STANFORD UNIVERSITY

THE STANFORD EMERGING TECHNOLOGY REVIEW 2026

A Report on Ten Key Technologies and Their Policy Implications

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08

ROBOTICS

KEY TAKEAWAYS

- Artificial intelligence holds significant potential to advance complex robotic systems, but the speed of future advances will depend on the availability of high-quality training data and the systematic integration of data-rich foundation models, simulated interactions between robots and their environment, and understanding of the real physical world.

- Humanoid robots show promise for specialized industrial and healthcare roles, although widespread adoption of them faces challenges linked to their cost, technical complexity, energy efficiency, safety, and training data quality.

- Advances in autonomous, low-cost, and communication-resilient robotic systems are transforming important aspects of modern warfare.

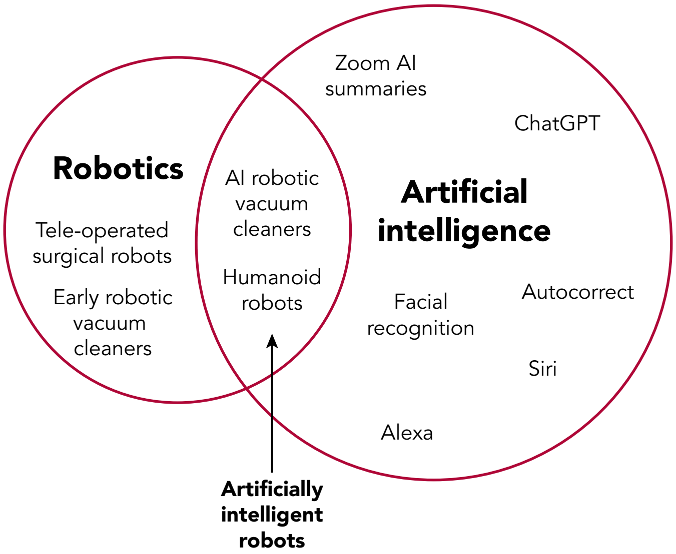
Overview

A robot is an engineered physical entity with ways of sensing itself or the world around it and of creating physical effects on that world.[1] Robots must integrate many different component technologies to combine perception of the environment with action in it. Perception requires generating representations of the robot's environment and its interaction with its surroundings. Action requires the robot to make physical changes to itself or the environment based on those perceptions.

The key engineering challenges in robotics involve the design of components, integration of these components within a robot's body, and algorithms that enable system-level functionality to allow a robot to perform intended tasks in different settings and environments. Important component technologies include:

- Actuators that enable movement, such as motors and grasping appendages.

FIGURE 8.1 Not all robots use artificial intelligence



- Sensors that receive real-time input about the immediate physical environment of the robot and the robot's own configuration.

- Control systems that decide what the robot should do based on sensor readings.

- Structural materials that robots are made of. Those built from rigid materials typically interact with their operating environments in highly prescribed and structured ways. "Soft" robots, which are flexible and conform to their surroundings, can offer better performance in more unstructured and chaotic environments.[2]

- Power sources that can be tethered to a robot or are untethered. A robot tethered to a "base station" can be energized from a power source on that base indefinitely, while untethered robots need self-contained power sources or sources that harvest energy from the environment.

- Real-time computing that determines the specific timeframes in which operations of robots take place ensures, for example, that a robotic arm in a workplace will stop very quickly if the robot detects a human in its immediate proximity.

Finally, some robots use computer vision and other types of artificial intelligence (AI) for understanding their environments and decision making, but robotics and AI do not always go together (see examples in figure 8.1). Robots with varying degrees of autonomy have been used in everything from delicate surgical procedures to space exploration.

Examples of robots include self-driving cars, drones, humanoids (i.e., a robot that mimics human form and motions), manipulators used in manufacturing and warehousing, and tele-operated surgical instruments. They can range in size from millimeter-scale soft medical devices that navigate vessels in the brain to large land vehicles and excavators for mining and construction.

The form factor of a robot—its overall size, shape, and physical layout—has far-reaching implications because it determines in large part what the robot can do, how well it can do it, and if and how people interact with it. A robot's form factor dictates how it moves, manipulates and senses things, and carries loads. It also influences the environments in which a robot can operate, its stability, and its capacity to withstand adverse conditions. Additionally, a robot's form factor affects its safety (including ease of use around people) and the cost of manufacturing it, its energy efficiency, and how easy or hard it is to repair and upgrade. Finally, a robot's size and appearance can also have significant regulatory and social implications, including how widely it is accepted by the public.

Key Developments

The development of robots is influenced by a complex mix of factors: technological advances in areas such as mechanical design, sensors, materials, actuators, AI, and control theory (i.e., the use of algorithms and feedback to manipulate the behavior of dynamical systems); their potential to solve specific tasks or problems; economic considerations including cost and market demand; safety and ethical regulations; global security concerns; and social acceptance shaped by cultural and human factors.

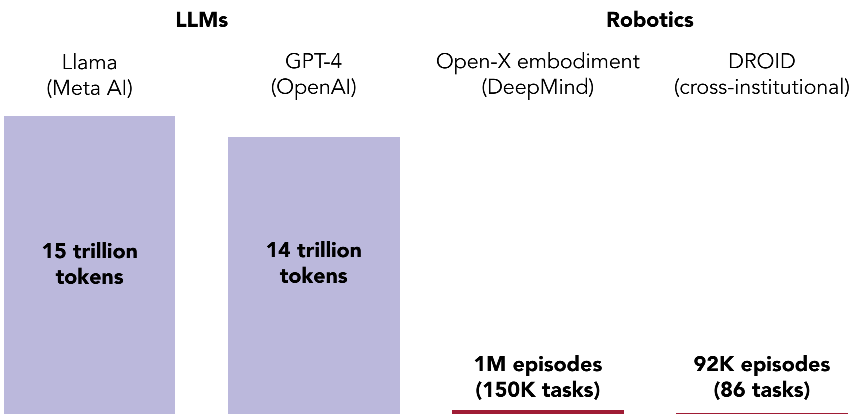
Some of the most important current developments in robotics are the role of data in AI for robotics, the development of humanoid robots, and the use of robotics in warfare.

The Role of Data in Artificial Intelligence for Robotics

The recent acceleration of AI, most notably through the creation of popular tools like ChatGPT, demonstrates how training AI models using large-scale data can drive remarkable technological advancements and economic gain. Robotics, however, faces unique challenges. Unlike digital text processing, which uses vast amounts of readily available textual data on the internet, robots require very detailed, specialized information, including visual data and sensor-based measurements of touch, precise motion, and machines' physical interactions with their surroundings.

Gathering such data at scale is both expensive and time-consuming, creating a significant bottleneck in the development of reliable, large-scale robot automation. As illustrated in figure 8.2, a large language model (LLM) today is typically trained on trillions

FIGURE 8.2 Tokens for LLMs versus episodes for robot models



Sources: Meta AI: "Introducing Meta Llama 3: The Most Capable Openly Available LLM to Date," Meta AI, April 18, 2024, https://ai.meta.com/blog/meta-llama-3/. Open AI: Julie Chang, host, *Tech News Briefing*, podcast, "The Internet May Be Too Small for the AI Boom, Researchers Say," WSJ Podcasts, April 15, 2024, https://www.wsj.com/podcasts/tech-news-briefing/the-internet-may-be-too-small-for-the-ai-boom-researchers-say/63680C0D-69FE-437C-98F8-B678DD1F7536. Industrial: Quan Vuong and Pannag Sanketi, "Scaling Up Learning Across Many Different Robot Types," Google DeepMind, October 3, 2023, https://deepmind.google/discover/blog/scaling-up-learning-across-many-different-robot-types/. Academic: Alexander Khazatsky, Karl Pertsch, Suraj Nair, et al., "DROID: A Large-Scale In-The-Wild Robot Manipulation Dataset," arXiv:2403.12945, preprint, arXiv, April 22, 2025, https://doi.org/10.48550/arXiv.2403.12945.

> **Viewed through a global lens, a race in robotic automation is already underway, driven primarily by the rapidly growing computational resources necessary to capture and analyze complex datasets.**

of tokens, whereas the largest datasets to date for robot models amount to at most a million or so episodes. (Tokens are the basic units that LLMs read and generate to process text; they can be a whole word, part of a word, or punctuation. Episodes are the basic units that robot foundation models process—a full sequence of observations, actions, and outcomes during one task, capturing what the robot saw and did over time.)

Simulation is often offered as a cheaper and safer alternative to collecting real-world data at scale for robot automation. Unfortunately, simulations frequently fail to replicate the complexity and unpredictability of physical environments and naturally favor scenarios for which they have already been prepared. The result is that using a simulation yields data with less effort but also with less fidelity to real-world situations. Simulations are still valuable tools, but their usefulness and reliability ultimately depend on calibrating them with extensive real-world data that provides some measure of ground truth.

To address these challenges, a hybrid strategy of blending advanced AI methods with proven engineering approaches is often necessary. This approach ensures that robots are more robust and capable of handling uncertainty. Crucially, high-quality data in large quantities is vital for successful outcomes. In efforts to collect such data, disparities between different regions of the world—and differences in things such as rules surrounding use of personal data—need to be taken into account. A healthcare model trained on Chinese data might perform poorly in the European Union due to differences in healthcare systems and demographics, leading to unintended consequences.

Viewed through a global lens, a race in robotic automation is already underway, driven primarily by the rapidly growing computational resources necessary to capture and analyze complex datasets. Even the most well-resourced academic institutions in the United States often have access to significantly less computational power compared to the resources available in private industry. Nevertheless, industry continues to rely heavily on foundational research conducted in academia, highlighting the importance of sustaining robust academic capabilities to maintain technological leadership.

Humanoid Robots

Robots may be useful for improving the US manufacturing base, reducing supply chain vulnerabilities, delivering eldercare, enhancing food production, tackling the housing shortage, improving energy sustainability, and performing almost any task involving physical presence. One type of device—the humanoid—is promoted as a solution to labor shortages in industries such as logistics, manufacturing, and hospitality. For example, humanoid robots have the potential to support healthcare and social services by assisting with lifting, mobility, or medication delivery in ways that would augment the capabilities of human caregivers rather than completely replace them.

An important factor driving interest in humanoid robots is that the physical world is designed around the human form factor. If robots are going to be helpful to humans in daily life, their resemblance to humans will benefit their integration into day-to-day activities because they will be better adapted to any given physical human environment than a robot in any other form factor. However, their form factor might also raise unrealistic expectations about their capabilities. As Rodney Brooks, a leading figure in the field of robotics, has noted, "The visual appearance of a robot makes a promise about what it can do and how smart it is. It needs to deliver or slightly over-deliver on that promise or it will not be accepted."[3]

The anthropomorphic design of humanoid robots suggests compatibility with environments built for humans, fueling expectations that they can perform a wide variety of tasks. Recent progress in humanoid robot autonomy has been enabled by advances in data-driven machine learning (ML). The underlying data must be of high quality and is typically obtained from observing the teleoperation of humanoid robots. Improving the quality, volume, and methods for collecting robot teleoperation data will be necessary to achieve human-level precision and dexterity, as well as to improve the autonomy of these robots in more generalizable contexts.

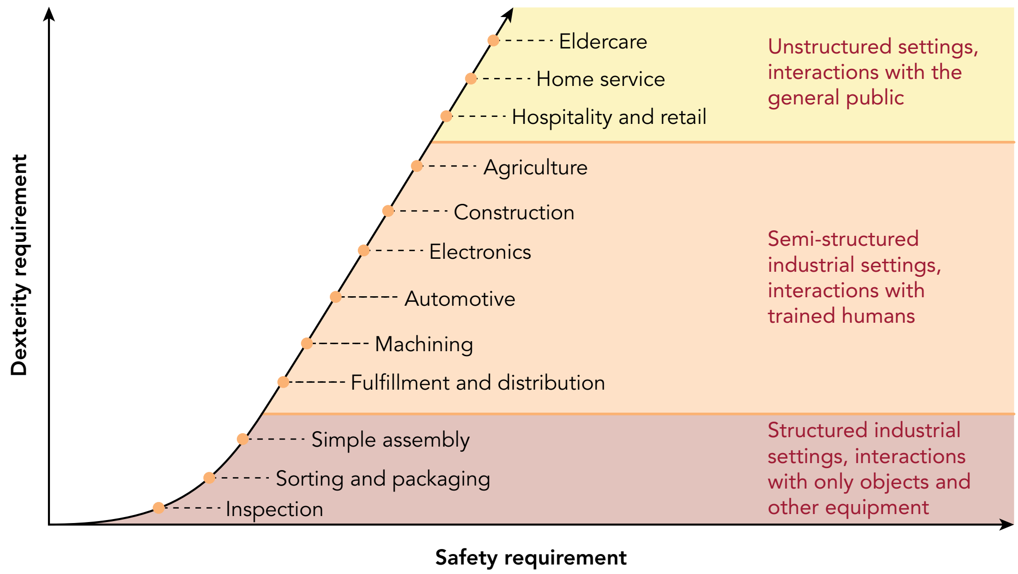
Humanoid robots are not optimally suited for all tasks. Many problems that they can solve—such as material handling or repetitive assembly—can be addressed more effectively with other kinds of robots. In such cases, replicating the full versatility of human movement increases cost and complexity without guaranteeing better performance. With high-value components such as robust actuators, dexterous hands, and force sensors, the high costs of humanoid robots, with average selling prices as high as $200,000 in 2024,[4] have thus far made it difficult to achieve widespread adoption in households. Energy inefficiency, limited battery life, and safety concerns also remain major barriers for everyday use of humanoids in household settings.

While humanoid robots may find specialized roles in industrial and healthcare contexts, wider use of them will depend on multiple factors. Progress in actuation, control, and AI will be critical for making humanoid robots a practical and sustainable solution for real-world applications. As autonomous capabilities improve, it will be particularly important that humanoid robots do not take away from human users' sense of agency, such as their ability to effectively override or alter robots' actions during certain interactions with them.

As shown in figure 8.3, some of today's humanoids are ready for deployment in relatively basic areas such as simple assembly tasks and inspection (the portion of the chart shaded in red), and are nearing levels of dexterity that will allow them to work in the vicinity of trained workers in industrial settings. Humanoid interactions with the general public will require greater dexterity, and in those cases, major technical challenges need to be surmounted to ensure the safety and reliability of humanoids.

Humanoid robots are not optimally suited for all tasks. Many problems that they can solve . . . can be addressed more effectively with other kinds of robots.

FIGURE 8.3 As safety and dexterity improve, humanoid robot deployment will expand to tasks requiring greater human interaction in less structured environments



Source: Adapted from "Humanoid Robots: From the Warehouse to Your House," *Agility Robotics*, blog, July 15, 2025, https://www.agilityrobotics.com/content/humanoid-robots-from-warehouse-to-your-house

Robotics in Warfare

Robotics is significantly reshaping modern warfare, driven by advances in autonomy, communications, and cost-effective robotic technologies. The realities of war in Ukraine and the threat of a conflict in the Taiwan Strait have spurred the Pentagon to reevaluate its combat capabilities. At the core of this reevaluation are autonomous robotic weapons systems. To adapt to this new paradigm, the Pentagon is looking to leverage more intelligent systems and cheap, scalable hardware from start-ups in Silicon Valley and elsewhere.

Examples of types and uses of military robots (which are also known by names such as "uncrewed" or "unmanned" vehicles and drones) include:

- Logistics and last-mile resupply, which can be performed by low-cost unmanned ground vehicles (UGVs) and autonomous convoys that move ammunition, water, and medical supplies under fire, reducing the exposure of human personnel (see figure 8.4). Using robots for casualty evacuation and blood/medicine delivery reduces the risks to medics and pilots.[5]

- Explosive ordnance disposal and route clearance, which can be done by tele-operated and semiautonomous ground robots that can clear mines and improvised explosive devices (IEDs) and inspect hazardous environments, helping to limit personnel's exposure to risk and preserving combat momentum. Robot-based sensing and reconnaissance in areas inaccessible to global positioning systems (GPS) and in subterranean areas (e.g., tunnels and trenches) enables targeting and force protection at lower cost.

- Surveillance drones and robots, which provide real-time situational awareness, persistent monitoring (see figure 8.5), and rapid data collection in contested or dangerous environments while reducing risks to human personnel during reconnaissance, patrol, and targeting operations. Such drones and robots can be deployed on land, at sea, underwater, and in the air.

- Armed drones and robots operated remotely, which enable precision attacks and persistent presence. These unmanned systems—which include UGVs carrying guns or grenade launchers, semiautonomous loitering munitions, seaborne drone boats, and kamikaze quadcopters—extend operational reach, provide rapid and flexible response, and can deliver targeted effects in hostile, contested, or denied environments.

An emerging defense concept integrates many of these robotic platforms with a networked infrastructure that complements the use of legacy crewed systems that are highly capable but also expensive.[6] This approach allows weapons platforms to deploy at scale with reduced human involvement, adapt to evolving combat conditions, and execute tasks such as rapid reconnaissance, precision strikes, and collaborative decision making. These capabilities enhance overall operational adaptability and efficiency and reduce casualties. Lessons from the war in Ukraine, where the high cost of conventional systems constrains their deployment, underscore the value of affordable and quick-to-acquire robotic platforms.[7]

While robots are increasingly being deployed in battlefield environments, the heavy presence of electronic jamming that impedes communication between operators and their remotely controlled platforms poses a challenge. Countering such jamming can be accomplished through creating platforms that are more autonomous (e.g., ones using AI-based capabilities that enable autonomous target recognition or navigation) or by deploying jam-resistant communications (e.g., fiber-optic cables attached to a drone or other platform that unspool as the platform flies through the air and maintain a physical connection to the operator).

Questions also remain around the reliability, accountability, cost, and cybersecurity of highly autonomous systems, and their effectiveness in real-world operations is still being evaluated. Moreover, autonomy in lethal operations introduces unresolved legal and ethical questions, while reliance on interconnected swarms exposes military networks to new vulnerabilities from cyberattacks and electronic warfare.

FIGURE 8.4 THeMIS UGV fifth generation

Source: Milrem Robotics, Wikimedia Commons, CC BY-SA 4.0

FIGURE 8.5 US Army unmanned aircraft system

Source: US Army photo by Pfc. Peter Bannister, Wikimedia Commons

While these and other challenges need to be taken into consideration when thinking about the use of robots by the military, efforts to accelerate the development and strategic integration of robotics in warfare are already helping to redefine combat strategies, increase military effectiveness, and alter geopolitical power dynamics.

Over the Horizon

Future Impacts of Robotic Technologies

MANUFACTURING

The US manufacturing sector, a vital part of the economy contributing over a tenth of US GDP and employing thirteen million people,[8] is facing significant challenges that robotics can help solve. One major issue is a persistent shortage of skilled labor, driven by people retiring and a declining rate of population growth. This scarcity threatens to leave millions of jobs unfilled and could impact the nation's prosperity and security. Widespread adoption of robots in the manufacturing sector is also an important pillar of support for the present push of the US government to emphasize domestic manufacturing by increasing its cost competitiveness compared to foreign manufacturing.

The manufacturing sector's reliance on global supply chains has also made it vulnerable to disruptions, as highlighted during the COVID-19 pandemic. Robotics offers solutions to this challenge through innovations like advanced robotic graspers and collaborative robots, or cobots, which can make manufacturing lines more adaptable and help alleviate labor shortages. These technologies also show promise for manufacturing in extreme environments, like in space or underwater, further enhancing the sector's capabilities and resilience.

THE "NOW" ECONOMY

The "now" economy, which focuses on the near-real-time delivery of goods and services, is leveraging robotics to overcome challenges in logistics and remote service provision. Robots, including delivery drones and autonomous vehicles, are being tested for last-mile deliveries to get products to customers quickly and efficiently. In healthcare, robot-assisted surgeries are becoming more common for remote procedures, while in homes, robots are automating basic services like floor cleaning. In agriculture, autonomous robots are being used as on-demand labor for seasonal tasks such as fruit picking.

However, the widespread adoption of these technologies faces challenges. These include ensuring the safety of delivery drones and privacy issues associated with them, developing robots with adaptable manipulation skills sufficient to handle various types of goods, and creating the necessary networking infrastructure to support reliable remote applications in fields like healthcare.

SUPPORTING AN AGING POPULATION

Robotic technologies are emerging as a crucial solution to the growing challenges of eldercare, which faces a significant shortage of qualified human caregivers. Demand is being driven by a population that is living longer, with a fifth of Americans expected to be over sixty-five by 2030.[9] To address this, robots are being developed to serve as assistive companions that help with daily tasks, exoskeletons that aid mobility, and smaller devices that monitor health and alert professionals to falls or other emergencies. These technologies aim to support human caregivers by handling routine tasks, making eldercare more manageable and accessible.

An aging population also requires more invasive medical care, including surgery. It's estimated that 30 percent of necessary surgeries worldwide go unperformed,[10] and robots can help by automating parts of routine procedures to make them safer and more efficient. Developments in force sensors and haptics (i.e., technology that interacts with human users through touch or other physical sensation) are also enabling telerobotics, which allows doctors to perform surgery on patients from a remote location. This is particularly beneficial for rural and low-income areas where access to specialists is limited.[11]

A major challenge for telesurgery is the complexity of surgical tasks, which varies greatly among patients. The safe implementation of these technologies relies on extensive training and testing, often through simulations, to ensure robots can handle the unpredictable nature of interaction with anatomy.

TACKLING THE HOUSING SHORTAGE

In the face of a housing crisis in the United States marked by high prices and low supply, the construction industry is struggling with a significant labor shortage.[12] Robotic technologies offer a potential solution by increasing productivity and enhancing worker safety. Robots are already commercially available for tasks like bricklaying, framing, and heavy lifting.[13] Beyond housing, robotics can also improve infrastructure projects by automating road paving, inspection, and repair with greater precision. However, integrating these robots into construction sites presents challenges, including the need to ensure they are able to safely navigate unpredictable environments and the necessity of training human workers to collaborate with and maintain these systems.

FOOD PRODUCTION

To keep up with a global population expected to reach ten billion by 2030,[14] food production needs to increase by 50 percent by 2050, a goal complicated by climate change. Robotics offers a solution to streamline food production and processing, with current applications including milking, seeding, and fruit picking. While challenges remain, particularly in tasks requiring high dexterity, like meat carving, the integration of robotics with AI and computer vision is critical. This allows robots to learn complex tasks through reinforcement learning and to capture valuable data on crop health and ripeness. This wealth of information supports precision agriculture—a strategy that uses data to optimize farming practices, reduce fertilizer and water use, and ultimately increase yields and improve soil health, all while helping the industry meet growing global demand.

ADVANCING SUSTAINABILITY

Robotics can play a significant role in advancing sustainable practices across multiple sectors. In renewable energy, robots are essential for the construction and maintenance of solar and wind farms. For example, robots can inspect and repair wind turbines, reducing costs and downtime. They can also help with sustainable resource gathering, such as harvesting lumber with minimal environmental impact and collecting materials from the ocean floor without damaging marine ecosystems. In waste management, AI-powered robots can precisely sort recyclables, making the process more efficient and safer for workers who handle hazardous materials.

Beyond energy and resource management, robotics is also transforming sustainable agriculture and infrastructure maintenance. In farming, technologies like John Deere's See & Spray use ML and cameras to apply herbicides with high precision, drastically reducing chemical use and waste. This technology also helps improve harvesting efficiency and can adapt to the challenges of a changing climate. For infrastructure, robots like Boston Dynamics' Spot can inspect industrial sites and detect gas leaks, preventing failures and improving safety. While the potential for robotics to advance sustainability is clear, continued investment in technology development is crucial to ensure these systems are reliable and can operate safely alongside humans in diverse and unpredictable environments.

Policy Issues

Adoption and Funding

To fully leverage robotics for economic growth and to address labor and supply chain challenges, the United States needs a concerted effort from both the government and the private sector. The US lags behind other leading nations in manufacturing-robot density,[15] with a slower adoption rate, especially among small and midsize businesses (figure 8.6). A key step is to establish clear regulatory guidelines and standards to ensure the safe and effective use of robots in sectors like construction.

Additionally, workforce development can help accelerate the adoption of robots if investments in education and training (e.g., efforts to help workers adapt to working with robots or to transition to new roles) are able to successfully address individual and societal anxieties and concerns about job displacement.

It is also noteworthy that wider adoption of industrial robots can have a significant positive impact on worker safety by moving employees away from dangerous tasks like welding and heavy-duty material handling. Studies indicate a substantial reduction in workplace accidents and fatalities in areas with high robot adoption.[16]

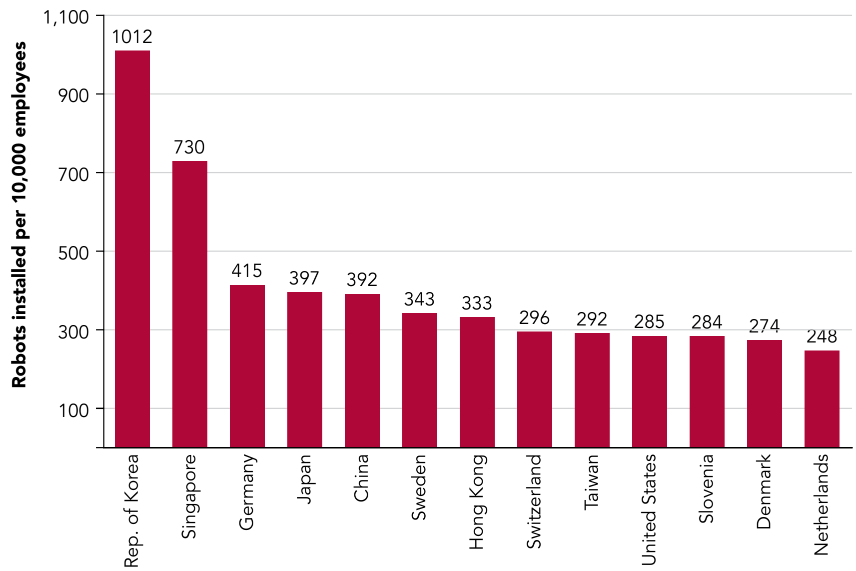
Ultimately, funding of robotics research and development (R&D) remains an issue. Despite efforts such as the National Robotics Initiative (2011–22), more R&D support will be needed if the United States is to make the most of the exciting and transformative opportunities that robotics offers.

Privacy and Consent

The exponential growth of data collection by robots in homes and hospitals for both training and operational purposes raises significant concerns about how this personal and sensitive information is handled and secured. Just as health information is heavily regulated to protect patient privacy, policies must be developed to safeguard the vast amounts of data that will be used in the future to train and operate robotic systems.

For example, standards for data privacy will need to be put in place if humanoid robots are to operate unsupervised around vulnerable individuals in

FIGURE 8.6 The United States lags behind many other countries in manufacturing-robot adoption



Source: Adapted from "Global Robotics Race: Korea, Singapore and Germany in the Lead," news release, International Federation of Robotics, January 10, 2024, https://ifr.org/ifr-press-releases/news/global-robotics-race-korea-singapore-and-germany-in-the-lead homes or care facilities, as there are currently no defined regulations or standardized certification processes for this. The use of data or AI models developed in countries like China may have reduced utility or fitness for purpose when applied within the US environment because of regulatory and contextual mismatches (e.g., different demographics in the populations that supply the data that are collected) and differing privacy regulations and data collection standards.

Inclusion and Integrity

The potential for bias in datasets used to train robots could lead to serious, harmful outcomes. For instance, a surgical robot might be less effective operating on patients from one demographic group if its training data is predominantly from another demographic group. To prevent such dangerous scenarios, it is critical to promote and enforce standards that ensure robot-training datasets accurately reflect relevant characteristics of different groups in the population at large.

Safety

The safety of robots, including physical and cybersecurity aspects, is a critical legal and ethical issue. A key challenge for public acceptance is whether safety standards should mirror human performance (or even above-average performance) or approach near perfection. The former is easier to achieve from a technical perspective, but public acceptance of such a standard is uncertain. Responsible adoption requires clear performance standards and robust cybersecurity, particularly in sensitive sectors like healthcare and national security.

Internationally, ISO 10218, a major update to the global standard for industrial robot safety, was released in early 2025.[17] This update provides clearer guidelines for robot manufacturers and integrators, especially concerning collaborative robots and cybersecurity, with forthcoming US versions of the standard expected to align with these changes.

Supply Chain

The robotics supply chain is central to robotics advancement, and the United States' access to key inputs is vulnerable to disruption due to concentrated dependencies in foreign countries and weak domestic capacity. For example, China dominates mining and processing of rare earth elements used in the high-strength permanent magnets needed for robotic motors and actuators.

Most of the key robot components described at the beginning of this chapter are produced at scale in China—and even when they are designed elsewhere, manufacturing and assembly often happen in Chinese factories due to lower costs and established infrastructure. Many robotics companies (including those from the United States, Europe, and Japan) source parts or assemble products in China because their suppliers are already there. Once a supply chain is concentrated, moving it is both costly and disruptive.

The robotics supply chain is central to robotics advancement, and the United States' access to key inputs is vulnerable to disruption.

Policy Activities to Promote Robotics

Policy in the United States regarding robotics in the past year has been heavily influenced by a new focus on AI and its role in national competitiveness, particularly against the backdrop of a new presidential administration. For example, as noted in chapter 1, on artificial intelligence, the Trump administration released America's AI Action Plan in July 2025.[18] The plan focuses on accelerating AI innovation, building domestic computing infrastructure, and leading in international diplomacy and security issues related to AI. However, the action plan includes little mention of robotics, relegating the topic to a short section on manufacturing.

There is a significant push from both the government and the robotics industry to establish a comprehensive national robotics strategy. Industry leaders and organizations like the Association for Advancing Automation (A3) have called for a dedicated federal office, tax incentives, and expanded workforce training programs to ensure the United States remains a leader in robotics. This comes as a response to global competition, particularly from countries like China, which has its own national strategy to lead in high-tech manufacturing, called "Made in China 2025."

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