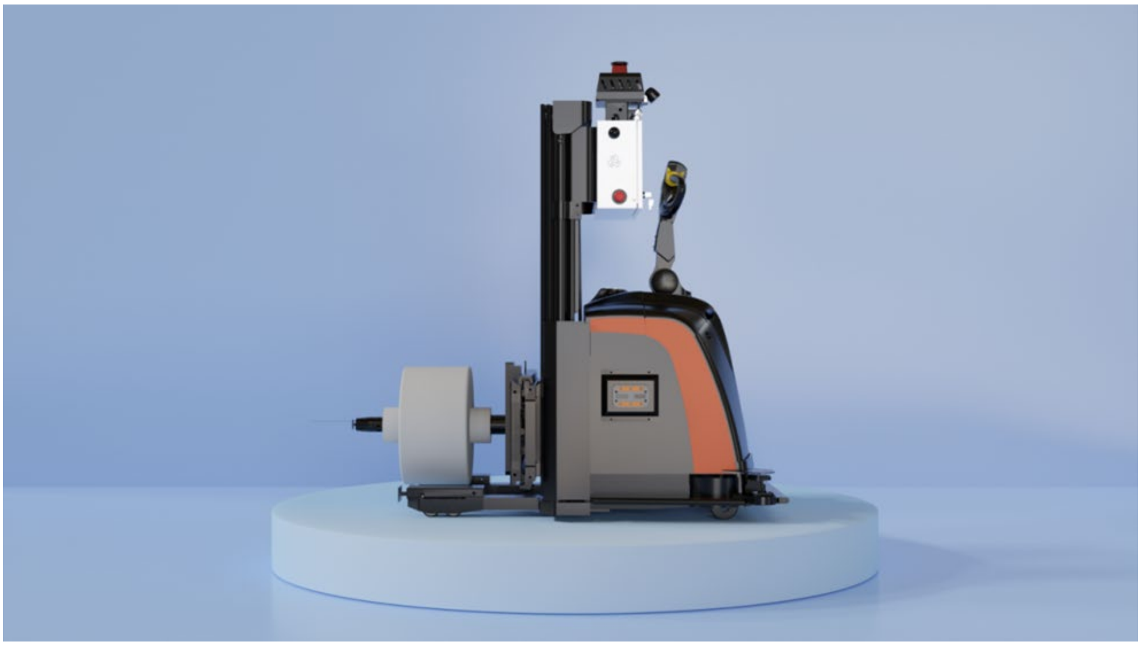


Figure 6.10: IPLUSMOBOT Omnidirectional Cantilever Forklift AMR. Image credit: IPLUSMOBOT.

Several Omnidirectional Cantilever Forklift AMRs are deployed in the coating and slitting sections for automated handling and logistics delivery of electrode rolls. The application of this AMR robot solves the industry problems of large load, high precision requirements and the need for a lot of manual assistance in electrode rolls loading and unloading scenarios; The AMRs use vision and laser fusion navigation technology to achieve ±5mm high-precision docking with onsite equipment and storage positions, meeting the user's production process requirements. Multiple safety measures ensure safe operation in narrow workshop passages.

Over ten cartridge-handling AMRs are used for loading, unloading, and buffering in the stacking area, ensuring autonomous transport and return of lamination cartridges. These AMRs dock with loading and unloading platforms with ±1mm precision, automatically moving full cartridges to the next stage and retrieving empty ones for return. In some workstations, the AMRs operate in narrow spaces, docking with machines in a confined 1,301mm aisle, handling loading and unloading tasks autonomously and efficiently. They communicate their status in real-time with equipment like air shower doors, elevators, and buffers, navigate through more than ten air shower and roller doors, operate seamlessly in mixed human-vehicle traffic, and autonomously call elevators to move between floors. The AMRs switch between visual and laser navigation based on the conditions on-site.

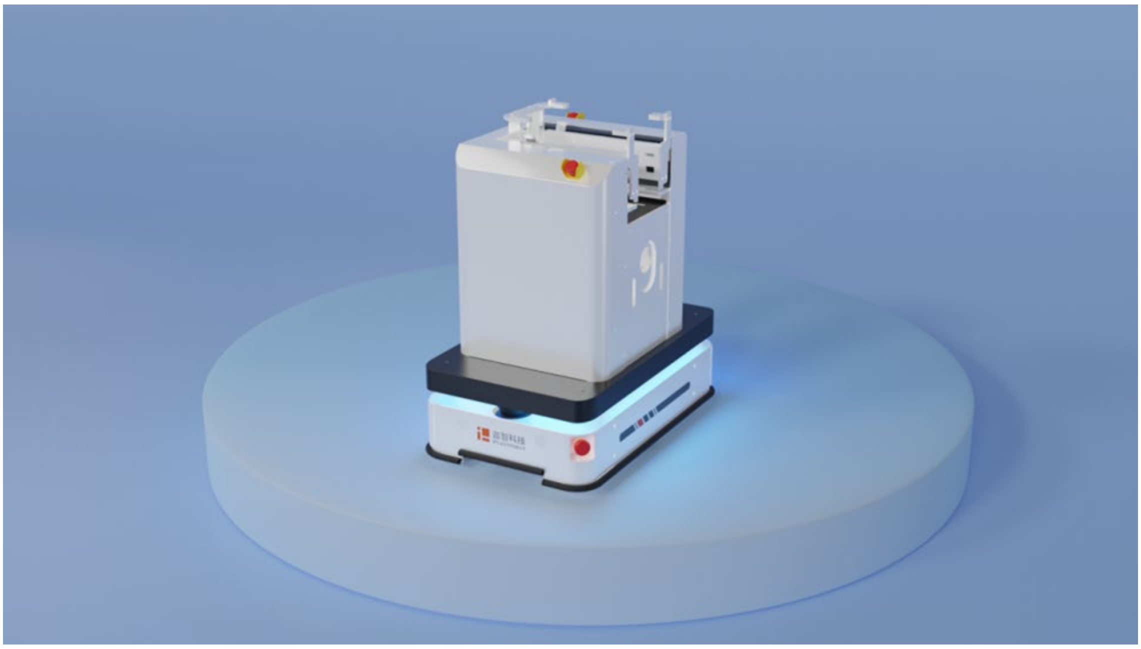


Figure 6.11: IPLUSMOBOT Cartridge-handling AMR. Image credit: IPLUSMOBOT.

In the user's workshop, all AMR models work collaboratively through cross-map traffic management. This makes material information fully traceable, enabling data-driven reports for analyzing production bottlenecks and achieving lean manufacturing. This intelligent logistics solution has improved the previously cumbersome and chaotic manual handling processes, to reducing costs and increasing efficiency. Practical calculations show that the AMR deployment saves the workshop nearly 2 million yuan annually, eliminating the need for eight cartridge-handling trolleys. This meets the high-frequency material turnover requirements, significantly improving the timeliness and accuracy of logistics distribution and boosting production efficiency.

6.6 CASE STUDY 5 - SOLAREDGE E-MOBILITY TRANSFORMS PRODUCTION PROCESSES WITH FASTHINK

By Stefano Candolfi, OMRON, Italy

SolarEdge e-Mobility, a supplier of power electronics, batteries, and electric traction systems for automotive OEMs, offers integrated electric mobility solutions for electric and hybrid vehicles. Their production facility in Umbertide (PG) houses an R&D team comprising over 60 engineers and technicians. They also maintain a presence in Terni, focused on Telematics, and in Germany, centered on e-Propulsion.

Their technical knowhow, coupled with agile development and rapid prototyping capabilities, enable SolarEdge e-Mobility to produce complex products in record time. Their portfolio includes electric propulsion systems, electric motors, transmissions, battery packs, battery management systems (BMS), chargers, vehicle control units (VCU), and specialized software for electric vehicles. Elisa Rossi, the Head of Finance at SolarEdge e-Mobility, highlights the company's drive for innovation, saying, "SolarEdge e-Mobility’s electrical systems and components stand out for their high power density and efficiency. To transition from prototypes to large-scale production, we need precision and rapid execution. This prompted our decision to overhaul our production processes."

Figure 6.12: In combination with the technologies of SolarEdge e-Mobility and OMRON’s AMR robots, FasThink was able to reach a new level of automation. Image credit: OMRON.

Understanding the needs of SolarEdge e-Mobility

To cater to the demands of their clientele, SolarEdge e-Mobility recognized the need to streamline warehouse operations, ensure punctual and accurate delivery to production lines, and minimize human errors. They also sought to digitize picking and dropping operations to provide real-time oversight of material flow. Elena Del Signore, the Logistics & Material Director of SolarEdge e-Mobility, elaborates, "We aimed to enhance and monitor warehouse operations in real-time, make necessary adjustments, and use a system that's both flexible and user-friendly. FasThink's solutions fit the bill perfectly, offering the advantage of customization for future enhancements."

Thanks to the adaptability of the solutions provided by FasThink, they were able to implement an application that met these requirements and could interact and exchange information with the SolarEdge e-Mobility management system.

The application at work

The application was developed for the SolarEdge e-Mobility production plant in Umbertide. FasThink introduced a smart and flexible solution that's easy to install. It can be quickly and simply reconfigured whenever there's a need for a layout change, either within the production area or inside the warehouse. FasThink integrated its proprietary wireless technologies, including the e-Kanban smart sensor (and its Push2Call variant) and the Pick2Light system, installing them in the shopfloor and warehouse environments. This was done to optimize supply with a lean approach to the production lines.

The wireless e-Kanban smart sensor manages real-time data, communicating automatically with the management system via an RF transceiver using LoRaWAN technology. This sensor was installed in the assembly area, near the mechanical conveyors on the shelves holding KLT containers, which are standardized containers often used in the automotive industry for small-sized components. Adhering to the full-empty logic: when a KLT container is emptied, the e-Kanban detects the change in status and automatically sends a replenishment request to the warehouse. Push2Call is a wireless system designed to enhance communication and integration between digital and IT systems. It aids in the management of large components, which are typically stored on racks and cantilevers, and also streamlines the retrieval of finished products. By doing so, it ensures that component availability is coordinated in a manner that conservatively uses the limited space available on production lines. On the other hand, Pick2Light, an innovative material retrieval system using light signals, has been installed on the warehouse shelves. This system aims to make the picking activity more dynamic and efficient, drastically reducing the chances of human error. When the e-Kanban sensors in the assembly area trigger a replenishment request, displays within the warehouse provide information on the type, location, and quantity of material to be retrieved for restocking.

Enhancing the FasThink application with autonomous robotics

The solution devised by FasThink took into account not only the phase of material retrieval and stock management but also the movement between the warehouse and the production areas. As an OMRON Solution Partner, FasThink successfully integrated the

AMR (Autonomous Mobile Robot) into the framework designed for SolarEdge e-Mobility, yielding significant performance benefits. The AMR was coordinated with the digital flows, and it was primarily tasked with the transportation of KLT containers from the storage zone to the shelving systems fitted with e-Kanban. This implementation, besides further streamlining the previously manual handling, optimized the efficiency of the staff. Specifically, the warehouse operator, under the guidance of the Pick2Light system, retrieves items and then entrusts the KLTs to the AMR. The robot, in turn, autonomously transports them and delivers to the assembly area, where another operator is responsible for stock replenishment. The autonomous navigation capabilities of the OMRON LD-60 mobile robot allow it to seamlessly navigate through the storage area of finished products, which are ready for dispatch. This is a zone frequented by employees and where trolleys move and maneuver large boxes and containers. Marco Mina, the OMRON Business Developer for Robotics, points out, "FasThink's applications are centered on logistics and intralogistics, facilitating a high-level integration within the realm of cutting-edge technologies. By integrating the OMRON AMR, combined with technologies such as Pick2Light, e-Kanban, and Push2Call, SolarEdge e-Mobility was empowered to tap into the full potential of logistic automation, benefiting from the precise insights into their production processes.

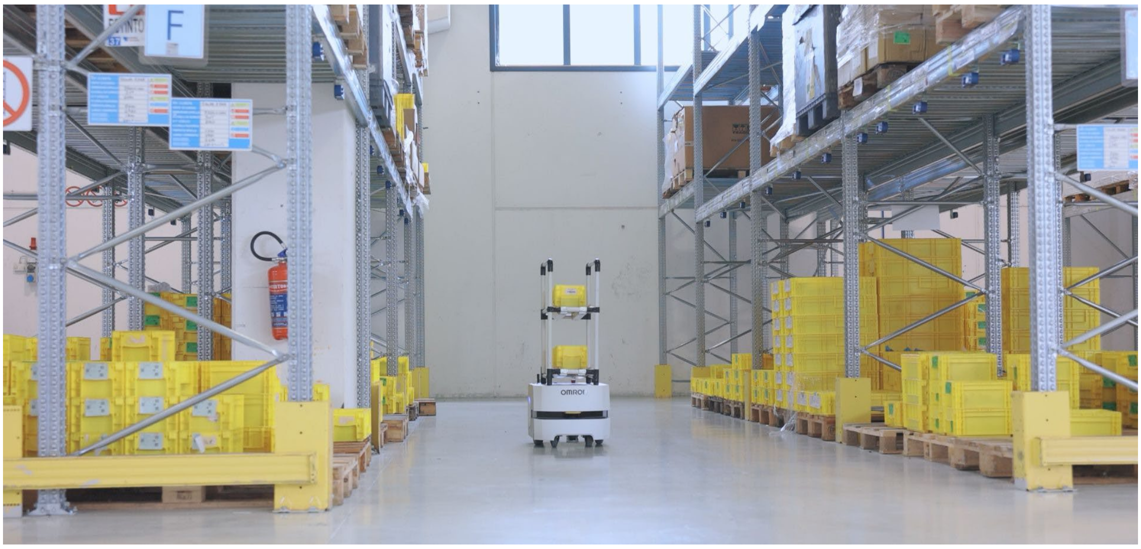


Figure 6.13: OMRON’s AMR robots transporting KLT containers, further optimizing the efficiency and safety of the day-to-day operations. Image credit: OMRON.

The harmonization of systems as added value

SolarEdge e-Mobility benefited from the added value derived from harmonizing the four solutions. The e-Kanban, Pick2Light, and Push2Call, synergistically linked with the OMRON AMR, allowed a seamless synchronization of picking and feeding operations, resulting in significant improvements in speed, efficiency, and accuracy.

Furthermore, the capability to monitor warehouse performance in real-time is ensured by a dedicated web-app customized by FasThink based on SolarEdge e-Mobility's requirements. This application allows various devices, such as handhelds, tablets, and monitors, to display the status of picking and line-feeding tasks. This facilitates timely corrective actions when needed. Additionally, with various indicator parameters, the app also supports the generation of reports and statistics at predetermined intervals to consistently monitor warehouse efficiency.

"The application developed in collaboration with SolarEdge e-Mobility is just one of many examples illustrating how it's possible to tailor-make a stock management system, warehouse and production flow starting from established application platforms. FasThink's mission is to redesign last-mile production processes through the integration of IT systems and OT technologies, specifically technologies like Pick2Light, e-Kanban, Push2Call, and the Connect Orchestrator platform. Delivering a solution like this, which integrates with existing management systems, represents a significant step toward the digitalization of industrial flows and using data for strategic operation planning," concludes Marco Marella, General Manager of FasThink.

Figure 6.14: Overall, the collaboration of SolarEdge e-Mobility, FasThink and OMRON showcases the impressive possibilities of customizing a stock management system. Image credit: OMRON.

Results

The solution provided by FasThink was easy to install and use, and it successfully met all the set objectives. Specifically, it eliminated supply errors and production downtimes caused by the absence of various materials. It also led to an increase in stock accuracy and optimized the performance of the warehouse team, resulting in a notable improvement in direct labor efficiency. Collaborating with FasThink highlighted values such as reliability, responsiveness, and precision. All these enhancements translated into a significant added value to the services and products of SolarEdge e-Mobility for the end-users.

6.7 CASE STUDY 6 - HOW COBOTS AND AI ARE BEING USED TO REVIVE CORAL REEFS

By Fleur Nielsen, Universal Robots, Denmark

In Western Australia, Coral Maker has partnered up with Autodesk to develop a system that uses collaborative robots (cobots) from Universal Robots to help revitalize the coral reefs of Australia.

The company's founder Dr. Taryn Foster, dreams of scaling the operation to have a world-wide impact and bring color and life back to the sea.

How did it all start?

After a catastrophic coral bleaching event in her home country, Australia, coral biologist Dr. Taryn Foster started the company Coral Maker, and has since worked on rebuilding the reefs that 25% of all marine species depend on. To follow this dream of bringing back some of the coral reef that has been lost and the biodiversity that comes with it, she needed help.

To combat the destructive effects of climate change on coral reefs, Dr. Foster and her team at Coral Maker partnered up with technology firm Autodesk to create an innovative solution for reef rehabilitation using AI, vision systems, and cobots from Universal Robots. The project aims to harness the power of collaborative robots and artificial intelligence to accelerate coral propagation and restore fragile marine ecosystems.

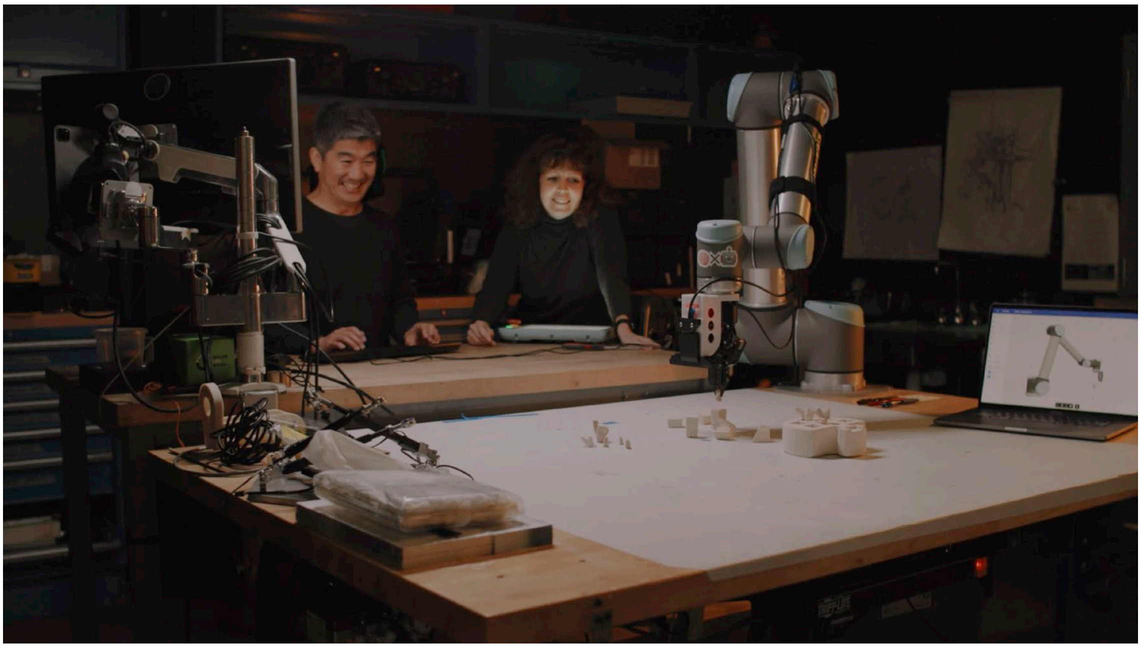


Figure 6.15: Autodesk researchers Dr. Nic Carey and Dr. Yotto Koga testing robotics technology for automated coral propagation. Image credit: Autodesk.

Automating the propagation process

The process of coral restoration involves transplanting tiny corals, cultivated in nurseries, onto damaged reef. This is done by grafting coral fragments into small plugs, that are then inserted into a molded stone base. However, the manual work is labor intensive, slow, and costly, and only a fraction of the reefs at risk are getting help, so Dr. Foster needed a way to automate the process.

The solution came through a partnership with Autodesk, which used their software and Design and Make Platform to train robots to pick up the tiny living corals and place them in the molds.

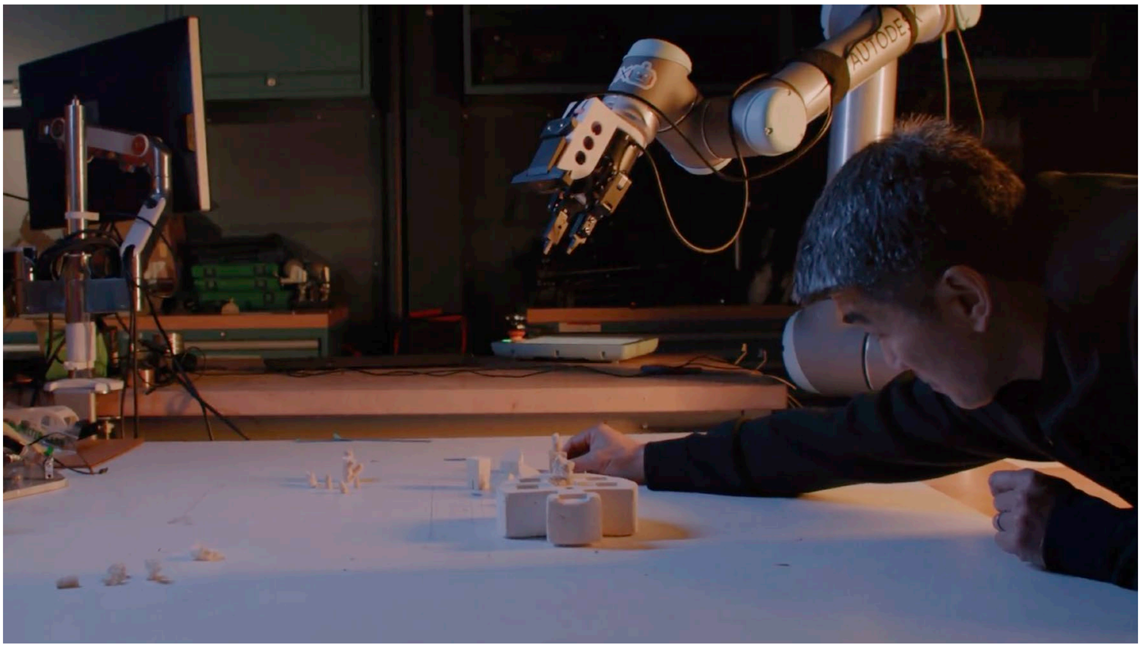


Figure 6.16: Dr Yotto Koga, researcher at Autodesk. Image credit: Dr Yotto Koga, researcher at Autodesk. Image credit: Autodesk.

The use for collaborative robots

According to Dr. Foster, one of the biggest problems in coral reef restoration is that it's hard to scale up, which would be necessary for it to have an impact at an ecosystem level.

The Great Barrier Reef is tens of millions of hectares in size, and right now reef restoration projects are only restoring about one hectare per year. The obstacle that restoration projects are facing is the cost of scaling up: "If we were to do this at the scale that we need to be, tens of millions of corals per year would need to be processed and propagated and picked and placed, and the cost becomes prohibitively expensive" explains Dr. Foster "To get to that scale, we need to automate the repetitive pick and place work and have people doing the many other complex tasks in the process."

Dr. Foster explains that some of these tasks in coral propagation are fairly simple, where the coral is picked up and placed on a spot of glue, or the plug is placed onto a coral skeleton.

For Coral Maker, the need was for adaptive robotics that could work alongside humans, operate with precision, and recognize coral fragments, as each coral is different and needs to be handled with care. This was achieved by using Autodesk's Design and Make platform, that coupled with AI and vision systems, trains the robots to locate, pick and place the corals.

"One of the main challenges is just bringing that cost down, so that we can scale it up" said Dr. Foster "I think the only way we're going to be able to do that is using automation and then specifically collaborative robots, because a lot of the work that we'll be doing will involve people working interactively with robots."

Senior Principal Research Scientist at Autodesk, Nic Carey, added: "The ability to scale restoration efforts is crucial, which is where robots come in. Automation and robotics are often used for large-scale manufacturing and product processing, and if applied to coral restoration efforts, it could have a huge impact. We are not able to scale efforts to meet the needs of ecosystem scale restoration by doing these repetitive tasks manually, so partnering with robots enables marine biologists to focus on more complex tasks that cannot be automated. Robotics also ensures that we can keep production running around the clock and outside of working hours to meet the need for larger scale efforts."

References

1. 11 Years On: TEPCO to Begin Fukushima N-Fuel Debris Removal, March 2022, https://sp.m.jiji.com/english/show/18342.

2. 2016 MHI Annual Industry Report – Accelerating change: How innovation is driving digital, always-on supply chains; http://cpbucket.fiu.edu/1168-geb6368x81168_emba-97075%2F2016-industry-report-2016-(1).pdf.

3. 2017 Census of Agriculture. US Department of Agriculture, 2017, issued 2019; https://www.nass.usda.gov/Publications/AgCensus/2017/Full_Report/Volume_1,_Chapter_1_US/usv1.pdf.

4. 8 Delivery Robot Startups for Last Mile Delivery, Nanalyze, April 27, 2018, https://www.nanalyze.com/2018/04/8-delivery-robot-startups-last-mile-delivery.

5. A detailed overview of the different types can be found here: https://www.toyotaforklift.com/resource-library/blog/toyota-products/forklift-types-and-classes; and here: https://www.agvnetwork.com/types-of-agv/types-of-robot-forklift.

6. Abaffy, L.:Pipe Inspection Robot Saves Alaska Pipeline Millions, August 19, 2015; http://enr.construction.com/technology/construction_technology/2015/0819-pipe-inspection-robot-saves-alaskan-pipeline-millions.asp.

7. Ackerman, E.: Boston Dynamics' Spot Is Helping Chernobyl Move Towards Safe Decommissioning, November 2020, https://spectrum.ieee.org/boston-dynamics-spot-chernobyl.

8. Ackermann, E.: Boston Dynamics’ Spot Is Helping Chernobyl Move Towards Safe Decommissioning, November 23, 2020; https://spectrum.ieee.org/automaton/robotics/robotics-hardware/boston-dynamics-spot-chernobyl.

9. Ackermann, E.: Panasonic Revives Hospital Delivery Robot, IEEE Spectrum, May 15, 2014, http://spectrum.ieee.org/automaton/robotics/medical-robots/panasonic-hospital-delivery-robot.

10. Ackermann, E.: Robotic Construction Platform Creates Large Buildings on Demand, IEEE Spectrum, April 26, 2017; https://spectrum.ieee.org/automaton/robotics/industrial-robots/robotic-construction-platform-creates-large-buildings-on-demand.

11. Ackermann, E.: Telepresence Robots Are Helping Take Pressure Off Hospital Staff, IEEE Spectrum, April 15, 2020; https://spectrum.ieee.org/automaton/robotics/medical-robots/telepresence-robots-are-helping-take-pressure-off-hospital-staff.

12. Ackermann, E.; Guizzo, E.: DARPA Robotics Challenge: Amazing Moments, Lessons Learned, and What's Next, IEEE Spectrum, June 11, 2015; http://spectrum.ieee.org/automaton/robotics/humanoids/darpa-robotics-challenge-amazing-moments-lessons-learned-whats-next

13. Agriculture Finance & Agriculture Insurance. The World Bank Group, September 23, 2019; https://www.worldbank.org/en/topic/financialsector/brief/agriculture-finance.

14. Albala, D.; Patel, V. R. (eds): Journal of Robotic Surgery. Publisher: Springer; http://www.springer.com/medicine/surgery/journal/11701.

15. Albrecht, C.: Blendid's Smoothie Robot Heads Off to the University of San Francisco. The Spoon, March 26, 2019; https://thespoon.tech/blendids-smoothie-robot-heads-off-to-the-university-of-san-francisco/.

16. Albrecht, C.: Flippy's Frying Pilot is a Hit at Dodger Stadium. The Spoon, September 24, 2018;

17. Albrecht, C.: Pazzi Opens Robotic Pizza Restaurant in Paris. The Spoon, July 7, 2021; https://thespoon.tech/pazzi-opens-robotic-pizza-restaurant-in-paris/.

18. Albrecht, C.: Switzerland: Smyze's Robot Barista Makes Coffee and Mocktail Drinks. The Spoon, June 17, 2021; https://thespoon.tech/switzerland-smyzes-robot-barista-makes-coffee-and-mocktail-drinks/.

19. Albrecht, C.: xRobotics' Pizza Assembling Robot Concludes Test with Dodo Pizza. The Spoon, April 22, 2021; https://thespoon.tech/xrobotics-pizza-assembling-robot-concludes-test-with-dodo-pizza/.

20. Alemzadeh, H.; Iyer, R.; Kalbarczyk, Z.; Leveson, N.; Raman, J.: Adverse Events in Robotic Surgery: A Retrospective Study of 14 Years of FDA Data, Presented as the J. Maxwell Chamberlain Memorial Paper for adult cardiac surgery at the 50th Annual Meeting of the Society of Thoracic Surgeons in January 2015; http://arxiv.org/ftp/arxiv/papers/1507/1507.03518.pdf.

21. Amazon plans to build delivery robot tech in Finland, CNBC, July 1, 2021; https://www.cnbc.com/2021/07/01/amazon-plans-to-build-scout-delivery-robot-tech-in-finland.html.

22. Amazon scales back Scout delivery robot program, TechCrunch October 7, 2022; https://techcrunch.com/2022/10/07/amazon-scales-back-scout-delivery-robot-program/.

23. Andreasson, H. et al.: Autonomous transport vehicles: Where we are and what is missing, IEEE Robotics & Automation Magazine, March 2015, pp. 64-75; https://ieeexplore.ieee.org/abstract/document/7059356.

24. Andreasson, H. et al.: Autonomous transport vehicles: Where we are and what is missing, IEEE Robotics & Automation Magazine, March 2015, pp. 64-75; https://ieeexplore.ieee.org/abstract/document/7059356.

25. Angelos, P.: Can robotic approaches be justified for the benefit of surgeons? Surgery, vol. 161, 2017, no. 3, pp. 639-640; https://pubmed.ncbi.nlm.nih.gov/27913034/.

26. Annual Report 2019. Nuclear Energy Agency, May 2020; http://www.oecd-nea.org/pub/activities/ar2019/ar2019.pdf.

27. ANSI/ITSDF B56.1 - 2020, Safety Standard for Driverless, Automatic Guided Industrial Vehicles and Automated Functions of Manned Industrial Vehicles EFFECTIVE, March 3, 2022; http://www.itsdf.org/cue/b56-standards.html.

28. Anvari, M.; Loughlin, C. (eds.): The International Journal of Medical Robotics and Computer Assisted Surgery; http://onlinelibrary.wiley.com/journal/10.1002/(ISSN)1478-596X.

29. Application of Robot Technology, Tepco; http://www.tepco.co.jp/en/decommision/principles/robot/index-e.html.

30. Arvin, F. et al.: Mona: an affordable open-source mobile robot for education and research. Journal of Intelligent & Robotic Systems vol. 94, 2019, 3-4, pp. 761-775; https://dl.acm.org/doi/10.1007/s10846-018-0866-9.

31. Automated straddle carrier facility wins Terminal of the Year Award, Cargotec, December 21, 2010; https://www.cargotec.com/en/old-news/automated-straddle-carrier-facility-wins-terminal-of-the-year-award-/.

32. Automating The Last Mile: Startups Chasing Robot Delivery By Land And Air, CB Insights, March 30, 2017; https://www.cbinsights.com/research/autonomous-drone-delivery-startups.

33. Automation in Construction; https://www.sciencedirect.com/journal/automation-in-construction.

34. Autonomous drilling robot debut, ABB robotics, December 19, 2019; https://new.abb.com/news/detail/53854/autonomous-drilling-robot-debut.

35. Autonomous intralogistics from indoors to outdoors: SICK and Stäubli WFT provide a seamless logistics chain for BASF, SICK Sensor Intelligence, June 20, 2022; https://www.sick.com/cz/cs/sick-sensor-blog/autonomous-intralogistics-from-indoors-to-outdoors-sick-and-staeubli-wft-provide-a-seamless-logistics-chain-for-basf/w/blog-autonomous-intralogistics-indoors-outdoors/.

36. Autonomous vehicles could be crucial in responding to future pandemics, March 26, 2020; https://www.therobotreport.com/autonomous-vehicles-vital-role-solving-future-pandemics/.

37. Baldwin, E.: Makr Shakr Opens Robotic Bars in Milan and London. ArchDaily, July 26, 2019; https://www.archdaily.com/921826/makr-shakr-opens-robotic-bars-in-milan-and-london.

38. Banker, S.: The Intelligent Forklift in the Age of the Industrial Internet of Things, Forbes, March 16, 2015; http://www.forbes.com/sites/stevebanker/2015/03/16/the-intelligent-forklift-in-the-age-of-the-industrial-internet-of-things/#21f526f57635.

39. Baptiste, I. et al.: Social Telepresence Robots: A Narrative Review of Experiments Involving Older Adults before and during the COVID-19 Pandemic, in: Int J Environ Res Public Health, April 2021; https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8037050/.

40. Barker, B.: Robots Take on Tough Tasks in Transmission and Distribution, EPRI Journal, 2020; https://eprijournal.com/robots-take-on-tough-tasks-in-transmission-and-distribution/.

41. Bechtsis, D.; Tsolakis, N.; Vlachos, D.; Iakovou, E.: Sustainable supply chain management in the digitalisation era: The impact of Automated Guided Vehicles, Journal of Cleaner Production, vol. 142, 2017; pp. 3970-3984.

42. Belpaeme, T.; Kennedy, J.; Ramachandran, A.; Scassellati, B.; Tanaka, F.: Social robots for education: A review. Science Robotics, vol. 3, 2018, 21, eaat5954; https://pubmed.ncbi.nlm.nih.gov/33141719/.

43. Bendale, T., Kharat, V.: Comparative analysis and future trends of robotics in nuclear power plants, 2017 International Conference on Intelligent Sustainable Systems (ICISS), Palladam, 2017, pp. 400-405; https://dl.acm.org/doi/abs/10.1145/3529763.3529769.

44. Benitti, F.: Exploring the educational potential of robotics in schools: A systematic review. Computers & Education vol. 58, 2012, 3, pp. 978-988;

45. Bhatarrai, A.; Penman, M.: Restaurants can't find workers because they've found better jobs. The Washington Post, February 3, 2023; https://www.washingtonpost.com/business/2023/02/03/worker-shortage-restaurants-hotels-economy/.

46. Blake, R.: Age Of Robo-Pizza, Lukewarm On Arrival, Heats Up. Forbes, September 25, 2020; https://www.forbes.com/sites/richblake1/2020/09/25/age-of-robo-pizza-lukewarm-on-arrival-heats-up/?sh=530bca214a61.

47. Bock, T.; Linner, T.: Robot Oriented Design: Design and Management Tools for the Deployment of Automation and Robotics in Construction. The Cambridge Handbooks in Construction Robotics, Cambridge University Press, 2015.

48. Boffard, R.: Tiny bots to embark on fantastic voyage, Engineering & Technology, vol. 10, 2015, no. 5, pp. 34-36.

49. Brown, L.: Blendid™ Opens Fourth Kiosk Location at Walmart in Bay Area. Cision PR Newswire, October 15, 2020; https://www.prnewswire.com/news-releases/blendid-opens-fourth-kiosk-location-at-walmart-in-bay-area-301152730.html.

50. Built Offsite: ABB Robotics targets prefabrication construction industry with advanced building technology; May 2021; https://builtoffsite.com.au/news/robotics-prefabrication/.

51. Burrows, L./SEAS Communications: A personalized exosuit for real-world walking, November 10, 2021; https://wyss.harvard.edu/news/a-personalized-exosuit-for-real-world-walking/.

52. Buzalka, M.: Blendid smoothie-making robot debuts at Sonoma State University dining services. Food Management, January 2, 2020;

53. Caballar, R. D.: This Bricklaying Robot Is Changing the Future of Construction, Autodesk.com, May 29, 2019; https://www.autodesk.com/design-make/articles/bricklaying-robot.

54. Cable robot for facade operations in the European Hephaestus Project: https://www.hephaestus-project.eu.

55. Caccamo, S.: Last Mile Delivery Robots; https://univrses.com/case-study/last-mile-delivery-robots/.

56. Capari, G. et al.: Highly Compact Robots for Inspection in Power Plants, Journal of Field Robotics, vol. 29, 2012, no. 1, pp. 47-69;

57. Carnegie Mellon Snake Robot Used in Search for Mexico Quake Survivors, Carnegie Mellon University, September 27, 2017; https://www.cmu.edu/news/stories/archives/2017/september/snakebot-mexico.html.

58. Castro, A.; Pereira, J. M.: Estimating efficiency in automatic milking system, Journal of Dairy Science, vol. 95, no. 2, 2012, pp. 929-936; https://www.researchgate.net/publication/317174754_Estimating_efficiency_in_automatic_milking_systems. And a newer source from Farmers Weekly 2019: https://www.fwi.co.uk/livestock/dairy/a-dairy-farmers-guide-to-switching-to-robotic-milking.

59. Castro, A.; Pereira, J. M.; Amiama, C.; Bueno, J.: Typologies of dairy farms with automatic milking system in northwest Spain and farmers' satisfaction, Italian Journal of Animal Science, vol. 14, no. 2, 2015, pp. 207-219; https://doi.org/10.4081/ijas.2015.3559.

60. Cepolina, F.; Razzoli, R. P.: An introductory review of robotically assisted surgical systems. Int J Med Robot. August 2022 18(4).

61. Cha, J.: Hyundai Motor Group Introduces Advanced Humanoid Robot ‘DAL-e’ for Automated Customer Services. January 25, 2021; https://www.hyundainews.com/en-us/releases/3242.

62. Charli cleans up at Creys-Malville, World Nuclear News, December 4, 2013; http://www.world-nuclear-news.org/C-Charli-cleans-up-at-Creys-Malville-0612137.html.

63. Chu, J.: “Blind” Cheetah 3 robot can climb stairs littered with obstacles, July 4, 2018; http://news.mit.edu/2018/blind-cheetah-robot-climb-stairs-obstacles-disaster-zones-0705.

64. Chun, W. H.; Papanikolopoulos, N.: Robot Surveillance and Security. In: Siciliano, B. and Khatib, O. (eds.): Springer Handbook of Robotics, 2nd Edition. Berlin, Heidelberg: Springer, 2016, pp. 1605-1626.

65. Chung, T.: DARPA Subterranean (SubT) Challenge: https://www.darpa.mil/program/darpa-subterranean-challenge.

66. Ciuti, G.; Caliò, R., Camboni; D., Neri, L.; Bianchi, F.; Arezzo, A.; Magnani, B.: Frontiers of robotic endoscopic capsules: a review, Journal of micro-bio robotics, vol. 11, 2016, pp. 1-18; https://pubmed.ncbi.nlm.nih.gov/29082124/.

67. Codified, e.g. by the United Nations Convention on the Rights of Persons with Disabilities in 2008.

68. Colombo, R.; Sanguineti, V. (eds.): Rehabilitation Robotics, Academic Press, March 10, 2018; https://www.elsevier.com/books/rehabilitation-robotics/colombo/978-0-12-811995-2.

69. Conner, M.: NASA Armstrong Fact Sheet: Ikhana Predator B Unmanned Science and Research Aircraft System, NASA, April 23, 2019; https://www.nasa.gov/armstrong/meda-resources/fact-sheets/#aircraft.

70. Construction Robotics; http://www.springer.com/engineering/control/journal/41693.

71. Cousineau, L.; Miura, N.: Construction robots. The Search for New Building Technology in Japan. Reston, VA: ASCE Press, 1998.

72. Crotti, N. : FDA warns about using surgical robots for cancer treatment, The Robot Report, March 2, 2019; https://www.therobotreport.com/surgical-robots-fda-warning-cancer/.

73. Crowe, S.: Built Robotics raises $33M for autonomous construction vehicles, September 19, 2019;

74. Crowe, S.: Dusty Robotics FieldPrinter automates building layout, December 2019; https://www.therobotreport.com/dusty-robotics-fieldprinter-automates-building-layout/.

75. Curran, A., O'Connor, B., Lowe, C., King, E.: Analyzing the Current Market of Hull Cleaning Robots, Washington DC, 2016; https://digital.wpi.edu/concern/student_works/ws859f89n?locale=zh.

76. Cybathlon ; https://cybathlon.ethz.ch.

77. D'Onfro, J.: How a billionaire who wrote Google's original code created a robot revolution. February 13, 2016; https://www.businessinsider.in/How-a-billionaire-who-wrote-Googles-original-code-created-a-robot-revolution/articleshow/50988306.cms.

78. Daim, T. U.; Yoon, B.-S.; Lindenberg, J., Grizzi, R.; Estep, J., Oliver, T.: Strategic roadmapping of robotics technologies for the power industry: A multicriteria technology assessment. Technological Forecasting and Social Change, vol. 131, pp. 49-66, 2018; https://ideas.repec.org/a/eee/tefoso/v131y2018icp49-66.html.

79. Dawson, C.: Children with autism could benefit from USC assistive robot. March 5, 2020; https://www.therobotreport.com/children-with-autism-could-benefit-from-usc-assistive-robot/.

80. Decommissioning Nuclear Facilities, World Nuclear Association, May 2021; http://www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-wastes/decommissioning-nuclear-facilities.aspx.

81. Deirmengian, C. A.; Lonner, J. H.: What's New in Adult Reconstructive Knee Surgery, The Journal of Bone and Joint Surgery, vol. 90, 2008, pp. 2556-2565;

82. Demaitre, E.: Coronavirus response growing from robotics companies, March 2, 2020; https://www.therobotreport.com/coronavirus-response-growing-robotics-companies/.

83. Demaitre, E.: Miko 2 educational robot coming to North America. October 29, 2019; https://www.therobotreport.com/miko-2-educational-robot-coming-north-america/.

84. Demaitre, E.: Tethys Enables Students to Code for SoftBank's Pepper Humanoid Robot. March 5, 2020; https://www.roboticsbusinessreview.com/news/tethys-enables-students-to-code-for-softbanks-pepper-humanoid-robot/.

85. Desai, J. P.; Patel, R. V., Ferreira, A.; Agrawal, S. K. (eds.): Encyclopedia of Medical Robotics. World Scientific, 2017; https://www.worldcat.org/de/title/encyclopedia-of-medical-robotics/oclc/1237230972.

86. Development of a Humanoid Robot Prototype, HRP-5P, Capable of Heavy Labor, AIST, November 16, 2018; https://www.aist.go.jp/aist_e/list/latest_research/2018/20181116/en20181116.html.

87. Díaz, C. E.; Fernández, R.; Armada, M.; García, F. X.: A research review on clinical needs, technical requirements, and normativity in the design of surgical robots, The International Journal of Medical Robotics and Computer Assisted Surgery, vol. 13, 2017, no. 4;

88. Digital Service Standards (DSS); https://www.developer.tech.gov.sg/guidelines/standards-and-best-practices/digital-service-standards.

89. Dijk, M.v. et al.: A meta-analysis of projected global food demand and population at risk of hunger for the period 2010–2050, nature food, 2021, no.2; https://www.nature.com/articles/s43016-021-00322-9.

90. Dohle, C. I. et al.: Pilot study of a robotic protocol to treat shoulder subluxation in patients with chronic stroke, Journal of NeuroEngineering and Rehabilitation, August 5, 2013; http://www.jneuroengrehab.com/content/pdf/1743-0003-10-88.pdf.

91. Dorfman, P.: How much will it really cost to decommission the aging French nuclear fleet? Energy Post, March 15, 2017; http://energypost.eu/how-much-will-it-really-cost-to-decommission-the-aging-french-nuclear-fleet.

92. Durrant-Whyte, H.; Pagac, D.; Rogers, B.; Stevens, M.; Nelmes, G.: Field and service applications - An autonomous straddle carrier for movement of shipping containers - From Research to Operational Autonomous Systems, IEEE Robotics & Automation Magazine, vol. 14, 2007, no. 3, pp. 14-23; and Hollamby, M.: The ease of automation. Automation is a key competitive advantage for Patrick’s container terminal at the Port of Brisbane, Australia, Kalmar Global; https://www.kalmarglobal.com/globalassets/customer-cases/all-customer-cases/patrick-brisbane-australia/case_patrick_brisbane_autostrad_web.pdf.

93. eBee X fixed-wing mapping drone, sensefly, 2021: https://www.sensefly.com/drone/ebee-x-fixed-wing-drone/.

94. Edwards, D.: ANYmal robot being put to work inspecting BASF facility, March 30, 2021; https://roboticsandautomationnews.com/2021/03/30/anymal-robot-being-put-to-work-inspecting-basf-facility/41990/.

95. EFFIROB study: https://www.ipa.fraunhofer.de/en/reference_projects/EFFIROB.html.

96. Elkmann, N., Hortig, J.; Fritzsche, M.: Cleaning automation. In: Nof, S. Y. (ed.): Springer Handbook of Automation. Berlin, Heidelberg: Springer, 2009, pp. 1253-1264.

97. ELROB – The European Land Robot Trial; ELROB: http://www.elrob.org.

98. Engelberger, J. F.: HelpMate, a service robot with experience, Industrial Robot: An International Journal, vol. 25, no. 2, 1998, pp. 101-104.

99. EU projects on smart agri-food systems: http://www.europarl.europa.eu/RegData/etudes/STUD/2016/581892/EPRS_STU(2016)581892_EN.pdf.

100. European Parliamentary Research Service (EPRS): Precision agriculture and the future of farming in Europe. Scientific Foresight Study, December 2016; http://www.europarl.europa.eu/RegData/etudes/STUD/2016/581892/EPRS_STU(2016)581892_EN.pdf.

101. Fazlollahtabar, H.; Saidi-Mehrabad, M.: Autonomous Guided Vehicles. Methods and Models for Optimal Path Planning, Studies in Systems, Decision and Control, vol. 20, Springer, 2015.

102. Fetch Robotics was acquired by Zebra Technologies: Crowe, S.: Fetch Robotics acquired by Zebra Technologies for USD290M, The Robot Report, July 1, 2021; https://www.therobotreport.com/fetch-robotics-acquired-by-zebra-technologies-for-290m/.

103. Field Robot Event 2024, 11.-13.06.2024, Erwitte/Lippstadt (GER); https://fieldrobot.nl/event/index.php/2023/11/27/field-robot-event-2024/.

104. Firefighting robots: https://allonrobots.com/firefighting-robots/.

105. FIRST (For Inspiration and Recognition of Science and Technology): https://www.firstinspires.org/about/vision-and-mission

106. Frearson, A.: 10 projects paving the way to a future robot-built architecture, dezeen magazine, May 10, 2016; http://www.dezeen.com/2016/05/10/10-projects-that-look-future-robotic-construction-robots-architecture.

107. Fukushima Daiichi Nuclear Power Plant Accident, Ten Years On, 2021; https://www.oecd-nea.org/jcms/pl_56742/fukushima-daiichi-nuclear-power-plant-accident-ten-years-on.

108. Gardecki, A.; Podpora, M.: Experience from the operation of the Pepper humanoid robots. In Progress in Applied Electrical Engineering (PAEE), 2017, pp. 1-6; https://ieeexplore.ieee.org/document/8008994.

109. Garingo, A.; Friedlich, P.; Chavez, T.: “Tele-rounding” with a remotely controlled mobile robot in the neonatal intensive care unit. In: Journal of Telemedicine and Telecare, vol. 22, 2015, no. 2; https://www.researchgate.net/publication/279300194_Tele-rounding_with_a_remotely_controlled_mobile_robot_in_the_neonatal_intensive_care_unit.

110. Garrec, P.; Perrot, Y.: Force Feedback Nuclear Telerobotics in France: R&D Results and Industrial Achievements, In: Puresafe Final Conference, CERN, Switzerland, January 2015; https://indico.cern.ch/event/346833/contributions/1751182/attachments/684457/940211/PURESAFE_CERN_january_2015_Garrec_Perrot.pdf.

111. Gauthier, M.; Andreff; N.; Dombre, E.: Intracorporeal Robotics: From Milliscale to Nanoscale, John Wiley & Sons, 2014.

112. Gilhooly, R.: Robots go deep inside Fukushima nuclear plant to map radiation. New Scientist, April 15, 2015, https://www.newscientist.com/article/mg22630172-300-robots-go-deep-inside-fukushima-nuclear-plant-to-map-radiation.

113. Gillet, S. et al.: “Robot gaze can mediate participation imbalance in groups with different skill levels.” Proceedings of the 2021 ACM/IEEE International Conference on Human-Robot Interaction. 2021; https://www.semanticscholar.org/paper/Learning-Gaze-Behaviors-for-Balancing-Participation-Gillet-Parreira/567d44c2a0c972ab9b39765f2802f85a2e73caa6.

114. Giuliani-Hofmann, F.: The first firefighting robot in America is here – and it has already helped fight a major fire in Los Angeles; October 2020. https://edition.cnn.com/2020/10/21/business/first-firefighting-robot-in-america-lafd-trnd/index.html

115. Gölder, M.; Herstatt, G.; Tietze, F.; Rehder S.: The Emergence of Care Robotics – A publication and patent analysis, March 2015, pp. 115-131; https://www.sciencedirect.com/science/article/pii/S0040162514002753.

116. Gossett, S.: 12 ways rescue robots save the day during disasters and emergencies, Built In, June 25, 2019; https://builtin.com/robotics/rescue-robots.

117. Graf, B.; King, R. S.; Schiller, C.: Development of an intelligent care cart and new supplies concepts for care homes and hospitals. In: 47th International Symposium on Robotics: Robotics in the Era of Digitalization. June 21-22, 2016, Munich, Germany. Berlin; Offenbach, 2016, pp. 446-451.

118. Guide for Evaluating, Purchasing, and Training with Response Robots Using DHS-NIST-ASTM International Standard Test Methods, NIST, ASTM International Standards Committee on Homeland Security Applications; Operational Equipment; Robots (E54.08.01): Standard Test Methods For

Response Robots; http://www.nist.gov/el/isd/ks/upload/DHS_NIST_ASTM_Robot_Test_Methods-2.pdf.

119. Hayes, M.: Bricklaying robot hits 200 blocks per hour, construction europe, June 8, 2020; https://www.khl.com/construction-europe/bricklaying-robot-hits-200-blocks-per-hour/144453.article.

120. He, Y.; Eguren, D., Luu, T. P.; Contreras-Vidal, J. L.: Risk management and regulations for lower limb medical exoskeletons: a review. Medical devices (Auckland, NZ), vol. 10, 2017, pp. 89-107; https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5431736.

121. Heater, B.: Rugged's construction layout robots land $9.4M; TechCrunch; March 2022; https://techcrunch.com/2022/03/23/ruggeds-construction-layout-robots-land-9-4m/.

122. Hertzfeld, E.: Singapore Hotel Jen properties install Relay autonomous robots, Hotel Management, November 21, 2017; https://www.hotelmanagement.net/tech/hotel-jen-installs-relay-autonomous-robots.

123. Hess, S.; Siegwart, R. Y.: University Technology Incubator: Technology Transfer of Early Stage Technologies in Cross-Border Collaboration with Industry, Business and Management Research, vol. 2, no. 2, 2013; http://www.sciedu.ca/journal/index.php/bmr/article/download/2859/1693.

124. Hillegersberg, M.m.j. Van: Robots benefit special education students, April 21, 2021, https://techxplore.com/news/2021-04-robots-benefit-special-students.html.Hintersdorf, C.: Automatisierte Roboterküche kommt nach Tübingen. HOGAPAGE, March 14, 2024 https://www.hogapage.de/nachrichten/messeneuheiten/technik-software-messe/automatisierte-roboterk%C3%BCche-kommt-nach-t%C3%BCbingen/.

125. Hogan, R.: Niska introduces robotic retail through ice cream. September 17, 2019; https://insidefmcg.com.au/2019/09/17/niska-introduces-robotic-retail-through-ice-cream/.

126. Holland, M.: Boston Dynamics: Roboter Spot für 74.500 US-Dollar zu kaufen, June 17, 2020; https://www.heise.de/news/Boston-Dynamics-Roboter-Spot-fuer-74-500-US-Dollar-zu-kaufen-4786299.html.

127. Holloway, L.; Wilkinson, K.; Bear, C.: Re-capturing bovine life: robot-cow relationships, freedom and control in dairy farming; http://orca.cf.ac.uk/39368/1/geogroboticsIBG%202011%20presentation.pdf.

128. Hornemann, M.: Antifouling Symposium 2003. Symposium at INTERBOOT, September 22, 2003, Friedrichshafen (Germany).

129. Hornyak, T.: How robots are becoming critical players in nuclear disaster cleanup. Science, March 3, 2016; http://www.sciencemag.org/news/2016/03/how-robots-are-becoming-critical-players-nuclear-disaster-cleanup.

130. Houser, K.: This Autonomous Robot Arm Feeds People Who Can't Feed Themselves, March 14, 2019; https://futurism.com/autonomous-robot-arm-feeds-people.

131. Howe & Howe Technologies: Thermite, 2021; https://www.howeandhowe.com/civil/thermite.

132. Hruska, J.: Colossal Achievement: Half-Ton Firefighting Robot Helps Save Notre Dame; ExtremeTech; April 17, 2019: https://www.extremetech.com/extreme/289693-colossal-achievement-half-ton-firefighting-robot-helps-save-notre-dame.

133. http://researchopen.lsbu.ac.uk/1594/1/Robotics%20for%20Nuclear%20work.pdf

134. http://stroke.ahajournals.org/content/43/4/1140.full.pdf?download=true.

135. http://welcome.isr.tecnico.ulisboa.pt/wp-content/uploads/2015/05/3419_p1635.pdf.

136. http://www.builtrobotics.com.

137. http://www.hydroquebec.com/robotics/generation-solutions-scompi.html.

138. https://accessprosthetics.com/15-limb-loss-statistics-may-surprise/.

139. https://apptronik.com/solutions/trailer-unloading.

140. https://bostondynamics.com/products/stretch.

141. https://braincorp.com/.

142. https://ces2024.deere.com/.

143. https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en.

144. https://cordis.europa.eu/project/id/643666/factsheet.

145. https://cordis.europa.eu/project/id/723611/de.

146. https://corporate.walmart.com/news/2024/04/11/a-fork-in-the-road-walmart-bets-on-associates-automation.

147. https://dok-ing.hr/products/mvf-5/.

148. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Farmers_and_the_agricultural_labour_force_-_statistics.

149. https://eu.statesman.com/story/business/technology/2023/08/29/apptronik-robotics-company-austin-humanoid-robot-apollo-commercialize-work-alongside-humans/70618882007/.

150. https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=celex:32013R0167.

151. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32006L0042.

152. https://experience.irobot.com/achieving-diversity-equity-and-inclusion-through-stem-education-white-paper.

153. https://github.com/RoboDesignLab/HOPPY-Project.

154. https://global.toyota/en/mobility/frontier-research/.

155. https://global.toyota/en/newsroom/corporate/28912712.html.

156. https://ieeexplore.ieee.org/abstract/document/6392475.

157. https://ifr.org/ifr-press-releases/news/robots-help-to-solve-japans-2024-problem.

158. https://link.springer.com/article/10.1007/s43154-020-00034-1.

159. https://markwideresearch.com/automated-forklift-trucks-market/.

160. https://markwideresearch.com/global-automated-truck-loading-system-market/.

161. https://meridian.allenpress.com/tscir/article/17/1/54/190916/Transferring-ARMin-to-the-Clinics-and-Industry.

162. https://mobilerobotguide.com/2022/03/28/boston-dynamics-stretch-ready-to-automate-trailer-unloading/.

163. https://mujin-corp.com/truckbot-automated-truck-unloader/.

164. https://nypost.com/2018/03/27/finland-schools-are-testing-out-robot-teachers/.

165. https://og.mhi.org/media/members/14259/133294184720615242.pdf.

166. https://pdfs.semanticscholar.org/d82b/865cbd68cd9526790614f1c76f74d21c7550.pdf.

167. https://phys.org/news/2018-08-robot-teachers-invade-chinese-kindergartens.html.

168. https://population.un.org/wpp/Graphs/DemographicProfiles/Pyramid/1829.

169. https://pubmed.ncbi.nlm.nih.gov/28105687/.

170. https://repositorio-aberto.up.pt/bitstream/10216/84607/2/138902.pdf.

171. https://robots.ros.org/tags/#education.

172. https://scienceandtechnology.jpl.nasa.gov/build-your-own-rover.

173. https://seaclear-project.eu.

174. https://segment-anything.com/.

175. https://smarttooling.eu/project-smart-tooling.

176. https://sprintrobotics.org/about/.

177. https://sps.honeywell.com/us/en/support/automation/resources/brochures/robotic-unloader.

178. https://thespoon.tech/flippys-frying-pilot-is-a-hit-at-dodger-stadium/.

179. https://tinyurl.com/Water-Tank-Cleaning2020.

180. https://unitedrobotics.group/en/news-events-press/press-releases/kevin-laboratory-robot.

181. https://us.softbankrobotics.com/blog/meet-tethys.

182. https://www.agdaily.com/technology/john-deere-unveils-precision-seed-fertilizer-at-ces-2023/.

183. https://www.agvnetwork.com/autonomous-forklift-costs.

184. https://www.agvnetwork.com/types-of-agv/types-of-robot-forklift.

185. https://www.ancra.nl/upload/docs/whitepaper-atls-technology-information-ancra-systems.pdf.

186. https://www.apexwarehousesystems.com/its-a-forklift-its-a-robot-no-its-a-robotic-forklift/.

187. https://www.bastiansolutions.com/solutions/technology/industrial-robotics/robotic-truck-loading/.

188. https://www.bearrobotics.ai/blog/bear-robotics-secures-60m-series-c-funding-led-by-lg-electronics.

189. https://www.bls.gov/iif/nonfatal-injuries-and-illnesses-tables/case-and-demographic-characteristics-table-r31-2020.htm.

190. https://www.bls.gov/iif/snapshots/osn-laborers-and-freight-stock-and-material-movers-hand-2016-20.htm.

191. https://www.cargotec.com/en/nasdaq/trade-press-release-kalmar/2019/kalmar-adds-automated-truck-handling-to-its-autostrad-offering.

192. https://www.darpa.mil/news-events/2023-12-14.

193. https://www.deere.com/en/news/all-news/autonomous-tractor-reveal.

194. https://www.dexterity.ai/blog/dexterity-ai-and-fedex-unveilfirst-of-its-kind-robotics-trailer-loading-technology.

195. https://www.dexterity.ai/product/robotic-truck-loading.

196. https://www.edf.org/ecosystems/resilient-agriculture/precision-agriculture.

197. https://www.engineerlive.com/content/robotic-tank-cleaning-technology.

198. https://www.epa.gov/agriculture/laws-and-regulations-apply-your-agricultural-operation-farm-activity.

199. https://www.epa.gov/caddis-vol2/herbicides#:~:text=The%20most%20direct%20effects%20of,macrophytes%2C%20periphyton%20and%20phytoplankton.

200. https://www.fao.org/faostat/en/#data/RP/visualize.

201. https://www.food-management.com/colleges-universities/blendid-smoothie-making-robot-debuts-sonoma-state-university-dining-services.

202. https://www.fraunhofer.it/en/Application-Centre-ARENA/Preliminary-research-and-applications/rosbim.html.

203. https://www.geekwire.com/2019/apple-picking-robots-gear-u-s-debut-washington-state.

204. https://www.google.com/maps/d/edit?mid=18St8TtmdVwpzZb9JVJI_XOOw3vE&ll=5.5652892073519595%2C0&z=2.

205. https://www.groundhandlinginternational.com/content/news/air-india-sats-invests-rs-55m-in-india-s-first-automated-aircraft-cleaning-robot/.

206. https://www.hastingscontemporary.org/learning/#robot-tours.

207. https://www.hastingscontemporary.org/learning/#robot-tours.

208. https://www.hilti.de/content/hilti/E3/DE/de/business/business/productivity/semi-autonomer-baustellenroboter-jaibot.html.

209. https://www.hitachi.com/rev/archive/2020/r2020_04/04d02/index.html.

210. https://www.intercleanshow.com/amsterdam/programme/activities#robotarena.

211. https://www.ipa.fraunhofer.de/en/press-media/press_releases/fraunhofer-ipa-presents-disinfection-robot-dekonbot.html.

212. https://www.ipa.fraunhofer.de/en/reference_projects/EFFIROB.html.

213. https://www.ipa.fraunhofer.de/en/reference_projects/free_navigation.html.

214. https://www.jnj.com/media-center/press-releases/johnson-johnson-medtech-provides-details-and-timeline-for-general-surgery-robot.

215. https://www.jstage.jst.go.jp/article/atcs/advpub/0/advpub_oa.14-00076/_pdf.

216. https://www.kma-online.de/aktuelles/medizintechnik/detail/neuer-herzkatheter-roboter-am-uniklinikum-freiburg-im-einsatz-a-45527.

217. https://www.leorover.tech/the-rover.

218. https://www.logisticstechoutlook.com/navflex.

219. https://www.makrshakr.com/special-projects/royal-caribbean.

220. https://www.marketdataforecast.com/market-reports/petroleum-tank-cleaning-market.

221. https://www.meilirobots.com/resources-list/robot-guide.

222. https://www.mm-logistik.vogel.de/ejner-versorgt-daenische-patienten-a-500471/.

223. https://www.navflex.com/references.

224. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4698499/.

225. https://www.neerjagroup.com/product/brokk/remote-controlled-demolition-robots.

226. https://www.niehs.nih.gov/health/topics/agents/pesticides/index.cfm.

227. https://www.nytimes.com/2004/03/05/world/machida-journal-japan-seeks-robotic-help-in-caring-for-the-aged.html.

228. https://openai.com/research/whisper.

229. https://www.poppy-education.org/.

230. https://www.prnewswire.com/news-releases/automation-is-making-work-more-human-global-research-reveals-300714154.html.

231. https://www.researchandmarkets.com/reports/338539/contract_cleaning_services_global_strategic.

232. https://www.research-collection.ethz.ch/bitstream/handle/20.500.11850/82240/eth-7796-01.pdf;jsessionid=65694A4B80C5660382F8E2585F955ABC?sequence=1.

233. https://www.robocup.org/.

234. https://www.robotics247.com/article/fox_robotics_surpasses_2.5_million_pallet_pulls_with_foxbot_autonomous_trailer_loader_unloader.

235. https://www.sciencedirect.com/science/article/abs/pii/S0360131511002508.

236. https://www.semanticscholar.org/paper/Construction-Robots%3A-The-Search-for-New-Building-in-CousineauMiura/a4960fc13b835e783eb853cec0071eb67eea4316.

237. https://www.smartrobottutor.com.

238. https://www.statista.com/statistics/606542/japan-age-distribution.

239. https://www.straitstimes.com/asia/east-asia/coronavirus-china-develops-robot-for-throat-swab-sampling.

240. https://www.textronsystems.com/our-company/news-events/articles/press-release/howe-howe-completes-first-domestic-sale-thermite-rs3.

241. https://www.therobotreport.com/built-robotics-33m-autonomous-construction-equipment/.

242. https://www.therobotreport.com/gaumard-gives-simulated-patients-realistic-symptoms-medical-training/.

243. https://www.therobotreport.com/nanobots-promise-change-medical-treatment/.

244. https://www.therobotreport.com/neo-2-cleaning-robot-includes-avidbots-updates-ai-fleet-management/.

245. https://www.therobotreport.com/slip-robotics-launches-new-trailer-pallet-unloading-solution/.

246. https://www.therobotreport.com/stryker-leads-orthopedic-surgery-robots/.

247. https://www.therobotreport.com/yomi-robot-neocis-gets-fda-nod-full-arch-dental-implants/.

248. https://www.therobotreport.com/yusen-logistics-pickle-robot-collaborate-streamline-container-unloading/.

249. https://www.theverge.com/21317052/mobile-autonomous-robot-lab-assistant-research-speed.

250. https://www.trendhunter.com/trends/human-washing-machine-avant-santelubain-999-applies-seaweed-packs-too.

251. https://www.umweltbundesamt.de/en/data/environmental-indicators/indicator-nitrate-in-groundwater#at-a-glance.

252. https://www.un.org/en/global-issues/ageing.

253. https://www.wsj.com/articles/hospitals-address-a-drug-problem-1392762765.

254. https://www.xprize.org/prizes/avatar.

255. https://www.youtube.com/watch?v=-ZxVm6QgLc8.

256. Hung, L.: Liu, C., Woldum, E.; Au-Yeung, A.; Berndt, A.; Wallsworth, C. et al.: The benefits of and barriers to using a social robot PARO in care settings: a scoping review. In: BMC Geriatr, vol. 19, 2019, no.1, DOI: 10.1186/s12877-019-1244-6; https://pubmed.ncbi.nlm.nih.gov/31443636/.

257. Huw, O.: France now has a robot-run pizza restaurant. Time Out, June 15, 2020; https://www.timeout.com/news/france-now-has-a-robot-run-pizza-restaurant-061520.

258. Ichimura, T.; Nakajima, S.: Performance Evaluation of a Beach Cleaning Robot “Hirottaro 3” in an Actual Working Environment; 2018 18th International Conference on Control, Automation and Systems (ICCAS 2018); https://ieeexplore.ieee.org/abstract/document/8571634.

259. Icub, an open source cognitive humanoid robotic platform; http://www.icub.org/.

260. IDEA and ECA GROUP present their first autonomous vehicle, IDEA group, September 30, 2021; https://www.groupe-idea.com/en/linfo-idea/idea-et-eca-group-presentent-leur-premier-vehicule-autonome.

261. Important Stories on Decommissioning 2018: Fukushima Daiichi Nuclear Power Station, now and in the future, Agency for Natural Resources and Energy, Ministry of Economy, Trade and Industry, March 2018 (updated in 2022); https://www.meti.go.jp/english/earthquake/nuclear/decommissioning/index.html.

262. In- und Auslandsumsatz der Landmaschinenindustrie¹ in Deutschland in den Jahren 2005 bis 2023 (in Millionen Euro) [Graph], Statistisches Bundesamt, March 18, 2024; https://de.statista.com/statistik/daten/studie/1237059/umfrage/in-und-auslandsumsatz-im-landmaschinenbau/.

263. Ingham, L.: Telepresence robots make lockdown graduation a reality for student. May 12, 2020; https://www.verdict.co.uk/telepresence-robots-graduation-students/.

264. International Association for Automation and Robotics in Construction (I.A.A.R.C.); conference proceedings http://www.iaarc.org/pe_publications.htm.

265. International Conference on Rehabilitation Robotics ICORR; https://icorr-c.org/.

266. International Workshop on the Use of Robotic Technologies at Nuclear Facilities; Gaithersburg, USA, February 2-4, 2016; https://www.nist.gov/news-events/events/2016/02/international-workshop-use-robotic-technologies-nuclear-facilities.

267. Iqbal, J.; Tahir, A. M.; Islam, R. ul; Riaz-un-Nabi: Robotics for Nuclear Power Plants – Challenges and Future Perspectives. In: Proceedings of the 2012 IEEE Second International Conference on Applied Robotics for the Power Industry (CARPI), ETH Zurich, Switzerland, September 11-13, 2012; https://www.semanticscholar.org/paper/Robotics-for-Nuclear-Power-Plants-%E2%80%94-Challenges-and-Iqbal-Tahir/c18978908cab97b173efd1d41fbf78ec74ec0885.

268. Iurchak, D.: 200-400 Nuclear reactors to be decommissioned by 2040, February 2020; https://energypost.eu/200-400-nuclear-reactors-to-be-decommissioned-by-2040/.

269. Jacobs, J. A.; Siegfort, J. M.: The impact of automatic milking systems on dairy cow management, behavior, health, and welfare, Journal of Dairy Science, vol. 95, no. 5, 2012, pp. 2227-2247.

270. Jain, S. et al.: “Modeling engagement in long-term, in-home socially assistive robot interventions for children with autism spectrum disorders.” Science Robotics 5, 39, 2020; DOI: https://doi.org/10.1126/scirobotics.aaz3791.

271. Japan to start Fukushima fuel debris retrieval in 2021, World Nuclear News, June 4, 2015; http://www.world-nuclear-news.org/WR-Japan-to-start-Fukushima-fuel-debris-removal-in-2021-04061501.html.

272. Joerss, M.; Schröder, J.; Neuhaus, F.; Klink, C.; Mann F: Parcel delivery - the future of last mile, McKinsey & Company, September 2016; https://bdkep.de/files/bdkep-dateien/pdf/2016_the_future_of_last_mile.pdf.

273. Johnson, D. O. et al.: Socially Assistive Robots: A Comprehensive Approach to Extending Independent Living. International Journal of Social Robotics, April 2014, Volume 6, Issue 2, pp. 195-211; https://link.springer.com/article/10.1007/s12369-013-0217-8.

274. Johnson, K.: Hospital Robots Are Helping Combat a Wave of Nurse Burnout, Wired, April 19, 2022; https://www.wired.com/story/moxi-hospital-robot-nurse-burnout-health-care.

275. Jones, B.: VROOM: Virtual Robot Overlay for Online Meetings; https://dl.acm.org/doi/fullHtml/10.1145/3334480.3382820.

276. Jovanovic, K. et al.: Digital Innovation Hubs in Health-Care Robotics Fighting COVID-19: Novel Support for Patients and Health-Care Workers Across Europe. In: IEEE Robotics & Automation Magazine. - Piscataway, NJ, USA: IEEE. ISSN: 1070-9932 - 28 (2021), no. 1, S. 40-47; https://ieeexplore.ieee.org/abstract/document/9330556.

277. Kahane, B.; Rosenfeld, Y.: Balancing Human-and-Robot Integration in Building Tasks. Computer-Aided Civil and Infrastructure Engineering, vol. 19, no. 6, 2004, pp. 393-410; https://onlinelibrary.wiley.com/doi/abs/10.1111/j.1467-8667.2004.00365.x.

278. Kajiwara, N. et al.: Cost-Benefit Performance of Robotic Surgery Compared with Video-Assisted Thoracoscopic Surgery under the Japanese National Health Insurance System, Annals of Thoracic and Cardiovascular Surgery. May 16, 2014;

279. Katz, S.: Baubot comes out with two new robots to aid in construction projects, TechXplore, April 15, 2021; https://techxplore.com/news/2021-04-baubot-robots-aid.html.

280. Kerntechnische Hilfsdienst GmbH; https://khg.bgz.de/en/.

281. Kickingereder, P.; Willeit, P.; Simon, T.; Ruge, M. I.: Diagnostic Value and Safety of Stereotactic Biopsy for Brainstem Tumors: A Systematic Review and Meta-analysis of 1480 Cases, Neurosurgery, vol. 72, 2013, no. 6, pp. 873-882; https://pubmed.ncbi.nlm.nih.gov/23426149/.

282. Knightscope Inc.: MaaS Subscription Price, 2021; https://www.knightscope.com/price/.

283. Kolodny, L.: Elon Musk shows off humanoid robot prototype at Tesla AI Day. CNBC, September 30 2022; https://www.cnbc.com/2022/09/30/elon-musk-shows-off-humanoid-robot-prototype-at-tesla-ai-day.html.

284. Konecranes receives 6th order in 5 years for additional AGVs to CTA in Hamburg, December 22, 2021; https://www.konecranes.com/press/releases/2021/konecranes-receives-6th-order-in-5-years-for-additional-agvs-to-cta-in-hamburg/.

285. Konecranes to provide 30 AGVs to Long Beach Container Terminal, May 19, 2020; https://www.ship-technology.com/news/konecranes-agvs-long-beach-container-terminal/

286. Koomen, A.: Aquatech Innovation award winners announced, November 2, 2021; https://www.aquatechtrade.com/news/event/autonomous-robot-wins-aquatech-innovation-award.

287. Kootstra, G. et al.: Selective harvesting robotics: current research, trends, and future directions. Current Robotics Reports, 2021, 2, No. 1, pp. 95-104;

288. Koulaouzidis, A.; Iakovidis, D.; Karargyris, A.; Rondonotti, E.: Wireless endoscopy in 2020: Will it still be a capsule? World Journal of Gastroenterology, vol. 21, 2015, no. 17 pp. 5119–5130; https://www.wjgnet.com/1007-9327/full/v21/i17/5119.htm.

289. Krebs, H. I.; Volpe, B. T.: Rehabilitation Robotics. In: Barnes, M. P.; Good, D. C. (eds.): Neurological rehabilitation. Handbook of clinical neurobiology, vol. 110, Edinburgh: Elsevier, 2013, pp. 283-294.

290. Kusuda, Y.: A remotely controlled robot operates construction machines, Industrial Robot, vol. 30, no. 5, 2003, pp. 422-425.

291. Landro, L.: Hospitals Address a Drug Problem: Software and Robots Help Secure and Monitor Medications, The Wall Street Journal, February 23, 2014;

292. Lattanzi, D., Miller, G.: Review of robotic infrastructure inspection systems, Journal of Infrastructure Systems, vol. 23, no. 3, 2017; https://ascelibrary.org/doi/10.1061/%28ASCE%29IS.1943-555X.0000353.

293. Leeson, C.: From an unfamiliar other to a cherished friend: The domestication of telenoid in the care of elderly and disabled people. Workshop on Portable Androids and their Applications. Aalborg. Presentation March 2, 2015; http://hil.atr.jp/projects/CREST/DenmarkSymposium/program.html.

294. Leipheimer, J. M.; Balter, M. L.; Chen, A. I.; Pantin, E. J.; Davidovich, A. E.; Labazzo, K. S.; Yarmush, M. L.: First-in-human evaluation of a hand-held

automated venipuncture device for rapid venous blood draws. In: Technology, vol. 7, 2019, no. 3-4, pp. 98-107. DOI: 10.1142/S2339547819500067; https://pubmed.ncbi.nlm.nih.gov/32292800/.

295. LG and Hyundai collaborate to bring robots and cars closer together. July 2, 2019; http://www.lgnewsroom.com/2019/07/beyond-news-lg-and-hyundai-collaborate-to-bring-robots-and-cars-closer-together/.

296. Li, J.; de Ávila, B. E. F.; Gao, W.; Zhang, L.; Wang, J.: Micro/nanorobots for biomedicine: Delivery, surgery, sensing, and detoxification, Science Robotics, vol. 2, 2017, no. 4, eaam6431; https://pubmed.ncbi.nlm.nih.gov/31552379/.

297. Li, L., Li, D., Li, Y., Zhang, B., Zhao, J., Zhang, C., Dai, Z.: A state-of-the-art survey of the robotics applied for the power industry in China, Applied Robotics for the Power Industry (CARPI), 2016, pp. 1-5; https://ieeexplore.ieee.org/document/7745634.

298. Li, R. Y. M.: Robots for the Construction Industry. In: Li, R. Y. M. (ed.): An Economic Analysis on Automated Construction Safety. Springer, Singapore, 2018, pp. 23-46; https://link.springer.com/book/10.1007/978-981-10-5771-7.

299. Logistics Trend Radar: Delivering insight today. Creating value tomorrow! Version 2022, DHL Customer Solutions & Innovation, 2022; https://www.dhl.com/global-en/home/insights-and-innovation/insights/logistics-trend-radar.html.

300. Love, A.: Piping inspections near completion, August 13, 2018; http://www.pwsrcac.org/observer/piping-inspections-near-completion

301. Mapara, S. S.; Patravale, V. B.: Medical capsule robots: A renaissance for diagnostics, drug delivery and surgical treatment, Journal of Controlled Release, vol. 261, 2017, pp. 337-351; https://pubmed.ncbi.nlm.nih.gov/28694029/.

302. Markis, A. et al.: Safety of Mobile Robot Systems in Industrial Applications, Proceedings of the ARW & OAGM Workshop, 2019; https://workshops.aapr.at/wp-content/uploads/2019/05/ARW-OAGM19_04.pdf.

303. Marzani, A.: 16 Drone Security Use Cases You've Never Thought Of, DARTdrones, April 4, 2017; https://www.dartdrones.com/blog/drone-security.

304. Mascarenhas, M.: Robotic Coffee Startup Cafe X Shutters Stores, Pivots To Airports. Crunchbase News, January 7, 2020; https://news.crunchbase.com/news/robotic-coffee-startup-cafe-x-shutters-stores-pivots-to-airports/.

305. Matarić, M. J.; Scassellati, B.: Socially assistive robotics. In: Siciliano, B. and Khatib, O. (eds.): Springer Handbook of Robotics, 2nd Edition. Berlin, Heidelberg: Springer, 2016, pp. 1973-1994.

306. Mazur, M.: Six Ways Drones Are Revolutionizing Agriculture MIT Technology Review, July 20, 2016; https://www.technologyreview.com/s/601935/six-ways-drones-are-revolutionizing-agriculture.

307. McGlynn, S., Walters, D.: Agricultural Robots: Future Trends for Autonomous Farming. JETIR, vol. 6, Issue 4, April 2019; http://www.jetir.org/papers/JETIRBB06180.pdf.

308. ME 328: Medical Robotics: http://www.stanford.edu/class/me328/; particularly http://www.stanford.edu/class/me328/lectures/lecture1-intro.pdf.

309. Medical Robots, IEEE Spectrum; https://spectrum.ieee.org/tag/medical-robots.

310. Meisenzahl, M.: An Indian hospital is using robots with thermal cameras to screen coronavirus patients – here's how they work. May 9, 2020; https://www.businessinsider.com/india-coronavirus-robot-uses-thermal-camera-to-take-temperature-2020-5?r=DE&IR=T.

311. Meisenzahl, M.: Flippy, the USD 30,000 automated robot fast-food cook, is now for sale with 'demand through the roof' — see how it grills burgers and fries onion rings. Business Insider; October 18, 2020; https://www.businessinsider.com/miso-robotics-flippy-robot-on-sale-for-300000-2020-10?r=

312. Melted fuel removal at Fukushima delayed by pandemic, December 24, 2020 https://techxplore.com/news/2020-12-fukushima-nuclear-debris-virus.html.

313. Menendez, O., Auat Cheein, F. A., Perez, M., Kouro, S.: Robotics in Power Systems: Enabling a More Reliable and Safe Grid, in IEEE Industrial Electronics Magazine, vol. 11, 2017, no. 2, pp. 22-34, doi: 10.1109/MIE.2017.2686458; https://ieeexplore.ieee.org/document/7956250.

314. MHI Develops Autonomous 'Water Cannon Robot' and 'Hose Extension Robot' for Use in Firefighting. Expected to Play Active Role in Hazardous Situations Inaccessible to Firefighting Crews, press release by Mitsubishi Heavy Industries, March 25, 2019; https://www.mhi.com/news/story/190325.html.

315. Mid-and-Long-Term Roadmap towards the Decommissioning of Fukushima Daiichi Nuclear Power Units 1-4, Ministry of Economy, Trade and Industry Japan; http://www.meti.go.jp/english/earthquake/nuclear/decommissioning.

316. Miller, B.; Feil-Seifer, D.: Embodiment, situatedness, and morphology for humanoid robots interacting with people. In: Goswami, A.; Vadakkepat, P. (eds): Humanoid Robotics: A Reference, 2017, pp. 1-23.

317. Miller, K.: This Icelandic Bar Is Utilizing Robot Bartenders For Its Reopening Plan. May 28, 2020; https://www.insidehook.com/daily_brief/restaurants-bars/iceland-robot-bartender-ice-fries.

318. Miller, R., Abbasi, F., Mohammadpour, J.: Power line robotic device for overhead line inspection and maintenance, Industrial Robot: An International Journal, vol. 44, no. 1, 2017, pp. 75-84; https://www.researchgate.net/publication/312956959_Power_line_robotic_device_for_overhead_line_inspection_and_maintenance.

319. Mobile Robots with novel environmental sensor for inspection of disaster sites with low visibility; EU Project H2020 ICT-23-2014-Robotics; 2021; http://www.smokebot.eu.

320. Monteiro, A.; Santos, S.; Gonçalves, P. Precision Agriculture for Crop and Livestock Farming—Brief Review. Animals 2021, 11, 2345; https://doi.org/10.3390/ani11082345.

321. Monteiro, A.; Santos, S.; Gonçalves, P. Precision Agriculture for Crop and Livestock Farming—Brief Review. Animals 2021, 11, 2345; https://doi.org/10.3390/ani11082345.

322. Moons, K.; Waeyenbergh; G.; Pintelon, L.: Measuring the logistics performance of internal hospital supply chains – a literature study. Omega, January 21, 2018; http://iranarze.ir/wp-content/uploads/2018/02/E5866-IranArze.pdf.

323. Moretz, L.: Mobile Robot Standard R15.08-1-2020 — What You Need to Know, Association for Advancing Automation Online, February 15, 2021; https://www.automate.org/industry-insights/mobile-robot-standard-r15-08-1-2020-what-you-need-to-know.

324. Morgan, B.; The 3 Best In-Store Robots And Why They Work. May 13, 2020; https://www.forbes.com/sites/blakemorgan/2020/05/13/the-3-best-in-store-robots-and-why-they-work/#1adffc1137b2.

325. Mori, M.: The Uncanny Valley. 2012; https://spectrum.ieee.org/the-uncanny-valley

326. Mori, N.; Nagase, K.; Oyama, Y.; Kuboki, K.; Murata, T; Ishihara, S.: Remote System to Remove and Collect Dry Sprayed Asbestos, Taisei Technology Center, no. 40, 2007; http://www.taisei.co.jp/giken/report/2007_40/abstract/B040_011.htm.

327. Morone, G. et al.: Who May Have Durable Benefit From Robotic Gait Training? Stroke, vol. 43, 2012, no. 4, pp. 1140-1142;

328. Murphy, R.: International Cooperation in Deploying Robots for Disasters: Lessons for the Future from the Great East Japan Earthquake, Journal of the Robotics Society of Japan, vol. 32, no. 2, April 15, 2014, pp. 104-109; https://doi.org/10.7210/jrsj.32.104.

329. Mu-Yhun, C.: LG installs noodle making robot in restaurant. ZDNet, November 24, 2019; https://www.zdnet.com/article/lg-installs-noodle-making-robot-in-restaurant/.

330. Myers, A.: How 'every day' AGV forklifts and fork trucks may bring warehouse automation to every company, Lantech Blog, February 9, 2017; https://www.lantech.com/blog/agv-forklifts-and-fork-trucks-and-warehouse-automation?region=2.

331. NCCR Robotics, Rescue Robotics; 2021: https://nccr-robotics.ch/research/rescue-robotics/.

332. Nef, T.; Guidali, M., Klamroth-Marganska, V.: Riener, R.: ARMin - Exoskeleton Robot for Stroke Rehabilitation, IFMBE Proceedings, vol. 25, 2009, no. 9, pp. 127-130; https://link.springer.com/content/pdf/10.1007/978-3-642-03889-1_35.pdf.

333. Novel approach to self-assembling mobile micromachines, Max Planck Institute for Intelligent Systems, June 25, 2019; https://is.mpg.de/news/novel-approach-to-self-assembling-mobile-micromachines.

334. Nuro's self-driving vehicles to deliver prescriptions for CVS Pharmacy, May 28, 2020 https://techcrunch.com/2020/05/28/nuros-self-driving-vehicles-to-delivery-prescriptions-for-cvs-pharmacy/

335. Offshore Network: Verlume progresses development of the RoboFish for efficient offshore inspections, March 2022; https://offsnet.com/content/gulf-of-mexico/verlume-progresses-development-of-the-robofish-for-efficient-offshore-inspections.

336. Oitzman, M.: 1st Hadrian X bricklaying robot arrives in U.S., July 12, 2024; https://www.therobotreport.com/1st-hadrian-x-bricklaying-robot-arrives-in-us/.

337. Pagnano, A. et al.: A Roadmap for Automated Power Line Inspection, Maintenance and Repair, Proceedings of the 8th CIRP Conference on Intelligent Computation in Manufacturing Engineering, 2012; https://www.sciencedirect.com/science/article/pii/S2212827113006823.

338. Palimaka, S.; Blackhouse, G.; Goeree, R.: Capsule endoscopy in the assessment of obscure gastrointestinal bleeding: an economic analysis, Ontario Health Technology Assessment Series, vol. 15, 2015, no. 2, pp. 1-32; https://www.ncbi.nlm.nih.gov/pubmed/26355732.

339. Peters, B. S.; Armijo, P. R.; Krause, C.; Choudhury, S. A.; Oleynikov, D.: Review of emerging surgical robotic technology, Surgical Endoscopy, vol. 32, 2018, no. 4, pp. 1-20; https://www.semanticscholar.org/paper/Review-of-emerging-surgical-robotic-technology-Peters-Armijo/9945b4682a415fc3b678dee6ea15fae54b8a111e.

340. Photos and Videos Library: http://photo.tepco.co.jp/en/index-e.html. A continuous update of main Fukushima activities: http://www.tepco.co.jp/en/press/corp-com/release/index_ho-e.html.

341. Pinto, A. C. P.: Advanced Mobile Manipulation for Logistics in Hospitals or Laboratories, M. Eng. Thesis, University of Porto, July 24, 2016.

342. Proceedings of the Hamlyn Symposium on Medical Robotics, Imperial College London, UK, June 24-27, 2018; https://www.imperial.ac.uk/hamlyn-centre/hamlyn-symposium/. The accompanying Surgical Robot Challenge: http://surgrob.blogspot.com/2018/02/hamlyn-challenge-2018.html.

343. Q2 2020 Investor Presentation: https://isrg.intuitive.com/.

344. Quirke, J.: Hadrian the bricklaying robot to build thousands of walls in Mexico, November 2021; https://www.globalconstructionreview.com/hadrian-the-bricklaying-robot-to-build-thousands-of-walls-in-mexico.

345. R&D and Innovation Needs for Decommissioning Nuclear Facilities, OECD, 2014; https://www.oecd-nea.org/rwm/pubs/2014/7191-rd-innovation-needs.pdf.

346. R&D and innovation needs for decommissioning nuclear facilities. Nuclear Energy Agency. OECD, 2014; https://www.oecd-nea.org/rwm/pubs/2014/7191-rd-innovation-needs.pdf.

347. R&D on fuel debris retrieval – IRID Research report FY 2019; https://irid.or.jp/en/research/20190000-2/.

348. Radioactive Waste Management Committee: The NEA co-operative programme on decommissioning; twenty-five years of progress; the last five years 2006 through 2010. Nuclear Energy Agency, September 21, 2011; https://www.oecd-nea.org/rwm/docs/2011/rwm-r2011-3.pdf.

349. Redondo-Cerezo, E.; Damián Sánchez-Capilla, E.; De La Torre-Rubio, P.; De Teresa, J.: Wireless capsule endoscopy: Perspectives beyond gastrointestinal bleeding, World Journal of Gastroenterology, vol. 20, 2014, no. 42, pp.15664–15673; https://pubmed.ncbi.nlm.nih.gov/25400450/

350. Reid, C.: The Atlas Robot Is Dead. Long Live the Atlas Robot, Wired, April 7 2024; https://www.wired.com/story/the-atlas-robot-is-dead-long-live-the-atlas-robot.

351. Research Project Balto: https://nachrichten.idw-online.de/2021/05/03/disinfection-robot-value-created-by-linking-up-to-building-data/.

352. Research Project MobDi: https://www.mobdi-projekt.de/en.html.

353. Richard P. et al.: LineRanger: Analysis and Field Testing of an Innovative Robot for Efficient Assessment of Bundled High-Voltage Powerlines, 2019 International Conference on Robotics and Automation (ICRA), Montreal, QC, Canada, 2019, pp. 9130-9136; https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=8794397

354. Ridden P.: DJI sets up education branch, launches first product. August 5, 2020; https://newatlas.com/robotics/dji-education-robomaster-ep-core/.

355. Riener, R. et al.: Transferring ARMin to the Clinics and Industry, Topics in Spinal Cord Injury Rehabilitation, vol. 17, 2011, no. 1, pp. 54-59;

356. Robinson, H.; MacDonald, B.; Broadbent, E.: The Role of Healthcare Robots for Older People at Home: A Review. International Journal of Social Robotics, July 2014, pp 575-591; https://link.springer.com/article/10.1007/s12369-014-0242-2.

357. RobocupRescue; 2021; https://www.robocup.org/domains/2.

358. Robot lifts bits of melted fuel at Japan's Fukushima plant, Phys.org, February 14, 2019; https://phys.org/news/2019-02-robot-bits-fuel-japan-fukushima.html.

359. Robot Port Cranes in Container Terminals Would See Stevedore Job Cuts, Handy Shipping Guide, February 23, 2016; http://www.handyshippingguide.com/shipping-news/robot-port-cranes-in-container-terminals-would-see-stevedore-job-cuts_6992.

360. Robotic collaboration in timber construction, press release by ETH Zurich, March 22, 2017; https://www.ethz.ch/en/news-and-events/eth-news/news/2018/03/spatial-timber-assemblies.html.

361. Robotic Firefighters Market Size is Expected to Reach US$ 2.9 Billion by 2031, 15 June 2023, https://www.globenewswire.com/en/news-release/2023/06/15/2689347/0/en/Robotic-Firefighters-Market-Size-is-Expected-to-Reach-US-2-9-Billion-by-2031-Rising-at-a-Market-Growth-of-9-7-CAGR-During-the-Forecast-Period-Transparency-Market-Research-Inc.html.

362. Robotic Technology at the U.S. Department of Energy, Savannah River Site; http://www.srs.gov/general/news/factsheets/srr_robotics.pdf.

363. Robotics in Logistics: A DPDHL perspective on implications and use cases for the logistics industry, DHL Customer Solutions & Innovation, March 2016; https://www.dhl.com/global-en/home/insights-and-innovation/thought-leadership/trend-reports/robotics-in-logistics.html.

364. Robotics Systems for Care: https://www.pflege-und-robotik.de/en/start-page/.

365. Robots can use eye contact to draw out reluctant participants in groups, March 10, 2021, https://www.sciencedaily.com/releases/2021/03/210310122608.htm.

366. Robots enlisted to survey Fukushima World Nuclear News, June 24, 2013; http://www.world-nuclear-news.org/C-Robots_enlisted_to_survey_Fukushima-2406134.html.

367. Roldán-Gómez, J. J. et al.: A Survey on Robotic Technologies for Forest Firefighting: Applying Drone Swarms to Improve Firefighters' Efficiency and Safety. Applied Sciences, vol. 11, no. 1, Jan. 2021, https://doi.org/10.3390/app11010363.

368. ROS navigation: http://wiki.ros.org/navigation.

369. Saidi, K. S.; Bock, T.; Georgoulas, C.: Robotics in Construction. In: Siciliano, B. and Khatib, O. (eds.): Springer Handbook of Robotics, 2nd Edition. Berlin, Heidelberg: Springer, 2016, pp. 1493-1591; http://handbookofrobotics.org/.

370. Salfer, J. A. et al.: Finances and returns for robotics diaries; including an online cost-benefit tool, 2017; http://dairy.unl.edu/documents/Salfer_EconomicsinRobots.pdf.

371. Salim, Z.: S'pore robot barista ELLA now at Raffles Place, the first out of 30 MRT stations by end 2022. Vulcan Post, March 2, 2022; https://vulcanpost.com/780179/robot-barista-ella-raffles-place-mrt-singapore/.

372. Sattar, T. P.: Robotics for Inspection and Decommissioning of Nuclear Power Plant; http://researchopen.lsbu.ac.uk/1594/1/Robotics%20for%20Nuclear%20work.pdf.

373. Saulwick, S.: Sydney's Patrick terminal goes automated, with fewer staff but dancing robots, The Sydney Morning Herald, June 18, 2015; https://www.smh.com.au/national/nsw/sydneys-patrick-terminal-goes-automated-with-fewer-staff-but-dancing-robots-20150617-ghqc24.html.

374. Schindler debuts breakthrough robotic system for elevators, October 2018; https://www.schindler.com/com/internet/en/media/press-releases-english/press-releases-2018/schindler-debuts-breakthrough-robotic-system-for-elevators.html.

375. Schneider, F. E.; Wildermuth, D.; Wolf, H.-L.: ELROB and EURATHLON: Improving Search & Rescue Robotics through Real-World Robot Competitions, Proceedings of the 10th International Workshop on Robot Motion and Control, Poznan University of Technology, Poland, July 6-8, 2015.; https://www.researchgate.net/publication/286354629_ELROB_and_EURATHLON_Improving_search_rescue_robotics_through_real-world_robot_competitions.

376. Seabed Rig and Energid Technologies Developing a Safer Oil Drilling System, PR Newswire, May 13, 2010; https://www.prnewswire.com/news-releases/seabed-rig-and-energid-technologies-developing-a-safer-oil-drilling-system-93678419.html.

377. https://www.iberdrola.com/innovation/educational-robots for a nice overview about the topic.

378. Shieber, J.: Building robotic safety inspectors nabs Gecko Robotics USD 40 million, December 16, 2019; https://techcrunch.com/2019/12/16/robotic-safety-inspectors-net-gecko-robotics-40-million/.

379. Several companies claim these numbers, see, e.g. https://www.gideon.ai/solutions/trey or http://foxrobotics.com.

380. Shang, L. et al.: How much can farmers pay for weeding robots? A Monte Carlo simulation study, Precision Agric 2023; https://www.researchgate.net/publication/369823126_How_much_can_farmers_pay_for_weeding_robots_A_Monte_Carlo_simulation_study.

381. Shao, L., Wang, Y., Guo, B.; Chen, X.: A review over state of the art of in-pipe robot, Mechatronics and Automation (ICMA), 2015, pp. 2180-2185; https://www.semanticscholar.org/paper/A-review-over-state-of-the-art-of-in-pipe-robot-ShaoWang/38658dbd617e61c0e083e72a66d766e845a20ea4.

382. Sheh, R.; Schwertfeger, S.; Visser, A.: 16 Years of RoboCup Rescue, vol. 30, 2016, no. 3-4, pp. 267-77; https://link.springer.com/article/10.1007/s13218-016-0444-x.

383. Shieber, J.: WHILL brings its autonomous wheelchairs to North American airports: https://techcrunch.com/2019/11/20/whill-brings-its-autonomous-wheelchairs-to-north-american-airports/.

384. Shortall, J. et al.: Investment appraisal of automatic milking and conventional milking technologies in a pasture-based dairy system, Journal of Dairy Science, vol. 99 no. 9, 2016, pp. 7700-7713.

385. Shukla, A.; Karki, H.: Application of robotics in onshore oil and gas industry – A review Part I, Robotics and Autonomous Systems, vol. 75, 2016, pp. 490-507; https://www.sciencedirect.com/science/article/pii/S0921889015002006.

386. SILVER: Supporting Independent Living for the Elderly through Robotics: https://cordis.europa.eu/project/id/287609.

387. Sim, W.: Singapore-made robot Ella serves up coffee at Tokyo, Yokohama train stations. The Straits Times, December 8, 2021; https://www.straitstimes.com/asia/east-asia/ella-the-singapore-made-robot-serves-up-coffee-at-tokyo-yokohama-stations.

388. Singeap, A.; Stanciu, C.; Trifan, A.: Capsule endoscopy: The road ahead, World Journal of Gastroenterology, vol. 22, 2016, no. 1, pp. 369-378;

389. Siqueira, E. B., Azzolin, R. Z., da Costa Botelho, S., Oliveira, V. M.: Inside Pipe Inspection: A Review Considering the Locomotion Systems, In: Garrido, P. et al. (eds.): CONTROLO 2016. Proceedings of the 12th Portuguese Conference on Automatic Control. Springer, 2017, pp. 449-458; https://www.researchgate.net/publication/307623670_Inside_Pipe_Inspection_A_Review_Considering_the_Locomotion_Systems"

390. Smajstrla, A.: Ford deploys Boston Dynamics' Spot robots to survey Michigan plant. engaged, July 27, 2020; https://www.engadget.com/ford-boston-dynamics-spot-robots-michigan-plant-153343909.html.

391. Small Unmanned Aircraft System industry news for professionals, business directory: http://www.suasnews.com/category/the-market

392. .Sogi, T., Kawaguchi, Y., Morisaki, H., Ohkawa, K., Kai, N., Hayakawa, H.: Inspection robot for spherical storage tanks, Proceedings of the IEEE IECON 2000 26th Annual Conference (Nagoya), vol. 1, October 22-28, 2000, pp. 393-398.

393. Sommer, A.: Industrial Robots for Patient Support. Ion Beam Therapy, Biological and Medical Physics, Biomedical Engineering, vol. 320, 2012, pp. 559-577; https://www.researchgate.net/publication/258733190_Industrial_Robots_for_Patient_Support.

394. Spice, B.: Carnegie Mellon Snake Robot Winds Its Way Through Pipes, Vessels of nuclear Power Plant, July 9, 2013; https://www.cmu.edu/news/stories/archives/2013/july/july9_snakerobot.html.

395. StaldTek – The Pigpens of the Future: http://www.dti.dk/inspiration/26383.

396. Starship Completes One Million Autonomous Deliveries, Medium, January 27, 2021; https://medium.com/starshiptechnologies/one-million-autonomous-deliveries-milestone-65fe56a41e4c.

397. Stevens, K. J., Lichti, K., Minchington, I. A., Janke-Gilman, N., Mactutis, T., Rook, D., Bondurant, P.: Conductor Damage Inspection System for overhead ACSR power cables CDIS on ACSR, 2013 Seventh International Conference on Sensing Technology (ICST), IEEE, pp. 901-905; https://ieeexplore.ieee.org/abstract/document/6727780.

398. Stretch RE1 Autonomy Demo: https://www.youtube.com/watch?v=QJxb89TMF68.

399. Strickland, E.: Fukushima's next 40 years, IEEE Spectrum, vol. 51, no. 3, March 2014, pp. 46-53; https://ieeexplore.ieee.org/document/6745884.

400. Strickland, E.: Meet the Robots of Fukushima Daiichi. A cleanup crew of automatons will go where humans fear to tread, IEEE Spectrum, February 28, 2014; http://spectrum.ieee.org/slideshow/robotics/industrial-robots/meet-the-robots-of-fukushima-daiichi.

401. Strickland, E.: ReWalk Robotics' New Exoskeleton Lets Paraplegic Stroll the Streets of NYC, IEEE Spectrum, July 15, 2015;

http://spectrum.ieee.org/automaton/robotics/medical-robots/rewalk-robotics-new-exoskeleton-lets-paraplegic-stroll-the-streets-of-nyc.

402. Stuntz, M.; Busko, K.; Irshad, S.; Paige, T.; Razhkova, V.; Coan, T.: Nationwide trends of clinical characteristics and economic burden of emergency department visits due to acute ischemic stroke, OAEM, vol. 9, 2018; https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5614785.

403. Sweet, R.: Block-laying robot Hadrian builds first two-storey house, October 28, 2020; https://www.globalconstructionreview.com/innovation/block-laying-robot-hadrian-builds-first-two-storey/.

404. Tan, C. F.; Liew, S. M.: Firefighting Mobile Robot: State of the Art and Recent Development, Australian Journal of Basic and Applied Sciences, vol. 7, no. 10, 2013, pp. 220-230; https://rauterberg.employee.id.tue.nl/publications/AJBAS2013journal-a.pdf. (A more recent source does not seem to be available.)

405. Tarantola, A.: Your next White Castle slider could be cooked by a robot. Miso Robotics' Flippy is part of an upcoming pilot program, July 14, 2020; https://www.engadget.com/your-next-white-castle-slider-could-be-cooked-by-a-robot-090012343.html.

406. Taylor, R.; Menciassi, A.; Fichtinger, G.; Dario, P.: Medical Robotics and Computer-Integrated Surgery. In: Siciliano, B. and Khatib, O. (eds.): Springer Handbook of Robotics, 2nd edition. Berlin, Heidelberg: Springer, 2016, pp. 1657-1683; http://handbookofrobotics.org/.

407. Telepresence robots: https://www.pinterest.de/slanderretche/telepresence-robots.

408. Tepco prepares to survey Fukushima Daiichi unit 2 fuel pool, May 14, 2020; https://www.world-nuclear-news.org/Articles/Tepco-readies-to-survey-Fukushima-Daiichi-unit-2-f.

409. Terntzer, D. N.: Rise of the Robots: The Future of Robotics is Social, Nasdaq, October 11, 2021; https://www.nasdaq.com/articles/rise-of-the-robots%3A-the-future-of-robotics-is-social-2021-10-11.

410. The 2022 IFAC Intelligent Autonomous Vehicles Symposium, Prague, July 6 to July 8, 2022; https://www.iav2022.eu. See also IFAC Technical Committee on Intelligent Autonomous Vehicles TC7.5: http://tc.ifac-control.org/7/5.

411. The DARPA Robotics Challenge, June 2015; https://www.darpa.mil/program/darpa-robotics-challenge.

412. The iBot is Back. Is the Second Time the Charm? https://www.newmobility.com/2019/07/the-ibot-is-back/.

413. Theodoridis, T.; Hu, H.: Toward Intelligent Security Robots: A Survey, IEEE Transactions on Systems, Man, and Cybernetics, vol. 42, 2012, no. 6, pp. 1219-1230;

414. This robot can scan the inventory of an entire supermarket in less than an hour, Bailiwick Express, April 2021; https://www.bailiwickexpress.com/jsy/life/technology/robot-can-inventory-entire-supermarket-less-hour/.

415. Thornton, J.: Schindler elevator installation robot deployed in Asia-Pacific, March 2022; https://www.roboticsandinnovation.co.uk/news/construction/schindler-elevator-installation-robot-deployed-in-asia-pacific.html.

416. Tijskens, L. M. M. et al.: From fruitlet to harvest: Modelling and predicting size and its distributions for tomato, apple and pepper fruit, Scientia Horticulturae, vol. 204, 2016, pp. 54-64; https://www.sciencedirect.com/science/article/pii/S0304423816301558.

417. Tokumatsu, G.: At Your Service! Hotel Robot Becomes Essential Amid Coronavirus Pandemic, NBC Los Angeles, June 23, 2020; https://www.nbclosangeles.com/news/local/at-your-service-hotel-robot-becomes-essential-amid-coronavirus-pandemic/2384865/.

418. Toyota Launches Rental Service for the Welwalk WW-1000 Rehabilitation Assist Robot in Japan, press release by Toyota, April 12, 2017; http://newsroom.toyota.co.jp/en/detail/15989382.

419. Toyota: Partner Robot Family; https://global.toyota/en/mobility/frontier-research/.

420. Turchetti, G.; Pierotti, F.; Palla, I.; Manetti, S.; Freschi, C.; Ferrari, V.; Cuschieri, A.: Comparative health technology assessment of robotic-assisted, direct manual laparoscopic and open surgery: a prospective study, Surgical Endoscopy, vol. 31, 2017, no. 2, pp. 543-551; https://link.springer.com/article/10.1007/s00464-016-4991-x.

421. Ullas, S.: this Bengaluru school, robots teach and teachers mentor (2019); https://timesofindia.indiatimes.com/city/bengaluru/at-this-bengaluru-school-robots-teach-and-teachers-mentor/articleshow/70867664.cms.

422. Ullrich, G.; Albrecht, T.: Automated guided vehicle systems. Berlin, Heidelberg, Springer, 2023; https://link.springer.com/book/10.1007/978-3-658-35387-2.

423. US Roadmap 2.0, Material Handling & Logistics, April 2017; https://www.supplychain247.com/paper/material_handling_logistics_us_roadmap_2_0/apics.

424. Using autonomous robots to drive supply chain innovation, Deloitte Development, 2017;

https://www2.deloitte.com/content/dam/Deloitte/us/Documents/manufacturing/us-manufacturing-autonomous-robots-supply-chain-innovation.pdf.

425. van den Berghe, R. et al.: Social robots for language learning: A review. Review of Educational Research vol. 89, 2019, 2, pp. 259-295; https://journals.sagepub.com/doi/pdf/10.3102/0034654318821286.

426. Van der Loos, M. et al.: Rehabilitation and Health Care Robotics. In: Siciliano, B.; Khatib, O. (eds.): Springer Handbook of Robotics, 2nd Edition. Berlin, Heidelberg: Springer, 2016, pp. 1685-1728; http://http://handbookofrobotics.org.

427. van Mulken, T. J. M.; Schols, R. M.; Scharmga, A. M. J.; Winkens, B.; Cau, R.; Schoenmakers, F. B. F. et al.: First-in-human robotic supermicrosurgery using a dedicated microsurgical robot for treating breast cancer-related lymphedema: a randomized pilot trial. In: Nat Commun vol. 11, 2020, no. 1. DOI: 10.1038/s41467-019-14188-w; https://www.nature.com/articles/s41467-019-14188-w/.

428. VDI-Fachbereich Technische Logistik VDI; https://www.vdi.de/richtlinien/details/vdi-2510-fahrerlose-transportsysteme-fts.

429. Vella, M.: Robots have failed Fukushima Daiichi and Japan, Fortune, March 20, 2013; https://fortune.com/2013/03/20/robots-have-failed-fukushima-daiichi-and-japan/.

430. Wakefield, J.: Tomorrow's Buildings: Construction industry goes robotic. BBC, May 4, 2016; http://www.bbc.com/news/technology-35746648.

431. Wang, F.; Ma, Y.: Noah Hospital Logistics Robot Received over Ten Million CNY in Series B+ Round, Equalocean, June 22, 2022; https://equalocean.com/news/2022062218322.

432. Ward, C. W.: Robots in Commercial Cleaning: The Coming Robot Tsunami, July 20, 2018; https://cybercleansystems.com/robottsunami.html.

433. Weber, I.; Funaki, K.; Sandberg, N.; Otsuka, I.: NEA support to Fukushima Daiichi decommissioning strategy planning, NEA News, no. 35.1, 2017; https://www.oecd-nea.org/nea-news/2017/35-1/nea-news-35-1.pdf.

434. Wessling, B.: Built Robotics digs up $64M for construction vehicle autonomy kits April 6, 2022; https://www.therobotreport.com/built-robotics-digs-up-64m-for-construction-vehicle-autonomy-kits/.

435. What Happens In the Supermarket at Night, Bremeninvest, August 4, 2021; https://www.wfb-bremen.de/en/page/bremen-invest/robotics-in-retail-ubica.

436. Witwicki, S. J. et al.: A Testbed for Autonomous Robot Surveillance (Demonstration), Proceedings of the 2014 international conference on Autonomous agents and multi-agent systems (AAMAS '14), Paris, May 5-9, 2014, pp. 1635-1636.

437. Wolf, M.: Cafe X's Robot Barista is Now Slinging Coffee in Tesla's Berlin Giga Factory. The Spoon, November 10, 2023; https://https://thespoon.tech/cafe-xs-robot-barista-is-now-slinging-coffee-in-teslas-berlin-giga-factory/.

438. Wolf, M.: French Robot Pizza Restaurant Startup Pazzi Shuts its Doors. The Spoon, October 7, 2022; https://thespoon.tech/french-robot-pizza-restaurant-startup-pazzi-shuts-its-doors.

439. Wolf, M.: Karakuri Semblr Food Robot To Feed Up to Four Thousand Employees at Ocado HQ. The Spoon, September 23, 2021; https://thespoon.tech/karakuri-semblr-food-robot-to-feed-up-to-four-thousand-employees-at-ocado-hq/.

440. Wolff, J.; Parker, C.; Borisoff, J.; Mortenson, W. B.; Mattie, H.: A survey of stakeholder perspectives on exoskeleton technology. Journal of Neuro Engineering and Rehabilitation, vol. 11, 2014; http://www.biomedcentral.com/content/pdf/1743-0003-11-169.pdf.

441. World Robot Summit, Disaster Robotics Category, Tokyo, October 7-21, 2018. There are also some results from December 2021 (https://wrs.nedo.go.jp/en/news).

442. Würtsen, F.; Hodel, C.: Revolutionising building sites, ETH Zürich, March 9, 2015; https://www.ethz.ch/en/news-and-events/eth-news/news/2015/03/revolutionising-building-sites.html.

443. Yakub, F.; Khudzairi, A. Z.; Mori, Y.: Recent trends for practical rehabilitation robotics, current challenges and the future, International Journal of Rehabilitation Research, vol. 37, 2014, no. 1, pp. 9-21; https://pubmed.ncbi.nlm.nih.gov/24126254/.

444. Yamaguchi, M.: Robot photos appear to show melted fuel at Fukushima reactor, February 2022; https://www.news4jax.com/tech/2022/02/10/robot-photos-appear-to-show-melted-fuel-at-fukushima-reactor/.

445. Yamazaki, R. et al.: Teleoperated Androids as an Embodied Communication Medium: A case study with demented elderlies in a care facility. In: 21st IEEE International Symposium on Robot and Human Interactive Communication, September 9-13, 2012, Paris, France 2012, pp. 1066-1071; https://pubmed.ncbi.nlm.nih.gov/3144/.

446. Yanagihara, Y.; Yoshinada, H.; Inoue, F.: Special Issue on Construction Robot, Journal of Robotics and Mechatronics, vol. 24, no. 6, 2012, p. 923; https://www.fujipress.jp/jrm/rb/robot002400060923/.

447. Yang, G. Z.; Cambias, J.; Cleary, K.; Daimler, E.; Drake, J.; Dupont, P. E.; Santos, V. J.: Medical robotics – Regulatory, ethical, and legal considerations for increasing levels of autonomy, Science Robotics, vol. 2, 2017, eaam8638; https://www.science.org/doi/10.1126/scirobotics.aam8638.

448. Yimei, L.: China's first firefighting robot unit now in service, May, 27, 2020; https://news.cgtn.com/news/2020-05-27/China-s-first-firefighting-robot-unit-now-in-service-QPjoan4UfK/index.html.

449. Zheng, Z.; Bekele, E.; Swanson, A.; Weitlauf, A.; Warren, Z.; Sarkar, N.: The impact of robots on children with autism spectrum disorder. In: Casanova, M. et al. (eds.): Autism Imaging and Devices, CRC Press, pp. 397-415.