Open Full-stack Intelligent Service Robot Ecosystem

MAKING AN IMPACT THAT MATTERS since 1845

Contents

Preface

As the global economy pivots toward intelligent industrial transformation, service robots are emerging as indispensable tools of productivity across various industries and a key force driving innovation and efficiency gains. At the same time, advancements in cutting-edge technologies, particularly artificial intelligence, are propelling the robotics industry toward an era of embodied AI. Yet, the path to large-scale deployment of service robots remains strewn with both promise and peril, shaped by shifting technology thresholds and untested business models.

To navigate increasingly complex market demands and a growing diversity of application scenarios—**coupled with the inflection point emerging in the second half of the commercial service robotics industry—Pudu Robotics has taken the lead globally in proposing an open, full-stack robotics ecosystem.** The aim is to foster a general-purpose platform that supports wide-ranging deployment and coordination of service robots through both technological and business model innovation.

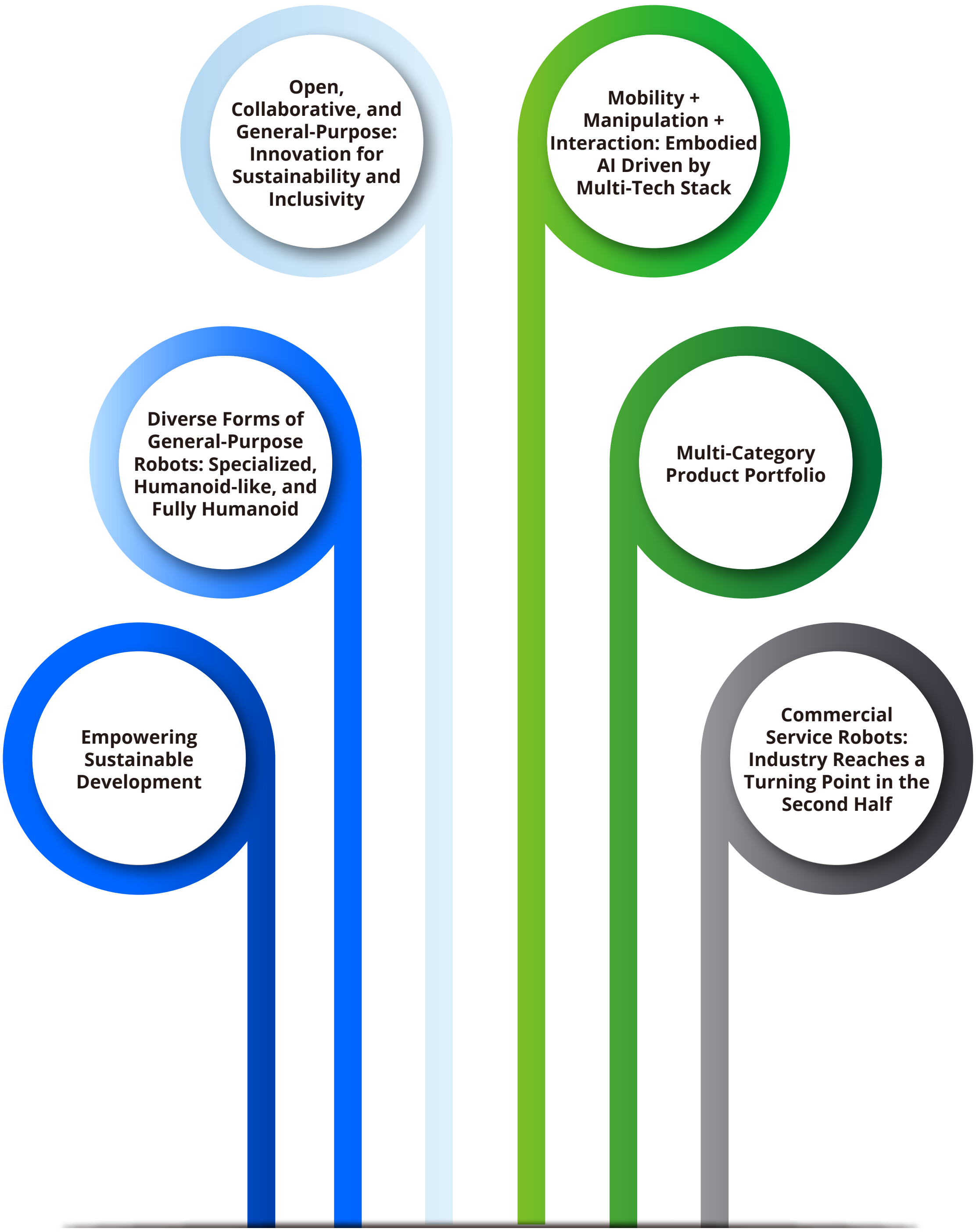
This ecosystem is not limited to a technical architecture; it also incorporates product technology and business model innovation. It is intended to support collaboration and integration of service robots across various service scenarios. By encouraging the development of industry standards and enabling innovation across multiple technology stacks, the ecosystem will help drive transformative change in the global service robotics industry and support the transition toward a new era of general-purpose embodied AI.

Within this ecosystem, robots are expected to gradually improve in learning and adaptivity, becoming better suited for handling a wide range of tasks and environments. This could expand their use across different settings and increase their practical value. In turn, such advancements will contribute to higher levels of efficiency and intelligence across industries, with broader economic and social benefits.

Cross-industry collaboration and resource sharing are also central to this ecosystem, which aims to deliver full-stack intelligent solutions tailored to specific operational needs. Overtime, this will help intelligent transformation across industries.

Realizing this vision will require progress on several fronts – including products diversification, integration of mobility, manipulation and interaction functions, and the development of multiple robotic forms, ranging from specialized platforms to humanoid designs. Success will depend on continued innovation in both technology and business practice.

If successful, this ecosystem will support not only the growth of the entire robotics industry itself by driving technology breakthrough, but also deeper transformation along the value chain, contributing to the development of a more intelligent, accessible, and efficient world.


Open, Collaborative, and General-Purpose: Innovation for Sustainability and Inclusivity
Mobility + Manipulation + Interaction: Embodied AI Driven by Multi-Tech Stack
Diverse Forms of General-Purpose Robots: Specialized, Humanoid-like, and Fully Humanoid
Multi-Category Product Portfolio
Empowering Sustainable Development
Commercial Service Robots: Industry Reaches a Turning Point in the Second Half

Chapter One:

Overview of the Global Service Robot Market

1.1. Concept definition and research scope

1.1.1. Concept definition of service robot

Robots are generally machine devices that perform tasks automatically. The International Organization for Standardization (ISO) defines a "service robot" as a "robot in personal use or professional use that performs useful tasks for humans or equipment". Tasks for personal and professional use include carrying items, inspection, monitoring, transporting people, providing information, cooking, food handling, as well as cleaning, among others.

Figure 1-1: Definition of service robots

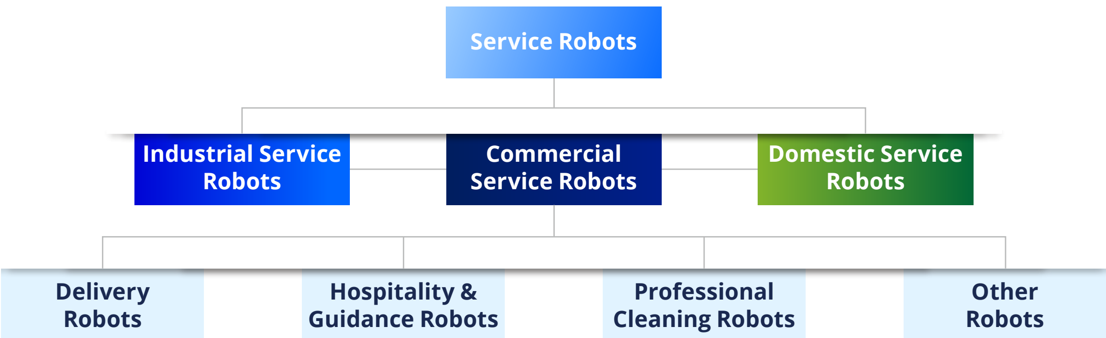
International institutions	Standard Regulations	Concept of Service Robots
International Organization for Standardization (ISO)	8373:2021 Robotics Vocabulary	Robots for personal or professional use that perform useful tasks for humans or equipment

Source: International Organization for Standardization (ISO)

1.1.2. Classification of service robots and the scope of the report's research

This report synthesizes the classification methods of international authoritative organizations and the mainstream academic community. The secondary classification of service robots refers to the Fraunhofer IPA standard, categorizing service robots into industrial service robots, domestic service robots, and commercial service robots according to different application scenarios. The tertiary classification combines the classification standard of the International Federation of Robotics, dividing service robots by function.

Figure 1-2: Classification of service robots



Source: Fraunhofer IPA, International Federation of Robotics, Deloitte Research

In recent years, an increasing number of service robots have been widely applied in various commercial and household scenarios. The application scenarios of service robots are complex and diverse, with a wide variety of specific subcategories. They can be used in numerous industries and scenarios such as catering, retail, warehousing logistics, hotels, industry, healthcare, education, aged care, and public services, realizing a variety of composite functions such as professional cleaning, logistics distribution, guiding reception, companion teaching, and security patrol. At the same time, service robots can optimize process effectiveness, enhance service experience, and improve efficiency as well as safety in various scenarios. This report mainly includes but is not limited to the research on service robots in commercial, industrial, and other scenarios.

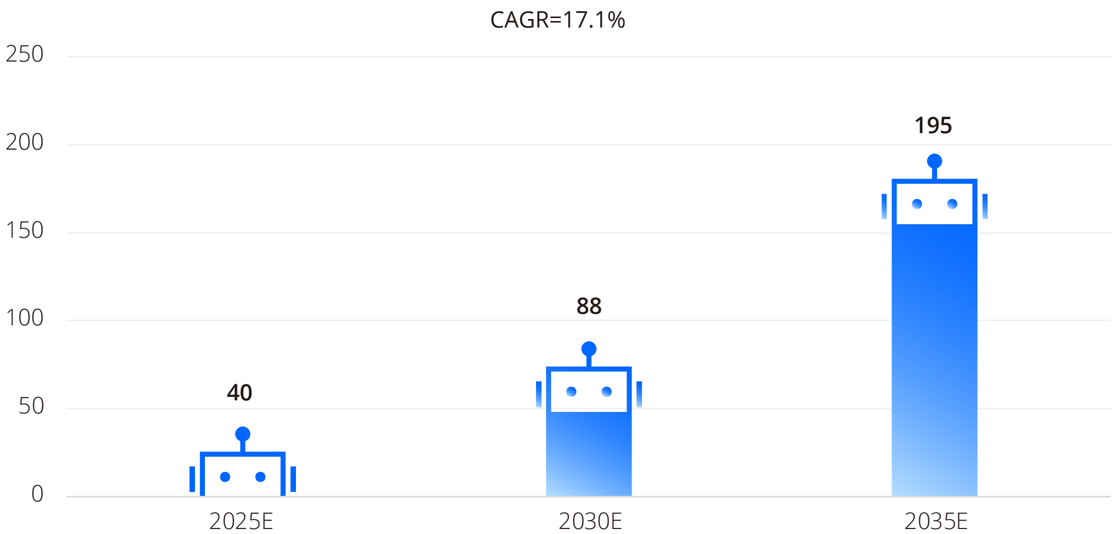
1.2. Analysis of global service robot industry development trends

1.2.1. The global service robot market is experiencing strong growth

The global service robot industry is entering a period of explosive growth

Research indicates that the global service robot industry is flourishing, with the industry scale continuing to grow. According to research data, the service robot sector has entered a period of rapid development, showing a strong market size growth. In 2025, the global market size for service robots, encompassing the entire value chain, is projected to reach $40 billion. Over the next decade, the market is expected to grow at a compound annual growth rate of 17.1%, with the global service robot market potentially reaching $195 billion by 2035, indicating significant growth potential.

Figure 1-3: Market size of global service robot (in billion USD)



Source: Deloitte Research, Global Market Insights, 2024

Meanwhile, under the combined impetus of strong policy promotion in various countries, industrial transformation and upgrading, changes in population structure, and support from key technologies, the service robot industry has entered a golden period of development, demonstrating immense market potential.

- From the perspective of technological upgrading, with the rapid development of artificial intelligence technology, the robotics industry has also entered a period of rapid growth. As artificial intelligence technologies such as large-scale models are deeply applied in the field of robotics, robots are rapidly iterating in key technologies like mobility, manipulation, and interaction, bringing new opportunities for the rapid development of the global service robotics industry.

- From the perspective of policies, the United States, the European Union, and China have all put forward strategies for the development of advanced manufacturing. For instance, the United States issued the "National Research and Development Strategic Plan for Artificial Intelligence," the European Union released the "New European Industrial Strategy" in 2020, Germany published the "Action Plan for Robotics Technology Research" in 2023, and China issued the "14th Five-Year Plan for the Development of the Robot Industry" in 2021. Robotics as a key enabler of manufacturing intelligence, has become a focus of attention in the industrial policies of many countries.

- From the perspective of population structure, the aging population is a long-term driving factor of the global demand for service robots, and it also prompts some countries and regions to use service robot technology to address the issue of labor shortage. Taking Japan as an example, with its severe aging population, significant labor shortage, and high labor costs, it has become one of the popular application markets for commercial service robots.

- From the perspective of industrial transformation, countries are boosting industries such as manufacturing and services to seize the development opportunities of intelligent transformation and upgrading, enhancing innovation capabilities and improving production efficiency, with service robots being important production equipment in the digital and intelligent transformation. The emergence of service robots will gradually assist humans in engaging in high-intensity, repetitive, and hazardous work, improving the operational efficiency of various industries.

Figure 1-4: Multiple factors driving the demand release of service robots

Support of Key Technology

- Driven by AI technology, the robot's movement, operation, interaction and other technologies have ushered in high-speed development
- Perception, computation, control and other technologies continue to iterate and upgrade, and the application of AI technologies such as image recognition, voice processing, deep cognitive learning and other technologies in the field of robotics is gradually deepening
- The application trend of artificial intelligence in the field of robotics and automation continues to grow, and the global service robotics industry has ushered in new opportunities for rapid development

Strong Policy Impetus

- Such as the United States released the National Artificial Intelligence Research and Development Strategic Plan, the European Union released the New European Industrial Strategy, Germany released the Action Plan for Robotics Research, and China released the “14th Five-Year Plan” for the development of the robotics industry
- Robotics, as an important driving force for manufacturing intelligence, is the focus of industrial policy and key support direction in various countries

Changes in Population Structure

- Aging population is a long-term driver for global demand for service robots
- “Difficult and expensive labor recruitment” is a common labor problem in many countries and regions
- Some countries and regions are responding to labor shortage through service robotics

Industrial Development Transformation

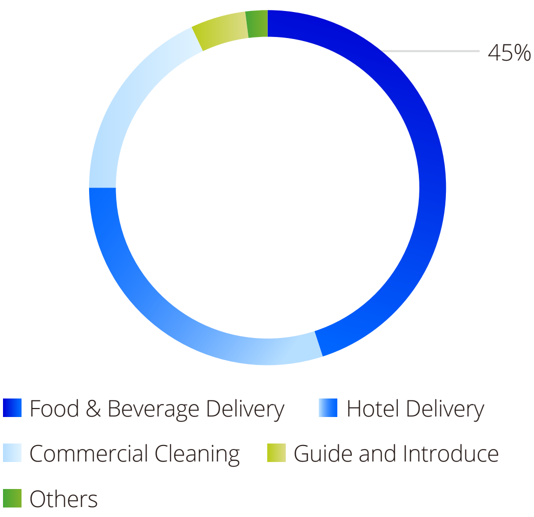
- Countries vigorously promote the intelligent transformation and upgrading of manufacturing, service and other industries
- Service robots will effectively improve production efficiency and help the transformation and development of industrial digital intelligence.

Source: World Economic Forum, Collected by Deloitte Research

Commercial service robots have become a key segment of the market

In the service robot market, commercial service robots represented by catering, hotel delivery, and cleaning are rapidly becoming the main force. Currently, commercial service robots are widely used in industries such as catering, hotels, retail, industry, healthcare, education, and aged care, providing services such as delivery, cleaning, guidance, and companionship. In the global commercial service robot market, the catering sector accounts for about 45% of the market share, becoming an important downstream application field. Among them, Pudu Robotics holds the leading position in the market share of catering service robots in both China and Japan.[1] With the advancement of technologies such as artificial intelligence and the Internet of Things, the advantages of commercial service robots in improving operational efficiency and optimizing service experience are increasingly prominent, and market demand continues to grow.

Figure 1-5: The global commercial service robot market distribution in 2023

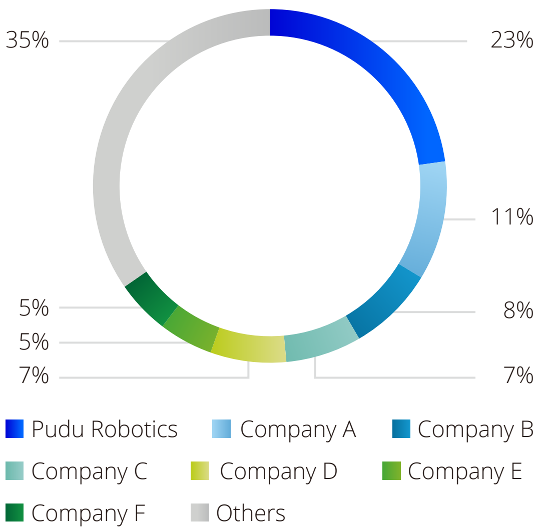


Source: Frost & Sullivan

Chinese companies lead the global market

Chinese companies, leveraging technological innovation and product advantages, have demonstrated strong competitiveness and influence in the global market, occupying a dominant position. According to a report released by the international research and consulting firm Frost & Sullivan, the top five companies in the global commercial service robot market share rankings in 2023 are all Chinese enterprises, with Pudu Robotics leading the world for a 23% market share. As one of the world's largest robot markets, China, driven by both policy support and market demand, has seen rapid development in the commercial service robot industry. With the acceleration of the global automation and intelligence process, the momentum of Chinese enterprises going abroad is strong, and companies of commercial service robots in China have ushered in unprecedented development opportunities, poised to lead the global market for a long time in the future.

Figure 1-6: Global commercial service robot market share in 2023 (by revenue)



Source: Frost & Sullivan

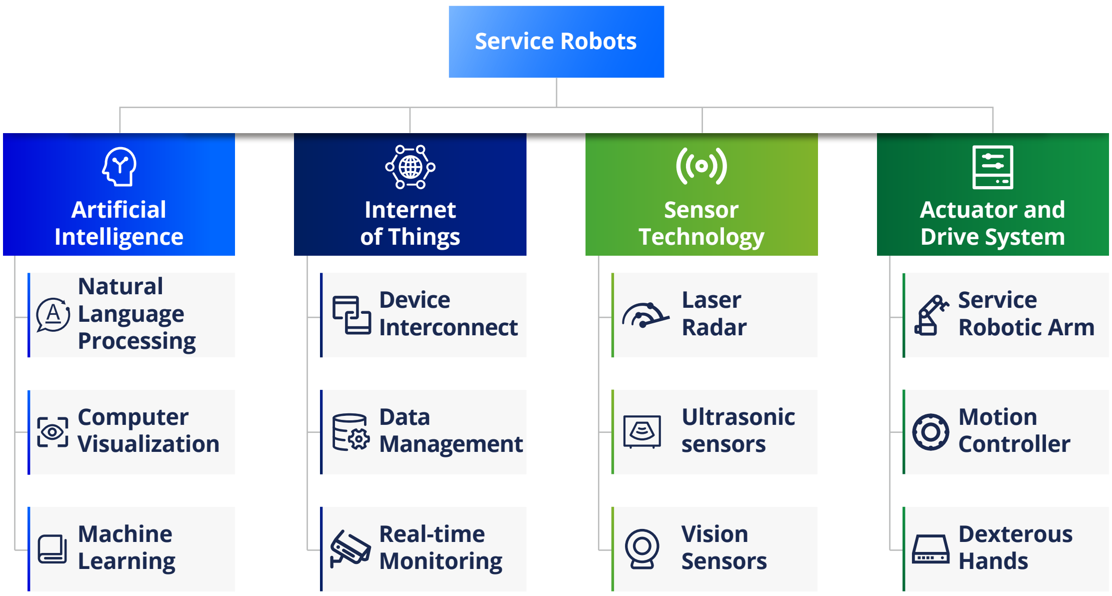
1. Source: Market Research on Global Commercial Service Robots (2023), Frost & Sullivan

1.2.2. Technological innovation drives industry development and innovation

With the advancement of technologies such as Artificial Intelligence (AI) and the Internet of Things (IoT), the service robot industry has seen continuous iteration and innovation. Robots have achieved key breakthroughs in core tech stack architectures such as mobility, manipulation, and interaction, driving innovation and development across the entire industry.

In terms of the enhancement of intelligent decision-making capabilities, deep learning and natural language processing have enabled robots to handle complex data, and to self-learn and adapt based on real-time data, thereby providing personalized interaction and services, which greatly improves the user experience. By combining advanced sensor technology with AI algorithms, service robots can perceive their surroundings in real-time, identify dynamic obstacles and react intelligently, ensuring safety while efficiently completing various service tasks. Moreover, the application of IoT technology allows service robots to form a fully interconnected ecosystem with surrounding devices, enabling them to work collaboratively in the environment, optimize scheduling, while users can remotely monitor and manage centrally through cloud based IoT solutions. Furthermore, the combination of AI and IoT has also driven the realization of multimodal interaction, allowing robots to communicate naturally with users through voice, gestures, and vision, among other methods. Ultimately, the evolution of these technologies has promoted the process of industry standardization, encouraged the sharing of best practices and technical experience, leading the rapid development of the entire industry. The drive of key technologies such as artificial intelligence and the Internet of Things has not only significantly improved the performance and solutions of service robots but also laid a solid foundation for the continuous innovation of the industry.

Figure 1-7: Key driving technologies of service robots



Source: International Federation of Robotics (IFR), Collected by Deloitte Research

1.2.3. Transitioning from specialized to general-purpose

With the advancement of technology and the continuous increase in market demand, the application scope of service robots is increasingly expanding, from the initial single industry to multiple fields, including catering, retail, hospitality, healthcare, elder care, entertainment and sports, industry, education, and public services. Service robots need to complete complex tasks across different scenarios, making the transition from specialized to general-purpose an inevitable trend.

However, the challenge that service robots face in practical applications is that traditional product design often bases on the specialized division of labor in a single industry, failing to fully consider the diverse needs of users in various scenarios. For example, a hotel may simultaneously require a room service robot with cross-floor delivery capabilities, robots that can complete food and beverage delivery, floor cleaning robots, as well as robots for greeting and information services. Similarly, B-end scenarios like supermarket retailing also face similar demands. Supermarkets use sale-promotional robots for customer guidance and at the same time need to be equipped with commercial cleaning robots for daily cleaning, in addition to heavy-load delivery robots responsible for restocking from the warehouse to the front desk. The need for service robots to address complex tasks urgently needs to be enhanced, in order to provide more comprehensive services.

Consumer demands are showing a trend of diversification and complexity. The unmet scenario demands from the past urgently need to be addressed, which means that enterprises need to provide **full stack general-purpose robotic products** to adapt to the constantly changing market and the multiple needs of users. By creating a comprehensive product matrix, users are offered a complex combination of products such as cleaning, delivery, and greeting guides, ensuring perfect scheduling and collaboration among various robots in the same scenario, thereby enhancing the consistency of user experience.

Figure 1-8: User demands are trending towards diversification and complexity

Applied Industries	Service Functions
Catering	Catering Delivery
Healthcare	Medication Delivery
Elder Care	Palliative Care
Retail	Greeting & Promotion
Education	Teaching & Tutoring
Hospitality	Housekeeping & Cleaning
Industrial	Cargo Handling
Public Services	People Monitoring & Security
Entertainment	Information Inquiry & Guidance

Source: Deloitte Research

In summary, what users need is not just "general-purpose robotics", but a "general-purpose robotic product system". This system should be able to flexibly adapt to multiple scenarios, with higher collaboration and compatibility, and it should also be more convenient in terms of usage and maintenance.

1.2.4. The commercial service robot industry enters the second half of its development

As the first segment within the service robotics industry to reach commercial scale, the commercial service robots play a pivot role in shaping and guiding the development trajectory of the broader robotics industry. Over the past decade or more, commercial service robots have experienced the first half of the industry, which is characterized by a single business model brought about by a single product and single technology. In terms of products, they are mainly specialized robots, which are typically designed for specific tasks or scenarios, such as catering delivery, cleaning, greeting, etc. Technologically, at this stage, the development of robots is focused on autonomous mobile technology, while their operational and interactive capabilities are relatively weak. Robot companies often focus on a single technology or product, lacking the ability to integrate across different fields. Most robot enterprises, from the perspective of professional division of labor, lack the ability and willingness to provide customers with one-stop product services and experiences. Points above have limited the global scale of service robots, leading to low efficiency within the industry and intensified homogeneous competition.

The industry has reached a crucial turning point, with commercial service robots taking the lead in entering the second half of their development, displaying several notable characteristics:

- **Multi-category Product Matrix:** With the advancement of technology and the diversification of market demand, specialized robots of a single category can no longer meet the complex and changing business environment. Leading companies are working on creating a diverse product matrix, covering robot products in various fields such as meal delivery, cleaning, and industrial distribution, to meet the specific needs of various application scenarios and achieve comprehensive coverage and optimization of services.

- **Integration of Multiple Technology Stacks:** The industry is starting to focus on the development of multiple technology stacks such as mobility, manipulation, and interaction. Based on the actual needs of users, service robots should not only be able to move autonomously but also possess manipulation capabilities and natural interaction skills to complete more complex tasks. In this context, the emergence of humanoid robots and robotic arm technologies is a precise grasp and positive response to the trend of multi-technology stacks development.

- **Integration of Globalization and Localization (Glocal):** As commercial service robots are widely deployed on a global scale, service robot companies need to establish localized commercial layouts in different countries and regions to adapt to local market characteristics and cultural differences. For service robot companies to succeed in the global market, it is largely dependent on the establishment of a global sales network and the precise execution of localized product strategies.

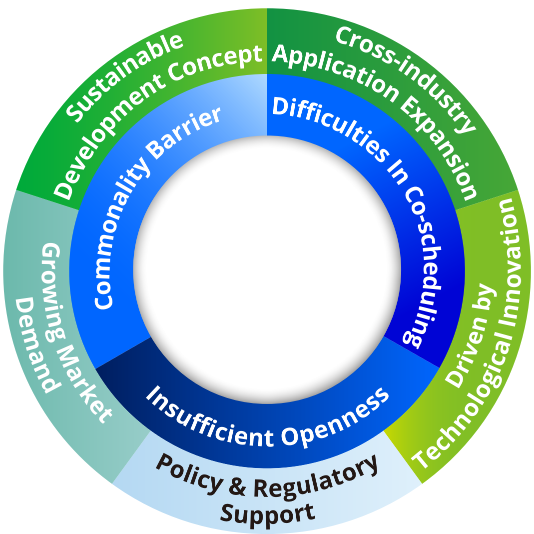
- **Transitioning from Specialized to General Use:** The second half of the industry focuses more on the generalization capabilities of robots in cross-scenario and complex environments. This requires robots to have higher operational capabilities and environmental adaptability to achieve the shift from specialized to general use.

The commercial service robot industry has entered the second half of its development stage, characterized by a diverse product matrix, multiple technology stacks, and a deep integration of globalization with localization. Companies need to shift from focusing on a single technology or product to offering one-stop solutions to meet the needs of global customers. **Industry leaders are achieving larger-scale global application of commercial service robots by building a diverse product matrix, developing multiple technology stacks, and adopting a strategy of deep integration of globalization with localization.** With continuous technological advancements and further growth in market demand, the commercial service robot industry is poised to embrace a broader development space.

1.3. Opportunities and challenges faced by the implementation of service robots

The global service robot market has entered a period of rapid growth. In summary, the overall industry scale and demand are increasing strongly. Although the market penetration rate of service robots in major countries and regions around the world is relatively low, the market potential is huge. For a long time, the closed ecosystem of the service robot industry has made it difficult to achieve interconnection and interoperability among different technologies, products, and systems. In addition, the barriers of versatility and generalization of robots have greatly hindered the widespread application of service robots.

Figure 1-9: Opportunities and challenges of service robot deployment



Source: Deloitte Research

1.3.1. Barriers to openness in the industry ecosystem

For a long time, the service robot industry has lacked unified protocols and standards, leading to difficulties in achieving interoperability between products and services from different vendors. Additionally, due to a combination of factors such as market protectionism and business models, the industry ecosystem tends to be closed, resulting in a slowdown in the pace of innovation and the emergence of technology silos. For users, the closed ecosystem limits the user experience, causing fragmentation and segmentation of the product experience. In the long run, a closed industry ecosystem will hinder the overall development and innovation of the industry. However, with the maturation of technology and the scaling of the market, open cooperation has become an inevitable trend to promote the healthy development of the industry and technological innovation. Therefore, it is urgent for the service robot industry to promote the unification of standards and establish a more open, inclusive, and beneficial industry ecosystem.

- **Lack of Industry Standards:** The absence of industry standards greatly hinders the healthy development of the service robot industry. Unified industry standards can regulate product design, safety, and performance requirements, and promote cooperation and sharing between technologies. However, at present, the standards in the service robot industry are not uniform, which causes inconvenience for users in selecting and using products, affecting user experience and market trust. In addition, the lack of standards may also lead to compatibility issues between products, thus affecting the possibility of different robots working together in collaboration.

- **Increased Integration Difficulty:** Technical barriers are the most obvious issue resulting from the closed nature of the industry ecosystem. Companies tend to develop independent technologies and products, relying on their respective technical platforms and standards, leading to a lack of unified technical specifications. This situation makes it difficult to achieve interoperability between service robots of different brands and types, limiting collaboration between products. For instance, in smart buildings, service robots need to be effectively integrated with elevators, access control systems, and other systems, but the lack of general-purpose interface standards complicates this connection, increasing the difficulty of integration. This inability to provide users with a full-stack intelligent experience.

- **Hampering Innovation and Development:** A closed ecosystem may stifle innovation within and across industries, restrict healthy market competition and development, and in addition, may lead to the emergence of technology silos, where solutions from different vendors cannot interconnect, thus reducing the overall efficiency and effectiveness of the industry.

- **Restricted User Experience:** As the variety of service robots increases, the difficulty of collaborative scheduling between robots of different categories or from different companies directly affects the customer service experience and the operational efficiency of businesses. For example, in integrated scenarios such as catering and hotels, users have complex needs that include "delivery + cleaning + greeting guidance" simultaneously. However, due to the lack of unified industry protocols and interfaces, it is difficult for robots from different companies or categories to form seamless collaborations. Addressing this issue often relies on the dominant party or integrators to coordinate, yet this approach involves non-standardized projects, leading to high coordination costs and difficulty in achieving large-scale promotion. Therefore, **companies with narrow product lines risk delivering fragmented and disjointed user experiences**, which not only increases the decision-making cost for users but also limits the pace of large-scale commercial deployment of service robots.

1.3.2. Barriers to the versatility and generalization of service robots

The versatility of service robots and their generalization in performing tasks are also key challenges for the industry's development. From a commercial perspective, although service robots have achieved application coverage in various scenarios across industries such as catering, hospitality, retail, industrial, medical, and more, and have achieved large-scale penetration in scenarios like catering, the nuanced scenarios within different industries have specific requirements for the functions and operations of robots, posing challenges to the versatility of cross-industry, cross-scenario robots. For example, in hotel and catering scenarios, there may be a simultaneous use of various types of service robots for delivery, cleaning, security, consultation, etc. However, in the past, due to technological limitations and the singularity of forms, most robots were unable to handle complex tasks, which greatly limited the application scope of service robots and increased deployment costs. Therefore, there is a growing market demand for service robots that can adeptly handle complex environments and diverse scenarios, with higher versatility and flexibility, and closer to the level of embodied AI. Promoting the research and development, as well as the application, of versatile robots will be the key to further large-scale implementation of service robots in the industry.

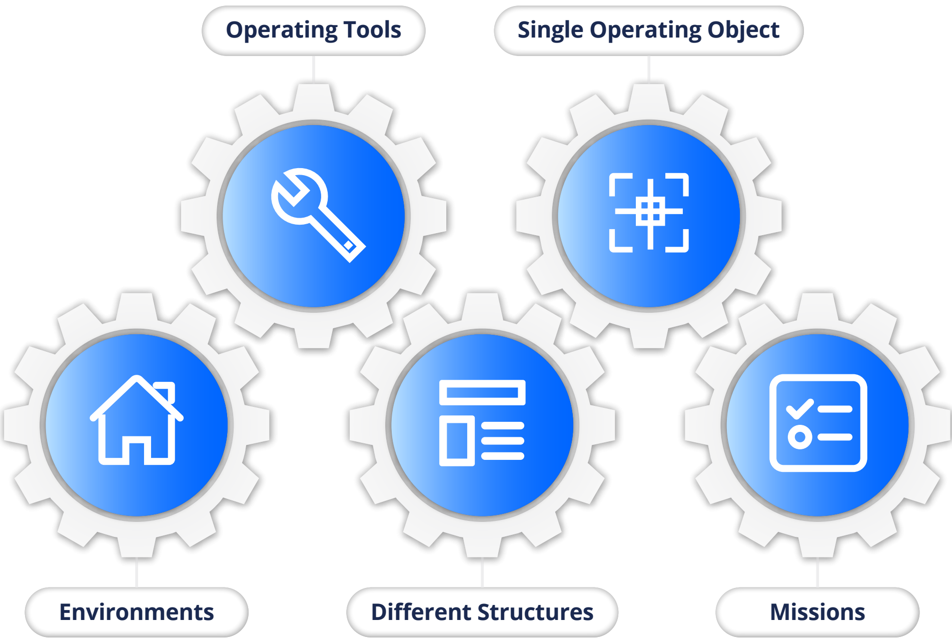
- **High migration costs:** The lack of versatility means that each industry needs to customize the design and production of service robots according to the application scenarios. This not only increases the customization costs of research and development, but may also limit the robots to specific tasks, reducing their migration ability and flexibility in different scenarios.

- **Difficulty in flexible deployment:** Companies need to redesign and configure robots for each niche scenario or task, and users are unable to quickly deploy and reconfigure robots in response to market changes, leading to costs and resource consumption. In contrast, general-purpose robots can quickly adapt to new tasks and environments, thus improving overall efficiency and productivity.

- **Increase integration difficulty:** Various robotic systems lack standardized and modular design, leading to an increase in the difficulty of integrating various systems.

- **Affecting the service experience:** Users need to manage and maintain a series of dedicated robotic products, each with its unique operating system and maintenance requirements, which increases the complexity of operation and use, as well as the cost of training and technical support.

Figure 1-10: Five generalization challenges of general-purpose embodied robots



Source: Deloitte Research

At the same time, **from a technical perspective, the versatility of service robots is limited by a range of generalization barriers across multiple dimensions. These barriers constrain the large-scale commercial deployment** and represent a complex set of challenges for service robots in achieving high versatility and generalization.

- **Generalization of Single Operational Object:** Service robots often need to grasp and manipulate objects of various shapes, materials, and weights. In this process, the capability to operate different objects presents a high technical challenge. Taking the catering scenario as an example, the robot's grasping skills need to adapt to various cup types and materials such as porcelain cups, stainless steel cups, and paper cups, which increases the complexity of operation.

- **Generalization of Operating Tools:** For example, in industrial scenarios, robots need to use different tools to complete tasks, such as requiring different types of screwdrivers and welding torches during assembly. Achieving the generalization of operating tools requires robots to have the ability to adapt to and flexibly use a variety of tools, which remains a technical challenge for traditional service robots.

- **Generalization of Environment:** Service robots need to adapt to the variability of the environment when performing tasks in different settings. A clean table and a cluttered work area present vastly different operational requirements for the robot, and these changes in environmental factors can directly affect the smooth progress of the robot's tasks, thereby impacting the ability of service robots to empower various industries.

- **Generalization of Tasks:** Service robots are typically designed for specific tasks, but users often wish for robots that can perform a variety of operations. Therefore, achieving a broader task generalization is also a challenge, which affects the practicality of robots. For instance, each type of task such as cleaning, transporting, and guiding has its specific operational procedures and requirements. Robots need to possess the ability to learn and execute across different tasks, which is the key challenge in achieving task generalization.

- **Generalization of Different Conformations:** The diverse forms of service robots make it difficult to apply a one-size-fits-all algorithm. However, personalized designs to meet the specific needs of various forms result in significant technical challenges and economic burdens, which directly limit the potential realization of general-purpose robots. The more variations in the form of a robot, the more diverse the required manipulation algorithms and strategies become, making the maintenance of unity and flexibility extremely complex.

Generalizability is an important challenge in achieving general-purpose embodied service robots, and these challenges involve aspects such as robot perception, cognition, manipulation, and learning. Continuous advancements in artificial intelligence, machine learning, and robotics are required to gradually address these challenges and push the general-purpose embodied service robots towards wider application scenarios.

1.4. ESG practice guidelines for the service robot industry

The development of the global service robot industry is expanding and delving into every aspect of social production and human life. Under this background, ensuring the sustained and stable development of this industry and advancing the construction of environment, social, and governance (ESG) through the adoption of practical and effective measures is particularly crucial.

- From the perspective of environmental protection, the sustainable development of the service robot industry requires special attention to the construction of a green supply chain. Enterprises should prioritize the use of renewable and eco-friendly materials and optimize production processes to reduce waste emissions. By introducing green supply chain management, service robot companies can not only minimize environmental damage during the manufacturing process but also establish a responsible and eco-conscious corporate image in the market. As society places increasing importance on sustainable development, consumers are increasingly inclined to choose products with environmental features, which provides a tremendous market opportunity for the service robot industry.

- From the perspective of social responsibility, service robot enterprises must ensure that their products comply with laws and regulations around the globe to ensure compliance and smooth entry into different markets. As service robots are widely applied in sensitive fields such as healthcare, education, and security, it is crucial to ensure compliance with international standards and local regulations, such as ISO, CE, UL certifications. This not only helps to enhance the market access capabilities and consumer trust of enterprises, but also demonstrates the commitment of enterprises to social responsibility. Global market compliance certifications can not only enhance product strength but also boost brand reputation, thereby increasing user loyalty and satisfaction.

- From the perspective of corporate governance, service robot enterprises should take measures to actively address the challenges of information security and user privacy protection. With the advancement of technology, it is crucial to establish a comprehensive information security management system for data collection related to robots. Enterprises should develop transparent privacy policies to ensure that users are fully informed about the collection and use of their data, thereby enhancing user trust. In the process of adhering to international and regional information protection regulations, enterprises should adopt effective systems and structures to fully safeguard and respect user's privacy. Good information security governance helps to enhance a company's competitiveness in the market and establish a responsible corporate image.

ESG practices can help global service robot ventures better identify and mitigate risks related to environmental, social, and governance factors, thus better addressing potential challenges. Service robot companies should always actively explore practices in sustainable development, leading the global service robot industry in sustainable development practices and progress.

This white paper will delve into the general solutions for the sustainable development of the service robot industry, establishing leading ESG practice guidelines for the industry with measures in three key areas: green supply chain (E), global compliance certification (S), and information security and privacy protection (G). Moreover, the ESG strategy for service robots is not limited to these key points but is a multidimensional framework covering a broader scope, including many other important environmental and sustainable development issues.

Figure 1-11: ESG practice guidelines for the service robot industry

Source: Deloitte Research

1.4.1. Green supply chain (E)

The service robot industry is characterized by technology innovation and multi-domain applications, and the impact of its production and use on the environment is particularly important. Currently, environmental protection regulations and policies are continuously strengthening globally, imposing higher requirements on the environmental responsibility of high-tech industries. Consumers and investors are increasingly concerned about corporate environmental responsibility, and a company's environmental performance directly affects the brand image and market competitiveness of service robot enterprises. This white paper, based on thorough research, demonstrates that the following strategies can effectively build a green supply chain in the service robot industry:

1. Choose environmentally friendly materials

Enterprises should adhere to the concept of sustainable development and actively adopt environmentally friendly materials in the production process of service robots. First, the product design strategy should ensure that the body shell uses no-painting technology to the greatest extent, selecting recyclable materials to reduce the release of harmful substances during the production process. Second, both the internal metal structure and the external support trays are made of materials that can be fully recycled and reused, which not only reduces the environmental burden of production but also promotes the circular use of resources.

2. Focus on product safety and health

Enterprises should pay special attention to the safety and health aspects of the materials selected during the production process. For instance, some of the silicone materials used in the trays have antibacterial properties, ensuring product safety and compliance with biocompatibility standards, and are harmless to user health during use. This material selection, which prioritizes user health, not only enhances product safety but also aligns with the increasingly stringent environmental protection regulations.

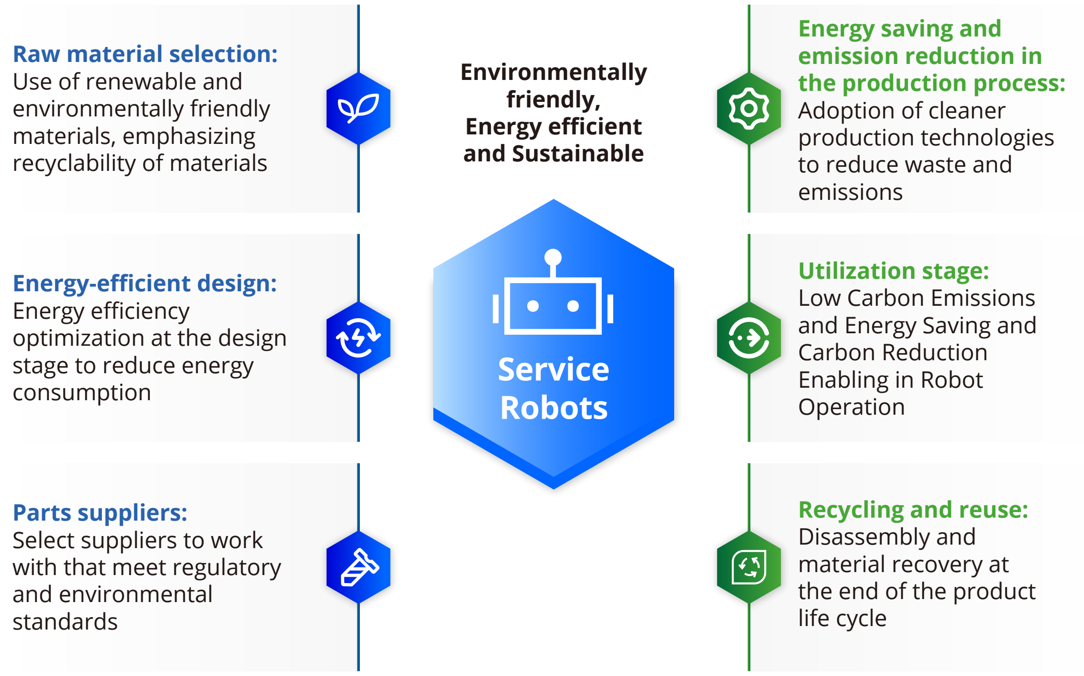
3. Ensure environmental compliance

In terms of environmental compliance, enterprises should strictly adhere to the **ROHS (Restriction of Hazardous Substances directive) and REACH (Registration, Evaluation, Authorisation and Restriction of Chemicals regulation) standards**. Apart from specific battery cells and hardware components, all structural parts used should meet the above regulations to ensure consumer's health and safety. Through compliance measures, the enterprise not only fulfills its environmental responsibilities but also establishes a good reputation in the market.

4. Energy saving and consumption reduction in the production process with traceability

Energy-saving and consumption-reduction measures in the robot production process are equally crucial. Service robot production factories should optimize energy efficiency during the production process by implementing energy management systems, thus reducing energy consumption and emissions. By adopting Internet of Things technology and through supplier collaboration, IPD process integration, production quality traceability, and warehouse management, the factory achieves intelligent management of the robot product lifecycle, prompting the venture to actively respond to global sustainable development goals in the production process.

Figure 1-12: Green supply chain architecture of service robots



Source: Deloitte Research

1.4.2. Global market compliance certification (S)

1. The importance of global market compliance certification is crucial in the context of service robots being widely used in fields such as healthcare, households, education, and public services.

Ensuring the safety and compliance of these robots in their design and operation is essential for improving the quality of life and social well-being. Compliance certification is not only a necessary condition for enterprises to enter the international market but also an important way to strengthen consumer and user trust. It is the path that service robot enterprises must take to establish global social responsibility.

2. Global Compliance Certification Practice Guidelines for Service Robot Enterprises: Enterprises should actively promote the compliance certification of service robots in global business practices, committed to meeting the highest social responsibility standards in various markets, including but not limited to:

Europe CE
America FCC
Korea KC
Australia RCM
Singapore IMDA
Japan TELEC
China CR
Malysia SIRIM

Source: Collected from public sources

Earning these certifications indicates that the service robot products meet stringent requirements and the highest standards in terms of quality and safety, electromagnetic compatibility, and radio frequency, not only fulfilling the market access criteria of different countries and regions but also reflecting the company's high emphasis on product quality and user safety.

3. The significance behind compliance certification

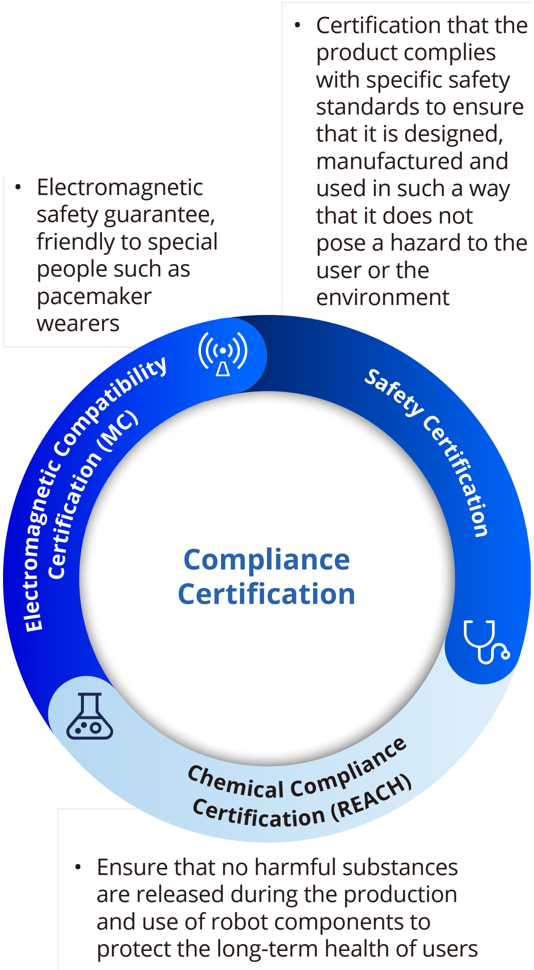
- **Ensuring User Health and Safety:** By obtaining internationally recognized compliance certifications, service robots assure consumers of the safety of their products in terms of design and functionality, reducing potential risks during use. For example:

  – Electromagnetic Compatibility (EMC): Ensuring that the robot does not interfere with surrounding electronic devices during operation, especially for users with pacemakers, where low electromagnetic radiation design is crucial. This certification protects the health of these individuals and reduces potential risks.

  – Safety Certification: Certification that the product meets specific safety standards, ensuring that it does not pose a risk to users or the environment during design, manufacturing, and use.

  – Compliance certification related to chemical substances (such as REACH): Ensure that the components of the robot do not release harmful substances during production and use, protecting the long-term health of the users, especially for robot products used in food and medical environments.

Figure 1-13: Compliance certification based on customer's health and safety assurance



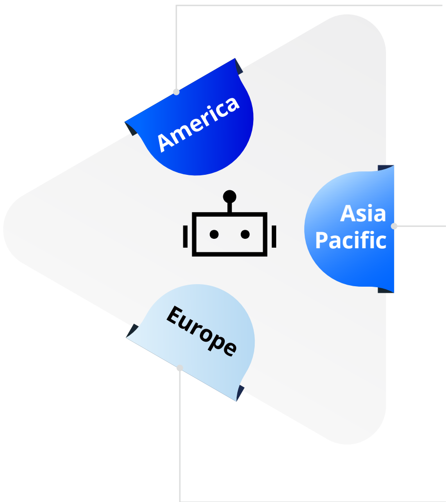
Source: Deloitte Research

- **Enhance Market Trust and Brand Image:** Global market compliance certification is the stepping stone for service robot companies to go global. Such compliance certifications not only increase consumer's trust in the brand but also enhance the company's market position. Generally speaking, consumers are more inclined to choose products that have undergone rigorous certification to ensure quality and safety.

- **Promote International Business Expansion:** Compliance certification allows a company's products to smoothly enter the markets of different countries and regions, quickly adapting to local regulations and standards. Compliance significantly reduces barriers to entering new markets, helping businesses to expand globally and increase their market share.

- **Support Environmental Protection and Sustainable Development:** Many international certifications take into account environmental standards, including aspects such as raw materials and production processes. Such measures reduce the impact on the environment, and while pursuing commercial success, enterprises also fulfill their social responsibilities.

Figure 1-14: Compliance certification guidelines for the service robot market



- **FCC Certification:** Ensures electromagnetic compatibility and protects users from interference.
- **UL Certification:** Ensure product safety.

- **KC Certification (Korea):** Confirms that products comply with safety standards.
- **RCM Certification (Australia):** Mandatory certification applicable to electrical products.
- **SIRIM Certification (Malaysia):** Ensures product safety and compliance with local standards.
- **IMDA Certification (Singapore):** Responsible for the regulation and review of wireless devices.
- **TELEC Certification (Japan):** Focuses on wireless product compliance.

- **CE-MD:** Machinery Directive, ensuring the free circulation of machinery and equipment on the market and safeguarding the safety and health of users.
- **CE-RED:** Wireless Devices Directive, which ensures the compliance of wireless devices.

Source: Collected from public sources

Building global market compliance certification is the foundation for the sustainable development of the service robot industry, especially in fields where service robots are primarily used, such as healthcare, education, and public services, which directly affect people's life quality. Through global market compliance certification, it not only ensures the health and safety of users but also enhances brand image, promotes market expansion, and effectively supports environmental protection. The establishment of compliance in service robot products will lead the industry towards higher social responsibility standards and boost innovation and development in the global service robot industry.

1.4.3. Information security and privacy protection (G)

In the service robot industry, information security and privacy protection (G) are of paramount importance. As an industry highly related to technology and data, robotics companies face complex legal, ethical, and data privacy issues. Good corporate governance not only helps to ensure compliance in these areas but also builds a good corporate reputation, enhancing the confidence of investors and consumers.

1. Privacy and Data Management

Enterprises should fully recognize the critical role of user privacy and data security in maintaining customer trust and business continuity. In the robotic design phase, robotics companies should ensure that no personal privacy data of users is collected or stored. For the operational state data of robots that must be stored for technical support and product performance improvements, strict compliance requirements should be followed, with the platform assuming responsibility to ensure the confidentiality, integrity, and availability of such data. An effective privacy protection mechanism is established by prohibiting unauthorized use and disclosure of data. In addition, enterprises should also establish the highest level of security governance framework and rules, protecting data information through strict data management policies to ensure that it is handled according to the highest standards. Effective privacy management solutions not only reduce legal risks but also build a strong sense of trust among consumers.

2. Security Technology and Policy

Enterprises should adopt a series of effective measures in terms of security technology, implement data backup mechanisms to ensure data stability and security, thereby effectively preventing data loss. By utilizing advanced encryption technology and security protocols, data on endpoints and in the cloud are protected, preventing unauthorized access and data breaches, enhancing overall security levels. At the same time, the internal information security governance of enterprises should also implement end-to-end protection processes, ensuring that each application system complies with the Security Development Lifecycle (SDLC) process at every stage of requirement analysis, development, testing, deployment, and operation. This comprehensive IT security defense system can ensure the security of endpoints, networks, applications, and cloud platforms. Enterprises should regularly conduct security assessments and penetration testings on robotic application systems, adhering to the security requirements of OWASP (Open Web Application Security Project). The absence of any S0/S1 level network security incidents and data breaches will be a significant performance indicator for enterprise information security governance.

3. Compliance and Standard Certification

In terms of information security and privacy protection, service robot companies should actively participate in internationally recognized information security and IT governance standards certifications and build a comprehensive information security management system based on these certifications. In China, companies' involvement in the China Academy of Information and Communications Technology's ZhuoXin Big Data Program and the Enterprise Data Security Initiative of China Digital Technology Development Working Committee will keep their information security and data privacy protection efforts at the forefront of the industry. Globally, enterprises should actively participate in DNV audits to obtain information security and privacy management system certifications that meet the ISO/IEC 27001 (2022) and ISO/IEC 27701 (2019) standards. These international standard certifications not only provide a clear security management framework for enterprises but also enhance customer trust in products and services.

By implementing comprehensive and efficient information security and privacy protection measures, service robot companies not only ensure the security of user data and enhance consumer trust, but also raise the corporate social responsibility and comprehensive governance capabilities. By continuously strengthening compliance governance and technical capabilities, they will promote sustained progress and development in the service robot industry regarding information security and privacy protection.

Figure 1-15: Information security governance and privacy protection framework in the service robot industry

Privacy & Data Management

- Data Encryption and Anonymization
- Data Access Rights Management
- Data Storage Compliance

Security Technology And Policy

- Secure Development Life Cycle (SDLC)
- End-to-end encryption
- Periodic security assessments and penetration testing

Compliance And Standards

- Compliance with ISO 27001 & ISO
- Compliant with regulations like GDPR, CCPA, etc.
- Membership in industry standardization organizations (e.g. OWASP)

User Education & Transparency

- Transparency of user privacy policies
- Provide data use education andProvide education and support on data use
- Establish user trust mechanisms

Source: Deloitte Research

Chapter Two:

The Open Full-stack Intelligent Service Robot Ecosystem

Service robots are rapidly finding applications across a wide range of global sectors, including food service, hospitality, retail, healthcare, education, and industry. By delivering intelligent services in areas such as delivery, cleaning, and guidance, they are making daily life and work more convenient while profoundly reshaping global industrial development.

The emergence of embodied AI—fusing physical robotic systems with artificial intelligence—marks a decisive shift in this evolution. As robots begin to perceive, interpret, and interact with their environments in increasingly human-like ways, this hybrid of hardware and software promises to make machines more autonomous, adaptable, and capable of sophisticated decision-making.

Yet serious hurdles remain. The industry remains fragmented and technologically siloed. Robots are often built for narrow, proprietary ecosystems and lack interoperability. Coordination across different brands or robot types is rare, and general-purpose capabilities remain elusive.

In response, Pudu Robotics has, for the first time globally, proposed an open, full-stack intelligent service robot ecosystem. The goal of this ecosystem is to create an open, collaborative, and generalizable platform for embodied AI—one that integrates advanced AI technologies with dedicated, humanoid, and semi-humanoid robots. By innovating across key technological stacks such as mobility, manipulation, and interaction, this ecosystem aims to offer a full-stack matrix of diversified products and comprehensive solutions, ultimately enabling sustainable growth in the service robotics sector.

In today's market, there is a rising demand across industries for versatile, multifunctional service robots. Yet issues such as fragmented services and disjointed workflows still restrict the ability to build a closed-loop system centered on user needs. To enable intelligent, end-to-end services across scenarios—especially in an era defined by automation and intelligence—there is an urgent need to improve the generalizability of service robots.

Here, the open full-stack blueprint offers a promising route forward. Its embrace of technological diversity—across robot types, product categories, and technical stacks—lays the groundwork for true embodied AI. By developing standards, encouraging hardware modularity, and enabling inter-robot communication, it arms machines with the capacity to adapt to new environments and take on increasingly complex tasks.

The implications go far beyond technical wizardry. A truly open ecosystem represents an inevitable trend toward the next stage of service robot evolution. By promoting technological integration and innovation, setting industry standards, and enabling resource sharing, the ecosystem will accelerate the development and application of new technologies, foster global collaboration, and create new opportunities for the service robotics industry.

The ecosystem will significantly enhance productivity and improve social efficiency. Not only will it strengthen enterprise competitiveness and reduce operational costs, but it will also contribute to broader societal well-being, playing a vital role in advancing global sustainable development goals. It may create a win-win model for both businesses and society, ushering in a new era of human–robot collaboration.

This is more than an industry upgrade—it is a new chapter in the story of human–robot collaboration. The construction of a full-stack ecosystem represents a watershed moment, not just for robotics but for the broader shift toward intelligent automation. As it redefines industry boundaries and rewires service delivery models, it will offer users more efficient, intelligent, and human-centric service experiences. The ecosystem will also drive service robots toward general-purpose embodied AI, opening up new possibilities for the industry's future and supporting the vision of a smart, interconnected, and sustainable world of robotics.

2.1. Define the ecosystem

An open, full-stack intelligent service robot ecosystem is an integrated innovation of both technological framework and business model. It aims to build an inclusive and open industry ecosystem driven by AI-centered multi-technology stacks and innovative business approaches. The goal is to enable intelligent interaction and seamless connectivity between service robots and all potential interaction targets—be it humans, environments, other robots, or software and hardware systems—thereby forming a general-purposed full-stack intelligent robot ecosystem.

At its core, the ecosystem champions openness and generality. By constructing a fully interoperable and seamlessly connected intelligent service robot ecosystem, it seeks to achieve deep integration and broad deployment of service robots across diverse application scenarios.

The development of this ecosystem rests on several key elements:

Technology Integration:

Build upon the integration of technologies such as artificial intelligence and the Internet of Things, with a focus on developing three core technology stacks—mobility, manipulation, and interaction—to enhance the autonomy, adaptability, and intelligence of service robots.

Open Ecosystem:

Integrate and coordinate the hardware, software, data, and interfaces of various service robots. Promote technology exchange and improve product compatibility through open APIs, SDKs, and standardized protocols. Lower the barriers to development and integration, encourage the creation of an open industry ecosystem, and foster collaboration and knowledge sharing to build a standardized, inclusive, and widely accessible service robotics industry.

Interaction Expansion:

Leverage general-purpose AI technologies such as natural language processing and emotion recognition to enable embodied AI and deliver a full-stack interactive experience.

Form Factor Diversification:

Develop a variety of robotic forms to meet specific needs across different scenarios—including specialized, humanoid, and semi-humanoid models—and encourage the parallel development of all three.

Business Model Innovation:

Establish a diversified product matrix that delivers full-stack solutions across various application scenarios, allowing service robots to better meet the complex needs of users.

Sustainability and Inclusiveness:

Promote the role of service robots in supporting sustainable development across industries, encourage innovation and collaboration both within and beyond the sector, and drive the sustainable and inclusive growth of the service robotics industry.

2.2. Ecosystem development pathway for the second half of the industry

As service robotics moves into its second act, the industry is shifting gears—from experimentation to scalable ecosystems. What lies ahead is a bold, multidimensional strategy: the construction of an open, full-stack intelligent robotics ecosystem that cuts across sectors and technologies.

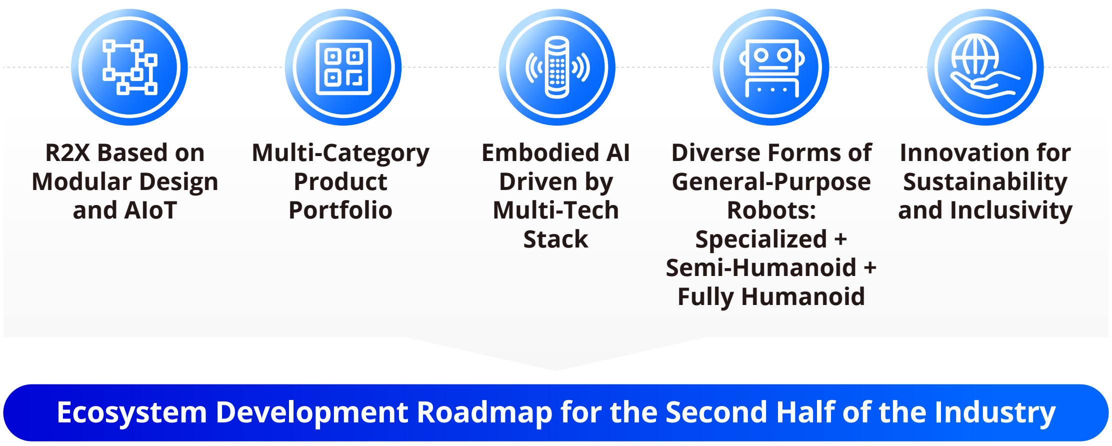
At its core is the vision of Robot-to-Everything (R2X)—a modular, AIoT-enabled architecture that allows machines to communicate and coordinate with their environments. Robots, once isolated automatons, are evolving into interconnected agents, seamlessly integrated into the wider digital and physical fabric.

Within this ecosystem, specialized, semi-humanoid, and humanoid robots play complementary and irreplaceable roles, collectively forming the future of the robotics landscape to accommodate diverse scenarios and tasks. This evolution is powered by multi-stack technologies integrating autonomous mobility, manipulation, and interaction—endowing robots with embodied AI that makes their behavior in the physical world smarter and more human-like.

Yet the technological leap is only half the story. The new ecosystem also reimagines how business model is innovated. A diverse product matrix enables robots to collaborate across roles, offering users a seamless experience. Innovation here is not just smarter—it is more inclusive and sustainable.

Ultimately, this pathway offers not only a practical strategy for large-scale commercial deployment of service robots, but also a shared platform for stakeholders across the industry to grow and innovate together.

Figure 2-1: Development pathway for the second half of the industry



Source: Deloitte Research

2.2.1. Ecosystem technological foundation: modular design and AIoT-Based R2X

In January 2024, Pudu Robotics became the first in the world to introduce the R2X technology architecture—short for Robot-to-Everything.

R2X promotes an open and standardized industry ecosystem. By unifying technical specifications and communication protocols, it enables better coordination among service robots of different brands and models, as well as seamless connectivity between robots and a wide range of ecosystem devices.

To break through the existing industry silos that remain closed and poorly integrated, R2X—built on modular design and the deep integration of artificial intelligence and the Internet of Things (AIoT)—serves as the foundational technology for developing an open, full-stack intelligent service robotics ecosystem.

Modular Design

In today's robotics industry, development frameworks vary significantly. Robots designed within closed ecosystems typically have fixed, proprietary hardware and software, resulting in poor compatibility and scalability, as well as high costs for maintenance and system migration.

Modular design offers a promising escape. By decomposing robotic systems into discrete software and hardware units, companies and users alike can tailor their machines to fit the task at hand. This approach doesn't just improve adaptability and scalability—it also accelerates innovation and underpins a more open, agile ecosystem for intelligent service robots. It lays the foundation for an open, full-stack intelligent service robotics ecosystem.

Modular design for service robots revolves around several key modules—mobility, manipulation, interaction, sensing, and data processing & communication. This flexible architecture significantly improves the robot's ability to handle complex tasks across diverse environments.

The key elements of modular service robot design include:

1. Mobility Module

The mobility module is the core component responsible for robot movement and navigation, typically comprising the chassis, drive system, and motion controller. Key functions include:

- Autonomous Navigation and Obstacle Avoidance: Combining LiDAR, sensors, and cameras with motion control systems enables real-time mapping, path planning, and obstacle avoidance.

- Multiple Locomotion Modes: Robots can employ wheeled, tracked, or legged configurations depending on environmental conditions and task requirements. For instance, wheeled platforms suit flat indoor surfaces, while legged systems offer better adaptability to uneven terrain.

2. Manipulation Module

The manipulation module is critical for executing specific tasks, including robotic arms, grippers, and actuators. It works in conjunction with both specialized and general-purpose algorithms to enhance dexterity and intelligence. Main functions include:

- Precision Operations: Robotic arms equipped with multi-degree-of-freedom joints can perform varied actions such as grasping, transporting, placing, and cleaning. General algorithms enable real-time adaptation to different objects and conditions.

- Interchangeable Tools: The module supports easy switching between tools such as grippers, dexterous hands, suction cups, or cleaning brushes—broadening functionality and enhancing versatility across scenarios.

- Complex Task Execution: Integrated with general-purpose algorithms, the robot can intelligently adjust its actions in dynamic settings—for example, delivering food and clearing dishes in a restaurant scenario.

3. Interaction Module

This module serves as the interface between the robot and users, enabling intelligent interaction. Core functions include:

- Multimodal Interaction: Using natural language processing (NLP) and computer vision, robots interact via speech, gestures, and visual cues to create more natural and approachable user experiences.

- Emotion Recognition and Response: AI algorithms allow robots to analyze user emotions and adapt tone and content accordingly, delivering personalized and empathetic service.

4. Sensing Module

The sensing module enables environmental awareness through integrated hardware and software. Its functions include:

- Environmental Monitoring: With modern sensors (e.g., LiDAR, ultrasonic, infrared) and real-time processing software, robots can accurately detect surrounding objects and environmental conditions to support intelligent decision-making.

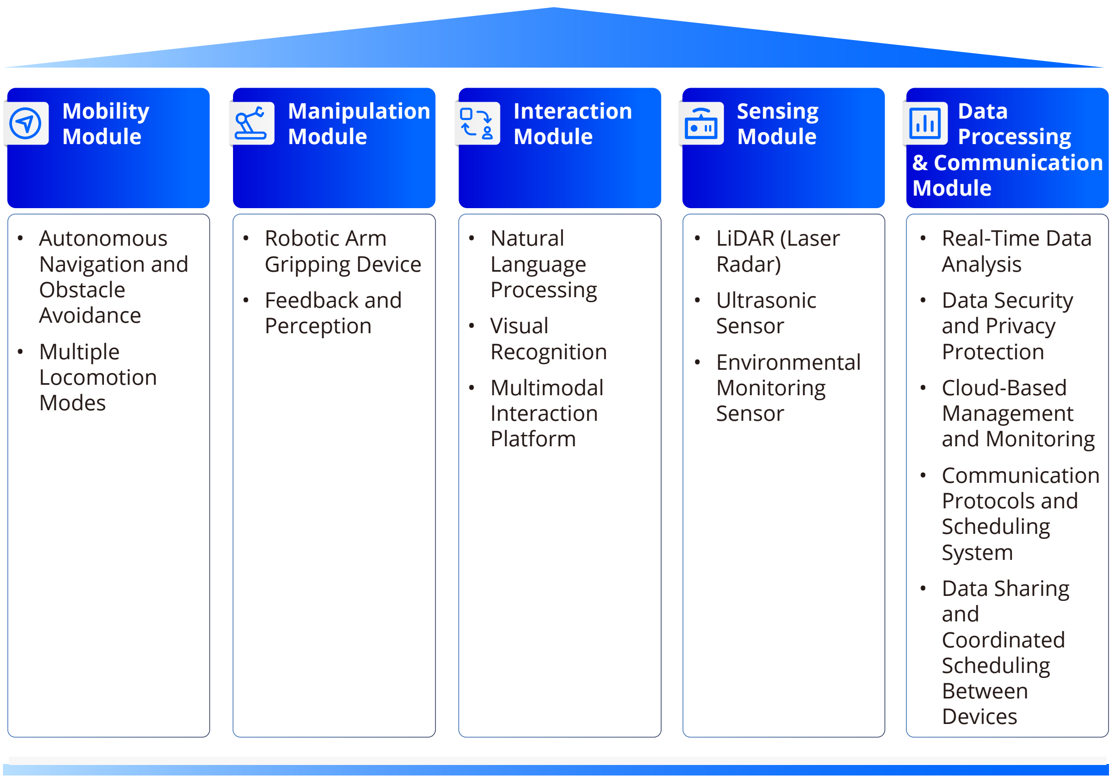
- Data Fusion: Through algorithmic processing, the robot can integrate inputs from multiple sensors, providing high-quality data to ensure effective operation in complex environments.

5. Data Processing & Communication Module

This module manages the collection, analysis, and governance of operational data. The software systems involved ensure data security and utility. Key functions include:

- Coordinated Scheduling: By establishing open communication protocols and efficient data-sharing mechanisms, different robot types can coordinate intelligently to optimize task allocation and execution efficiency.

Figure 2-2: R2X modular design architecture



Source: Deloitte Research

The application of modular design brings a number of advantages:

1. Flexible Configuration

The core advantage of modular design lies in its flexibility. By decomposing a service robot into multiple functional modules (such as delivery, cleaning, reception), each independently replaceable, companies can rapidly adjust product configurations to meet specific customer needs. For instance, **a cleaning robot can be equipped with optional external modules such as cameras, enabling it to perform inspection tasks besides carrying out cleaning operations**. This flexible configuration allows service robots to easily adapt to diverse business scenarios, thereby improving overall service efficiency.

2. Reduced R&D and Operational Costs

Modular design helps cut down both development and operational costs. When developing new products, companies can reuse existing modules, avoiding the need to start from scratch and thus saving time and money while improving technical efficiency. Moreover, since each module can be tested and maintained independently, maintenance is simplified, further reducing ongoing management expenses.

3. Facilitating Technology Integration and Innovation

Modular design offers a robust platform for technological innovation. Within an R2X technical architecture, individual modules can be continuously optimized in line with the latest technological trends. As AI and sensor technologies evolve, robotics companies can quickly integrate these advancements into existing modules without having to redesign the entire system. This agile R&D environment fosters ongoing innovation and allows firms to respond swiftly to market shifts.

4. Enabling R2X Interconnectivity

The combination of modular design and the Internet of Things (IoT) facilitates intelligent connectivity between service robots and other devices. Each module can be easily connected to various systems via standardized interfaces. For example, building service robots can integrate with elevators, access control systems, telephony, and more, achieving automated scheduling and operations via shared APIs. This connectivity enhances operational efficiency, reduces human intervention, and improves user experience—laying the foundation for a full-stack robotics ecosystem.

5. Establishing Industry Standards and Norms

Modular design also paves the way for unified industry standards and protocols. In an open, full-stack intelligent service robot ecosystem, the integration and coordination of hardware, software, data, and interfaces create a flexible and scalable service system. With open APIs and SDKs, different modules can seamlessly interconnect.

Modular design complements emerging industry standards for service robots (such as VDA 5050). While Modular design allows functional units to be separated at both the hardware and software levels, industry standards ensure effective collaboration among robots from different companies and of various types, achieving seamless interoperability.

Standardized interfaces and communication protocols enable modules to be interchangeable across systems, enhancing ecosystem flexibility. At the same time, the widespread adoption of modular design can further accelerate standardization across the industry, promote collaboration among vendors, and unlock new synergies for innovation.

The core of the modular design lies in the following key areas:

- Open and Unified Interfaces: At the heart of modularity is the quest for seamless integration. That requires open, standardized hardware interfaces and software APIs—capable of bridging diverse companies and disparate functionalities. Flexibility is not optional; it is essential for achieving compatibility across the full spectrum of device types and technical architectures.

- Industry Standards and Protocols: Formulate and adhere to consistent industry standards and protocols to ensure the widespread recognition and adoption of modular design across the service robotics industry. These standards should cover everything from physical connector specifications to data transmission formats, as well as safety protocols and error-handling mechanisms.

- Inter-Module Communication: Ensure consistent and efficient communication between modules by adopting standardized data exchange formats and communication protocols—such as MQTT, DDS, or ROS 2.0—to facilitate data sharing and task coordination among different modules.

AIoT

AIoT technology, which integrates the advantages of artificial intelligence and the Internet of Things, equips service robots with intelligent perception, real-time data processing, and interconnectivity. It enables seamless collaboration between robots and various devices within the ecosystem, making it a core enabler of the full-stack intelligent service robotics ecosystem.

The empowerment of service robots through AIoT technology is mainly reflected in the following areas:

1. Enabling real-time connectivity across devices

The value proposition of AIoT starts with connectivity. By embedding IoT capabilities, service robots gain the ability to interface with a range of building systems—elevators, access control units, intercoms, and beyond. This connectivity transitions robots from isolated endpoints to dynamic agents in a distributed intelligent environment. In smart buildings, for example, robots can autonomously call and ride elevators, offering users a frictionless end-to-end service experience.Data sharing and intelligent task scheduling.

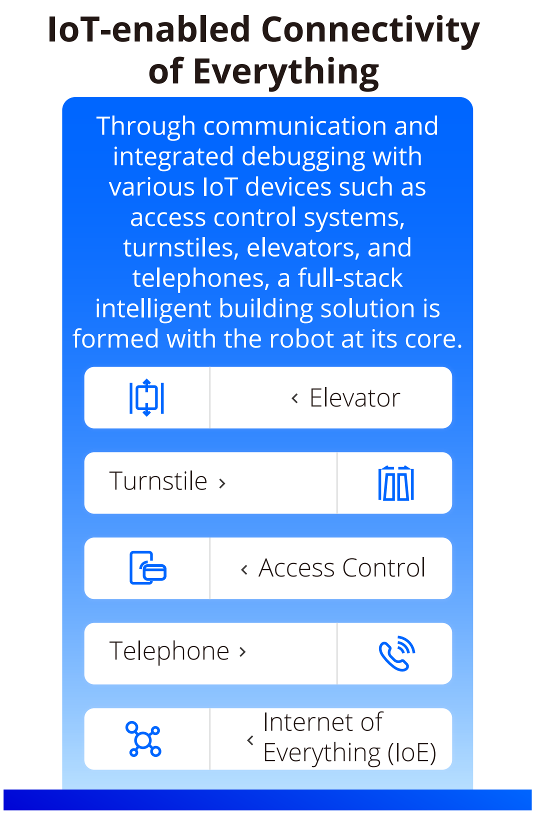
2. Leveraging shared data for task scheduling optimization

With AIoT, service robots can collect real-time data from their surroundings and connected devices. **This data is processed either locally or on the cloud to support intelligent decision-making and enable centralized cloud-based management.** When performing tasks like delivery or cleaning, robots can dynamically optimize their sequence and path based on real-time data. In retail scenarios, for example, cleaning robots can adjust their working schedules based on customer foot traffic, avoiding peak hours and enhancing workflow efficiency.

3. Driving collaboration across devices

One of AIoT's most transformative capabilities is enabling cross-device orchestration. When a robot must coordinate across multiple systems or functional modules, AIoT offers strong technical support. Using open APIs and standardized communication protocols, service robots from different companies and of different functional types can coordinate seamlessly. Consider a hospital scenario: medication delivery robots can seamlessly interact with reception robots, cleaning and disinfection bots, alarm systems, and surveillance equipment—creating a fully integrated intelligent ecosystem for hospitals.

Figure 2-3: AIoT-powered ubiquitous connectivity



Source: Deloitte Research

Pudu Robotics' Leading Practice — Dual Elevator Control Solutions Powred by R2X Architecture

Service robots become increasingly prevalent in commercial settings—ranging from hotels to office complexes and medical facilities However, these commercial settings are often complex and dynamic. To fulfill tasks that span multiple floors, robots must be able to move freely and interact seamlessly with elevator systems. This calls for integration with existing building management systems – particularly elevator control - and requires broad compatibility across diverse elevator brands and models.

These needs have revealed several customer pain points. Notably, the significant variation across elevator systems from different companies necessitates that robots be compatible with a wide range of elevator types to operate effectively in diverse environments. Moreover, establishing communication between robots and elevators often involves hardware retrofits—an approach that can be both costly and disruptive, potentially impacting the elevator's aesthetics and normal operations.

To address these challenges and offer customers greater flexibility, Pudu Robotics has introduced a dual-solution approach for elevator integration - leveraging its R2X architecture to offer both hardware-based and cloud-based elevator control models. It effectively resolves the elevator integration challenge for service robots operating in complex buildings, offering diverse and customizable options for users in hotels, office buildings, and beyond.

1. Hardware-Based Elevator Control

The hardware-based solution involves installing elevator control module & motion controller on elevators, enabling real-time communication between robots and the elevator system. Key attributes include:

- **High Compatibility:**
  Compatible with 90% of elevator models in the market, this solution significantly expands the applicability of service robots across various commercial environments regardless of elevator brand.

- **Strong Stability:**
  Operates effectively in low-connectivity or offline environments, ensuring service continuity.

- **Cost Efficiency:**
  Compared to more complex software solutions, the one-time hardware upgrade investment that supports multiple robots access, reducing total cost of ownership over time.

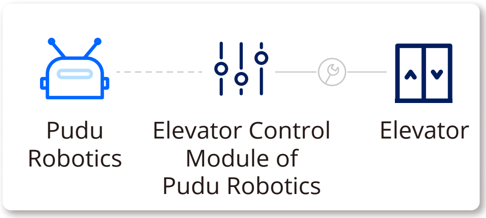
- **Multi-Robot Usability:**
  Once installed, the hardware modules can support various robot types, further improving efficiency and amortizing upgrade investments across a broader fleet.

- **Ease of Maintenance and Upgrades:**
  As physical devices, these modules are straightforward to maintain and upgrade. In the event of a malfunction, issues can be quickly identified and resolved or the module replaced, minimizing system downtime.

- **Enhanced Security Protection:** Independent communication channels are established using hardware-level isolation to mitigate cybersecurity risks at the source. Control commands are transmitted using end-to-end encryption, effectively preventing signal hijacking and data leakage. In addition, a dual-authentication mechanism—based on both the robot ID and the elevator control module—is implemented to strictly manage access rights. This ensures that only authorized robots can initiate elevator operations, meeting the stringent compliance requirements of high-security environments such as healthcare and finance.

Hardware Upgrade for Elevator Retrofit:

Installation and deployment of pudu robotics' elevator control module

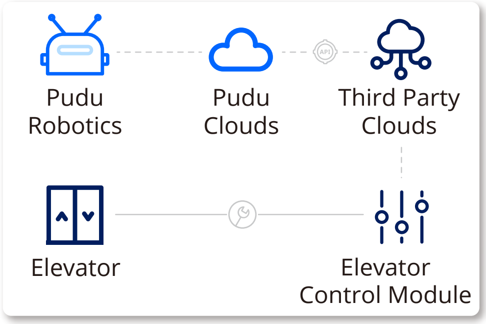


2. Cloud-Based Elevator Control

Cloud-based elevator control enables data interaction with the elevator system through cloud-based API interfaces. Service robots can access and operate the elevator system over the network without requiring any hardware modifications to the elevator itself. This approach relies on the real-time processing and data analytics capabilities of cloud computing platforms.

Cloud-Based Elevator Control:

Elevator companies/elevator control companies provide API interfaces, and Pudu develops and integrates with third-party cloud elevator control systems.



Key advantages of the cloud-based solution include:

- **Zero Hardware Retrofit:** Eliminates costly and disruptive physical upgrades, maintaining elevator aesthetics and operational continuity.
- **High Compatibility:** Based on standardized API interfaces, the cloud solution supports cross-brand, cross-model robot collaboration in a single environment, greatly expanding service robot deployment scenarios. The cloud-based elevator control solution offers a high degree of flexibility, enabling customized functionality through elevator interfaces based on varying elevator usage requirements. This adaptability allows the solution to quickly respond to new application needs, whether deployed in newly constructed buildings or used to upgrade services in existing facilities.
- **Cloud Computing Power:** Delivers real-time processing and analytics, enhancing robot responsiveness and enabling intelligent upgrades over time.

- **Remote Management and Updates:**
  As a network-based solution, cloud-based elevator control supports remote management and software updates. This enables rapid deployment of new features, timely issue resolution, and centralized elevator access control for service robots across global operations.

- **Enhanced Reliability:**
  The solution enhances elevator safety and reliability through network-based monitoring and logging. Any abnormal behavior can be detected and addressed in real time, improving security and ensuring reliable elevator usage for both robots and human passengers.

- **Advanced Customization Capabilities:**
  Cloud elevator control supports flexible configuration of robot elevator behaviors. Users can customize parameters such as robot entry/exit direction, door wait time, and floor stop strategies to suit different building layouts and operational requirements. The system also adapts to multi-scenario modes—such as emergency access in healthcare or peak-time scheduling in hotels—and dynamically optimizes command logic through real-time data analysis. This ensures both safety and compliance while significantly improving cross-floor collaboration efficiency and scenario adaptability.

By providing both hardware-based and cloud-based elevator control options, Pudu Robotics has delivered a comprehensive response to the elevator access challenges facing service robots in complex environments. Hardware solutions offer superior stability and wide compatibility, while cloud solutions provide a flexible, future-ready integration model. Together, they support a full-stack intelligent service robot ecosystem and enable broader deployment across building environments.

R2X Interaction

In the future, as technology continues to advance, the full-stack robotics ecosystem will gradually evolve toward a higher level of R2X interaction. According to the historical development of robot interaction, four levels can be identified:

- **HCI (Human-Computer Interaction)** – traditional human-machine interaction
- **HRI (Human-Robot Interaction)** – interaction between humans and robots
- **RRI (Robot-Robot Interaction)** – interaction between robots
- **RXI (Robot-Everything Interaction)** – interaction with all connected things

At present, most service robots remain within the first three stages. They are capable of responding to pre-set commands such as voice prompts or gestures, but lack the ability to deliver personalized feedback tailored to different scenarios and user profiles.

Empowered by artificial intelligence, the full-stack robotics ecosystem is rapidly evolving. With the continuous application and iteration of advanced sensor technologies, natural language processing, and emotion recognition algorithms, human-robot interaction is set to transcend traditional voice and visual modes—ushering in a new era of ubiquitous, full-stack intelligent interaction that delivers more attentive and empathetic service experiences to users.

Figure 2-4: Evolution of interaction modes in service robotics

HCI Phase - Traditional Human-Machine Interaction	HRI Phase - Interaction Between Humans And Robots	RRI Phase – Interaction Between Robots	RXI Phase – Interaction With All Connected Things
Primarily refers to interactions on the robot's control screen, representing connectivity between software and hardware.	The mobility of robots is continuously improving, gradually gaining autonomy and intelligence. Interaction between humans and robots is increasing, with emerging needs such as voice interaction, facial recognition, gesture recognition, following, perception-based obstacle avoidance, tactile feedback, and even robot dancing.	Includes collision avoidance, traffic coordination, and task scheduling not only among robots from a single company but also across different brands.	Refers to interconnection and interaction between robots and external devices such as elevators, access gates, door control systems, telephones, production lines, and warehouses.
Graphical User Interfaces And Command Language	Sensors, Control Technology, And Intelligence	Multi-robot Collaboration And System-Level	R2X – Full-stack Intelligent Ecosystem

Source: Deloitte Research

R2X interaction represents a multidimensional leap over traditional robot interaction models, transforming the way users engage with service robots across scenarios, content, and interaction modalities:

- **From Single-Point Interaction to Full-Stack Engagement**
  Traditional interaction modes are often confined to specific devices or scenarios. In contrast, the R2X ecosystem enables users to engage with robots anywhere, anytime, through any mode—be it voice, gesture, touch, or emotional expression—within the broader intelligent ecosystem.

  This open and immersive interaction framework deepens the connection between users and service robots. Robots are no longer merely task executors, but instead become companions integrated into users' daily lives, enhancing satisfaction and overall user experience.

- **From Basic Interaction to AI-Driven Personalization**
  In an R2X-powered ecosystem, advances in interaction technologies allow service robots to leverage AI foundation models to deeply understand and learn user needs and preferences.

  Unlike traditional robots that rely on fixed command-response routines, R2X-enabled robots can interpret user context and emotional cues to provide personalized, intelligent responses.

  For example, in a restaurant setting, a service robot can proactively recommend dishes or adjust service delivery based on a customer's dietary habits and flavor preferences—offering a truly tailored service experience.

- **From Reactive to Proactive Interaction**
  Traditionally, robots have operated in a reactive manner—executing tasks only after receiving explicit user commands. In the R2X ecosystem, the transition to proactive interaction marks a significant leap toward embodied AI.

  Consider eldercare scenarios: robots equipped with fall detection capabilities can monitor the health status of elderly individuals in real time. Upon detecting an abnormal event, the robot can instantly issue an alert and notify caregivers or family members.

  This ability to autonomously monitor and respond not only improves service timeliness but also enhances the sense of safety and reassurance for users.

2.2.2. Business model transformation: multi-category product matrix empowering full-stack embodied AI

As discussed in the previous section, R2X, based on modular design and AIoT, serves as the technological foundation for a full-stack robotics ecosystem and represents a long-term direction for future technological innovation. However, a core challenge facing the current robotics industry is the lack of unified technical standards and protocols, which makes efficient collaboration and seamless interoperability between robots of different brands and types difficult in real-world scenarios.

This fragmentation not only increases user costs but also significantly undermines the application value of service robots in complex environments—ultimately constraining the industry's ability to scale.

At the same time, customer demands in the service robotics market are undergoing profound changes. Users are no longer satisfied with single-function robotic devices—they now expect comprehensive, scenario-based solutions that address a range of needs. This requires companies to have the capability to integrate products across categories and application scenarios, delivering a seamless, end-to-end service experience. By offering a complete product matrix, service robotics companies can lower the cognitive and operational barriers for users, significantly improve service efficiency, and drive natural customer migration and repeat purchases—creating a win-win situation for both users and providers.

As service robots continue to expand rapidly across sectors such as food & beverage, retail, warehousing and logistics, hospitality, manufacturing, healthcare, education, eldercare, and public services, their functional boundaries are also being continually extended and deepened. Despite the diversity of use cases, common, compound needs—such as transport, cleaning, and interactive reception—persist across these different scenarios.

Take the hotel sector as an example: reception robots, cleaning robots, and delivery robots are often required to work in coordination. A similar pattern is found in retail, where users need robots to provide both product guidance and consultation, as well as floor cleaning and industrial-grade goods handling.

From a business model perspective, as the industry enters a more mature phase, leading companies must respond by organically combining multi-category product matrices to address deeper customer demands across diverse settings, and deliver a consistent, efficient user experience.

Looking ahead, the service robotics industry is set to experience not only rapid technological innovation, but also a significant shift in business models—driven by the rise of a multi-category product matrix. **While humanoid robots may offer broad versatility, achieving full-stack embodied AI in a future filled with diverse robot forms will require more than a one-size-fits-all approach. Developing a multi-category product matrix is not just about building general-purpose robots—it is about establishing a flexible, scalable product system that can adopt to a wide range of scenarios. This will be critical to realizing the vision of a truly intelligent, fully integrated service robotics ecosystem.**

Figure 2-5: Full-scope scenario solutions based on a multi-category product matrix

Source: Deloitte Research

2.2.3. Generalized and diverse forms: specialized + semi-humanoid + humanoid

With continuous technological advancement, the versatility and generalizability of service robots have significantly improved, laying a solid foundation for their deployment across a wide range of application scenarios. In terms of physical design and functional implementation, service robots have moved beyond traditionally single-purpose models and are evolving toward greater generalization and morphological diversity. This transformation is not only a natural outcome of technological progress but also a necessary response to increasingly complex and dynamic market demands.

As the adoption of robots deepens across industries, it is becoming clear that humanoid robots are not the ultimate or sole form of service robots. Rather than a linear evolution, the development of robot forms is progressing through complementary and coexistent diversity.

In line with this industry trend, specialized robots, semi-humanoid robots, and humanoid robots are each taking on distinct functional roles, together forming the core pillars of the service robotics ecosystem. By leveraging the strengths of these three forms, robots can become more adaptable and capable across a broader range of tasks—supporting the development of general-purpose robotics system. This morphological diversity enables seamless collaboration among different robot types in various scenarios, effectively addressing the challenges of cross-functional integration and advancing the vision of a full-stack robotics ecosystem.

In the future, these three robot forms will coexist, and each deliver unique value:

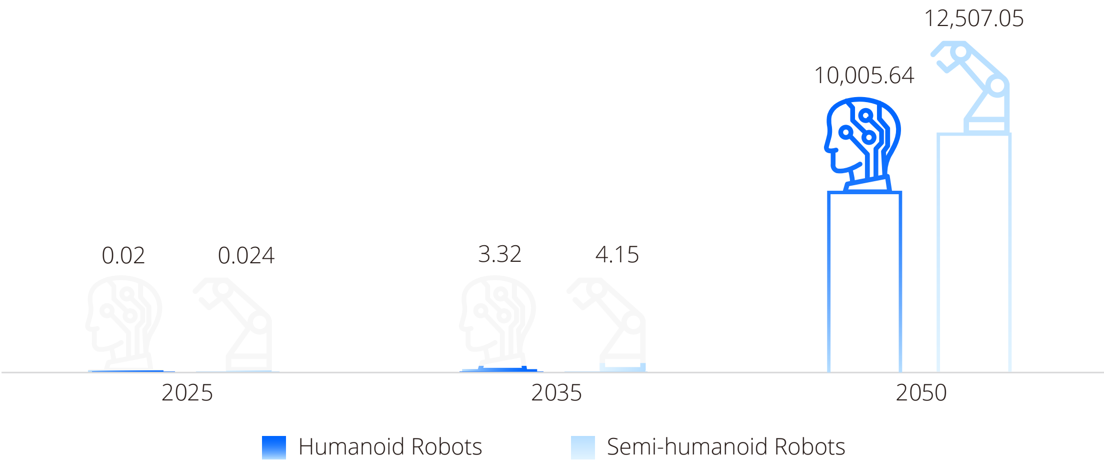
- **Specialized Robots:**
  Focused on specific scenarios or tasks—such as cleaning, delivery, or reception guidance—specialized robots are optimized for single-function execution and deliver the highest task efficiency within their niche.

- **Semi-Humanoid Robots:**
  Featuring a wheeled chassis and robotic arms, semi-humanoid robots offer multi-functional capabilities. They strike a balance between operational diversity and efficiency, making them well-suited for generalized task performance across different environments.

- **Humanoid Robots:**
  As the robot form most similar to the human body, humanoid robots possess a high degree of freedom, enabling them to perform complex and delicate operations. They stand out in interaction experience, spatial adaptability, and operational flexibility, making them uniquely suited for high-touch and dynamic environments.

Figure 2-6: Global shipment forecast of humanoid and semi-humanoid robots

(In million units)



Source: Deloitte Research

To clearly distinguish the types of work scenarios best suited to each of the three robot forms, **this white paper references Pudu Robotics' pioneering concept of "Degrees of Freedom per Unit Work Area."** This innovative metric evaluates the adaptability of each robot form by calculating the ratio between the robot's total degrees of freedom and its operating area. The goal is to identify the form that delivers the highest commercial potential for embodied AI, thereby accelerating the development of a full-stack robotics ecosystem.

By using the "Degrees of Freedom per Unit Work Area" as a benchmark, we can better understand the unique strengths and ideal applications of specialized, semi-humanoid, and humanoid robots—and how to select the most suitable form based on specific use-case requirements. This approach supports the rational construction and evolution of the robotics ecosystem.

Figure 2-7: Degrees of freedom per unit work area across three robot forms

Specialized Robots
3 Degrees of Freedom / 1,000 m²

Target Scenarios

Designed for single-task functions such as goods transport and floor cleaning. Offers the most cost-effective and efficient solution for focused operational needs.

Semi-Humanoid Robots
300 Degrees of Freedom / 1,000 m²

Target Scenarios

Combines the mobility of a wheeled base with the flexibility of robotic arms. Merges traits of both specialized and humanoid robots, significantly enhancing task versatility at a relatively high cost-efficiency.

Humanoid Robots
30,000 Degrees of Freedom / 1,000 m²

Target Scenarios

The most human-like and general-purpose form. Ideal for complex environments, diverse task requirements, and scenarios demanding high levels of human-robot interaction, intelligence, and precision.

Source: Pudu Robotics, Deloitte Research

Viewing robot design through the lens of "degrees of freedom per unit work area" helps clarify the complementary relationship among the three primary robot forms. The future of robotics will not be dominated by a single form. Instead, specialized robots, semi-humanoid robots, and humanoid robots will each serve distinct roles, working in tandem to form a complete and versatile system for embodied general-purpose service robotics.

At the core of building a full-stack robotics ecosystem is the development of a general-purpose service robotics framework—one that can meet a wide range of task requirements across diverse environments. Under the concept of "generalized multi-form architecture," these three types of robots form a flexible, comprehensive ecosystem capable of adapting to varied and evolving needs.

1. Broad Scenario Coverage

A full-stack service robot ecosystem must operate across residential, commercial, and industrial domains—covering industries such as food service, healthcare, logistics, and education. Each sector has unique demands and usage scenarios, and no single robot form can fulfill all requirements. A combination of robot types enables greater application coverage.

- **Specialized Robots:** These are highly optimized for single tasks in specific environments, such as hospitals or restaurants. For instance, a delivery robot can efficiently transport items between locations, ensuring speed and accuracy in logistics operations.

- **Semi-Humanoid Robots:** These robots combine wheeled mobility with robotic arms, allowing them to perform a wide variety of tasks. In a restaurant setting, for example, a single robot can handle food pickup, delivery, dish return, and floor cleaning—offering a more personalized and efficient user experience.

- **Humanoid Robots:** With high degrees of freedom and complex manipulation capabilities, humanoid robots excel in environments requiring fine motor skills and interactive experiences—such as education, medical assistance, or in-home care. Their versatility supports a wide range of high-level tasks.

2. Delivering End-to-End Solutions
A full-stack ecosystem must go beyond isolated tasks to enable seamless, end-to-end service delivery. In such a system, different robot forms collaborate intelligently, significantly improving overall operational efficiency.

For example, in a busy hotel, a specialized delivery robot and a humanoid service robot can work together to complete a workflow. The specialized robot quickly delivers items to rooms, while the humanoid robot handles customer interaction, guest guidance, and in-room cleaning—together forming a coherent and efficient service loop.

3. Bridging Task Silos Across Scenarios
Traditional service robots are often limited to a single task or scenario, making it difficult to deliver closed-loop service experiences. Multi-form general-purpose robots solve this bottleneck, enabling seamless, end-to-end task execution across diverse environments.

In the food service industry, for example, semi-humanoid and humanoid robots can jointly handle food delivery, plating, and table clearing, automating the full-service process while reducing human intervention and boosting customer satisfaction.

In hotel environments, humanoid robots can cover everything from welcoming guests to deliveries and cleaning—ensuring full-service continuity. Take cleaning as a specific case: current solutions rely on docking stations for tasks like water refilling and wastewater disposal, which often require water system retrofitting—an expensive and intrusive process that many customers are unwilling or unable to accommodate. Instead, semi-humanoid robots with manipulators can independently handle tasks such as refilling, waste disposal, trash removal, and component replacement—achieving true unattended, intelligent cleaning. These examples demonstrate the irreplaceable role and value of all three robot forms in realizing a full-stack intelligent service ecosystem.

4. Overcoming Technical Constraints and Reducing Deployment Costs
Robotic systems relying solely on IoT often face limitations in building full-stack intelligent service ecosystems. Many conventional solutions require physical modifications to infrastructure—such as elevators and access control systems—leading to high costs and complex regulatory hurdles.

In contrast, semi-humanoid robots can perform physical interactions via robotic arms, eliminating the need to retrofit existing infrastructure. This significantly lowers deployment barriers and accelerates global market expansion.

The coordinated development of specialized, semi-humanoid, and humanoid robots is essential for the future of full-stack robotics ecosystems. These forms not only enhance task flexibility and execution efficiency, but also enable end-to-end services across industries and environments, tailored to meet diverse user needs. Furthermore, the collaborative synergy among these robot types reduces deployment costs and simplifies technical integration—supporting the emergence of industry standards and accelerating technological advancement. This multi-form strategy lays a strong foundation for the global scalability of intelligent service robotics, paving the way for broader commercialization across the world.

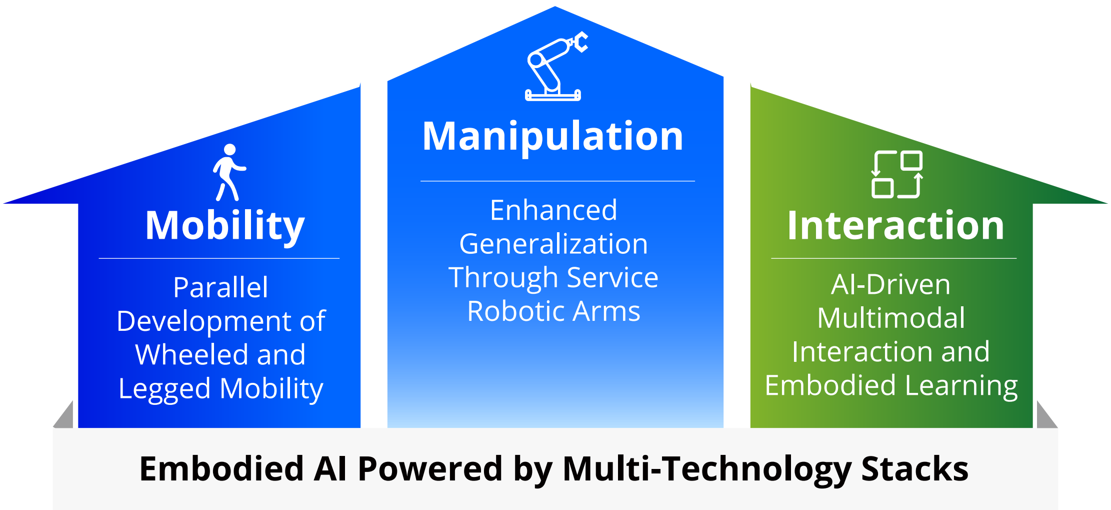
2.2.4. Embodied AI powered by multi-technology stacks: mobility + manipulation + interaction

As mentioned earlier, the service robotics industry has historically focused on the advancement of single technologies—such as voice interaction or autonomous navigation. However, this single-tech trajectory has constrained product functionality, making it difficult to meet users' increasingly complex and multi-dimensional demands.

As the industry moves into a more mature phase, a siloed approach to technology is no longer sufficient. Navigating the second half of the industry's development pathway requires a broader perspective. In building a full-stack robotics ecosystem, the integration of multiple technology stacks has become not just a choice, but a necessity.

From a technology evolution standpoint, the service robotics sector is undergoing a critical transition—from relying on single-function mobility capabilities to integrating mobility, manipulation, and interaction into a unified architecture. Driven by this multi-tech-stack model, the rise of embodied AI—characterized by multimodal perception, autonomous decision-making, and dexterous operation—will become the key force propelling the full-stack robotics ecosystem forward.

Figure 2-8: Embodied AI powered by multi-technology stacks: mobility + manipulation + interaction



Source: Deloitte Research

Mobility: Advancing Wheel-Based and Legged Platforms in Parallel

Mobility is one of the core technology stacks in service robotics, as it directly determines both application breadth and operational efficiency. Robots must possess efficient autonomous navigation and agile obstacle avoidance to operate reliably in dynamic, complex environments.

With significant progress in sensor technology, computing power, and algorithmic optimization, robotic mobility has rapidly evolved. Use cases have expanded beyond indoor navigation to include semi-outdoor and more complex real-world environments. As the industry enters its next phase, mobility will continue to play a pivotal role.

Today, both wheeled and legged locomotion platforms are demonstrating unique advantages across the three primary robot forms, each proving valuable in different scenarios. The strategic deployment of these two mobility approaches is critical to the development of a diversified robotics ecosystem.

Wheeled Mobility

Wheeled robots have a clear advantage in indoor environments with flat surfaces, offering higher movement efficiency than their legged counterparts. While wheeled platforms excel on smooth terrain, legged robots are more suited to complex, uneven terrain. Together, they create a complementary approach, allowing robots to be deployed based on specific environmental needs.

Wheeled robots are especially effective in 2D environments, making them ideal for standardized commercial settings such as malls, office buildings, and healthcare facilities. They deliver strong performance in cross-scenario deployments and long-sequence tasks, with high reliability and consistent uptime.

Current advancements in wheeled mobility focus on enhancing environmental adaptability and intelligence, including the development of omnidirectional movement capabilities and zero-radius turning for improved maneuverability in tight spaces. Integrating cutting-edge sensors and intelligent algorithms—such as LiDAR and SLAM—has enabled more precise autonomous navigation and dynamic obstacle avoidance.

Wheeled mobility has reached a high level of technological maturity. It offers reliable and energy-efficient movement on smooth surfaces and has been widely deployed in industries like logistics, cleaning, and indoor inspection. Its design and manufacturing have become increasingly standardized, enabling mass production and deployment at scale. Moreover, wheeled platforms typically require lower maintenance costs, a hallmark of their maturity. As technology continues to evolve, wheeled robots are expected to gain further in intelligence and environmental adaptability, broadening their role in full-stack intelligent ecosystems.

Core Advantages:

1. **Efficient Mobility:** Wheeled robots move quickly and consume less energy on flat surfaces, making them well-suited for long-distance travel in indoor environments or along predefined routes.

2. **Cost-Effective:** With a relatively simple structure, wheeled robots are less expensive to manufacture and maintain—ideal for large-scale deployment.

3. **High Maneuverability:** They offer precise directional control and agile turning capabilities, including omnidirectional movement and zero-radius turning.

4. **Mature Technology:** Wheeled mobility is a well-established and proven technology, supporting standardization and scalable production.

Application Scenarios:

- Indoor environments such as warehouses, hospitals, shopping malls, and offices.

- Logistics and inspection tasks along predefined paths.

- Service robots requiring frequent and rapid movement, such as cleaning robots and patrol robots.

Legged Mobility

Legged robot technology has made great strides through reinforcement learning and now delivers satisfying performance in complex terrain. The core strength of legged robots lies in their ability to navigate irregular surfaces—including stairs, slopes, and rugged urban terrain.

Thanks to innovative algorithms, legged robots can now adopt ultra-light gaits, enhancing flexibility and minimizing operational noise in human-centric environments. They also support seamless transitions between different forms of movement—standing, walking, and running—while optimizing energy use for natural, lightweight motion.

Another key advantage of legged robots is their structural similarity to the human body, which allows them to train effectively on human motion data and deliver more natural and intuitive interactions. In terms of perception and navigation, they rely on high-precision sensors to capture environmental data in real time, build 3D semantic maps, and achieve precise localization and dynamic maneuvering.

Core Advantages:

1. **Terrain Adaptability:** Legged robots can navigate complex and uneven terrains, including stairs, rough surfaces, and outdoor environments.

2. **Stability:** With multiple points of ground contact, legged robots offer enhanced stability and grip.

3. **Flexibility:** They can mimic human walking patterns, allowing for agile movement in narrow or crowded spaces.

4. **Obstacle Avoidance:** Legged robots are better equipped to avoid obstacles, especially in dynamic or unpredictable environments.

Application Scenarios:

- Scenarios that require navigating obstacles or uneven terrain, such as multi-floor service delivery or in-room hospitality robots

- Outdoor settings, including public spaces like plazas or pedestrian zones.

- Use cases that involve close human interaction or require mimicking human behavior, such as humanoid service robots.

The choice between wheeled and legged mobility ultimately depends on application requirements and environmental conditions. Wheeled solutions—being efficient, economical, and mature—are well-suited for structured environments. In contrast, legged robots excel in unstructured or dynamic settings, where adaptability and terrain response are critical. In a future ecosystem where multiple robot forms coexist, **these two locomotion technologies will complement each other, unlocking unique value across a wide range of scenarios.**

Manipulation: Service Robotic Arms Driving Generalization

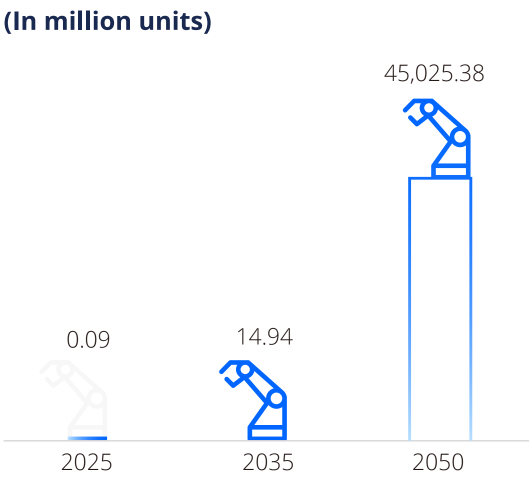
Manipulation capabilities refer to a robot's ability to perform precise tasks such as grasping, moving, placing, and cleaning objects. These capabilities rely on components like robotic arms and dexterous hands. With advanced manipulation functions, service robots can go beyond mobility and navigation to execute more complex, high-precision operations, enabling them to adapt to a broader range of real-world applications. With continuous technological advancement and innovation, the application of robotic arms in service robots is rapidly evolving towards addressing generalization and achieving general-purpose capabilities.

The use of robotic arms can be traced back to the 1960s. Since the introduction of the first industrial six-axis robotic arm in 1966, robotic manipulators have been widely used in manufacturing and industrial automation. Although industrial arms share the hardware structure of general-purpose robots, their performance has long been constrained by fragmented and narrowly scoped algorithms, limiting market scalability. Today, thanks to advancements in AI foundation models, service robotic arms are now capable of generalized manipulation—a breakthrough that significantly expands their market potential. As a result, robotic arms are expected to become a critical enabler for the global scale-up of general-purpose service robots.

Manipulation is a core technology stack that underpins robot generalization, making it a foundational element of the full-stack robotics ecosystem. As a key component of this ecosystem, service robotic arms enhance robot adaptability and operational flexibility by addressing the challenge of task generalization—enabling robots to perform varied tasks across different scenarios.

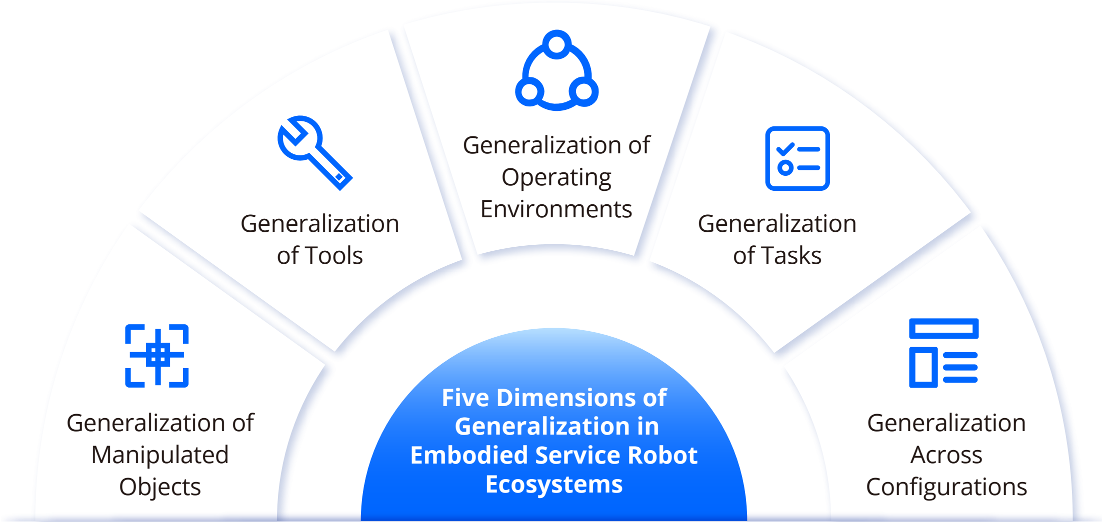
According to earlier projections, global shipments of humanoid and semi-humanoid robots are expected to reach 10 billion and 12.5 billion units, respectively, by 2050. Assuming each robot is equipped with two robotic arms, the total global demand for service robotic arms could exceed 45 billion units.

Figure 2-9: Global shipment forecast of service robotic arms



Source: Deloitte Research

Figure 2-10: Five dimensions of generalization in embodied service robot ecosystems



Source: Deloitte Research

1. Generalization of Manipulated Objects

As outlined in Chapter one, the first major challenge in building a full-stack intelligent ecosystem—and truly general-purpose service robots—is the ability to manipulate a wide variety of objects.

To address this, service robotic arms adopt adaptive grasping technologies that enable them to recognize and respond to different object types. Through a combination of machine vision and force feedback systems, robotic arms can adjust their grip in real time based on an object's shape, material, and weight.

For example, when grasping cups of various designs, the robotic arm can detect differences in shape, material, and center of gravity, and then determine the optimal grasping method and force. This adaptability significantly enhances performance in diverse environments and allows the robot to take on a broader range of tasks.

2. Generalization of Tools

In many industrial applications, robotic arms must handle a variety of tools—such as screwdrivers of different shapes or welding equipment. The emergence of dexterous hands at the end-effector level has greatly expanded robotic arms' ability to perform fine, complex operations with greater precision and flexibility.

3. Generalization of Operating Environments

By integrating advanced sensors and environmental perception technologies, service robotic arms can detect and respond to their surroundings in real time.

Even in poorly lit conditions, robotic arms can use infrared sensors and depth cameras to operate effectively. This real-time adaptability enables robots to overcome barriers posed by changing environments, improving reliability and consistency across use cases.

4. Generalization of Tasks
With complex control algorithms and AI integration, robotic arms can understand and execute a wide range of tasks—from basic object transport to more complex activities such as assembly and maintenance. This multi-tasking capability increases their value across a variety of industries and strengthens the robot's ability to adapt to different operational requirements.

5. Generalization Across Configurations
While robotic arms may vary in form depending on their application, general-purpose algorithms ensure that each configuration can still perform optimally. Through continuous algorithm updates and iteration, service robotic arms can rapidly adjust operational strategies to suit different physical structures, ensuring consistent performance across formats.

Operational Technologies Enabling the Global Commercialization of Service Robots

As one of the first segments within robotics to achieve commercial-scale deployment, service robots have enormous long-term growth potential. However, to scale further, enhancing manipulation capabilities is essential to solving key pain points in real-world application.

Take the food service industry as an example, while delivery robots can bring meals to a table or room, humans are still needed to serve the food. In hotels, robots can handle guest reception and in-room delivery, but cleaning and room service remain largely manual. In the cleaning scenario, the current mainstream solution is to install docking stations for robots to refill water and handle wastewater. However, this requires a large variety of hardware SKUs and carries high costs. Most customers—such as those operating hotels or shopping malls—lack the space, budget, or willingness to retrofit plumbing infrastructure. These changes often compromise aesthetics and limit the customer value that robots are intended to deliver.

In addition, commercial service robots often need to integrate with elevators, access control systems, and other infrastructure through IoT connectivity. Yet in many regions, modifying elevator hardware is restricted by local regulations. As a result, companies must opt for cloud-based integrations with elevator companies, which brings high deployment costs, recurring retrofit expenses, and dependency on third-party hardware vendors—significantly slowing down global-scale commercial adoption.

For the reasons outlined above, enhanced operational capabilities will become a key enabler for the global expansion of service robots. Humanoid robots equipped **with robotic arms can press elevator buttons, enabling a breakthrough from 2D to 3D operations**. This innovation helps bypass existing limitations of cloud-based or hardware-integrated elevator control systems and opens access to vast international markets. Currently, elevator companies charge an average of USD 10,000–20,000 per elevator per year for cloud-based elevator control services. **By enabling robots to press elevator buttons autonomously via robotic arms, it is estimated that approximately USD 1.8 billion in global deployment costs could be saved annually.** This breakthrough represents a significant step forward in accelerating the global commercialization of service robots.

It's clear that mobility alone is no longer enough for service robots operating in complex, dynamic environments. To enable true cross-scenario generalization, robotic systems must significantly enhance their manipulation capabilities.

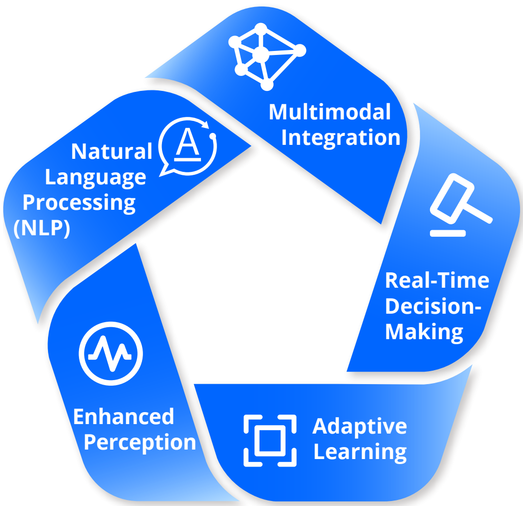
From semi-humanoid to humanoid robots, service robotic arms dramatically extend the range of tasks robots can perform. When paired with dexterous hands, robots gain the ability to autonomously handle a variety of everyday tasks, such as delivering food and clearing plates, pressing elevator buttons or tapping access cards, and opening or knocking on doors. In the case of cleaning robots, enhanced manipulation allows them to refill water, dispose of wastewater, empty trash, and replace cleaning components—all without human supervision. This level of autonomy eliminates the need for physical infrastructure modifications, while boosting cross-scenario capabilities.

Ultimately, it is this leap in manipulation functionality that will allow service robots to fully realize a generalized, full-stack intelligent ecosystem—scaling smarter, more autonomous robotics solutions across real-world environments.

AI-Driven Multimodal Interaction and Embodied Learning

Within the multi-technology stack powering next-generation robots, artificial intelligence (AI) plays a pivotal role. Foundation models are transforming not only robots' ability to interact, but also enhancing their capabilities in manipulation and mobility. AI empowers robots with deeper embodied learning, enabling them to perform more complex tasks and engage in more natural interactions—forming the technological backbone of a full-stack intelligent ecosystem.

Figure 2-11: AI-powered multimodal interaction



Source: Deloitte Research

- **Enhanced perception:** AI is able to acquire and analyze data from a variety of sensors, such as cameras, lidars, and sound sensors, through deep learning and computer vision technologies. This allows robots to more accurately understand and recognize their surroundings, including objects, obstacles, and human users, for more complex interactions.

- **Natural language processing (NLP):** Natural language processing in AI technology enables robots to understand and generate natural language, which facilitates the interaction between humans and machines. The user can communicate with the robot through voice commands, and the robot is able to understand and respond to these instructions, allowing for more natural human-machine interaction.

- **Multimodal integration:** AI can integrate data from different senses (e.g., visual, auditory, and tactile) to improve understanding of the environment through complementarity and fusion between modalities. For example, robots can use both image recognition and sound recognition to determine the orientation and nature of target objects, enabling more intelligent navigation and operation.

- **Real-time decision-making:** AI's real-time computation and decision-making capabilities enable robots to react instantly based on acquired multimodal information. This rapid response capability is especially important in dynamic environments, such as avoiding a crowd or performing tasks under uncertain conditions.

- **Adaptive learning:** AI uses machine learning algorithms to continuously update and optimize interaction strategies based on user feedback and changes in the environment, making multimodal interactions smoother and more efficient.

Figure 2-12: Embodied learning capabilities powered by AI

Source: Deloitte Research

- **Imitation Learning:** Robots can learn tasks by observing human actions or other intelligent agents. This allows them to quickly acquire basic operational skills without having to program every step manually.
- **Reinforcement Learning:** AI enables trial-and-error learning in both real and simulated environments. Robots receive rewards or penalties based on their actions, gradually adjusting behavior to optimize task performance.
- **Hierarchical Learning:** By employing layered learning architectures, AI allows robots to learn in stages—starting with basic movements and progressively acquiring more complex behaviors or strategies. This structured approach improves learning efficiency.
- **Environmental Awareness and Adaptability:** Robots equipped with AI and advanced sensors continuously gather environmental data, using deep learning models to adjust their behavior in real time. This adaptability is essential for overcoming unpredictability in real-world applications.
- **Knowledge Transfer:** AI enables knowledge gained in one task to be applied to another, related task—allowing robots to quickly adapt to new environments or roles with minimal retraining.
- **Data-Driven Evolution:** AI systems improve over time by training on vast datasets—including both simulation and real-world operation data. This enhances robots' understanding of complex environments and enables ongoing improvement in embodied learning capabilities.

AI-driven multimodal interaction and embodied learning are central pillars of future robotics. Mobility and manipulation capabilities are increasingly reliant on AI to achieve precision, adaptability, and autonomy. As the development of general-purpose embodied robots accelerates, AI will remain at the forefront—advancing how robots learn, interact, and evolve in complex, real-world environments.

Within a full-stack robotics ecosystem, intelligent interaction is achieved by integrating perception, decision-making, and execution systems into a unified architecture. This approach is data-driven and supported by a layered model framework, representing an innovative direction for the development of embodied AI.

The system adopts a dual-model architecture that separates the "embodied AI large model" from the "cerebellum large model", allowing it to better adapt to complex and dynamic environments and tasks. In this framework:

- The cerebrum model connects to large AI models for perception and high-level planning.

- The cerebellum model translates the skill sequences output by the cerebrum into executable commands to control the robot’s physical actions.

This architectural choice reflects the optimal solution at the current stage of technological development. While future advancements in neural networks and machine learning may allow for a more unified modeling approach, the current separation strategy offers clear advantages in terms of performance, risk management, and training efficiency.

The evolution of embodied AI is increasingly enabled by continuous learning and cross-scenario generalization. According to the Scaling Law, model performance improves with increases in model size, dataset size, and computing power. To maximize data utility, a multi-tiered data learning strategy is employed—leveraging direct operation data, semi-simulated data, and large-scale internet data. By extracting the most valuable insights from each data type, robots can improve learning efficiency and better generalize across environments and tasks. During training, robots are fed a diverse set of inputs—including motion capture data, teleoperation records, and video feeds—to ensure both data volume and quality are high. This hybrid approach, combining imitation learning with reinforcement learning, allows robots to quickly acquire foundational skills and continuously refine their motion control and adaptability. Large-scale data training also empowers robots with the ability to perceive their environment, understand tasks, and coordinate actions autonomously.

This multi-tiered learning strategy is key to enabling robot generalization. By training on diverse and layered datasets, robots are better equipped to handle varied environments and tasks. Even when faced with unfamiliar objects or novel surroundings, a sufficiently trained robot can adapt quickly and perform effectively. Ultimately, this strategy fosters continuous evolution, strengthens task generalization capabilities, and breaks through the limitations of traditional scenario-specific deployments—laying the groundwork for realizing a truly full-stack intelligent service robot ecosystem.

2.2.5. Open, collaborative, and general-purpose: driving innovation for a more sustainable and inclusive future

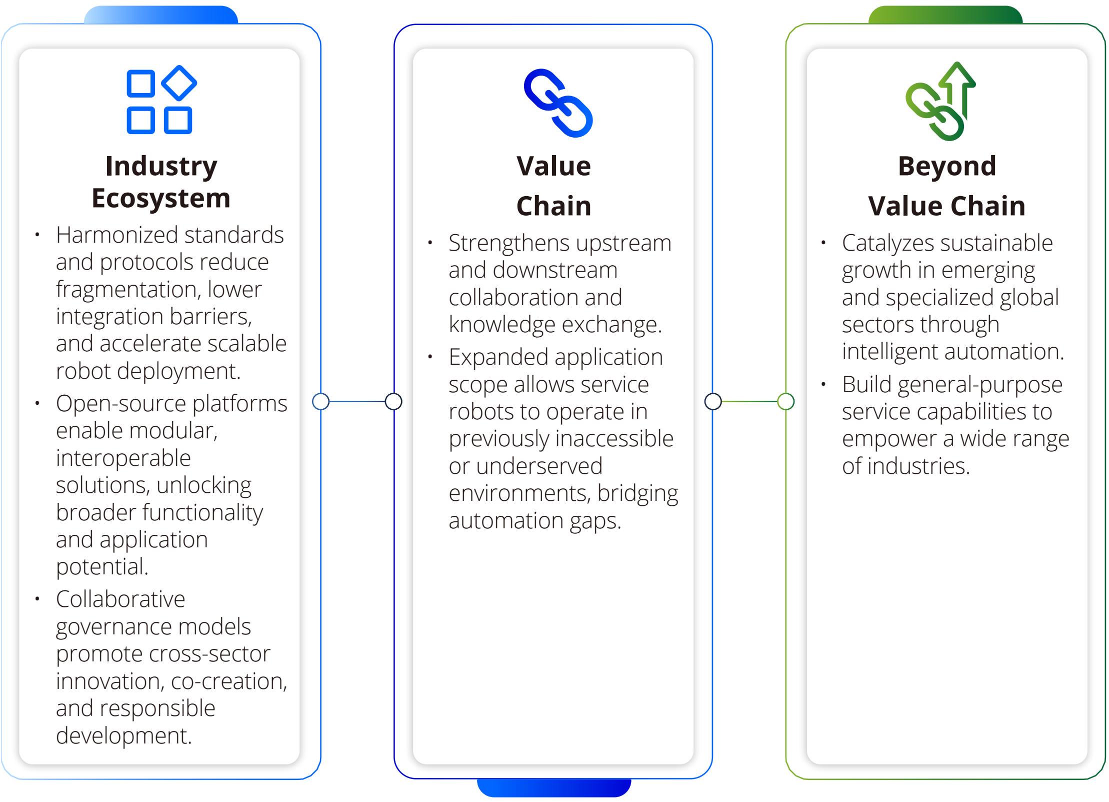
By building an open full-stack intelligent service robotics ecosystem, service robots are poised to become a powerful engine driving global sustainable development. An open technological framework—rooted in standardized protocols and interoperability—will break down industry silos and enable R2X connectivity across all things. This will significantly lower the barriers to adopting service robots, making them more accessible and easier to deploy for a broader range of users.

One-stop, multi-robot collaborative solutions can streamline operations across industries, substantially reduce energy consumption and carbon emissions, and improve overall resource efficiency. Led by pioneering companies and their innovative business models, a general-purpose product matrix integrating mobility, manipulation, and interaction technology stacks is emerging. This product system spans specialized, semi-humanoid, and humanoid forms, allowing intelligent services to reach areas previously beyond the scope of traditional automation.

From in-hospital medication delivery to companionship and care in eldercare settings, from auxiliary logistics in industrial environments to lightweight applications for small businesses, service robots are increasingly breaking free from scenario and industry limitations. This is accelerating the widespread, inclusive adoption of intelligent technologies.

This innovation paradigm not only reduces the carbon footprint from an environmental perspective, but also lowers the economic cost of digital transformation, and enhances human well-being and service accessibility from a social perspective. It creates a virtuous cycle of technological empowerment and sustainable development, shaping a new model for an inclusive and sustainable service robotics industry.

Figure 2-13: Achieving full-stack intelligent service robotics through sustainable and inclusive innovation



Source: Deloitte Research

2.3. Unlocking ecosystem value

The value of a full-stack robotics ecosystem extends far beyond improved service efficiency and cost optimization. Highly automated and intelligent service models not only free human workers from repetitive, low-value tasks, but also introduce empathy and care into service interactions. Moreover, by fostering an open and collaborative environment, the ecosystem can in turn fuel new business models and technological innovation. In this way, its value expands beyond economic gains, extending into social impact and innovation-driven growth—benefiting users, robotics companies, and the broader industry alike.

- **Users: Enhanced Experience and Simplicity**
  For users, an open full-stack intelligent service robot ecosystem delivers a more convenient, efficient, and seamless experience. A unified operating system reduces the learning curve and simplifies usage, management, and maintenance—dramatically improving the overall customer experience.

  Users can easily control and manage a variety of service robots without needing to learn different operating methods for each device. This one-stop solution streamlines daily tasks, increases productivity, and reduces the complexity of maintenance—ultimately maximizing user value.

- **Robotics Companies: Smarter Coordination and System-Level Efficiency**
  For robotics companies, an open ecosystem enables cross-brand and cross-category coordination, allowing different types of robots—developed by different vendors—to work together within the same environment.

  This collaborative framework enables multi-robot systems to optimize task routes, avoid operational conflicts, and close the loop on complex workflows. Robots function not as isolated units, but as part of a coordinated system, offering greater flexibility and higher service efficiency.

  For vendors, this shift from siloed product competition to multi-category ecosystem building is key to capturing emerging market opportunities and sustaining long-term growth.

- **Industry: Driving Standardization and Sustainable Development**
  At the industry level, an open full-stack intelligent robot ecosystem serves as a critical enabler of both technological advancement and market expansion.

  By promoting unified industry standards, the ecosystem reduces technical barriers and facilitates seamless integration between vendors and service providers. Standardization ensures system compatibility and reliability, accelerates the adoption of service robotics, and increases penetration across sectors.

  As standards become more established, new innovations and service models will emerge—driving healthier and more sustainable growth across the industry.

Figure 2-14: The value of an open, full-stack intelligent service robot ecosystem

Users

- Reduced learning, operation, management, and maintenance costs.
- One-stop solutions that simplify daily tasks and boost productivity.
- A smoother, more efficient user experience.

Robotics Companies

- Cross-brand and cross-category coordination enables system-level orchestration.
- Agile, high-efficiency services unlock new markets and deployment scenarios.

Industry Ecosystem

- Harmonized standards promote interoperability and reduce fragmentation.
- Seamless integration between vendors and service providers.
- Ensured compatibility and reliability of robotic systems.
- Accelerated adoption and application of service robotics technologies.

Source: Deloitte Research

Chapter Three:

Global Implementation Across Industries

The realization of a full-stack robotics ecosystem will empower thousands of industries globally, and service robots are currently accelerating the penetration of many industries such as catering, hospitality, retail, education, healthcare, industry, and public services. This chapter will introduce the application trends and market prospects of relevant representative segments.

At the same time, Pudu Robotics will be used as an example to introduce its segmented scenario solutions based on its multi-category product matrix, which will provide references and lessons for the comprehensive practice of full-stack intelligent ecological construction of the global segmented industries in the service robotics industry.

Figure 3-1: Market trends in key industries and application scenarios for service robots

Manufacturing

As the proportion of service robots performing tasks such as distribution and cleaning in factory floor or warehouse continues to rise, its market size is expected **to reach USD 14.06 billion by 2035**

Healthcare

In medical scenarios, service robots mainly undertake tasks such as drug delivery, cleaning and sterilization. **Service robots are expected to accelerate penetration and reach a market size of $4.4 billion by 2035**

Hotel

With the global hospitality industry accelerating the deployment of service robots to improve service efficiency and optimize customer experience, the hospitality industry service robots market is expected **to reach USD 12.46 billion by 2035**

Wellness

With the rapidly expanding global demand for intelligent wellness services, **the market size for wellness service robots is expected to reach $22.05 billion by 2035**

Catering

As the functionality of service robots extends from delivery to food preparation and production, the market size of food service robots **is expected to explode to USD 21.44 billion by 2035**

Airports

With the acceleration of intelligent transformation of infrastructure, the size of global service robots applied in airports, railway stations, terminals, and other large-scale transportation **hubs is expected to reach USD 5.79 billion by 2035**

Retailing

Application of Retail Service Robots Scenarios mainly include in-store service, inventory management, sanitation and cleaning, and shopping guide marketing. According to estimation, **the market size is expected to reach USD 57.31 billion by 2035**

The future of service robots will continue to extend to more industries to empower ……

Source: Grand view research, Verifiedmarketreports, Marketresearchfuture, Dataintelo, Fortunebusinessinsights, Deloitte Research

3.1. Industry applications and field experiences

3.1.1. Manufacturing

Industry overview

Along with the development of technology, robots are gradually penetrating into various aspects of industrial manufacturing. Manufacturing scenarios, as typical composite demand scenarios, require robots to be able to adapt to different production processes and environments, and to be deeply involved in a variety of tasks such as distribution and cleaning. According to estimates, the global industrial service robot market size is expected to reach $14.06 billion by 2035.

Pain points

Automation technology has been used quite extensively in the modern industrial scene, especially in the main production process. However, to truly move towards full-process automation still faces the following challenges:

1. **Insufficient automation of auxiliary processes:** auxiliary handling tasks in industrial enterprises, such as replenishment handling from raw material warehouses to production lines, flow handling of semi-finished products between processes, and sample sampling and inspection deliveries, etc., are still relying on manual cart operations, which are inefficient.
2. **Lack of specialized products:** There is a lack of products on the market specifically designed for auxiliary process handling, making it difficult for industrial enterprises to find a suitable solution.
3. **Limitations of manual handling:** Even the top international manufacturing enterprises often rely on manual labor and carts for the handling of auxiliary processes, which is not only inefficient, but also poses safety risks.
4. **Lack of automated cleaning solutions:** high-end equipment and precision manufacturing industries often need a complete set of automated cleaning solutions to achieve the hygiene requirements of the clean room, and the current lack of related products and solutions on the market.

Solutions

In response to the pain points of logistics and cleaning in the above manufacturing scenarios, the distribution plus cleaning solution based on multi-category product matrix synergy provides an effective solution: industrial distribution robots with autonomous networking capabilities and high load performance can independently complete the material transportation tasks on the production line without the need to communicate with the MES/WMS system, thus realizing flexible deployment; Intelligent cleaning robots, including floor sweeping and deep cleaning models, can realize 24-hour unmanned automated cleaning to meet the hygiene requirements of clean workshops; at the same time, cleaning robots form process linkage with industrial distribution robots through dynamic task scheduling, for example, identifying garbage and automatically triggering the cleaning operation instructions during material transportation to realize the seamless linkage of the operation area and form a full-stack intelligent ecosystem that covers distribution and cleaning tasks.

Value

Robots drive improvements in the manufacturing sector through:

1. **Improvement of efficiency and safety:** through automation to assist the process handling, reduces manual operation, improves work efficiency and safety.
2. **Cost Reduction:** Reduces reliance on manual handling and lowers long-term labor costs.
3. **Flexible deployment:** high flexibility and scalability, can be quickly deployed, and single or multiple robots can be used independently or self-organized network collaboration, to meet the needs of industrial enterprises of different sizes.
4. **Human-machine mixing:** All types of robots can realize human-machine mixing in industrial environments without the need for separate zones, which reduces the burden of using robots in factories and improves the efficiency of space utilization.
5. **Comprehensive solution:** Based on the combined operation of multiple types of robots in a multi-product matrix, it forms a complete solution from distribution to cleaning, and improves the level of operation automation in industrial scenarios.

In the manufacturing scenario, through the full-stack robotics ecosystem based on a complete product matrix, it not only solves the composite needs in the industrial scenario, but also fills in the blank links that have not been reached by industrial automation in the past through cross-robot co-scheduling.

Figure 3-2: Service robot intelligent manufacturing solutions

3.1.2. Hotel

Industry overview

With the popularity of e-commerce and takeaway services, hospitality buildings need to not only meet the growing expectations of occupants for home delivery, but also provide an efficient and consistent service experience, as well as maintain cleanliness and safety in public areas. According to estimates, the global market for service robots in the hospitality industry is expected to reach $12.46 billion by 2035.

Pain points

The hotel building scenario, as a typical service scenario, is also facing the challenge of composite demand:

1. **Building Delivery Service:** Occupants want to enjoy convenient home delivery service, but the last 30 meters of delivery will consume a lot of time of the delivery person, so this part of the capacity is often insufficient. Households also pay attention to the purchase of goods and the privacy of residential areas, and delivery workers, as strangers, may disturb the households, causing privacy and security risks. In addition, there are also some conflicts between property management and delivery workers.
2. **Pressure on hotel services:** Hotel receptionists need to handle many inquiries, and there is a need for multi-language communication. Especially when there is a shortage of manpower at night, it is difficult to respond to room delivery requests in a timely manner, resulting in guest complaints. High-frequency room deliveries, such as take-out and express delivery, also pose potential risks in terms of security management and privacy protection.
3. **Cleaning requirements:** the public areas of hotels and residences need to be always kept clean (e.g., aisle vacuuming), and the daily living garbage generated by residents needs to be cleaned up in a timely manner.
4. **Security patrol requirements:** hotel buildings need to carry out environmental safety inspections and cleanliness inspections to reduce the difficulty of property management and optimize the residents' experience.

Solution

1. **Intelligent distribution:** building distribution robots can connect entrance guard, automatic gates and elevators to realize cross-floor distribution, delivery of express, takeaway, documents, etc., reducing the disturbance of tenants and realizing contactless distribution, fully protecting the safety and privacy of tenants. While scaling ladder control and hardware ladder control provide more choices for property managers, the humanoid service robot is also able to operate the elevator autonomously through the robotic arm, allowing users to have more diversified choices.
2. **AI front desk service:** service robots can easily respond to a large number of inquiries in different languages by accessing a variety of AI models, providing a consistent service experience. Various types of robots, such as guide delivery, are also equipped with check-in and check-out handling, room leading, luggage carrying, etc., providing 24-hour call services at any time.

3. **24-hour automatic cleaning:** Intelligent cleaning robots can autonomously perform large-area cleaning tasks and implement dynamic and enhanced cleaning for key dirty areas. The digital management platform can monitor the cleaning coverage and operation quality in real time, forming a closed loop of visualized operation and maintenance.
4. Security inspection: The cleaning robot supports rich external devices through R2X modular expansion, and through optional camera components, it can carry out environmental safety inspection and cleaning condition inspection, constructing a "cleaning - security" dual-function operation network, optimizing the tenants' experience, and improving the efficiency of property operation and maintenance and emergency response capability.

Value

Robots enable improvements in the hotel sector in the following areas:

1. **Enhanced service efficiency:** robotic delivery and front desk guidance services enhance the operational efficiency of the hotel, while improving the service response speed.
2. **Enhance resident experience:** Robotic services reduce disturbance to residents, protect their privacy, and enhance the living experience.
3. **Keeping the environment clean:** 24-hour unmanned automated cleaning ensures continuous cleanliness in public areas and improves property management.
4. **Guaranteeing safety:** Security patrols enhance the safety of residents, detecting and dealing with potential safety issues in a timely manner.
5. **Digital management**: Through the digital platform, property managers are able to manage cleaning work more effectively and achieve optimal allocation of resources.

Figure 3-3: service robot intelligent hotel building solutions

3.1.3. Catering

Industry overview

The catering scene is one of the earliest industries in which service robots are commercially deployed, and it is also the core application scenario for commercial service robots. Against the backdrop of the rapid development of the Internet of Things (IoT), big data and artificial intelligence (AI) technologies, the catering industry has embarked on a new round of digital transformation and upgrading to meet growing customer demand and enhance market competitiveness. As the functionality of service robots extends from delivery to food preparation and production, the market size is expected to grow explosively to USD 21.44 billion by 2035.

Pain points

To enhance operational effectiveness and optimize customer experience, the catering industry still faces the following challenges:

1. **Difficulty in marketing and attracting customers:** the popularity of differentiated front door design makes it more difficult to attract customers overall. Waiters responsible for soliciting customers at the door need to have excellent eloquence, which is difficult to train. And the factors affecting customers' dining choices are diverse, not only based on taste, but also related to the topic, experience and so on.
2. **Large workload of employees, service experience is difficult to improve:** dining hours of clearing the table, welcoming guests, leading a large number of manpower and other tasks, resulting in a slow turnover of the table, the customer waiting time is long, while the waiter's emotions and stress is too large, affecting the service attitude.
3. **Catering cleaning is difficult, health problems is obvious:** oil and other stains need to be cleaned up in time but difficult to clean up, cleaning costs are high, while the repetitive nature of the cleaning work also leads to a high turnover rate of its employees.
4. **Difficulties in management standardization:** the work of chain restaurants is difficult to quantify, and it is impossible to unify the assessment, leading to increased management difficulties.

Solution

1. **Marketing attraction:** the service robot dynamically displays dishes through the large advertising screen, actively welcomes customers, provides interactive communication, and increases the conversion rate of customers entering the store.
2. **Auxiliary labor, reduce work intensity:** service robots take on repetitive work such as leading position, passing dishes, returning plates, etc., so that waiters can focus on customer service.
3. **Improve cleaning efficiency:** the cleaning robot can realize unmanned automatic cleaning, reduce the time and cost of cleaning, and improve the cleaning efficiency.
4. **Intelligent whole chain:** from taking a number and waiting for a place, welcoming and leading a place to ordering food and serving, and paying, the service robot, through the interconnection and interoperability with the management system of the catering store, builds up a closed loop covering the whole process of intelligent service of "queuing-ordering-food-serving-payment-cleaning", and assists in the creation of a full-stack intelligent restaurant.

Value

Robots enable improvements in catering services in the following areas:

1. **Enhance customer experience:** It increases the sense of fun and technology of dining, enhances the customer's dining experience, and helps attract more consumers.
2. **Improve operational efficiency:** service robots take on a large number of repetitive tasks, reducing the workload of employees and improving table-turning speed and service quality.
3. **Improve cleaning efficiency:** Cleaning robots are able to realize unmanned automatic cleaning, reducing the time and cost of cleaning and improving cleaning efficiency.
4. **Improve hygiene standards:** Service robots for delivery and cleaning significantly reduce personnel contact links, and improve the hygiene standards of food service.
5. **Digital management:** It makes the management of restaurants more standardized and easy to replicate on a large scale, improving management efficiency and operational effectiveness.
6. **Enhance brand image:** Robot service, as part of differentiated marketing, enhances brand image and improves customer recognition and loyalty to the restaurant.

Figure 3-4: Service robot smart restaurant solution

3.1.4. Retailing

Industry overview

The retail super industry, as a typical composite demand scenario, is seeking to reduce operating costs, improve customer experience, and achieve more efficient inventory management through intelligent upgrades, to better meet the dual challenges from operational efficiency and customer experience. The current application scenarios of retail service robots mainly include welcome guide, inventory management, marketing attraction, store cleaning, replenishment and transportation. According to estimates, the global retail service robot market size is expected to reach $57.31 billion by 2035.

Pain points

To face the above challenges, the retail superstore industry has the following issues that need to be addressed:

1. High operating costs: Along with the development of global Internet e-commerce, the operating costs of offline retail stores are high, from shelf replenishment, cashier settlement to cleaning and maintenance all need to invest a lot of costs.
2. Insufficient service responsiveness: customers rely on manual response for inquiries, product search, and fitting guidance, which can lead to service blind spots during peak traffic hours, resulting in lower customer satisfaction. Some scenes (e.g. night business) cannot provide full-time service due to labor limitations.
3. Single marketing method: Supermarkets have fixed display methods, limited promotional spots, and lack of novelty in marketing mode, which makes it difficult to meet diversified display and promotional needs and restricts the marketing effect.

Solution

1. Intelligent shopping guide: The service robot realizes intelligent shopping guide service through artificial intelligence interaction, providing personalized shopping guide service, answering customers' questions, providing product recommendations and promotional information, and guiding customers to browse different areas of the superstore.
2. Intelligent operation: Marketing service robots and industrial-grade delivery robots and other types of robots collaborate with each other and combine with RFID and visual recognition technologies to realize real-time monitoring of shelf inventory, provide self-payment checkout, intelligent replenishment and other services for retail scenarios, and realize the intelligence of the key links in retail.
3. Dynamic digital advertising platform: The service robot provides a dynamic digital advertising platform, realizing the display and management of dynamic advertising content, reducing the cost of updating advertising materials, and improving the flexibility and attractiveness of advertising.
4. Unmanned Autonomous Cleaning: The cleaning robots cooperate with the workstations to automatically add water and drainage, automatically charge, and realize 24-hour automatic floor cleaning by setting up automatic timed cleaning tasks in different areas, providing customers with a clean shopping environment.

Value

Robots enable improvements in the retailing sector in the following areas:

1. Marketing innovation: The delivery service robot displays the latest advertisements through the advertising screen to attract customers' attention, and provides a unified content management platform to flexibly update the marketing content and improve the marketing effect.
2. Enhance customer experience: By accessing a variety of large models, the service robot is able to realize AI intelligent shopping guide, providing accurate and professional shopping guide suggestions for consumers of different groups and languages, which greatly improves the shopping experience.
3. Optimize inventory management: the robot automatically performs shelf scanning, confirms the demand for replenishment of goods or the demand for replacement of expired goods, reduces the workload of warehouse handling, and realizes the automatic management of inventory.
4. Improve cleaning efficiency: the cleaning robot can efficiently complete the cleaning of a large area, through the active identification of key dirty places to repeat the cleaning, to improve the cleaning efficiency and cleanliness of the supermarket environment.
5. Safety inspection: through the optional external inspection module, the service robot can carry out safety inspection and cleanliness inspection of the environment to improve the safety management level of the superstore.

Figure 3-5: Service robot smart retail solution

3.1.5. Healthcare

Industry overview

Hospitals, as places of public health, are vital to standardize their service processes. With an aging population and increased demand for healthcare, hospital service processes are under increasing pressure. The hospital environment is complex, the process is numerous, and the patient experience needs to be improved. In healthcare scenarios, service robots are mainly responsible for tasks such as drug delivery, cleaning and sterilization. By 2035, service robots are expected to accelerate penetration and reach a market size of $4.4 billion.

Pain points

With the aging of the population and the increasing demand for healthcare, hospitals are facing expanding pressures, and the following problems have come to the fore:

1. **Large crowds and poor patient experience**
   - Large amount of information on consultation and advice: patients have a high demand for information on consultation and advice, and at the same time, there are also higher requirements for clarity and unambiguity of the information.
   - Complex hospital environment: the hospital environment is huge, the terminology is complex, the medical process is long, and patients need to run around between multiple departments, which increases the difficulty and time cost of consultation.
2. **Distribution of a large variety of items, easy to make mistakes**
   - Item storehouse dispersion: the hospital drugs and various internal items of a wide variety of types, and the storehouse is relatively dispersed, there is a large number of distribution needs.
   - Segregated distribution for special wards: Some special wards require segregated distribution, increasing the complexity and difficulty of distribution.
3. **Hospitals require a high degree of cleanliness and hygiene**
   - High flow of people leads to high cleaning difficulty: hospitals have a high flow of people, creating a lot of dust and garbage, and a large amount of cleaning workload.
   - Urgent medical waste disposal: medical waste is generated quickly and needs to be cleaned up as soon as possible to keep the hospital environment clean and hygienic.

Solution

1. **The demonstration medical guidance robot is able to realize AI intelligent consultation guidance by accessing a variety of AI big models.** Equipped with speech recognition and natural language processing technologies, the robot can communicate with patients, help them find the appropriate department and doctor, and provide guidance on the consultation process.
2. **Intelligent logistics:** In different departments such as the hospital's laboratory, robots can be used to realize intelligent surgical management and the transportation of tests and medicines. Robots can perform test specimen delivery to improve overall efficiency. In addition, the robots can also perform drug delivery tasks with the function of authenticating the door opening to ensure that the drugs are delivered to the doctors in an accurate and timely manner. Such smart logistics solutions can improve hospital efficiency and process management.

3. **Cleaning and disinfection:** cleaning robots and disinfection robots work in tandem to achieve round-the-clock cleaning and disinfection. Especially in areas with high infection control requirements, such as operating rooms, ICUs and infection departments in hospitals, the robots are able to meet the infection control requirements for floors made of different materials. This cleaning solution can help hospitals improve hygiene standards and ensure the safety of patients and healthcare workers.

Value

Robots enable improvements in the healthcare sector in the following areas:

1. **Enhance doctor-patient communication and service efficiency:** it can provide patients with intelligent guidance, delivery of medication and other services, shorten patients' waiting time and improve the medical experience. Robots can assist healthcare professionals in their work, such as answering patients' frequently asked questions and conducting simple examinations, thus reducing the workload of healthcare professionals and allowing them to focus more on more important medical services.
2. **Optimize medical processes and improve efficiency:** robots take on the task of in-hospital logistics and distribution, such as delivering medicines, consumables, test samples, etc., thus improving the efficiency of medical processes.
3. **Promote the intelligence of medical services:** It can promote the intelligent development of medical services and provide patients with more convenient, efficient and accurate medical services.

Figure 3-6: Service robot smart hospital solution

3.1.6. Elderly Care

Industry overview

As the phenomenon of global ageing intensifies, the problem of elderly care is becoming more and more prominent. According to the World Social Report 2023, published by the United Nations, it is projected that by mid-century, one out of every six persons in the world will be over 65 years of age, and the number of persons aged 80 years or over will triple. In order to achieve a sustainable future, the rights and well-being of older persons must be prioritized. The global trend towards an ageing population is placing greater demands and challenges on family care and long-term care facilities. It is estimated that the market size of recreational and healthcare service robots is expected to reach $22.05 billion by 2035 as the demand for intelligent recreational and healthcare services is expanding rapidly globally.

Pain points

Accelerated aging makes nursing, health care and other needs increasingly complex, family care and long-term care institutions are facing different forms of demand and challenges:

1. **The degree of service refinement is not high:** there are significant differences in the physical condition of the elderly group, cognitive level, living environment, etc., and it is difficult to cover the full spectrum of needs such as “nursing care - medication reminder - rehabilitation training - emotional accompaniment” with a single robotic product, therefore, in the aging scenarios, a variety of types and functions of robots are needed to meet a variety of composite needs.
2. **Caregiver work pressure and training issues:** Caregivers undertake a number of tasks such as meal preparation and delivery in senior living organizations, which results in high work pressure. In addition, the lack of professional training for employees may affect the quality of food service.
3. **Operation and management problems:** Nursing institutions need to manage a large number of caregivers, cooks, waiters and other personnel, which is difficult to manage and has a high cost of manpower investment.
4. **Safe environment:** The safety of the elderly in senior care institutions is a key issue. Slippery floors after cleaning can easily cause the elderly to fall and get hurt. Traditional cleaning methods require time for the ground to dry, and cannot meet the needs of the elderly for an immediate safe environment.

Solution

1. **Whole-process intelligent health care:** In order to cope with the challenges of service fragmentation and diversified demand in the elderly care scene, a full-cycle health care ecology covering "assisted living - health monitoring - rehabilitation support - emotional care" is constructed based on the intelligent service robot system with multi-category and multi-form robot collaboration. The distribution robot relies on autonomous navigation ability to complete the accurate distribution of drugs and materials. The companion robots equipped with AI large model and emotional interaction algorithm provides personalized dialogue and cognitive support; The flexible bionic rehabilitation robot can adapt to people with different mobility and provide customized training programs. The inspection and care robot is equipped with the fall prevention monitoring function to provide timely response to the frequent fall accidents of the elderly group. All kinds of service robots form a collaborative service network of "perception - decision - execution" to build an all-weather, multi-dimensional intelligent care system for the elderly.

2. **Intelligent Cleaning:** Cleaning and disinfection robots can collaborate to provide a clean environment for elderly institutions and can disinfect through dry mist or ultraviolet light and other disinfecting methods, to carry out disinfection within the environment, as well as to carry out washing, sweeping, sucking and mopping standardized cleaning, to provide a safe and hygienic living environment for the elderly.

Value

Robots enable improvements in elderly care services in the following areas:

1. **Excellent care and intelligent recuperation for elderly:** robots undertake high-frequency repetitive labor such as delivering medicines and cleaning, and release caregivers to invest in high-value services such as emotional care. The project not only systematically solves the efficiency, safety and cost problems of elderly services through intelligent means, but also reshapes the balance between the quality of life and dignity protection for the elderly with the core of "technology for the good", provides a replicable and evolvable intelligent elderly paradigm for the aging society, and helps realize the social vision of "the old have excellent care".
2. **Reducing the pressure of senior care services:** the application of service robots can reduce the pressure of senior care services, make up for the gap of insufficient human resources in senior care services, improve the efficiency of senior care services, and reduce the cost of senior care services.
3. **Promote the intelligent development of senior care services:** the application of service robots in the whole chain of intelligent recreation can promote the intelligent development of senior care services, provide more humanized and personalized senior care services for the elderly, and lead the senior care service industry to a new stage of development.

Figure 3-7: Service robot intelligent wellness solution

3.1.7. Large transport hubs (airports as an example)

Industry overview

Airports, as representative places of large transportation hubs in modern societies, are responsible for a huge volume of passenger transportation. They are not only important gateways to cities, but also important indicators of the economic vitality of countries and regions. As globalization continues to grow, passenger traffic at airports continues to increase, placing higher demands on service efficiency and quality. The service robots for large transportation hubs are expected to reach $5.79 billion by 2035.

Pain points

The increase in passenger flow has brought more pressure to the service of airports and other transportation hubs, and the following problems have emerged that need to be improved:

1. **Individualization of passenger service demand:** passengers come from different regions, with large differences in cultural background and travel needs, and it is difficult to satisfy all the individual needs of all passengers.
2. **Inefficient manual service:** the transportation hub has a large flow of people, the manual service is inefficient, and the waiting time of passengers in the queue may be too long, leading to a decline in service quality.
3. **Outstanding safety hazards:** transportation hubs are crowded places with outstanding safety hazards, which require strengthening of safety management and emergency response capability.
4. **Difficulty in ensuring environmental health:** transportation hubs have a large flow of people, and it is difficult to ensure environmental health, which is likely to deteriorate the travel experience of passengers.

Solution

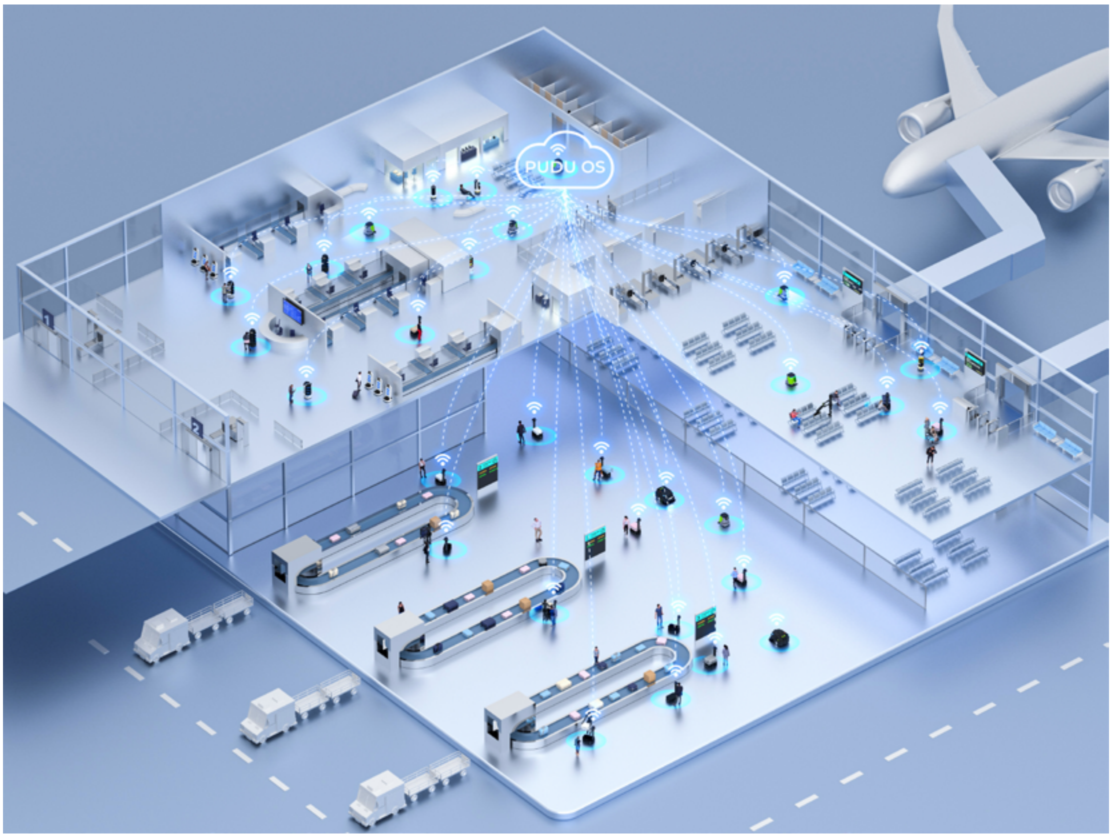
1. **Intelligent guidance:** The service robot accesses a variety of AI models and can provide passengers with intelligent guidance services, help passengers quickly find the corresponding boarding gates, ticket gates, transfer lanes, etc., and provide route guidance and flight information inquiry services.
2. **Intelligent inquiry:** The robot can provide intelligent inquiry service for passengers, answering their questions about flight information, ticketing, transportation routes, etc. It also provides multi-language translation service, which facilitates the communication of passengers with different languages.
3. **Intelligent Meal Dispensing:** Customers can order meals at the boarding gate, and the robot will perform the delivery task, delivering the meals to the passengers accurately and timely to improve the passengers' dining experience.
4. **Intelligent cleaning:** the robot can provide a clean environment for the transportation hub, and can disinfect the environment through dry fog or ultraviolet rays and other disinfection methods, as well as carry out washing, sweeping, sucking and dragging standardized cleaning to provide travelers with a safe and hygienic travel environment.
5. **Baggage Handling:** the industrial-grade delivery service robot can provide baggage handling services, following travelers to the check-in area, security check area or shopping area through the intelligent following mode, providing more detailed value-added services for airport travelers, including people with disabilities.

Value

Robots enable improvements in the large transport hubs in the following areas:

1. **Enhancing traveler experience:** through intelligent guidance and inquiry services, the service robot enhances the travel experience of travelers, reduces waiting time and improves service efficiency.
2. **Enhance safety and security:** The service security patrol robot enhances the safety and security capability of the transportation hub through intelligent monitoring and emergency response and improves the level of safety management.
3. **Improvement of environmental hygiene:** the large scene AI intelligent cleaning robot can effectively improve the environmental hygiene of the transportation hub, providing travelers with a more comfortable and hygienic travel environment.
4. **Improve operational efficiency:** the introduction of service robots reduces the pressure of manual service and improves the operational efficiency of airports.

Figure3-8: Service robot intelligent airport solution



3.2. Service robotics enabling sustainable development

Service robots, as the core carrier of intelligent transformation in various industries, will deeply empower the ESG practices of various industries through full-stack eco-solutions. This section combines Pudu Robotics' global leading practices, as well as Deloitte's quantitative modeling and industry research, to systematically analyze the comprehensive benefits generated by service robots in key industries in terms of environment (E), society (S) and governance (G).

3.2.1. Hotel & building scenarios: energy saving, carbon reduction and privacy protection

3.2.1.1 Intelligent Delivery and Scheduling Optimization

Application practice

With the continuous development of AI technology, service robots are increasingly used in the hotel industry. These robots are able to carry out intelligent centralized scheduling of cross-floor delivery tasks through AI path planning algorithms. This not only effectively reduces the empty load rate of the elevator, but also significantly improves the task efficiency of a single delivery. In this context, hotel service robots have become an important tool for optimizing resource allocation, improving service quality, and reducing operating costs, bringing a new intelligent service experience to the hotel industry, and at the same time promoting the development of the entire industry in the direction of energy saving and efficiency.

Quantitative benefits

- **Energy consumption reduction:** 28% reduction in the average number of elevator runs per day, with annual electricity savings of 12,800 kWh (estimate based on 10 elevators and 200 runs per day).
- **Carbon emission reduction:** Estimate based on China's electricity CO_2 emission factor of 0.5366 kg CO_2/kWh in 2022, the annual carbon reduction is about 7.5 tons, equivalent to planting 410 adult trees.
- **Economic benefits:** The hotel saves ￥15,000 in electricity costs per year.

3.2.1.2 Privacy Protection and Data Security

Application practice

Greeting robots have become an innovative solution for improving service efficiency and customer satisfaction in the hospitality industry. These robots adopt advanced end-to-end data encryption technology to ensure the security of guest information during the check-in process. No human intervention is required during the entire process, which greatly avoids the risk of leakage of guest identity information. Delivery robots perform in-room deliveries, and through contactless delivery methods and the use of anonymized task records, these robots not only improve delivery efficiency, but also ensure user privacy compliance such as compliance with the international standard ISO 27701.

ISO 27001 Certified · ISO27701

Quantitative benefits

- **Privacy risk reduction:** 90% reduction in data breach issues.
- **Compliance cost savings:** Hotels save ￥800,000 per year in potential compliance costs.

3.2.1.3 Unmanned Cleaning and Water Conservation

Application practice

Under the full-stack robotics ecosystem, the use of cleaning robots can realize 24-hour unattended automated cleaning. According to the estimation of The Water Conservancy, an international environmental protection agency, the cleaning robot can save 42.5-142.5 liters of water per 1,000 square meters compared with traditional equipment and manual cleaning, realizing a 95% water saving in cleaning operations. At the same time, the cleaning agent used by the robot is only 10% of that used manually, which reduces the emission of chemical substances and makes a positive contribution to sustainable development and environmental protection. In addition, the use of cleaning robots that meet the Smart Drop Certified standard can help users or companies enhance their environmental image and promote their green development goals.

SMART DROP Certified

Quantitative benefits:

Water saving: Water consumption per 1,000 square meters of cleaning is reduced from 150 to 7.5 liters for manual cleaning, saving 225,000 liters of water per year (ftaking a hotel with an area of 50,000 square meters as an example).

Chemical emission reduction: The amount of cleaning agent used is reduced by 90%, reducing the emission of harmful chemical substances by 1.2 tons per year.

3.2.2. Manufacturing scenarios: cleaner emission reduction and labor well-being

3.2.2.1 Green Logistics and Circular Economy

Application practice

Industrial distribution robots are playing an increasingly important role in material handling and supply chain management. These robots can easily handle goods of up to 300 kilograms by virtue of their powerful single load capacity, which significantly improves the transportation efficiency of intra-factory logistics. To further increase the efficiency of distribution, industrial distribution robots optimize handling paths through algorithms to achieve high-performance distribution.

Quantitative benefits

Transportation efficiency improvement: 15% increase in logistics efficiency, 8,000 liters of forklift fuel consumption reduction per year compared to conventional forklifts (estimate based on average daily handling of 50 tons).

Carbon emission reduction: 21.8 tons of carbon reduction (estimate based on diesel carbon emission factor of 2.68 kg CO_2/L).

Occupational health protection: Reduce the risk of occupational injuries under heavy-duty handling, with the industry's average annual injury rate falling by 12%.

Precise material distribution: Robots collaborate with MES system to reduce production waste by 5%, saving ￥1.2 million in raw material costs annually (taking automobile manufacturing plants as an example).

3.2.2.2. Unmanned Cleaning and Reduction of Chemical Releases

Application practice

On the automotive factory floor, keeping the environment clean is critical to ensuring product quality and improving employee productivity. The use of cleaning robots represents a significant advancement in automated cleaning technology in manufacturing. These robots provide 24-hour unattended self-service cleaning and significantly reduce the use of chemical cleaners, thus optimizing shop floor O&M.

Quantitative benefits

Water saving: Up to 142.5 liters per 1,000 square meters, 14,250 tons per year estimated based on a 100,000 square meter plant, which is equivalent to the capacity of 10 standard swimming pools;

Carbon emission reduction: 15 tons of carbon emissions from the production of cleaners (estimate based on on BASF's Chemical Carbon Emission Factor).

Chemical emission reduction: Cleaner usage is only 10% of manual labor, reducing hazardous substance emissions by 8 tons per year.

3.2.3. Medical scenarios: health governance

3.2.3.1 Drug Delivery and Infection Control

Application practice

In modern healthcare systems, healthcare delivery robots have become an increasingly popular option to improve patient safety and hospital operational efficiency. These robots are usually equipped with advanced technology modules, which also include ultraviolet light sterilization functions, and assist manual distribution, which can effectively kill pathogens during the distribution process and reduce the rate of nosocomial infection.

Quantitative benefits

Infection rate reduction: 30% reduction in the risk of in-hospital cross-infection.

Medical cost savings: Taking a 500-bed hospital as an example, it can save ￥2 million in medical costs every year.

3.2.3.2 Medical Waste Disposal

Application practice

As the healthcare industry continues to place greater emphasis on environmental protection and waste management, recycling distribution robots have become a revolutionary solution. These robots are capable of sorting and recycling according to different waste types, thus significantly improving the efficiency of medical waste disposal and reducing environmental pollution caused by improper disposal.

Quantitative benefits

Disposal efficiency improvement: 40% increase in medical waste disposal efficiency

3.2.4. Retail scenarios: energy saving and green cleaning

3.2.4.1 Intelligent Cleaning and Energy Consumption Optimization

Application practice

In the retail industry, especially in large-scale superstore environments, it is crucial to maintain a clean and tidy shopping space for customers to enhance customer experience and brand image. The introduction of cleaning robots marks an important step towards intelligent and energy-efficient cleaning operations. The robots are able to achieve 24-hour unattended cleaning services through dynamic path planning. Water consumption per 1,000 square meters has been reduced from 150 liters for manual cleaning to 7.5 liters, and the use of chemical detergents has been reduced by 90%, which greatly improves cleaning efficiency while significantly reducing resource consumption.

Quantitative benefits

Water saving: 14,250 tons of water saved per year (equivalent to the capacity of 10 standard swimming pools);

Chemical emission reduction: 8 tons of phosphorus-containing detergent discharged per year, reducing the risk of eutrophication in water bodies;

Carbon reduction: 15 tons of carbon emissions from detergent production (estimate based on the BASF chemical carbon emission factor);

Electricity savings: The robot cleans at night during non-business hours, and can be operated with the lighting system of the store turned off, resulting in an annual energy saving of 18,000 kWh (equivalent to 10.5 of carbon reduction).

3.2.4.2 Intelligent replenishment and energy-saving coolers

Application practice

Replenishment and delivery robots have become an important part of improving the operational efficiency of stores. The replenishment robot can be closely linked with the store's freezer sensors to monitor the inventory situation in real time, so as to intelligently complete the replenishment task and ensure an adequate supply of freezer goods. This ensures that the cooler is well supplied with goods and effectively avoids idling and power consumption.

Quantitative benefits

Electricity saving and carbon reduction: Annual electricity saving of 3,200 kWh (equivalent to 1.87 tons of carbon reduction).

3.2.4.3 Paperless Operation

Application practice

The marketing and distribution robots have changed the traditional shopping and payment methods by integrating electronic price tags and self-service settlement systems, greatly reducing the use of paper and promoting paperless transactions.

Quantitative benefits

Paper consumption reduction: Reduces paper usage by 90%. Estimated based on an average daily printing of 5,000 labels and a sheet weight of 4g, the average single store saves 1.2 tons of paper per year (equivalent to 17 trees).

3.2.5. Elderly care scenario: elderly care assistance and humanized service

3.2.5.1 Companionship and Care

Application practice

In elderly care and rehabilitation centers, wellness delivery service robots are becoming an important tool to enhance service levels. By integrating advanced voice interaction and behavior perception technologies, these robots can not only meet the daily needs of the elderly, but also play an important role in emotional communication and nursing assistance, demonstrating the warm power of technology in humanistic care.

Quantitative benefits

Increased social interaction: Service robots increase the frequency of social interaction by 40%, reducing the risk of depression.

Increased nursing efficiency: The robot assists nursing staff in their daily tasks, increasing nursing efficiency by 30%, reducing the burden on staff while reducing the risk of cross-infection brought about by the mobility of caregivers.

Anti-fall detection: The response time for accident detection is improved to within 5 seconds, increasing processing efficiency by 80%.

3.2.6. Scenarios for large transport hubs (airports as an example): public service and security governance

3.2.6.1Guidance and Service

Application practice

In airports, guidance and inquiry service robots can provide real-time passenger guidance and information inquiry services, help passengers quickly locate their destinations, and at the same time reduce the burden of manual baggage handling and optimize passenger flow management through intelligent technology. It not only improves the service level of the transportation hub, but also creates a smarter and more convenient travel environment for passengers and promotes the service upgrading and technological innovation of the transportation industry.

Quantitative benefits

Increased efficiency of crowd flow: Average passenger waiting time reduced by 20%, improving the efficiency of airport access.

Improved passenger satisfaction: 15% increase in passenger satisfaction.

3.2.6.2 Public Safety Patrol and Privacy Protection

Application practice

In public places such as parks, shopping malls, stations, etc., the application of service robots is rewriting the traditional patrol mode. These robots can be equipped with a variety of external accessories, such as high-definition cameras, infrared detectors, etc. Combined with artificial intelligence algorithms, they can monitor abnormal behaviors (e.g., items left behind, crowd gathering) in real time, realizing all-round monitoring and real-time response to the security of the venue; at the same time, through the encrypted data transmission to the central control system, to avoid leakage of the monitoring screen.

Quantitative benefits

- **Improvement of security response time:** The discovery speed of abnormal events is improved to within 30 seconds (the traditional average takes 5 minutes), and the annual reduction of security vulnerabilities is 80%;
- **Privacy compliance:** The encrypted storage of data complies with the ISO 27001 standard, which saves ￥2 million in annual privacy compliance costs.

3.2.6.3 Green Cleaning and Water Saving and Consumption Reduction

Application practice

In the modern airport environment, the cleaning robot, as a representative of the cleaning technology, significantly improves the cleaning efficiency through its advanced dynamic path planning and recycled water filtration system, while significantly reducing the resource consumption. Compared to traditional manual cleaning, the cleaning robot's water consumption per 1,000 square meters has decreased from 150 to 7.5 liters, achieving a 95% water saving, while the amount of cleaning agent used is only 10% of the traditional method.

Quantitative benefits

- **Water saving:** 26,006 tons of water saved annually, equivalent to the capacity of 10 standard swimming pools;
- **Chemical emission reduction:** 3. 2 tons of phosphorus-containing detergent emissions reduced annually, reducing the risk of water pollution;
- **Carbon emission reduction:** 12 tons of carbon emissions from the production and transportation of the detergent (estimate based on BASF's Chemical Carbon Emission Factor).

Measurement modeling framework

Dimensions	Indicators	Calculation formula
Environment(E)	Amount of electricity saved (kWh)	**Average daily tasks × single energy consumption× numbers of days of operation × energy saving rate**
	Carbon reduction (tCO_2)	**Power Saving × grid carbon emission coefficient**
Society(S)	Decrease in injury rate (%)	**(Baseline injury rate-injury rate after robot after robot application) / Baseline injury rate**
Governance(G)	Compliance cost savings(ten thousand CNY)	**Manual inspection cost-robot inspection cost**
	Data privacy protection benefits (ten thousand CNY)	**Cost savings from generated privacy protection measures**

Source: Deloitte Research

Figure 3-1: ESG practices for service robots in key application industries

Hotel Building

Welcome robot adopts end-to-end data encryption technology, eliminating the need for human intervention throughout the check-in process and avoiding leakage of residents' identity information. When the robot performs room delivery tasks, it ensures user privacy compliance through contactless delivery and anonymized task records.

90%
reduction in data breaches

Manufacturing

In industrial scenarios, industrial delivery robots can replace some of the light-duty delivery tasks that would otherwise be transported by traditional forklift trucks, and increase logistics efficiency by 15%. Based on an average daily handling of 50 tons, this is equivalent to an annual reduction of 8,000 liters of forklift fuel consumption and 21.8 tons of carbon emissions

15%
improvement in logistics efficiency

Healthcare

Medical delivery robots with UV elimination and assisted with manual delivery are able to effectively kill pathogens during the delivery process and reduce the rate of nosocomial infections

30%
reduction in the risk of in-hospital cross-infection

Retailing

Cleaning robots are applied to large-scale superstores, realizing 24-hour unattended cleaning through dynamic path planning, reducing water consumption per 1,000 square meters from 150 to 7.5 liters per 1,000 square meters manually, and reducing the amount of detergent used by 90%

90%
cleaner usage

Elderly Care

The service robot has a fall detection function, real-time monitoring of the elderly falls, and the response speed is increased to within 5 seconds Elderly The service robot has a fall detection function, real-time monitoring of the elderly falls, and the Response speed is increased to within 5 seconds, and accident handling time is increased by 80%

30%
improvement in nursing efficiency

Large Transport hubs (airports as an example)

In large transportation hub scenarios such as airports, guidance robots can monitor abnormal behaviors (e.g., items left behind, crowds gathering) in real time with infrared cameras and AI algorithms

< 30s
timeframe for responding to security incidents

Source: Deloitte Research

Service robots have constructed a quantifiable ESG empowerment system in the dimensions of energy saving and carbon reduction, resource recycling and labor well-being through a full-stack robotics ecosystem. Taking Purdue Robotics as an example, its solutions have landed in more than 60 scenarios in 10 key industries around the world, with an average annual carbon reduction of more than 50,000 tons, which is equivalent to recreating 2.7 thousand hectares of forest. In the future, with technology iteration and ecological openness, service robots will become the core fulcrum of corporate ESG strategy, promoting the realization of global sustainable development goals.

Data Source

1. International Energy Agency (IEA): 2023 Global Energy and Carbon Emissions Report

2. UN World Water Development Report 2024

3. International Labor Organization (ILO)

4. Pudu Robotics ESG Database: 2020-2024 end-customer case measurement data

5. Deloitte Corporate Compliance Client Service Experience

Note: The actual benefits need to be dynamically adjusted with the parameters of the specific scenarios, and it is recommended that the end-customer companies Access to IoT platform to realize real-time carbon footprint tracking.

Conclusion

Currently, the service robot industry is ushering in unprecedented development opportunities. With the deep integration of artificial intelligence, Internet of Things and other technologies, service robot application scenarios are rapidly penetrating multiple industries such as manufacturing, retail, hospitality, and healthcare. This growing adoption is not only driving efficiency improvement, but also accelerating industrial upgrading and supporting sustainable social development.

As the industry enters its next phase, the future heading players are expected to jointly build an open full-stack intelligent service robot ecosystem. This will be achieved through the integration of multiple technology stack-mobility, manipulation, and interaction- enabled by modular design and AIoT-powered R2X interaction framework. At the business model level, companies will establish diversified product matrix and promote the synergistic development of the specialized, semi-humanoid, and humanoid robots. Together, these advancements aim to break through the current barriers of fragmentation, lack of collaboration, and limited generalizability across the industry, and paves a win-win road of collaborative innovation for the industry.

Looking to the future, an open full-stack intelligent service robot ecosystem will become an important direction for the industry. It will not only help optimize user experience and improve service efficiency, but also promote cross-field collaboration and innovation, injecting new vitality into various industries. With the combined efforts of robotics companies, users and stakeholders across the value chain, service robots will empower thousands of industries in a more efficient and smarter way, ultimately serving as a vital bridge towards an intelligent future for humanity.