# Humanoid Robots
## —Technological Advancements Driven by Generative AI and the Launch of Pilot Programs—

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## Why This Technology?

Advances in AI have greatly improved control precision, enabling delicate operations that were previously difficult. Manufacturing costs have also decreased substantially, making mass production a realistic possibility. As a result, Amazon(US) and BMW(Germany) have launched pilot programs at their logistic warehouse and automobile factory in the United States, accelerating the movement toward real-world implementation. At this stage, it is unclear whether humanoid robots will become widely integrated into society but this will be an opportunity to take a broad view of the situation and consider how it may impact your business domain.

## Summary

- In 2024, a large amount of capital flowed into humanoid robot startups, with the amount of investment in humanoid robot startups reaching a record high. Large companies are also working to develop the technology, and there is a growing trend toward collaborations.
- Although challenges remain, such as safety concerns and cost issues, the economic impact of general-purpose humanoid robots could be immense. Their adoption is expected in industries facing future labor shortages and fields involving hazardous tasks.

## 1. What is a Humanoid Robot?

### 1-1. Definition of Humanoid Robot

While there is no strict definition of humanoid robot (hereafter “humanoid;”), the term typically refers to a general-purpose, bipedal robot modeled after human form and capabilities. Most humanoids are designed to handle a wide range of tasks. These include industrial applications, such as grasping objects, moving containers, and positioning parts, as well as household services, such as folding laundry and engaging in conversation with humans (Figure 1).

Having a human-like form makes humanoids more socially acceptable and easier to integrate into human-centric system. In the future, they are expected to assist or replace human labor.

### 1-2. Advances in Technologies Supporting Humanoid Robots

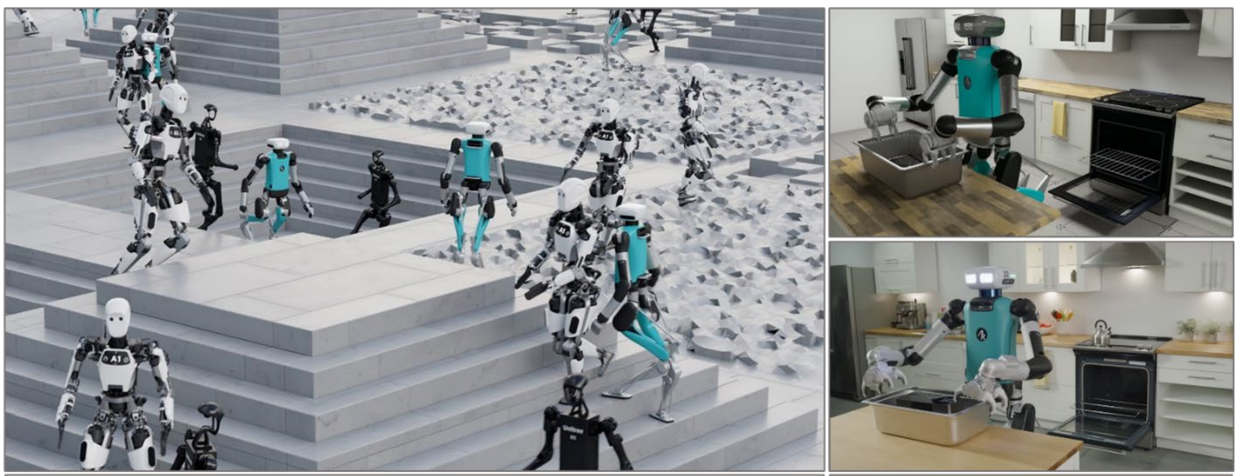
Humanoid technology encompasses a wide range of software and hardware, requiring comprehensive technological capabilities. Among these, AI technology has advanced significantly in recent years. Previously, training AI models with real-world data required substantial costs and time. However, with the ability to concurrently simulate multiple humanoids in virtual environments, AI can now efficiently learn various actions such as walking, falling, and object manipulation, leading to major improvements in motion control (Figure 2). Despite these

**Figure 1: Characteristics of humanoid robots**

| Element | Characteristics | Illustration |
|---|---|---|
| Form | Many humanoid robots have a head, torso, arms, and legs similar to those of a human, and are often close to human height and build in size. Some have structural differences, such as joints that bend in the opposite direction from human joints. |  |
| Movement | Can walk on two legs with smooth and natural movement. Ideally, they should be capable of grasping objects with their hands and performing other fine motor tasks, although some models lack individual fingers. | |
| Function | Expected to make decisions and perform actions autonomously similar to humans. Designed to work in various roles, including factory work, nursing, security, and reception tasks. | |

Source: Compiled by MGSSI based on various company materials (Illustration: Los Angeles Times https://www.latimes.com/business/story/2024-10-15/tesla-optimus-bots-were-remotely-operated-at-cybercab-event (Accessed December 28, 2024))

**Figure 2: Learning in a virtual space**



**Humanoids learning to walk on steps and over obstacles in a virtual space**

**Reproducing movements learned in the virtual space (upper) in the real world (lower)**

Source: Compiled by MGSSI based on various company materials
(Illustration: left: NVIDIA Isaac https://developer.nvidia.com/isaac, right (both upper and lower): NVIDIA's Youtube https://youtu.be/kr7FaZPFp6M?feature=shared

advancements, fully replicating the real world in a virtual environment remains challenging. When applying virtual training results to real-world scenarios, discrepancies can occur, necessitating adjustments. Therefore, real-world data continues to be important. Nvidia (US) offers the "Isaac," a development platform that enables robot AI training in virtual environments. Just as the CUDA software for GPUs established Nvidia's dominance in AI development and attracted many researchers, the company appears to be positioning itself as a leader in robot AI technology.

Recent advancements have also introduced learning methods such as end-to-end learning and methods where AI autonomously learns from human behavioral data such as large-scale behavior models, and further progress in these areas is expected in the future. Beyond AI, improvements in actuators and the maturation of sensing technologies have also contributed to improving robot precision (Figure 3).

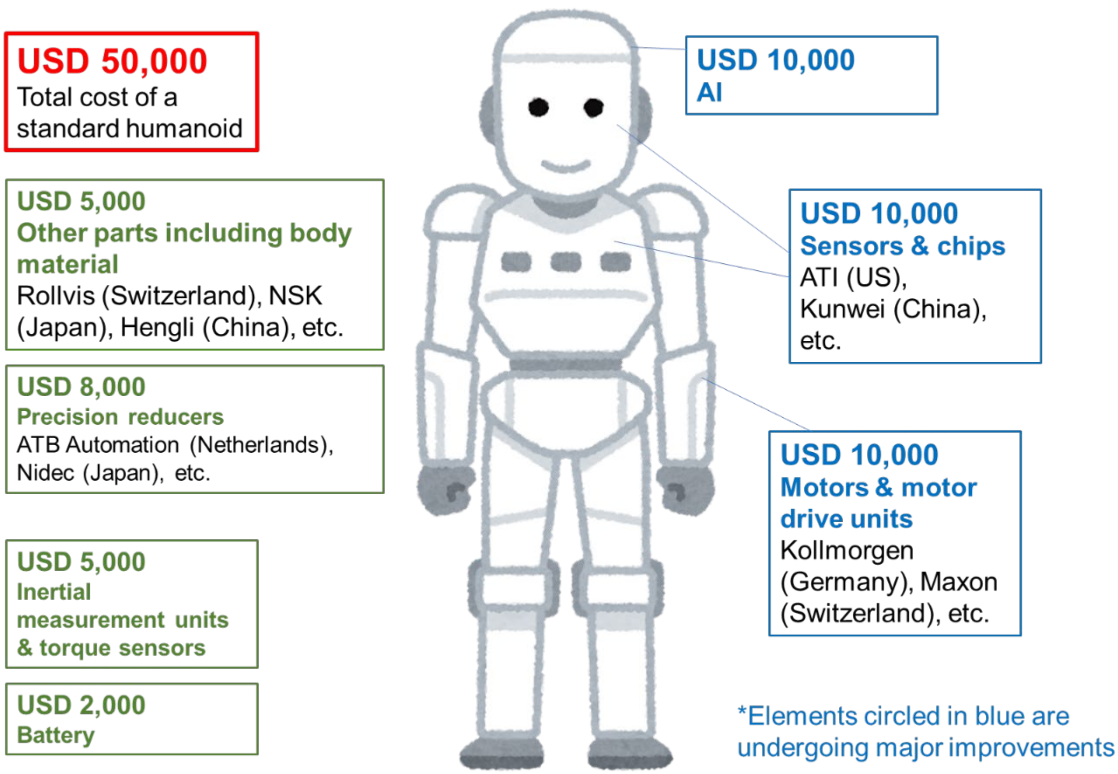
**Figure 3: Technologies contributing to improved control precision in humanoids**

| Element | Characteristics |
|---|---|
| AI | ● Sim2Real: A method for applying learning from virtual environments to real-world scenarios<br>● End-to-End Learning (E2E learning): An AI learning approach that processes the entire learning pipeline in a single step, rather than dividing it into separate stages such as recognition and movement<br>● Robot Foundation Model: A base model for robots trained on large datasets, including language, images, and behavioral data<br>● Large Behavior Model (LBM): A model trained by observing and learning from human behavioral data |
| Hardware | ● Actuators: In general, the transition from hydraulic to electric drive systems has reduced costs. Tesla's Optimus reportedly uses linear actuators such as ball screws and planetary rollers to enable high-precision control<br>● Sensor: Different types of sensing data such as LiDAR and cameras can now be integrated and handled |

Source: Compiled by MGSSI based on various company materials

On the cost front, the manufacturing cost per unit, which had long remained in the range of tens to hundreds of millions of JPY, has significantly decreased. As of 2023 estimates, the cost has dropped to around USD 50,000, and is approaching a realistic price for mass production (Figure 4).

**Figure 4: Humanoid robot components/costs (2023 estimates) and major suppliers**




Source: Compiled by MGSSI based on materials of Global X and others

## 2. Notable Trends

Companies developing humanoids are securing massive funding. In the period of January to March, 2024, funding for humanoid-related projects reached USD 775 million, already surpassing all previous full-year funding records[1]. The majority of this funding was raised by Figure AI (US), which secured USD 675 million from a number

[1] Based on the CB Insights report "Humanoid Robotics in 5 Charts: AI drives funding to record levels" (published March 7, 2024, last accessed on December 28, 2024).

of well-known organizations, including OpenAI (US), Nvidia, Microsoft (US) and Jeff Bezos' investment firm in February 2024. Although Figure AI dominates in terms of funding volume, 2024 has seen numerous other startups securing investments, including Agility Robotics (US), Unitree Robotics (China), 1X Technologies (Norway), Sanctuary AI (Canada), Fourier Intelligence (China), and Apptronik (US) (Figure 5). The number of startups that have raised over USD 100 million cumulatively is also increasing, highlighting the growing interest in this sector.

**Figure 5: Startups developing humanoids and their funding status**

| Company name | Series (Most recent month of funding) | Estimated cumulative funding | Estimated company value | Major investors |
|---|---|---|---|---|
| Figure AI | Series B (Feb 2024) | USD 845 million | USD 2.7 billion (as of Feb 2024) | ● OpenAI Startup Fund<br>● NVIDIA<br>● Microsoft<br>● Bezos Expeditions<br>● Intel<br>● Libera Gaming Operations (Japan) |
| Agility Robotics | Series B (Jul 2024) | USD 178 million | USD 1 billion (as of Oct 2024) | ● Amazon<br>● Sony Innovation Fund<br>● TDK Corporation |
| Unitree Robotics | Series C (Sept 2024) | USD 150 million | USD 1.1 billion (as of Sept 2024) | ● Beijing Robot Industry Fund<br>● Zhongguancun Science City Science |
| 1X Technologies | Series B (Jan 2024) | USD 140 million | USD 400 to 600 million (as of Jan 2024) | ● OpenAI<br>● Samsung Next |
| Sanctuary AI | Series A (Jun 2024) | USD 140 million | — | ● Accenture Ventures<br>● BDC Capital |
| Fourier Intelligence | Series D (Jan 2024) | USD 94.5 million | — | ● Softbank Investment Advisors |
| Apptronik | Seed (May 2024) | USD 65.3 million | USD 250 million (as of Aug 2024) | ● Assembly Ventures<br>● BlueLake Ventures |

Source: Compiled by MGSSI based on Crunchbase, PitchBook and others

Companies other than startups are also working on humanoid development. Examples of companies working on their own humanoid projects include Tesla (US), UBTECH (China), and Toyota (Japan). Another key player is Boston Dynamics (US), which has long been a leader in humanoid development and became a subsidiary of Hyundai (South Korea) in 2020. Among the Big Tech companies, Google (US), Meta (US), and Nvidia (US) are actively working on AI technologies for humanoids, development of robotic arms, and the like. Collaborations between companies are also progressing. Figure AI and OpenAI share capital ties. In October 2024, Boston Dynamics announced a partnership with Toyota Research Institute for humanoid development. In December 2024, Apptronik announced a partnership with Google (Figure 6). Regarding current technical capabilities, Western companies are considered strong in advanced control technologies, such as delicate hand and finger manipulation, while Chinese companies are making significant progress toward mass production.

**Figure 6: Major development partnerships among humanoid development companies**

| Humanoid development company | Partner(s) | Initiatives |
|---|---|---|
| Figure AI | Open AI | Open AI builds AI models for Figure AI's humanoids. |
| Boston Dynamics | Toyota Research Institute (TRI) | Implementing TRI's AI technology on Boston Dynamics hardware. |
| Apptronik | Google Deep Mind | Combining Apptronik's robotics platform with Google Deep Mind's AI expertise. |

Source: Compiled by MGSSI

Humanoids are being increasingly tested across various industries, including in automobile manufacturing plants, fulfillment centers, commercial facilities, and iPhone production factories. While Tesla, which operates its own facilities, is conducting independent trials, most other humanoid development companies are partnering with facility operators to conduct tests (Figure 7).

Among humanoid developers, three companies stand out as key players.

1. Figure AI's Figure 02

   BMW has introduced Figure AI's humanoid robot, Figure 02, into its automobile production line for chassis assembly and parts transportation. As of November 2024, a few months after its deployment, Figure 02 has undergone functional upgrades, resulting in a 400% increase in movement speed compared to its initial introduction. This enhancement allows the robot to place up to 1,000 automotive components per day.

2. Agility Robotics' Digit

   Agility Robotics' Digit is a humanoid robot with reverse-jointed legs. It has been trialed in Amazon's fulfillment centers and GXO Logistics' (US) factories, where it is responsible for box transportation and other repetitive tasks.

3. Tesla's Optimus

   Optimus is expected to be deployed in Tesla's automobile manufacturing plants. The robot is scheduled for commercial release by 2026, with an estimated price of USD 20,000 to USD 30,000. Designed as a general-purpose robot, Optimus is intended to perform a wide range of tasks, including shopping, lawn mowing, and even babysitting.

**Figure 7: Key features of major humanoids and pilot program examples**

| Development company (Robot name) | Figure AI (Figure 02) | Agility Robotics (Digit) | Tesla (Optimus) |
|---|---|---|---|
| Example pilot program (Time of launch) | BMW's US automobile manufacturing plant<br><br>(Aug 2024) | Amazon's US fulfillment centers<br><br>(Oct 2023) | Own automobile manufacturing plants<br><br>(scheduled) |
| Work | ● Assembly of chassis and transportation of parts<br>● 1,000 parts placed per day (as of November 2024) | ● Transportation and shelving of boxes | ● Demonstration video shows installation and transportation of parts |
| Characteristics (including plans) | ● 168cm, 70kg<br>● Degrees of freedom: 41<br>● Payload: 20 kg<br>➢ Conversation possible | ● 175cm, 65kg<br>● Degrees of freedom: 32<br>● Payload: 16 kg<br>➢ No fingers | ● 173cm, 57kg<br>● Degrees of freedom: 42<br>● Payload: 20 kg<br>➢ Utilizing autonomous driving technology for environmental recognition |
| Photo | <br>Figure 02 **assembling** a chassis | <br>Digit **transporting** boxes | <br><br>**Optimus Gen2** handling eggs without breaking them |

| Development company (Robot name) | Apptronik (Apollo) | Sanctuary AI (Phenix) | UBTECH (Walker S1) |
|---|---|---|---|
| Example pilot program (Time of launch) | Amplifier's US fulfillment centers<br>(Dec 2024) | Canadian Tire's Canadian apparel stores<br>(Mar 2023) | Foxconn's iPhone manufacturing plants<br>(scheduled) |
| Work | ● Sort goods by shipping container for multiple carriers | ● 110 tasks such as picking, packing, cleaning, tagging, labeling, and folding merchandise | ● Work that could cause worker health problems in the iPhone assembly process |
| Characteristics (including plans) | ● 173cm, 73kg<br>● Degrees of freedom: –<br>● Payload: 25 kg<br>➢ Communication possible via monitor on chest, etc. | ● 170cm, 70kg<br>● Degrees of freedom: 21 for hand only<br>● Payload: 25 kg<br>➢ Housing made of carbon | ● 172cm, 76kg<br>● Degrees of freedom: 41<br>● Payload: 15 kg<br>➢ Emergency stop button on chest |
| Photo | <br>**Apollo** sorting goods | <br><br>Phenix (5th generation) **displaying** goods | <br>**Walker S1** transporting a box |

*Degrees of freedom refers to the number of joints or axes in a robot's movable parts

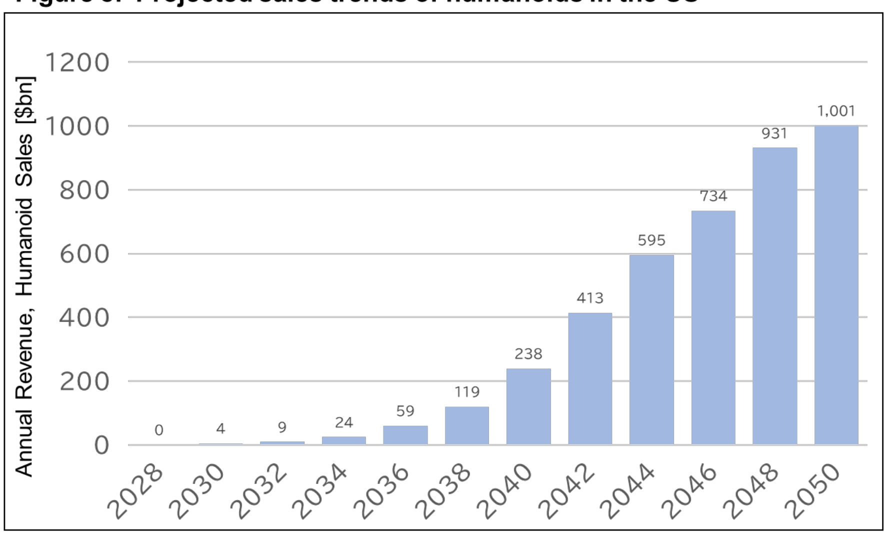
Source: Compiled by MGSSI based on various company materials (Illustration: upper left: BMW's website https://www.press.bmwgroup.com/global/article/detail/T0444265EN/successful-test-of-humanoid- robots-at-bmw-group-plant-spartanburg?language=en, upper center: Agility Robotics' website https://agilityrobotics.com/products, upper right: Tesla's Youtube https://youtu.be/cpraXaw7dyc?feature=shared, lower left: Apptronik's X https://x.com/Apptronik/status/1872326657979421153/photo/1, lower center: Sanctuary AI's website https://sanctuaryai.substack.com/p/sanctuary-ai-deploys-first-humanoid, lower right: UBTECH's Youtube https://youtu.be/UBbk18oZbTc?feature=shared (Accessed December 28, 2024))

## 3. Future Prospects

One of the key challenges regarding humanoids is improving the interpretability[2] of AI models. AI technologies based on deep learning are difficult for humans to understand in terms of how they arrive at their decisions. As a result, identifying the cause of problems is challenging, making AI difficult to use in safety-critical environments. Ensuring physical safety is another major issue. Humanoids weigh roughly as much as an adult and are designed to collaborate in close proximity with humans. If they make unexpected movements, they could cause significant physical harm. Other challenges include enhancing precision, achieving mass production, and reducing costs. Overcoming these obstacles will likely accelerate wider industrial adoption.

Currently, humanoids are still in the trial deployment phase, where their usefulness is being evaluated. In the near term, they will likely be outperformed by specialized task-specific robots in both performance and cost. However, given the rapid pace of technological advancements and increasing investment, humanoids could surpass specialized robots within the next decade or so. If this happens, general-purpose humanoids could see widespread adoption across various fields. In addition to logistics, manufacturing, retail, healthcare, and household applications, as discussed in Section 2, humanoids could play a crucial role in industries facing labor shortages due to population decline, such as food service and construction. They could also be deployed in areas where minimizing human presence is desirable, such as defense and disaster response. In the United States, the number of humanoids is projected to grow from 40,000 units in 2030 to 8 million in 2040 and 63 million in 2050, with total revenue expected to reach USD 1 trillion[3]. Given these projections, humanoids may integrate into society more rapidly and extensively than anticipated (Figure 8).

**Figure 8: Projected sales trends of humanoids in the US**




Source: Compiled by MGSSI based on Morgan Stanley

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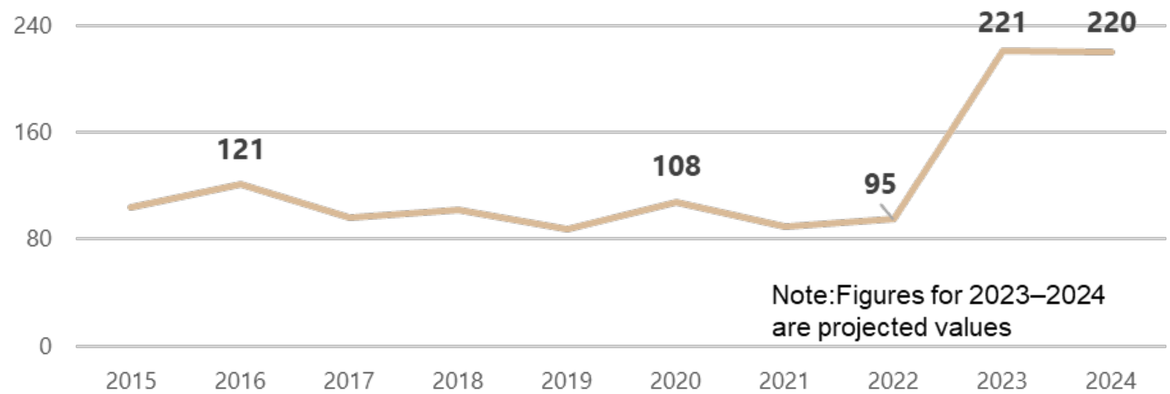
[2] Whether humans can interpret the processes and reasoning behind the predictions or inferences made by AI models based on deep learning.

[3] Based on the Morgan Stanley report "Could AI Robots Help Fill the Labor Gap?" (published on August 13, 2024, last accessed on December 28, 2024).

# IP Analysis of Humanoid Robots

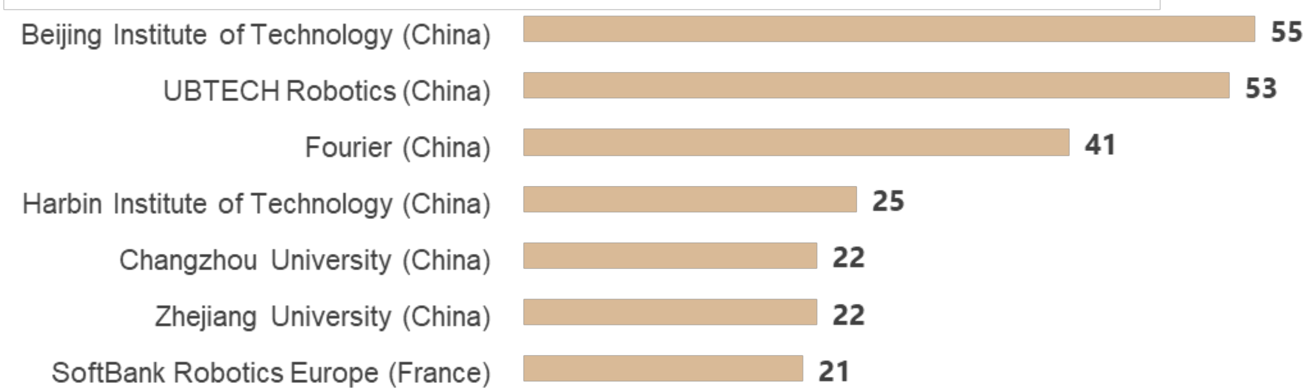
For the IP analysis of humanoid robots, patent data tagged with "Humanoid Robot" was extracted from documents using AI, and analyzed to assess the technological landscape. The analysis covered 1,121 patent families filed between 2015 and 2024, identified using the global patent search tool PatSnap.

**Figure 9: Annual patent filings related to humanoid robots**




Source: Compiled by MGSSI

**Figure 10: Top ranking of patent applicants by number of filings (2015–2024)**




Source: Compiled by MGSSI

As shown in Figure 9, while the number of patent applications surged in 2023, there was a steady flow of filings from 2015 to 2022, indicating that research and development in this field have been ongoing for many years. As illustrated by Figure 10, the majority of top patent filers are Chinese companies and universities. The only European company on the list is SoftBank Robotics Europe, known for developing the humanoid robot "Pepper." However, most of its 21 patent filings were made in 2015, and no further patent activity has been observed in recent years.

Meanwhile, companies outside of China are also advancing their own humanoid robot technologies. For example, Agility Robotics, mentioned above, has filed patents for robotic grippers and systems to enhance robot mobility, which serve as fundamental technologies in robotics. While these technologies are not exclusive to humanoid robots and therefore fall outside the scope of this search, they represent important patents demonstrating the company's technological capabilities. Although not ranked among the top filers, Kawasaki Heavy Industries (Japan), which developed the humanoid robot "Friends," has filed 15 patent applications that suggest potential applications in industrial and service sectors. While Chinese entities lead in patent filings, companies and research institutions worldwide are pursuing diverse approaches to humanoid robot development. As a result, future market competition and the emergence of new technologies in this field will be closely watched.

**Figure 11: Technical topic classification**

| Technical topic | Rate of increase since 2020 | Changes in filing trends |
|---|---|---|
| **Sensing technology** | 68% | **Integration of multiple sensors** is advancing, with increasing emphasis on environmental recognition technologies that combine visual, tactile, and audio data. |
| **Robot bodies** | 62% | Focus shifting from durability and stability; acceleration of **modular and lightweight designs**<br>Pursuit of manufacturing cost reductions and improved maintainability |
| **Artificial intelligence & learning algorithms** | 56% | Increased development of **environment-adaptive algorithms** and self-learning functions using machine learning and reinforcement learning |
| **Control systems** | 50% | In addition to improved motion precision, advancements are being made in **cooperative control and real-time control**.<br>Focus on cooperation between multiple robots |
| **Drive & actuation** | 41% | Shift from conventional drive systems (pneumatics/hydraulics) toward **electric actuators and flexible drive mechanisms** |

Source: Compiled by MGSSI

Figure 11 shows the patent data on humanoid robots classified by technology topic. Since 2020, the fastest-growing technology topic in terms of patent filings has been sensing technology. Notable inventions in this category include vision sensors focused on high-precision 3D image processing and environmental recognition algorithms, tactile sensors designed to enhance real-time processing of touch, and sensor integration technologies that enable real-time processing of multimodal data. The competitive advantages provided by advancements in sensing technology include improved real-time responsiveness (allowing robots to instantly recognize their environment and select optimal actions), high-precision operation (precise detection of force and touch to enable delicate tasks), natural human-robot interaction (integrated vision and tactile technologies enabling recognition of human facial expressions and movements and appropriate response).

Patent data suggests that humanoid robot development is primarily driven by efforts to address three major societal challenges: (1) labor shortages, (2) safety, and (3) social acceptance. These advancements are expected to accelerate humanoid adoption across industrial, healthcare/nursing, and household/service sectors.

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