2

History of Robotics

> Precisely because the clock did not start as a practical tool shaped for a single purpose, it was destined to be the mother of machines. . . . The enduring legacy of the pioneer clockmakers, though nothing could have been further from their minds, was the basic technology of machine tools.
>
> D. J. Boorstin (1983, p. 64)

2.1 Universal Machines

The clock was the first universal machine. Its invention and development influenced many discoveries, such as the prediction of seasons for agriculture, the measurement of longitude for navigational exploration and discovery, the measurement of heart rates, and the coordination of military maneuvers. The development and significance of the "mother of machines" is traced by Boorstin from water clocks, to clocks that called people to prayers, to the eighteenth century androids (Boorstin, 1983).

The automobile is also a universal machine. The gasoline engine is totally integrated into modern civilization. The digital computer is another example of a universal machine. Its contributions to planetary exploration, industry, medicine, the military, and, more recently, domestic applications are well known.

The industrial robot is our most recent development of a universal machine and ranks in importance with the clock, automobile, and computer. Its applications in industry are well known; however, the expansion to agricultural, space and sea exploration, medical, and domestic applications has already begun.

To fully appreciate the capabilities of the modern industrial robot, it is useful to trace the confluence of mechanical, electrical, and industrial technologies that led to its development. This is a difficult task. In this chapter, we present a selected, brief introduction to these developments. We do this so that we may not only understand how robotics got where it is today, but might also perceive where the field is going tomorrow.

The modern robot has existed only since the 1950s, but the idea of a device that can move about under its own power and control has been important to humankind for millenia. For example, the Egyptians in 3000 B.C. built water clocks and water-powered, jointed, moving figures. The ancient Greeks also had life-sized, automatic puppets that were used in dramatic productions (Boorstin, 1983, p. 93; Malone, 1978, p. 24). The Chinese and Ethiopians also built devices that performed interesting or amusing sequences of motions (Albus, 1981, p. 229). From the fourteenth through the eighteenth centuries, many mechanical devices were built that were very lifelike and performed some realistic actions. These automata culminated in the fascinating automatons of Jacquet-Droz and Maillardet (Geduld and Gottesman, 1978, p. 22).

The principles of the wheel, lever, winch, screw, and windlass with rope and pulley, powered by various sources, such as water, steam, combustion, or human or animal effort, were used to develop all automated machines. Each new machine and power source represented another step toward modern robots.

2.2 The Industrial Revolution

The basic developments that led to the modern industrial robot were started during the industrial revolution, when automatic power sources, machined parts, and controllers were developed. The industrial age was ushered into our work by machines that used steam power to perform tasks. The general use of this power source led to the design of a new class of automated machines. For example, in the textile industry, new machines could produce goods much faster than could humans using traditional, hand methods. With the invention of the steam engine by James Watt in 1769, Edmund Cartwright's power loom in 1785, and Eli Whitney's cotton gin, automation was here to stay.

The next step in the development of the robot was in machines that could build machine parts. In 1800, the metal lathe was invented by Henry Maudslay. His lathe design, in which the part to be shaped is rotated about a horizontal axis and shaped by a fixed tool, is still used today for metal working. In 1818, Eli Whitney invented the milling machine. In this milling machine, the cutting tool is rotated against the work-piece, turning out uniform parts. He, Samuel Colt, and other gun manufacturers used these milling machines and lathes to produce standard, interchangeable, precision parts that were assembled on a mass-production line (*Science and Invention Encyclopedia*, Vol. 2, p. 162).

The final step toward robots was the development of controllers. In 1805, Joseph Marie Jacquard perfected a punched-card control mechanism for his automatic looms. His design is considered to be the main precursor of the stored program computer. Some 10 years later, Charles Babbage, who had successfully built a six-digit adding machine, started the construction of his difference engine to produce the trigonometric, logarithmic, and other mathematical tables needed in navigation and mathematics.

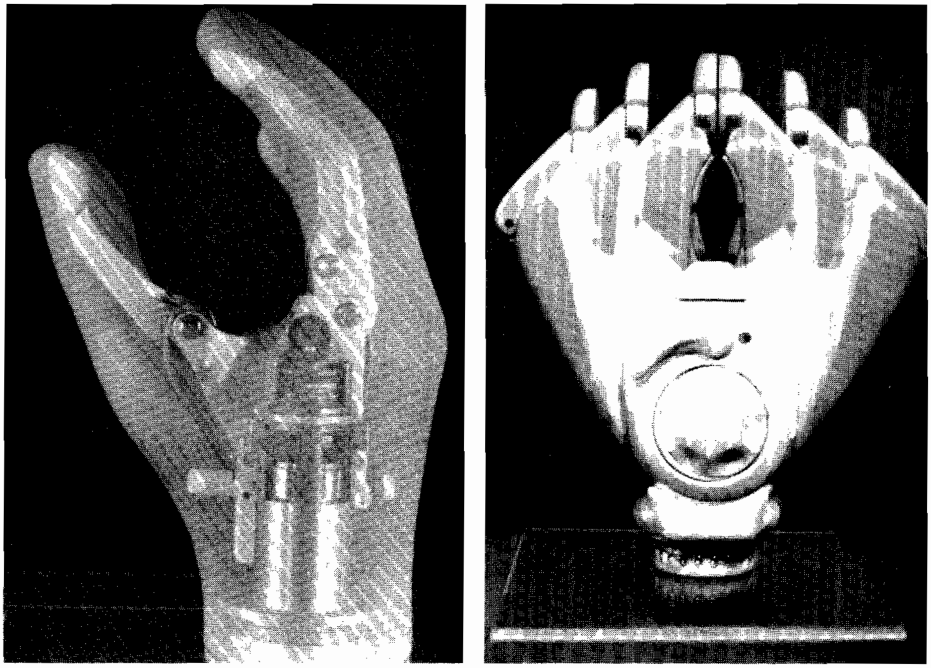
Although the general-purpose robot had still not yet been conceived, a motorized rotary crane with a gripper was designed and patented by Steward S. Babbitt in 1892 for removing hot ingots from furnaces (U.S. patent 484,870). Then, in the 1930s, a device for spray painting was invented. This device permitted the operator to move the painting apparatus through a series of motions while the signals were recorded on magnetic storage media. These signals could then be played back to control the painting motion. Inventions of this type were patented by Willard L. V. Pollard (U.S. patent 2,286,571;1942) and Harold A. Roselund (U.S. patent 2,344,108;1944), and may be considered precursors of the modern painting robot.

2.3 Prosthetic Devices

Studies and work in prosthetics were also important to the development of the modern industrial robot. In designing artificial limbs, scientists had to study the human mechanisms that made our movements and abilities possible, which led machine designers to think about how the human arm, hand, and fingers function together to do work. An early example of a prosthetic device was described by Herodotus in 500 B.C. He told of a captive who severed his own foot at the instep to free himself from his bonds, then designed a wooden foot to replace it. In the Second Punic Wars, about 218 B.C., a Roman general named Marcus Sergius lost his right hand. He had an iron replacement made that reportedly served him quite well in battle. War injuries provided an impetus to develop more sophisticated types of prosthetics to replace severed limbs. During the 1500s, Götz von Berlichingen lost his hand in battle and replaced it with a mechanical hand with movable fingers.

Prosthetic arms were developed in the sixteenth century. These were important developments toward transmission and control mechanisms that permitted the movement of mechanical fingers and thumbs so that the user could perform simple tasks, like grasping and holding. In this century, electrically powered artificial hands were developed. These were powered by electrical impulses picked up from nerve endings in the wearer's severed limb and magnified and transmitted to the hand to power its movements. These worked well until the thalidomide disaster of the 1960s. Thalidomide victims were born with stunted limbs and had no nerve endings to which electrodes in the standard prostheses could be attached. This led to the development of artificial limbs that could be operated pneumatically through compressed gas connected to pistons inside the artificial arm. These devices responded to the bulge or hardness of a contracting muscle. One of the latest developments has been the myoelectric arm. This type of device can be operated either by electric motors or compressed gas, and again pick up the electrical impulses sent to muscles to activate the device. Wire electrodes are inserted into the muscle to pick up these electrical potentials, and when the muscle is signaled to contract, these electrodes pick up the signal and amplify it, so that patients can use the same impulses to control an artificial hand as they would a real one. A modern artificial hand is shown in Figure 2–1.

The development of artificial limbs contributed much to robotics because they provided studies in transmission, manipulation, and control systems. The same designs used to construct artificial arms and hands were later used to design remote manipulators and, subsequently, the robot manipulator. Conversely, the study of robotics is now leading to further developments in prosthetics.



(a) (b)

Figure 2–1. A modern prosthetic hand. (a) This x-ray image of the device shows the outer covering, the internal mechanical structure, and the servo motors. (b) The prosthetic hand's gripping action is shown in this multiple-exposure x-ray image. (Courtesy of Otto Bock Orthopedic Industry, Inc., Minneapolis, Minnesota.)

2.4 Remote Manipulators

John Naisbitt states in his book, *Megatrends*, that "robots for dangerous tasks and toys were following the path of least resistance" (Naisbitt, 1982). One of the first areas of remote manipulator applications was in the handling of radioactive materials. During the 1940s, "hot cells," which were protected rooms containing radioactive elements, were set up for research. Radioactive materials could be safely stored and transported in lead containers called "pigs," but removing the material for use in the hot cell was a problem. Some method for manipulating this material without direct human contact was necessary due to its toxic nature. This led to the development of the "master-slave" manipulator. In this system, the "slave" mechanical arm inside the radioactive environment mimics the motions made by the "master" arm outside the hot cell.

The first master-slave manipulator was developed by Ray C. Goertz and others at the Argonne National Laboratory in 1944. In this manipulator, the master arm outside the hot cell was linked mechanically to the slave arm inside the hot cell. The human operator directed the motion of the master arm, which in turn directed the motion of the slave arm. However, these mechanical linkages often provided awkward or difficult manipulation of the slave arm because the operator could not feel the collision of the slave arm with obstacles or objects. Goertz described the operations of his manipulator as a series of collisions, as follows: "In all these operations, the manipulator must come into physical contact with the object before the desired force and movements can be made on it. A collision occurs when the manipulator makes this contact. General purpose manipulation consists essentially of a series of collisions with unwanted forces, the application of wanted forces, and the application of desired motions" (Goertz, 1963).

Goertz's design was improved upon by Bergland in 1946 to handle the radioactive materials required by the Manhattan Project, and a major advance took place in 1949, when force feedback was added to the manipulator. Now the forces encountered by the slave arm were relayed to the operator by backdriving the master arm. This permitted the operator to "feel" the collisions of the slave arm with obstacles, providing better control. Another major advance was made when the mechanical linkages of the manipulators were replaced by electrical connections. This was accomplished by using variable resistance devices called potentiometers, or "pots," to measure the motion of the master or slave joints and transmit these electrical signals to servo motors used to drive the manipulator joints.

The next major advance was equipping these manipulators with a communications link, or "telephone." These devices, which are called "teleoperators," eventually permitted the modern use of remote manipulators in outer space (Heer, 1973). The teleoperator concept was extended a great deal by the Jet Propulsion Laboratory (JPL) researchers for the National Aeronautics and Space Administration (NASA) in their search for a general-purpose, dexterous machine for their space experiments. The machines had to be operable over extreme distances and provide for precise control. NASA and the Department of Energy used and continued the development of teleoperators into very sophisticated devices. Various remote manipulator experiments are shown in Figure 2–2. NASA now officially describes a teleoperator as a general-purpose, dexterous, cybernetic machine. A human controller commands the device with the aid of controls and displays. The device is located in a remote environment and has actuators to respond to human commands and sensors to feed information back to the human. The sensors might be television (TV) or force, auditory, or tactile sensors. The barrier between the human and the device can be a concrete wall, such as would occur in the handling of radioactive materials, or extreme distance, as in space applications.

The first machines on the Moon and Mars were teleoperator devices, which helped pave the way for Neil Armstrong and other astronauts. However, there was a problem caused by the long communication delay times between the human operator and the teleoperator. Even for the Lunar Lander, the delay time was too long to permit some operations that might otherwise have been performed. A delay time even as short as 1.3 seconds proved frustrating and difficult for the human operators. Therefore, the development of computer augmentation was necessitated. Local "autonomous reactions," such as those enabling the rover to stop before it fell into a hole, had to be done automatically. This evoked the addition of a computer to the remote device and sensors to permit it to develop "local reflexes," as shown in Figure 2–3. This was a major motivation for studies in intelligent machines.

To study this problem in a bit more detail, let's consider a control problem

Figure 2–2. Remote manipulators in experiments in various control modes. Top left: a slave manipulator equipped with stereo cameras. Bottom left: A mobile manipulator equipped with grippers and camera systems. Top right: The control boards showing the monitors for camera viewing, and the joysticks and switches for manipulator control. Bottom left: A side view of the mobile manipulator. (Courtesy of JPL/NASA.)

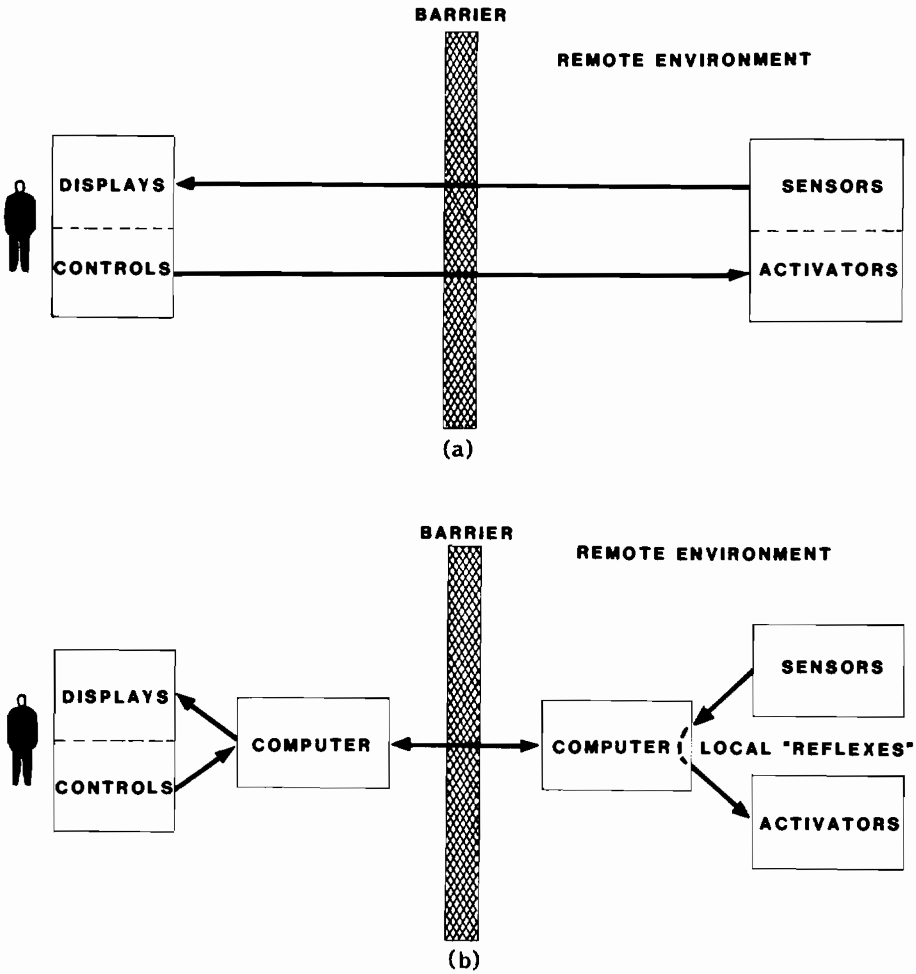


Figure 2–3. The basic concept of a master-slave manipulator. (a) The human, through the use of controls and displays, controls the activators and monitors the sensors in the remote environment. (b) The remote manipulator with local reflexes built into the manipulator. The use of some human control and some machine control is often required in difficult problems. (Courtesy of Microbot, Inc., Mountain View, California.)

encountered in the lunar experiments. The delay time in transmitting a signal from the Earth to the Moon was considered significant. Suppose the lunar rover was about to fall into a crater. If the transmission time for a STOP command took too long, the rover could plunge into the crater. To solve this problem, scientists at the Jet Propulsion Laboratory in Pasadena, California, started to design "local reflexes" or autonomous reactions into their teleoperators, such as that shown in Figure 2–4. This represents as important a step

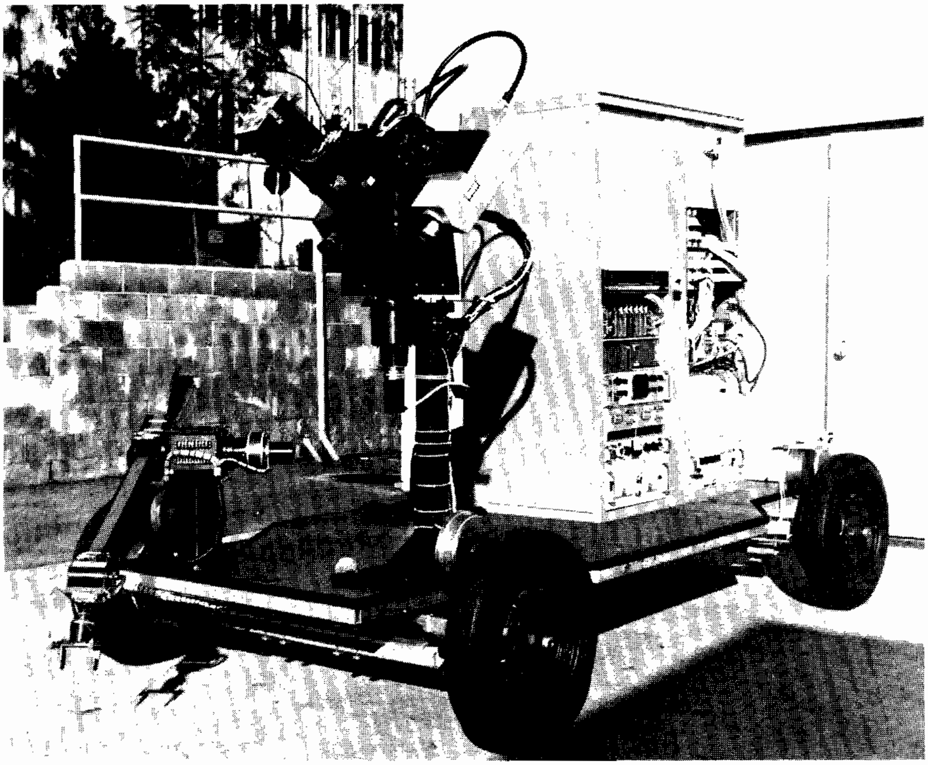


Figure 2–4. A robotic rover designed as a study tool to develop a rover to explore the surface of Mars or one of Jupiter's or Saturn's satellites. The rover is equipped with on-board computers that guide the robotic hand-eye system. The rover vision system under development consists of two television cameras mounted on masts above the chassis. The cameras allow the rover to interpret its surroundings, noting obstacles or objects of interest, and working in conjunction with a manipulator arm (lower left) to retrieve rocks. The rover, unlike other robots, will perform numerous tasks with a single command. (Courtesy of JPL/NASA.)

in the evolution of robots as it was in the evolution of animals. Many human reactions used in walking are controlled by local reflex control signals coming more from the spinal cord nerves than from the brain. Much of today's work in intelligent robots is in attempting to build local reflexes into our machines. Further advances, such as the addition of sensors and voice control, make today's remote manipulators quite sophisticated, such as those used at the Oak Ridge National Laboratory, shown in Figure 2–5. Other advances include using a mobile base, two arms, force feedback, audio feedback, stereo vision, computer control, and voice commands.

The early robot manipulators were very simple. A human had to control their motions. The addition of a computer control to these manipulators extended their capabilities. The computer became the "brains" of the manipulator "body." Eventually, computer and manipulator technology developed together to achieve the precise movements needed to perform many different kinds of work. Today's remote manipulators are still useful because they bridge the gap between operations that require some human control and operations that may be fully automated. Such tasks as the remote maintenance of equipment are being studied because these tasks are still too difficult for totally automated procedures. Some of the operational tasks are even too difficult for a single human and require complex control stations. Currently, robotics and remote handling in hostile environments are major research areas (*Proc. of Robotics and Remote Handling in Hostile Environments,* 1984).

2.5 Key Events in the Recent History of Robotics

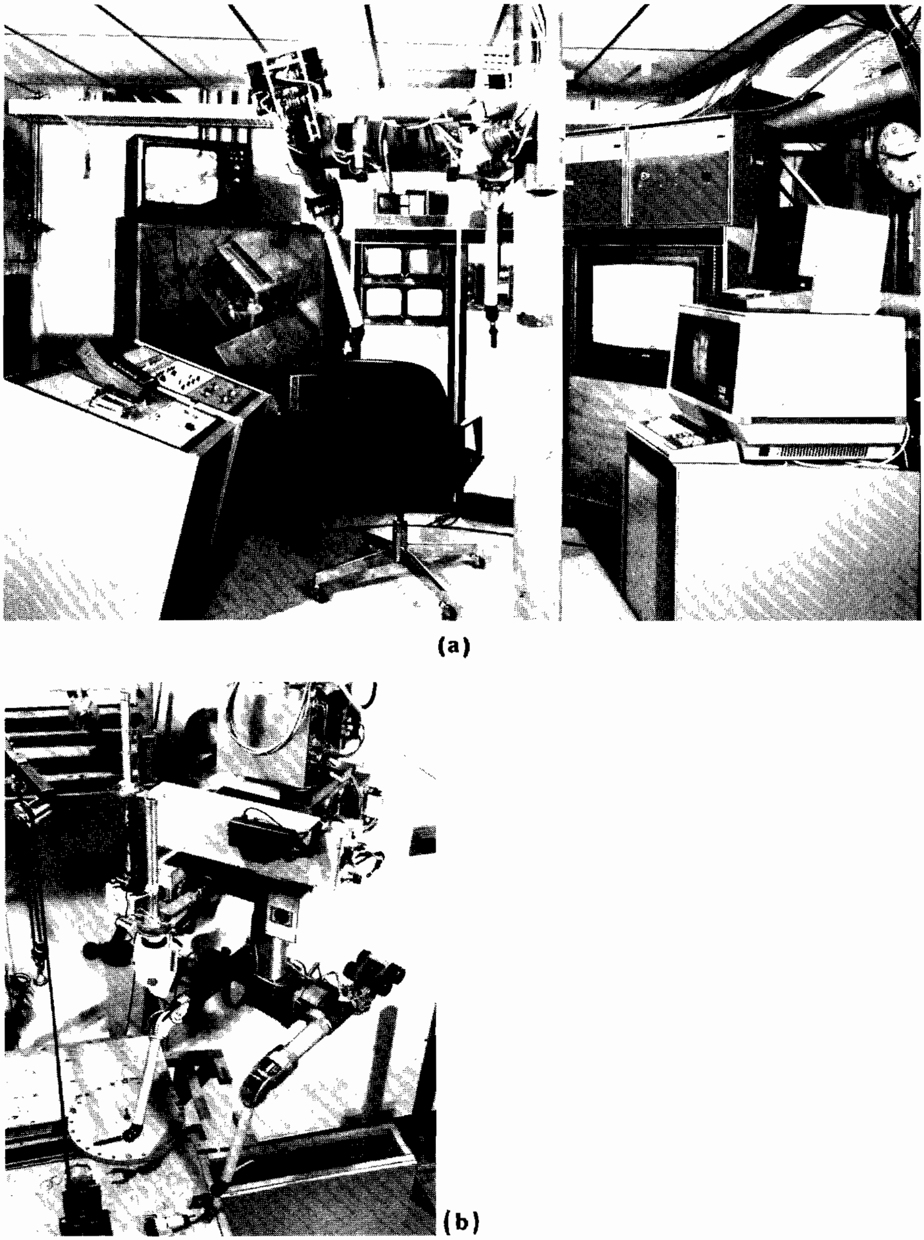
In the 1940s, the war spurred the greatest government-industry-university cooperation ever achieved, and the results were astounding. This period was one of the most technologically productive eras in our history. Inventions that came from this era include modern communications, radar, sonar, great advances in automobile, aircraft, and ship manufacturing, the computer, and the atomic bomb. Computers as we know them today evolved rapidly.

Between 1940 and 1942, an automatic sequence controller was built at Harvard University. From 1943 to 1948, ENIAC, the first electronic computer, was built at the University of Pennsylvania. It was hardly the neat, compact device we know today, but a collection of electronic hardware that filled an entire room, which made it rather impractical for many applications. The next major invention that followed solved this problem.

At about the same time the manipulator was invented, a major electronic invention was made. In 1948, the transistor was invented by Bardeen, Bratton, and Shockley at Bell Telephone Laboratories. In the same year, EDSAC, the first stored program computer, was developed at Cambridge University.

Since computing capability could now be built into machines, the combination of the intelligence capabilities of the computer and the mechanical capabilities of the machines intrigued some of our greatest scientists. Claude Shannon was such a scientist. In 1952, he developed a robot mouse that could "learn" and run a maze. Shannon and his creation are shown in Figure 2–6.

At the same time that IBM ushered in the beginning of the computer age with its IBM 701 computer in 1952, an electromechanical feedback device called the "servo" was patented by George Devol. Devol's patents were to become the technical basis for the formation of Unimation, Inc., the first major robot manufacturer. In 1956, numerically controlled machine tools were offered by Cincinnati Milacron. These machines were programmed off-line, and a punched paper tape contained the commands for the machine. When the tape was read back into the machine tool, the programmed actions were carried out. In 1959, Planet Corporation offered the first commercial industrial robot (Ayres and Miller, 1983, p. 21). It was a pick-and-place device controlled by limit switches and cams. In 1961, Unimation introduced the first servo-controlled industrial



(a)

(b)

Figure 2–5. Modern remote manipulator developed at the Oak Ridge National Laboratory for material reprocessing. (a) Master manipulator and control room, which contains a lightweight pair of master arms, large screen and stereo viewing, voice control, and control computers. (b) Slave manipulator located in a remote hot cell. The bridge, carriage, and hoist provide 3 degrees of mobility. Each of the two manipulator arms has 6 degrees of freedom. The stereo mounted cameras have pan, tilt, zoom, and focus under voice control. The large number of degrees of freedom (19) makes the system difficult for a human to operate. The time required to complete a task can be 100 times greater than that required by humans. (Courtesy of Oak Ridge National Laboratory, Oak Ridge, Tennessee.)

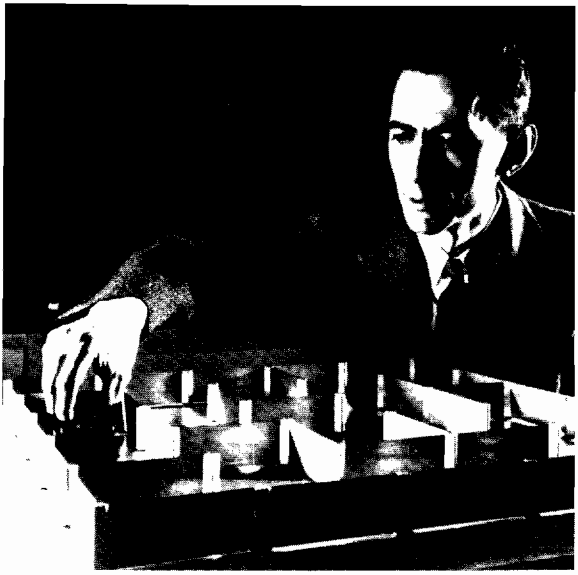


Figure 2–6. Claude Shannon is shown here with his robot mouse, which could navigate a maze of 25 squares in 15 seconds. The robot "learned" its way through the maze after a 2-minute trial-and-error run. (Courtesy of the Massachusetts Institute of Technology Museum, Cambridge, Massachusetts.)

robot, similar in design to the robot shown in Figure 2–7. In the same year, INTEL Corporation was formed by Gordon Moore and Robert Noyce, which was to develop and market the first microprocessor. During this same time, work in plastics and electronics led to the previously mentioned prostheses (Ayres and Miller, 1983, p. 16). At the Massachusetts Institute of Technology, H. A. Ernst (1961), as part of his doctoral studies, connected a teleoperator slave arm equipped with touch sensors to a computer at the Lincoln Laboratory. This early connection of a computer and manipulator helped pave the way for future industrial robots.

In 1963, the American Machine and Foundry Company (AMF) introduced the VERSATRAN commercial robot. Starting in this same year, various arm designs for manipulators were developed, such as the Roehampton arm and the Edinburgh arm.

Meanwhile, other countries (Japan, particularly) began to see the potential of industrial robots. As early as 1968, the Japanese company, Kawasaki Heavy Industries, negotiated a license from Unimation for its robots. Japan's enthusiasm for the robot has since been astronomical.

One of the more unusual developments in robots occurred in 1969, when an experimental walking truck was developed by General Electric Company for the U.S. Army. This device is shown in Figure 2–8. Its control proved to be a very difficult problem even for a human and encouraged more investigation into automatic control. The large number of degrees of freedom required in the four-legged devices was a

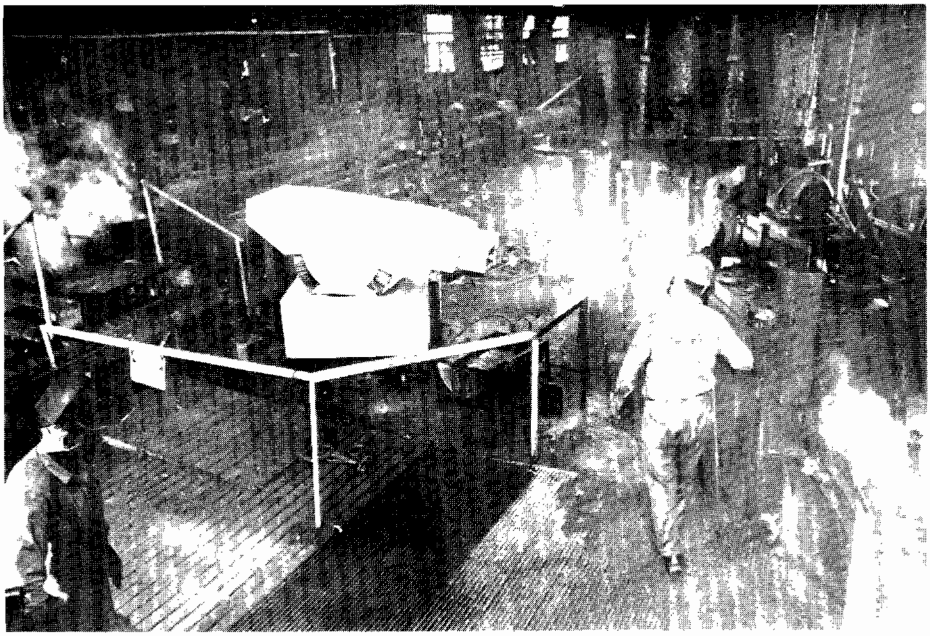


Figure 2–7. A Unimate robot similar to the first servo-controlled industrial robot, working in a hazardous industrial foundry application. This robot is unloading hot ingots from a furnace. (Courtesy of Joseph F. Engelberger.)

fundamental problem in control. In the same year, the Boston arm was developed, and the following year, the Stanford arm was developed, which was equipped with a camera and computer controller, and some of the most serious work in robotics began as these arms were used as robot manipulators. One experiment with the Stanford arm consisted of automatically stacking blocks according to various strategies. This was very sophisticated work for an automated robot at this time.

In 1970, the first national meeting for roboticists, the National Symposium on Industrial Robots, was held in the United States. In 1971, the Japan Industrial Robot Association was formed to foster the use of robots. In 1974, Cincinnati Milacron introduced the first computer-controlled industrial robot. Called "The Tomorrow Tool," or T3, it could lift over 100 pounds as well as track moving objects on an assembly line.

In 1975, the Robot Institute of America was formed from manufacturers and users of industrial robots. The British Robot Association was formed in 1977. In 1981, Robotics International of the Society of Manufacturing Engineers was formed as an individual member organization for those interested in robots, offering various certification and educational programs.

In barely 20 years, industrial robot installations in the United States went from zero to over 6000. Like the confluence of rivers, mechanical, electrical, and industrial technology combined to produce the modern industrial robot. As work in intelligent

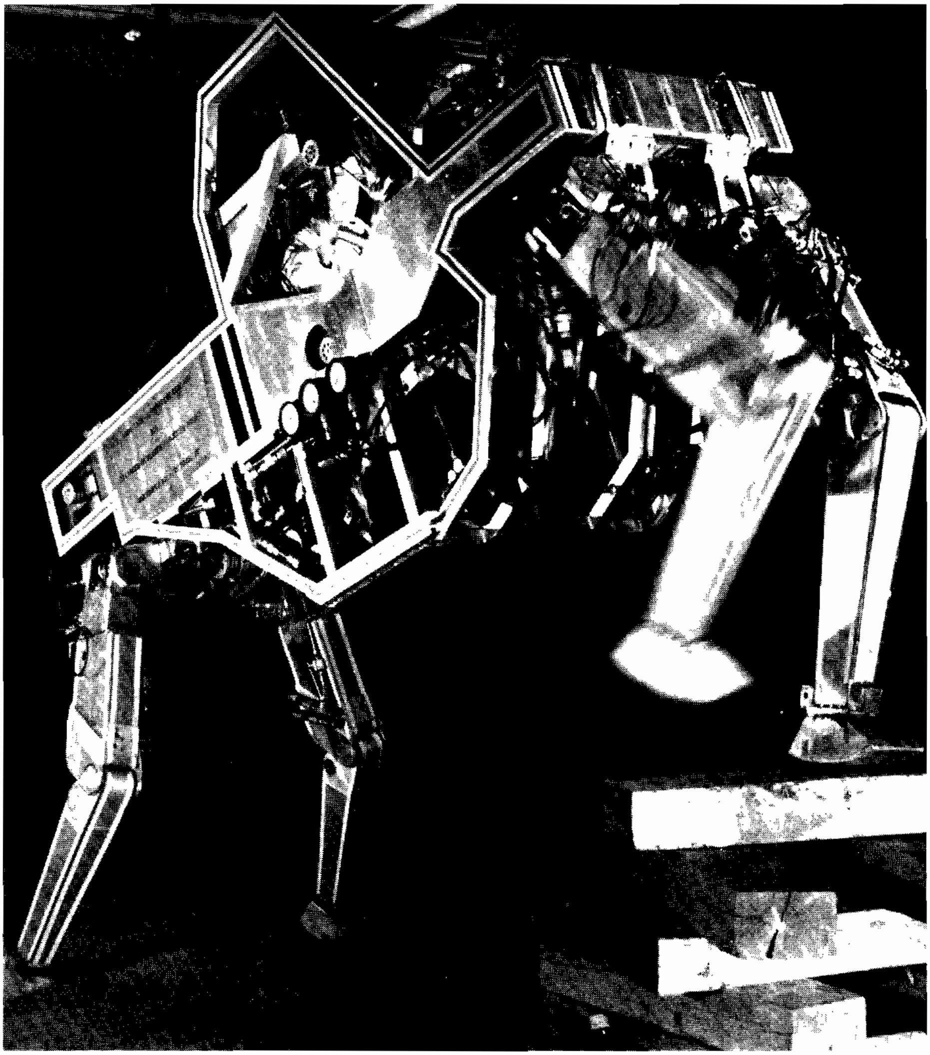


Figure 2–8. Research prototype of a four-legged quadruped machine, fabricated by General Electric Company engineers under a U.S. Army contract, was designed to spur development of equipment to improve the mobility and materials-handling capabilities of the foot soldier under the most severe conditions. By means of an advanced control system, the machine mimics and amplifies the linear movements of its operator. The right front leg of the unit is controlled by the operator's right arm, its left front leg by the operator's left arm, its right rear leg by the operator's right leg, and its left rear leg by the operator's left leg. The research prototype, 11 feet high and 3000 pounds in weight, was built by the GE Specialty Materials Handling Products Operation under a project sponsored jointly by the Advanced Research Projects Agency, Department of Defense, and the Department of the Army. The U.S. Army Tank-Automotive Command has acted as the contracting agency and has provided technical supervision of the project. The walking remote manipulator proved to be a difficult machine to control because of the large number of degrees of freedom required by the human operator. (Courtesy of General Electric Company, Bridgeport, Connecticut.)

robots makes these machines evermore versatile and capable, it is possible that robot installations could increase very rapidly in the coming years. Robotics has advanced from science fiction to reality in an amazingly short time. It is not hard to project that future robotics developments will exceed anything that has yet been anticipated, especially in the area of intelligent robots. Computers are becoming smaller, smarter, and cheaper every year. Thus, robots are also to become smaller, smarter, and cheaper as time goes on. New advances in electronics, computers, controls, and power systems will have significance for robot designers. There appears to be no limit to the mechanical applications of specialized robots. Perhaps the robot will rank with the clock someday in changing the way we perceive our world.

Chronology of Events in the History of Industrial Robots

Time	Technology
3000 B.C.	Egyptian water clocks and figures.
500 B.C.	Herodotus describes the wooden foot of Hegesistratus.
218 B.C.	Roman general Marcus Sergius has an iron replacement made for his severed hand.
1400s	Swiss and German android clocks developed.
1500–1700	**Scientific revolution**
1509	Götz von Berlichingen's iron hand is made with gearing for manipulating mechanical fingers and thumb.
1720	Bouchon and Falcon in Lyons, France, design looms for weaving patterns into silk.
1750–1850	**Industrial Revolution**
1770	Android automatons reach their peak.
1800	Metal lathe invented by Henry Maudslay.
1805	Joseph Marie Jacquard invents an automatic loom with punched card control.
1818	Milling machine invented by Eli Whitney.
1823	Construction of Charles Babbage's difference engine for calculating mathematical tables for navigation is begun.
1892	Motorized rotary crane with gripper for removing ingots invented by Steward Babbitt (U.S. Patent 484,870).
1930s	Spray-painting machines with recorded paths invented.
1940	**Government-industry-university cooperation**
1940–1942	Automatic sequence controller developed at Harvard.
1943–1948	ENIAC, the first electronic computer, developed at the University of Pennsylvania.
1944	Master-slave manipulator invented by Goertz (U.S. Patent 2,695,715, 1954).
1946	Electromechanical feedback manipulator invented by George Devol (U.S. Patent 2,590,091, 1952).
1948	Transistor invented by Bardeen, Bratton, and Shockley at Bell Laboratories.
1949	EDSAC, the first stored program computer, developed at Cambridge University.
	Force feedback added to remote manipulators.
1952	IBM's first commercial computer, the IBM 701, is marketed.

Chronology of Events in the History of Industrial Robots (continued)

Time	Technology
1956	Numerical control machine tool introduced by Cincinnati Milacron.
1959	First commercial robot is introduced by Planet, a pick-and-place device controlled by limit switches and cams.
1961	Unimation introduces the first servo-controlled industrial robot (Devol, U.S. Patent 2,988, 237).
	INTEL is formed by Gordon Moore and Robert Noyce.
	Collins prosthetic hand developed.
	Ernst arm, a teleoperator slave arm equipped with touch sensors, is connected to a computer at MIT's Lincoln Laboratory.
1963	AMF's VERSATRAN commercial robot introduced. American Machine and Foundry Versatile Transfer developed (Prab).
1963–1976	Roehampton arm developed.
	Edinburgh arm developed.
1968	Kawasaki Heavy Industries negotiates license from Unimation.
1969	Experimental walking truck is developed by General Electric for the U.S. Army.
	Boston arm developed.
1970	Stanford arm, with arm, camera, and computer connected that could stack colored blocks.
	First National Symposium on Industrial Robots.
1971	Japan Industrial Robot Association formed.
1974	Cincinnati Milacron introduces the T3, the first computer-controlled industrial robot, which could track objects on a moving conveyor.
1974	ASEA introduced electric drive industrial robot.
1975	Robot Institute of America formed.
1976	Viking II lands on Mars.
1977	British Robot Association formed.
1980	Fujitsu Fanuc Company of Japan develops automated factory.
	MAZAK flexible manufacturing factory is built in Florence, Kentucky.
1981	Robotics International/SME formed.
1982	First educational robots introduced by Microbot and Rhino.

Questions

1. What is a universal machine?
2. What was the main precursor of the modern industrial robot?
3. When was the first industrial robot offered commercially?
4. What is a teleoperator?
5. What are some of the problems roboticists face in robot control, and how do you think they might be overcome?