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A Report on Ten Key Technologies and Their Policy Implications

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ROBOTICS

KEY TAKEAWAYS

- Although robots today are mostly used for the Three Ds (dull, dirty, or dangerous tasks), in the future they could be used for almost any task involving physical presence, because of recent advances in AI, decreasing costs of mobile component technologies (e.g., cameras in smartphones), and designs enabled by new materials and structures.
- Robotics has and will transform many industries through elimination, modification, or creation of jobs and functions.
- Understanding and communicating how robots will affect people's lives directly in their physical spaces (e.g., security robots in malls) as well as more existentially (e.g., transitioning jobs like truck driving from human-driven to autonomous vehicles) will shape how the United States accepts and benefits from robotic technologies.

Overview

What is a robot? Researchers do not universally agree on the definition of a robot, but a consensus seems to have emerged that at the very least a robot is a human-made physical entity with ways of sensing itself or the world around it and ways of creating physical effects on that world.[1]

The global robotics market is estimated at $25 billion today and poised for strong growth over the next decade. While projections vary greatly, some consultancies estimate that the global market could be worth between $160 billion and $260 billion by 2030.[2] The adoption of professional service robots is expected to drive this growth. These types of robots currently occupy a small sliver of the market, but as technology continues to improve, they will find greater adoption in industries like medicine, agriculture, and construction. The United States is projected to maintain a plurality of global robotics revenues for the next few years.

Importantly, robots must integrate many different component technologies to combine perception of the environment with action on the environment. Perception requires generating a representation of the robot's environment and interaction with it. 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 (e.g., enabling visual or other perception) and then integrating them within a physical or mechanical structure to perform the robot's intended tasks (e.g., using perception to guide motions and actions) in different settings in a given environment. The physical structure could be regarded as a robot's body. Further, different types of robots operate in different environments (e.g., factories, homes, and even space), and each environment raises distinct complexities beyond just technical performance. For example, working alongside humans raises critical issues of safety and liability.

The dependence of robotics on many different component technologies and nontechnological considerations has an important practical consequence—it takes a huge interdisciplinary effort, not just from technologists but also from experts in other fields, to move from a working prototype in a research lab to a useful functional robot in the market.

Important component technologies include:

- **Actuators** These components enable movement (e.g., motors, grasping appendages). Today, mechanical actuators are typically rigid, restricting the environments where robots can operate. These inflexible actuators make operating in confined spaces and on irregular terrain or performing dexterous movements in unknown environments challenging.

- **Sensors** These receive real-time input about the immediate physical environment of the robot and the robot's own configuration. Such inputs inform decisions about what the robot should be doing in the next moment in time.

- **Control systems** These components decide how actuators should move based on readings from sensors.

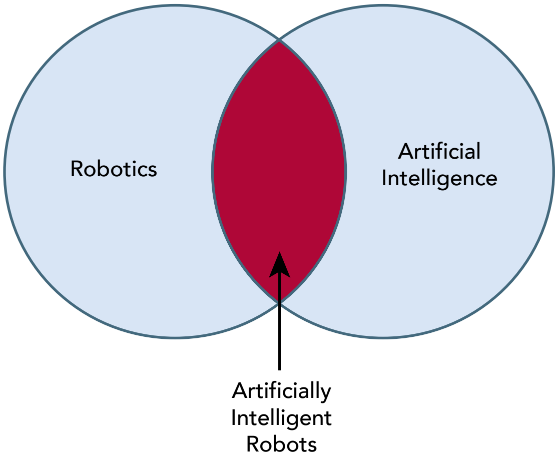
- **Materials** Constructed of rigid materials and with joints based on ordinary bearings, traditional robots interact with their operating environments in highly prescribed and structured ways. "Soft" robots that are flexible and conform to the environment can offer better performance in the more unstructured and chaotic environments that characterize most of the world, but the construction of soft robots often entails the creation of new materials or structures.

- **Power sources** Tethered robots can be energized from a power source on the "mother ship" indefinitely, while untethered robots need self-contained power sources or sources that harvest energy from the environment. A common portable power source is batteries, which drain themselves quickly—too quickly for many practical applications of robots.

- **Real-time programming** As physical devices, robots operate in real time and their components must operate within the boundaries of physical timelines determined by the operation of the robot. An actuator that moves a tenth of a second too early may cause a robot hand to fail at grasping an object. Deviations in timing may have nothing to do with the programming of the real-time microprocessor, but rather occur because another subsystem in the robot failed to operate on time or because something unexpected happened in the robot's environment.

While some robots use computer vision and other types of AI for understanding their environments and decision making, robotics and AI do not always

FIGURE 7.1 Not all robots use artificial intelligence



go together (see figure 7.1). Some robots, for example, are tele-operated, requiring a human operator to control or direct most aspects of the robot's behavior.[3] Other robots can do a few things autonomously without AI, such as maintaining themselves in a fixed position or entering a "cruise control" mode, like the early versions of the Roomba, a series of robotic vacuum cleaners introduced in 2002. There are robots that rely on AI for extensive capabilities for autonomous behavior and decision making, such as the self-driving taxis approved for business in San Francisco in 2023. Robots with varying degrees of autonomy have been used in everything from delicate surgical procedures to space exploration.

Robots are used primarily for the Three Ds: human work that is dull, dirty, or dangerous. Human attention to a task waxes and wanes, whereas robots do not get bored. Human life and well-being are precious compared to the physical damage that a robot might experience in doing a task. And robots can survive in much more hazardous or extreme environments—cleaning up nuclear reactors and exploring Mars, for example—than humans can.[4]

Key Developments

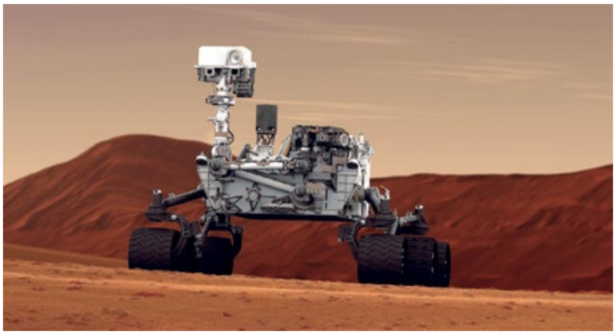
Robots are used across a wide range of sectors in a variety of ways. Prominent examples include:

- **Manufacturing** Many assembly lines use stationary robots (see figure 7.2) to undertake repetitive tasks such as welding at high speeds and with great precision.[5] The environment around such robots is highly structured and carefully controlled to minimize the need for robot cognizance of surroundings. In most cases, these robots work in isolated cells without any physical interaction with humans.
- **Warehouse logistics** Autonomous robots bring merchandise stored in very large warehouses to a central point for packaging.
- **Surgery** Mostly tele-operated today, surgical robots assist with minimally invasive surgery. Surgeons can reduce the size of the incisions that are needed for treatments and thus reduce surgical risks.[6] A surgical robot typically includes a camera arm and surgical instruments attached to mechanical arms controlled by a surgeon at a console operating the robot.

FIGURE 7.2 Automotive assembly line robots

Source: Carol M. Highsmith Collection, Library of Congress

FIGURE 7.3 Mars *Curiosity* rover



Source: NASA

FIGURE 7.4 *Sentry* autonomous underwater vehicle, Woods Hole Oceanographic Institution

Source: NOAA Ocean Exploration

FIGURE 7.5 Search-and-rescue robot

Source: National Institute for Standards and Technology

- **Science and exploration** Robots have been used to explore other planets,[7] the vast littoral ocean zones,[8] buildings,[9] the insect world,[10] and the human body.[11] Planetary rovers (see figure 7.3) and remotely operated underwater vehicles (see figure 7.4) are two examples of such robots.

- **Food production** Agricultural robots[12] can help harvest crops by picking fruit and maintain farmland by weeding. Drones can inexpensively survey farmland, and robot-operated greenhouses enable food production.

- **Disaster assistance robots** These robots can maneuver in collapsed spaces to reach victims underneath rubble, bringing communications, oxygen, food, or medicine (see figure 7.5).[13]

- **Security** Mobile robots in parking lots and buildings such as shopping malls provide telepresence for centrally located security personnel.

- **Military services** Robots have been developed that help to perform a variety of military services, including load transport, surveillance and reconnaissance, mine clearance, and armed sentry duty.

- **Transportation** Autonomous vehicles and trucks are the most common examples.[14]

Robots excel at working in structured environments like manufacturing plants where conditions are predictable. Their precision, speed, and tirelessness allow robots to surpass human performance in repetitive tasks on the assembly line. However, humans still outperform robots in unstructured or poorly structured environments. Constraints on power, fuel supplies (e.g., battery life), and sensors also limit the ability of robots to compete with humans.

Most important, human intelligence and adaptability give people a major advantage in chaotic, real-world environments. For example, robots struggle to navigate cluttered spaces or manipulate unfamiliar objects. Even advanced robots cannot yet match humans' intuitive understanding of physics and the ability to improvise solutions. Robots rely heavily on precise planning and control, so encountering small, unexpected changes may cause catastrophic failure. Humans, on the other hand, can apply their past experiences and reasoning to adapt to unfamiliar situations on the fly.

Over the Horizon

New Robotic Technologies

A growing direction in robotics is the one where robots and humans work together to capitalize on the advantages of each.

Advances in artificial intelligence and soft robotics may help robots become more capable in unstructured spaces. Machine-learning algorithms could enable robots to perform well in environments that they have never seen before or never been programmed to encounter. Flexible, nonrigid robots can perform in a variety of environments, even those inaccessible by humans.

Advances in robotics will be linked to advances in artificial intelligence, the decreasing cost of mobile components, and novel designs enabled by new materials. Researchers in robotics today[15] are working in areas such as:

Haptic technology for robots Sensations of touch and feel are useful in manipulation and many social interactions—for example, touch feedback is vital to a surgeon when palpating tissue. Haptic technology enables doctors to use touch as an input device to robotic surgical systems and tele-operated robots, facilitating more intuitive control and stronger physical connections with remote environments.[16]

Robotic movement through self-deformation Soft robots are safer for humans—a human–soft robot collision creates an impact between soft human tissue and a soft robot body and is less likely to result in injury. Soft robots' ability to deform also affords novel methods of locomotion and manipulation. Soft robot technology can be applied in haptic interfaces, search and rescue, and medicine.[17] Soft robots can also use materials that are "continuum, configurable, and adaptable with functionalities relying on high degrees of freedom shape morphing."[18]

Robot design New types of robots may be needed for operation in difficult-to-access or uncertain environments. For example, robots for space exploration include small free-flying robots to operate with space stations, robot manipulator systems for use on craft that orbit planets, rovers that can jump in low-gravity environments, and robots that can move by stepping with adhesive pads.[19]

Wearable robots A wearable robot such as an exoskeleton enhances human mobility during activities like walking and running and may assist people with physical impairments.[20] They can also be used to augment human muscle power (see figure 7.6), thereby enabling people to lift large loads.

Robotic manipulation Situations in which grasping an object is necessary often do not provide perfect

FIGURE 7.6 Sarcos Guardian XO Max wearable exoskeleton

Source: Sarcos Technology and Robotics Corporation

information about the object, the grasping device, and the relative positions of everything in the environment. So it's important to develop manipulation sequences that work with uncertainty.[21]

Bio-inspired robots These are designed based on fundamental biological principles and could include living components.[22]

Robot swarms These small, modular robotic components act in coordination as a team to perform tasks.[23]

Artificial intelligence for robotics This refers to the challenge of giving robots the ability to learn how to learn and exhibit commonsense, intelligent behaviors.

Human-robot interaction (HRI) HRI focuses on understanding, designing, and evaluating robots for use by or with humans.[24] Humans and robots working closely together, for example, may have unpredicted, unintentional physical contact that may disrupt robot operation and cause safety issues for the human.[25] Another challenge is the design of these interactions in ways that accommodate social norms, are natural and seamless, and allow robots to exhibit more familiar and comfortable behaviors to humans.

Challenges of Innovation and Implementation

Supply chain issues are one of the most important near-term infrastructure challenges in robotics. The robotics field involves the integration of multiple foundational technologies, which means progress is heavily reliant on global supply chains for parts such as chips and materials. The more far-flung and complex the international innovation supply chain, the more slowly innovation will move when disruptions to the supply chain occur.

To illustrate, DJI is a Chinese company that controls a large share of the airborne drone market. One important reason for this dominance is the entire supply chain for DJI drones is self-contained

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within one region of China. Start-up companies in the United States working in this space are generally forced to turn to Chinese suppliers as the US supply chain for drones is fragmented, making it cumbersome, expensive, and slow to deliver.

Policy, Legal, and Regulatory Issues

ROBOTS AND THE FUTURE OF WORK

Robots have enormous potential to affect jobs involving physical labor and presence in much the same way that AI might affect jobs involving knowledge and expertise. When realized in the marketplace, robotics is likely to eliminate some job types, create new job types, and modify the responsibilities and duties of jobs that remain.

Consider truck driving, one of the few well-paying jobs available to Americans without a college degree. The profession is likely to experience the following:

Job elimination Long-haul truck driving is likely to be one of the first jobs eliminated when autonomous land vehicles become feasible because fuel costs can be significantly reduced when trucks drive close to one another on highways—possible only with machine-speed reaction times rather than human reaction times.

Job modification Many truck-driving jobs entail both long-haul and local driving. Automation may take on more responsibility for long-haul driving, but navigating local driving conditions in a far less structured environment will take much longer to automate, which means truck-driving jobs may become more local in nature. But whether more local truck-driving jobs will continue to offer comparable compensation to those jobs of today is not at all clear.

Job creation Robot repair and technician jobs are likely to be a major job category as robots gain traction in the economy. If self-driving trucks come to dominate the landscape, we might see positions in logistics and fleet management increase, although these kinds of jobs entail a different skill set than that required for driving trucks.

ACCOUNTABILITY, REGULATION, AND LIABILITY

Societies routinely hold people accountable for harmful actions. People who cause accidents that harm people or property face liability for that harm. Soldiers in war who kill civilians because they use their weapons indiscriminately are guilty of war crimes. But as robots assume roles that call for similar decision making, how should concepts of individual accountability evolve?

Some questions include:

- What parties should be held accountable for harm occurring when robots are involved and how should those determinations be made?
- How and to what extent, if any, do robots involved in incidents that harm people or destroy property disproportionately or improperly attract liability lawsuits?
- How can existing regulatory regimes for transportation safety and medical safety, for example, keep pace with evolving robotics technology?
- How and to what extent, if any, are lethal autonomous weapons ethically and morally permissible?
- How is the safety of robot operation best assured? How, if at all, should safety trade off against other performance objectives?
- What are the appropriate standards of performance for robots? Robots often perform tasks that humans also perform. Should the standard be that the robot does the task nearly perfectly? Or is it adequate to perform it better than a human being?

If the latter, should the reference human being be an average person or a person who performs the task much better than most other humans?

SOCIETAL ACCEPTANCE

For robots to be widely used throughout society, their presence and operations should not cause human discomfort, unease, or fear. Experience suggests that many humans are disturbed by robots that look like humans (see figure 7.7), such as in healthcare settings.

Some advocate the use of robots for eldercare, suggesting that an aging population will create demands for services that cannot be met by future pools of workers interested in and qualified to perform those jobs.[26] It has been suggested that robots could help the elderly care for themselves by providing emotional support or cognitive therapy; enabling remote access for doctors and nurses; and entertaining home dwellers, monitoring them for falls, and helping them with housekeeping, lifting, and bathing needs. By assuming part of the eldercare labor force, robots could allow a limited number of care workers to do their jobs more efficiently and easily.

However, in one study of robots for eldercare in a nursing home, several challenges emerged, including the imposition of additional work burdens on human caregivers, the need for close monitoring of the robots, and the displacement of social and communication-oriented tasks that reduced opportunities for human connection.[27]

FIGURE 7.7 A very human-looking robot

Source: International Telecommunication Union, via Wikimedia Commons, CC BY 2.0

ROBOETHICS

Roboethics addresses what ethical guidance should be programmed into robots so they do not behave in ways that humans regard as unethical or lead to unethical outcomes. A related definition suggests that roboethics refers not to the ethics of robots but rather to the human ethics of robot designers, manufacturers, and users.[28]

One particularly clear example of roboethics arises in a military context of lethal autonomous weapons systems that can select a target and then act to destroy it without human intervention. Given military pressures to act more rapidly on the battlefield, many observers believe that such decisions will inevitably be turned over to computers. Others recoil at the prospect, arguing it is ethically wrong to make decisions in matters of life and death without human input.

But ethical issues also arise in more benign contexts. For example, what are the ethics of large-scale deployments of eldercare robots? Granting that many of the issues faced by an aging population relate to physical needs that either robots or home health caregivers could meet, what of their emotional needs? How and to what extent, if any, can interactions with an artificially intelligent eldercare robot provide comfort, empathy, and compassion for the person under its care?

PRIVACY AND SECURITY

Robots—especially mobile robots—often raise privacy and security concerns in unexpected ways. Cameras mounted on drones appear to raise many more privacy concerns than stationary cameras. Drones have also recently demonstrated the ability to open closed doors and therefore fly into areas that were once guaranteed to be drone-free.

IMPORTANCE OF MULTIDISCIPLINARY CENTERS

Robotics is a multidisciplinary field. Key developments will occur not only in labs that are studying "robotics" but also in those studying the underlying technologies that make robotics possible. These key fields include materials science, computer science, and artificial intelligence. For example, if new materials are developed by a materials science research group, they could increase the capabilities of a robotic gripper by allowing it to be equally strong but with less weight. Algorithms designed by computer scientists could greatly improve the predictive power used by autonomous vehicles.

Multidisciplinary centers that bring together contributing research labs can facilitate cooperation. Individual labs can be focused on specific areas and perform their research in the context of an overall robotics framework; the center itself can take the role of integrating technologies to see how they fit together.

Robotics research in academia is often coupled closely to industrial counterparts. The confluence is natural because research in robotics focuses so heavily on applications—and applications are the focus of industrial attention. In some subareas of robotics research, such as human-robot interactions, the sophistication of industrial activity outstrips that of academia. In some other areas, academic research pushes in directions that industry is not pursuing, such as theoretical aspects of robotics.

Multidisciplinary centers like the Stanford Robotics Center (SRC) are also useful for providing points of engagement with industry, pairing private companies with researchers on campus who have similar interests. In return for funding, corporate partners can more easily access new research and future employees.

RESEARCH FUNDING

Funding for robotics research comes from a variety of sources. The National Science Foundation supports foundational robotics research. Medical robots can be funded by the National Institutes of Health. Funding by the Defense Advanced Research Projects Agency (DARPA) is also common, with the Department of Defense sponsoring robot competitions to drive innovations they believe could be applicable to their use cases.

Another important source of research funding is the private sector. Tech companies like Google and Amazon want to know what is coming down the pipeline regarding robotics. They invest in academic labs and contribute to affiliate programs like those of Stanford's SystemX Alliance and the Stanford Robotics Center.

The amount of industrial funding devoted to robotics research and development far outstrips the amount available to academic researchers. Partly as a consequence, robotics faculty are being lured away from academia with compensation packages large enough to warrant concern at universities.[29]

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