INDUSTRIAL ROBOTS

Czech playwright Karel Čapek coined the word *robot* (Czech for worker) in his 1922 play *Rossum's Universal Robots.* Science fiction writer Isaac Asimov used the word *robotics* in 1940. Almost a generation later, fiction had become reality. George C. Devol was awarded patent number 2,988,237 in 1961 for a programmable manipulator. A wide range of other patents followed, and these innovations collectively dictated and laid the foundation in establishing the fundamental principles for the modern-day industrial robot. By 1956, Unimation Inc. had been founded and incorporated by George Devol and Joseph Engelberger. Unimation is currently owned by a Swiss company and is now called Stäubli Unimation Ltd. An example of packaging and palletizing with a Stäubli Unimation robot is shown in Fig. 1.

Devol and Engelberger had made dozens of trips to automotive assembly plants and other diverse industrial establishments to conduct a detailed study for the implementation of robots in certain carefully selected manufacturing operations. They observed that there was a high percentage of wait time for an average part in a typical batch manufacturing shop. Metal-cutting machines were in operation only 25% of the time. The remaining 75% of the time was dedicated to machine setup, positioning, tool changing, gauging, loading (and unloading), wait time, and repair. Productive use of capital equipment was less than 10% in an entire year. Weekends, holidays, vacation time, incomplete second and third shifts, idle time, gauge setup, loading, and unloading accounted for the remaining 90%. There was an obvious need for some appropriate new technology.

Nonetheless, these data did not convince the US manufacturing industry to quickly accept the concept of robots. The Japanese, however, were excited and enthusiastic about the revolutionary concept and the new technology. They began showing great interest in Unimation's ideas and visited their facilities in the US. In 1967, the Japanese invited Engelberger to address 700 manufacturing engineering executives in Tokyo. The very next year Kawasaki Heavy Industries obtained a license for all of Unimation's technology. In 1971, the Japan Industrial Robot Association (JIRA) was formed. The rest of the world caught up after them, and, in 1975, the Robot Institute of America (RIA) was founded.

Robots designed for industrial applications today need to be very precise and accurate. Total quality management has been the slogan of the industry in recent years, and there is no doubt that robots have played a dominant role in producing high-quality products during the past three decades. It is widely acknowledged that the installation of an industrial robot should result in increased productivity, improved quality, minimized waste, and reduced costs. These robots must offer repeatable, consistent performance over long operating hours. However, it should be observed that many industrial robots are not exceptionally fast. In some cases, they may be a bit slower than their human counterparts. Regardless, a well-engineered industrial robot provides mistake-proof performance, whereas human beings can become prone to errors as a result of fatigue and carelessness. Industrial robotics has grown quickly since the late 1960s and is a multibillion-dollar business that supports hundreds of other ancillary industries worldwide. More than 200,000 industrial robots are estimated to be operational just in North American factories. The population of robots is constantly growing because robot applications have moved away from the traditional factory floor and have ventured into exploring new horizons such as space exploration, movies, and medicine.

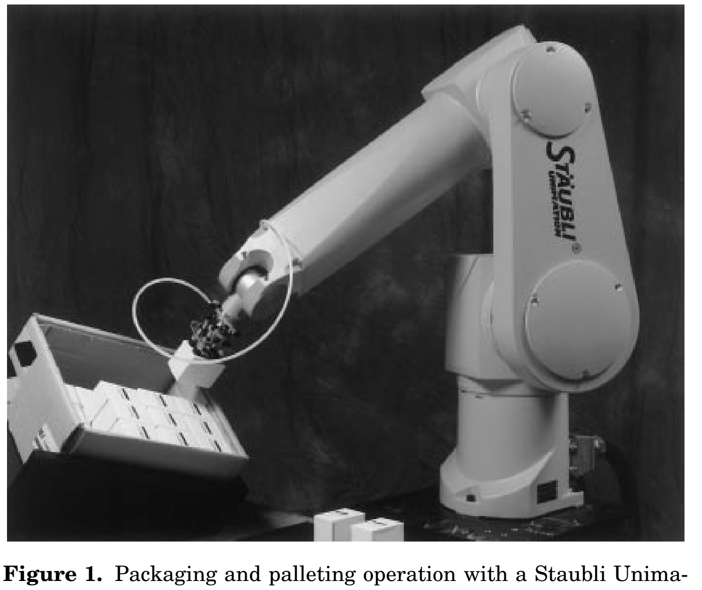

Figure 1. Packaging and palleting operation with a Staubli Unimation robot. Courtesy of Staubli Corporation, Duncan, SC.

Robotics is destined to be one of the most important industries of the next century. Robots are almost indispensable in the automotive industry. Only robots can offer the most economical solution for certain jobs and processes such as high-quality spot welding. Today, modern industrial robots are handling more sophisticated tasks such as arc welding of automotive components. Figure 2 shows an automotive component being arc-welded by the Fanuc Robotics ARC Mate 100 welding robot. It is almost impossible for human beings to perform precision welding or soldering operations demanded by the present-day electronics industry, which specializes in microminiaturization. Ergonomic problems have been eliminated by the successful implementation of robots in certain assembly operations. The industrial robot aims to increase productivity by reducing the waiting and idle time on machining centers. These "steel-collar" workers can handle a crucible of molten metal from a hot furnace. In addition, industrial robots consistently provide accurate, precise, reliable, and repeatable performance under dusty atmospheric conditions, greasy surroundings, and dangerous and hostile environments with poor temperature regulation.

The operation of an industrial robot can be studied by dividing the robot into four major component-oriented subsystems. These four subsystems are designed to accomplish different tasks. They all communicate with each other to yield an impressive final result.

THE MANIPULATOR

The manipulator is the arm of the industrial robot. This device helps the robot to pick and place objects. It must be appropriately designed to accommodate end-of-arm tooling and handle designed payload requirements. A robot manipulator can be viewed as an assembly of links and joints. The joints may provide linear or rotational movement between two solid links. All robots have a base. The base may be horizontal for a floor-mounted robot or suspended for an overhead gantry robot. The base is considered to be vertical for a wall-mounted robot. A solid manipulator link connected to the base via a joint provides the robot with a certain designated type of motion. This is called a degree of freedom. Additional manipulator links are then added to this first link by means of new and different joints. Each additional joint provides the robot with additional degrees of freedom. Typically, a robot possesses six degrees of freedom. Three of these six degrees of freedom are usually concentrated at the wrist of the robot.

THE POWER SYSTEM

The power system provides the necessary hydraulic, pneumatic, or electric power needed by the driving mechanisms, the manipulator, and the end effector through the control system using a preprogrammed motion routine.

Hydraulic Systems

Industry has been using hydraulic systems for many years. They use a fluid such as oil to transmit energy and supply power to the robots. Hydraulic systems can lift and move large loads with seemingly little effort. Hydraulic systems are used in both servo and nonservo robots. These are simple systems compared with more complicated mechanical contrivances such as cranks, camshafts, levers, gears, rods, and linkages. In an environment where electric arcs and sparks are unacceptable, hydraulic systems perform very well and offer an alternative solution. However, they suffer from the fact

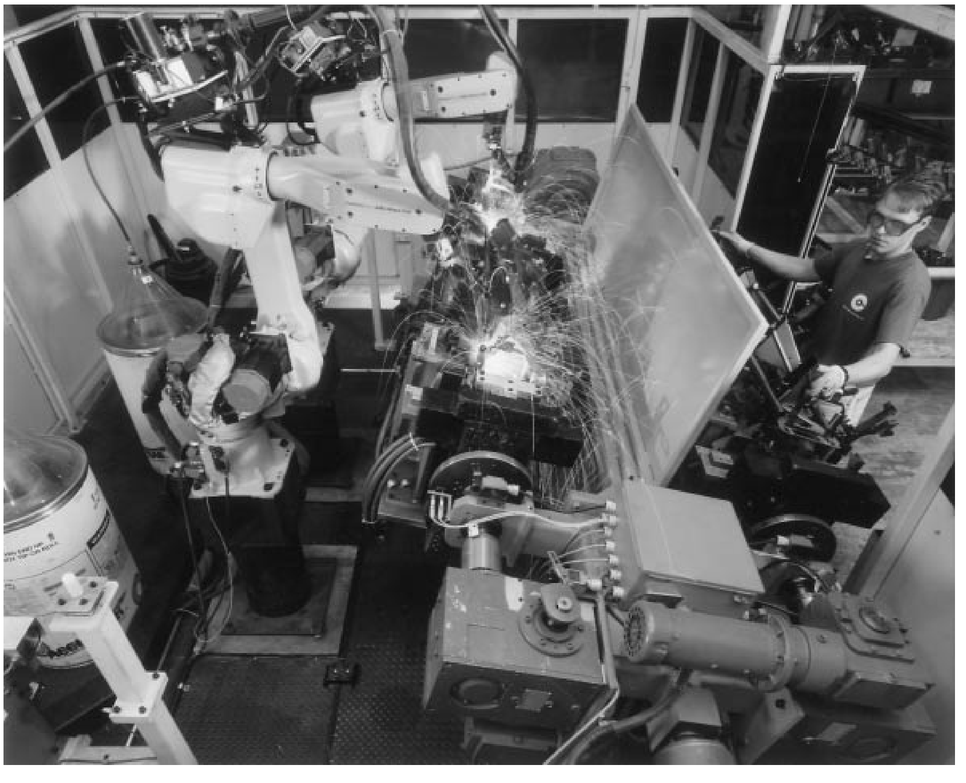

Figure 2. Arc welding of automotive components with Fanuc Robotics ARC Mate F100 Robot. Courtesy of Fanuc Robotics.

that the company has to maintain separate hydraulic pumps and oil storage facilities. They also suffer from uncleanliness and leakage problems that need frequent attention and appropriate maintenance.

Pneumatic Systems

When compressed gas, instead of oil, is used to power the robots, such robots are called pneumatically powered (*pneuma* means breath in Greek). Pneumatic systems are similar to hydraulic systems because a gas is also a fluid. Most industries maintain a supply of compressed air; as a result, separate installation and maintenance problems are eliminated. In some cases, the capacity of the system may need to be increased. Hydraulic fluid compresses very little; however, the compressibility of gas acts as a natural shock absorber. Fluctuations in load are easily accommodated because the air in the system will compress like a spring, thereby absorbing and dampening out fluctuations and vibrations.

Electric Systems

Electrically powered robots are gaining in popularity because of their simplicity and ease of accessibility. Both hydraulic and pneumatic systems require plumbing and storage of fluids under pressure. They are prone to leaks and require constant attention and repeated maintenance. Previously, robot electric motors could not handle heavy loads, but recent advances in computer technology, servo motors, and stepper motors have paved the way for the successful deployment of electrically driven robots in a wide variety of industrial settings.

THE CONTROL SYSTEM

The control system may consist of computer memory, detectors, and sensors, all of which provide feedback information that dictates the precise movement of the manipulator and the end effector. Computer control has permitted robots to perform more precise industrial operations such as seam welding, spray painting, and precision assembly. The robots are simply programmed to perform a series of repetitive tasks; they cannot sense their external environmental surroundings. Ideally, any interference with the preprogrammed task should result in the robot's overcoming the obstacle and "thinking" its way out of the problem situation. Therefore, for robots to become more efficient, maintenance-free, and productive, they must be able to sense external conditions and think very much like an operator. The application of artificial intelligence and sensory perception can provide industrial robots with such capabilities.

END-OF-ARM TOOLING

End-of-arm tooling consists of a "wrist" and an "end effector." This setup actually serves as the interface between the robot and the particular manufacturing operation in question. It could be a simple gripper mechanism that can grasp objects to be transported and placed in a different location or a dispensing mechanism that can be used to apply melt (special chemical or thermoplastic adhesive dispensed at elevated temperatures). It could also be a vacuum suction cup that picks up an automobile windshield, a welding torch holder, a sealing applicator that is specifically designed to seal the back panels of refrigerators, or a very sophisticated sensor-equipped five-fingered dexterous "hand."

RECENT FEATURES

Robotic Vision Systems

Often considered adjunct to robotics, vision systems in conjunction with artificial intelligence have enabled robots to "see." The addition of a camera helps in a variety of applications such as robotic guidance and inspection and quality control. There are three components to a vision system: the sensor, the data converter, and the vision processor. First, an appropriate technique must be developed to capture the image reliably within the limits of a specified accuracy. Appropriate lighting, well-designed optics, and precise sensors are needed. A matrix camera may capture light reflected off an image and transfer it to a matrix of light-sensitive elements called pixels. For example, a matrix of 512×512 pixels can capture the image of a printed circuit board ready for electronic assembly. In contrast, a line camera is used for objects that need only to be scanned. The line camera provides only one line of pixels (e.g., 1024 pixels long). The images arriving from the camera may be in the gray-scale, binary, or color forms. Color systems, however, require multiple cameras to acquire the red, yellow, and blue portions of the image.

Tremendous progress has been made during the past decades, and vision systems have contributed significantly to part identification and recognition, accuracy gauging, process verification, inspection, and quality control. For example, a simple robotic vision system can inspect a bolt to determine whether the threading operation has been completed. Vision may help robots with information regarding the current position of an object that needs to be grasped and delivered to an assembly operation. In an inspection system, the camera mounted on the robot may be programmed to look for a desired feature or an undesired feature on a particular part, the robotic manipulator can then be directed to accept or reject the part. Vision systems in food packaging and processing can inspect apples, for example, and reject the bruised apples. X-ray vision systems have helped to detect blowholes and hairline cracks in huge castings. Robotic vision systems have increased the speed of inspection and have yielded inspection consistency. In many cases, every part (instead of only a selected sample) can be inspected for a variety of features. Lasers have been used successfully to provide information about part contours. Optimized stereo techniques and multiple cameras have been developed by GMF Robotics to locate a particular body in three-dimensional space.

Vision is a powerful and complicated sense, and a general-purpose robotic vision system may be impossible to achieve. However, modern-day scientists have been fortunate to have more powerful computers and higher-resolution pictures to help them ease their task. High-speed computers and the judicious use of mathematical modeling can help designers test industrial robots in a virtual-reality environment. For the Mars Pathfinder Robotic Rover Project, the NASA Ames Research Center built a virtual robot that linked in real time to an actual robot. This system was created with SENSE8 Corporation's World Toolkit (Fig. 3).

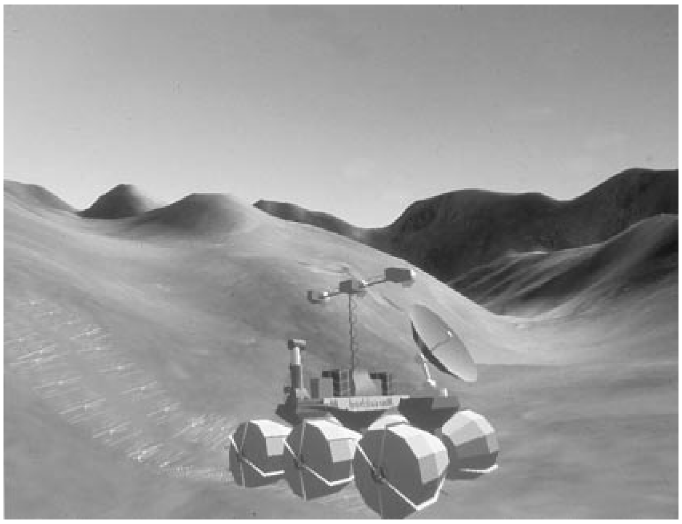

Figure 3. For the Mars Rover project, NASA Ames Research Center built a virtual robot that links in real-time to an actual robot. Courtesy of SENSE8 Corporation.

Artificial Intelligence and Expert Systems

Artificial intelligence (AI) deals with developing machines that are capable of imitating human reasoning. For example, they may be able to diagnose a particular fault and impose correcting actions to alleviate the problem (Fig. 4). They can sense and receive information from their surroundings and respond appropriately. Robots equipped with vision systems, tactile (touch) sensing systems, voice activation systems, and range-finding and navigation systems can perform tasks that require intelligent decision-making. Many industries have successfully developed such intelligent robots; for example, robotic hands as dexterous as a five-fingered human hand have been successfully developed using tactile sensing devices. They can hold a delicate object such as an egg without crushing it.

Corporations, research laboratories, and universities have developed systems that can diagnose infectious diseases, recognize human speech, conduct chemical analyses, and help in the exploration of minerals, oil, and natural gas, among other activities. The 21st century will see tremendous strides in the rapid development of AI, and industrial robots can exploit this new technology for creating a safer and more productive workplace for human beings.

ROBOT APPLICATIONS

Robots have revolutionized modern-day manufacturing processes in two major areas. Robots need to relieve human beings from carrying out monotonous and repetitive jobs as well as hazardous jobs.

Repetitive Jobs

The industry uses robot technology to a large extent in eliminating repetitive jobs. Several traditional, routine manufacturing operations require a human being to behave more like a machine. Some of these jobs require little skill; however, the task must be completed as a part of a structured manufacturing process. An example may be picking up a relatively heavy finished product and placing it in a box to prepare it for shipping. Several operators may be required to accomplish this task, wasting human intelligence, skill, and judgment. An industrial robot can successfully replace these operators, allowing the human beings to be reassigned to more creative jobs. Industrial robots perform value-added jobs as well as non-value-added jobs. For example, a robot may be deployed to retrieve a finished product from a belt conveyor and place it on a truck bed or a pallet. In fact, palletizing is an area

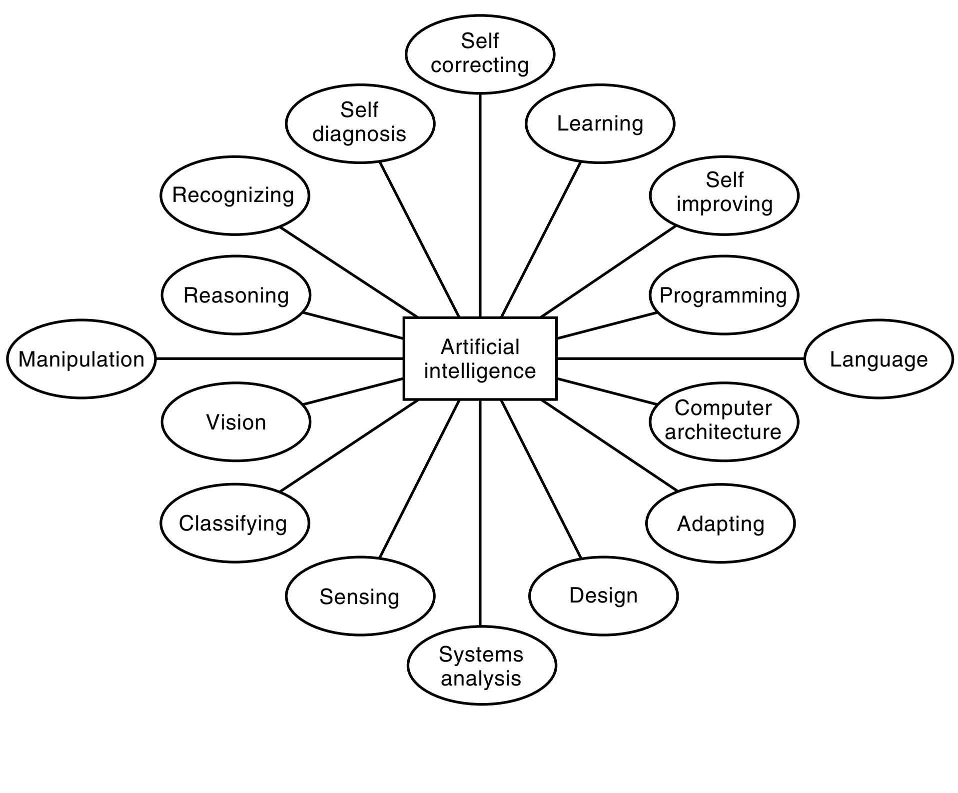

Figure 4. Artificial intelligence attempts to replicate the actions of the human brain.

Figure 5. Robotic case palletizing of frozen meat patties with an M-400 robot from Fanuc Robotics. Courtesy of Fanuc Robotics.

where industrial robots have made a significant impact on the manufacturing and process industries. Figure 5 shows robotic case palletizing with an M-400 robot from Fanuc Robotics.

Hazardous Jobs

Industrial robots have also relieved humans from dangerous jobs. Implementation of robotics has become almost indispensable in certain industrial situations that pose adverse conditions. Examples include but are not limited to the following:

1. The handling of radioactive wastes, corrosive chemicals, caustic substances, concentrated acids, or toxic material.
2. Functioning in dangerous temperature conditions.
3. Transporting or processing excessively heavy materials.
4. Spray painting applications that emit dangerous fumes.
5. Greasy surroundings that cause slippery conditions.
6. Functioning in a dusty atmosphere that can cause respiratory problems.
7. Heavily vibrating high-speed rotating machinery that may pose a deadly situation.
8. Deep-sea exploration.
9. Outer space planetary exploration.
10. Fire-prone environmental conditions or potentially explosive situations.

Early robots were simple mechanical devices with cams and limit switches that performed simple pick-and place operations. Recent advances in the area of microprocessors and computer technology have revolutionized the way industrial robots are being deployed. Feedback control systems incorporated into the robots have enabled sophisticated precision assembly operations. Widespread usage of robots for spot welding and arc welding applications gained popularity during the late 1960s and the early 1970s. Figure 6 shows an example of robotic arc welding using an ARC Mate 120 Fanuc robot.

Custom-built automated machines may try to copy the operations of a robot. A specially designed machine can carry out, for example, machine loading and unloading operations. However, it is very important to recognize that an industrial robot is not simply another automated machine. An automated machine is designed to perform and carry out a specific job repetitively, with an acceptable accuracy and precision. A robot, on the contrary, can perform a variety of jobs. The job description for the robot can be changed just by reprogramming its control systems. However, in industry, most robots are dedicated to perform a specific operation. It is very unlikely that a spot welding robot will be removed from service, reprogrammed, and reinstalled in a precision assembly operation.

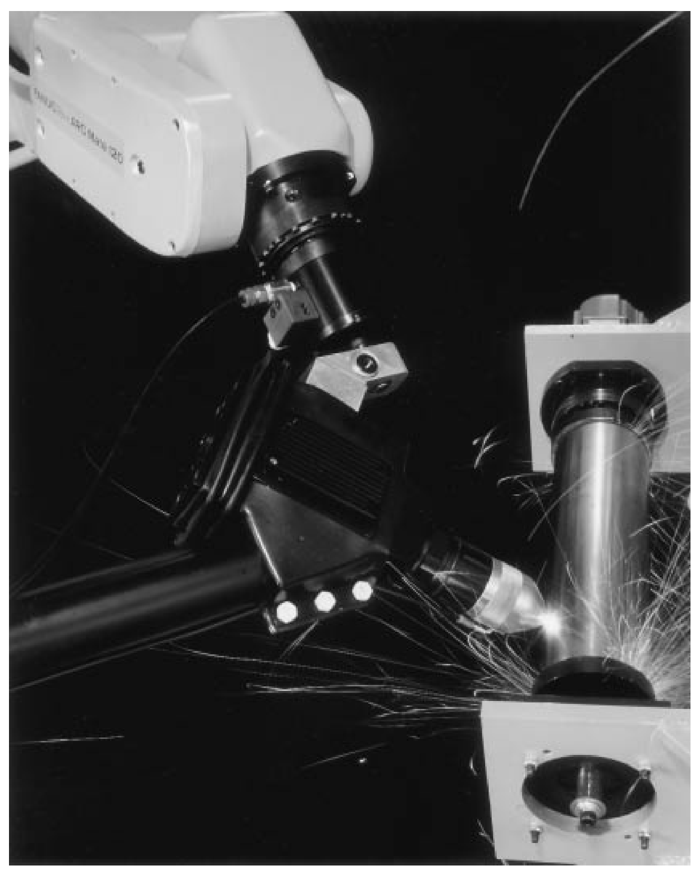

Figure 6. Robotic arc welding with ARC Mate 120. Courtesy of Fanuc Robotics.

Payload is an important indication of the carrying capacity of the robot. Payload is calculated based on the weight, moment, and inertial load the robot can handle with good accuracy and repeatability. Most industrial robots handle relatively heavy loads, the maximum being as high as 200 kg (500 lb). Therefore, many of these large robots are floor/pedestal mounted and firmly secured to the shop floor using foundation bolts. Some robots used in industry are of the overhead or gantry type. These gantry robots are extremely useful when heavy objects must be transported over long distances covering the length and breadth of the factory floor, and they conserve valuable factory floor space.

Cost is a very important factor that drives the use of robotic technologies. However, decisions to automate are based on other factors as well. These may include minimized waste, improved precision, consistent quality, greater accuracies, streamlined inventory control, and faster delivery times.

Many industrial robots are stationary, and work is normally brought to them. Overhead gantry robots add mobility to these machines and facilitate easy transportation. Some special-purpose needs in industry demand a different kind of mobility. This unique requirement posed an interesting as well as a challenging problem to Odetics of Anaheim, California. It pioneered "walking" robots that could work in locations inaccessible to conventional wheeled or tracked vehicles. Figure 7 shows the Odetics pioneer robot Odex I, which was designed to work in hazardous environments. This 168 kg (370 lb) robot "walks" on six legs and is maneuvered using a remote joystick control unit. Introduced in 1983, the robot can negotiate stairs and uneven terrain without previous knowledge of those surroundings. It uses video cameras for transmitting imagery to a remote human operator. The power and strength of this unique walking machine is demonstrated in Fig. 8. Odex I can lift the back end of a 1000 kg (2200 lb) truck and walk across the floor. It can also climb in and out of the truck's bed with ease.

Figure 7. Odex I, Odetics' first walking robot. Courtesy of Odetics, Inc., Anaheim, CA.

Figure 8. Odex I demonstrates its strength by lifting the back end of a 1000 kg (2200 lb) truck and walking across the floor. Courtesy of Odetics, Inc., Anaheim, CA.

Definition of Application

The motion control mechanism repeatedly employed by the industrial robot defines the purpose and application of the robot.

Pick and Place. Pick-and-place robots are an excellent choice for basic materials-handling jobs. They are the simplest and the least expensive compared with the other three varieties. Their mean time between failure (MTBF) is very large, and as such they operate for a very long time with repeatable accuracies. A robot manufacturer may specify MTBF as 50 months to indicate that its equipment operates with substantial reliability. In other words, the robot should be able to provide trouble-free service and operation without a breakdown for as long as 50 months. The maintenance of these robots is relatively easy, and the operator hardly needs any special skill or training. These non-servo robots operate between two end points. Therefore, they cannot perform even slightly sophisticated materials-handling task such as palletizing or depalletizing.

Point to Point. These servo-controlled robots are the most common of all the industrial robots. They are very versatile and can be programmed and "taught" to move between any two chosen points within their work envelope. This is normally accomplished by pushing appropriate buttons on a "teach pendant," which resembles the control box of an overhead crane and will contain simple instructions such as up, down, left, right, clockwise, counterclockwise, step forward, and step backward. The operator uses these commands to accomplish a given task. In many cases, this movement of the robotic gripper and arm may take place in an unpredictable and arbitrary fashion developed by the control mechanism algorithm, and this need not be a straight line. Applications

Figure 9. Odex II, A walking robot that can support up to (50 lb). Courtesy of Odetics, Inc., Anaheim, CA.

include spot welding, assembly, grinding, inspection, and palletizing and depalletizing.

Controlled Path. In most cases, the exact trajectory followed by the robot manipulator cannot be predicted easily. The path followed may be of no importance at all in certain materials-handling operations. However, in certain specialized assembly operations, rectilinear operation of the end effector may prove to be very precise and essential. This is a special case of a point-to-point robot in which the robot end effector always follows a straight line path between the two taught points. Precision assembly operations, which require perfect collinear and straight-line orientations, use a controlled path robot. Other applications include arc welding, drilling through solid steel blocks, hole-boring operations in heavy metal castings, and uniform polishing operations.

Continuous Path. In this application, the robot can be programmed to follow any desired path. The operator grabs the manipulator arm of the robot and "shows" or "leads" the robot to "follow" a particular trajectory. The microprocessor and memory modules of the robot control systems "remember" this path and execute the shown path repeatedly with very good accuracy. The robot remembers not only the exact path but also the speed of movement of the end effector and the manipulator arm. This robot can be viewed as a highly sophisticated type of point-to-point robot and can be used for a variety of industrial applications. The microprocessor control mechanism examines the desired path, digitizes it, and breaks it down to several thousands of digitized data locations (depending upon the resolution). This is stored in its memory for playback at a later time, on demand.

Specialized Applications

Walking robots that can support up to 23 kg (50 lb) have been successfully developed by Odetics of Anaheim, CA. Figure 9 shows Odex II, a walking robotic manipulator assembly, complete with several cameras and grippers that can reach anywhere around its platform and extend to a length of more than 1.5 m (5 ft). This incorporates full-force reflection feedback in the articulator leg assemblies for use on soft or giving surfaces.

Some robot manufacturers specialize in robotic equipment that is not found on the factory floor. These specialized machines may be delivering mail in an office. They are sometimes called robot carts or automated guided vehicles (AGV). They travel through the office on a set path. The robot is guided by a visible or an invisible trail on the floor. Automatic storage and retrieval systems use robotic technologies and have helped in inventory management. Robot submarines can help in underwater searches for lost ships and treasure, deto-

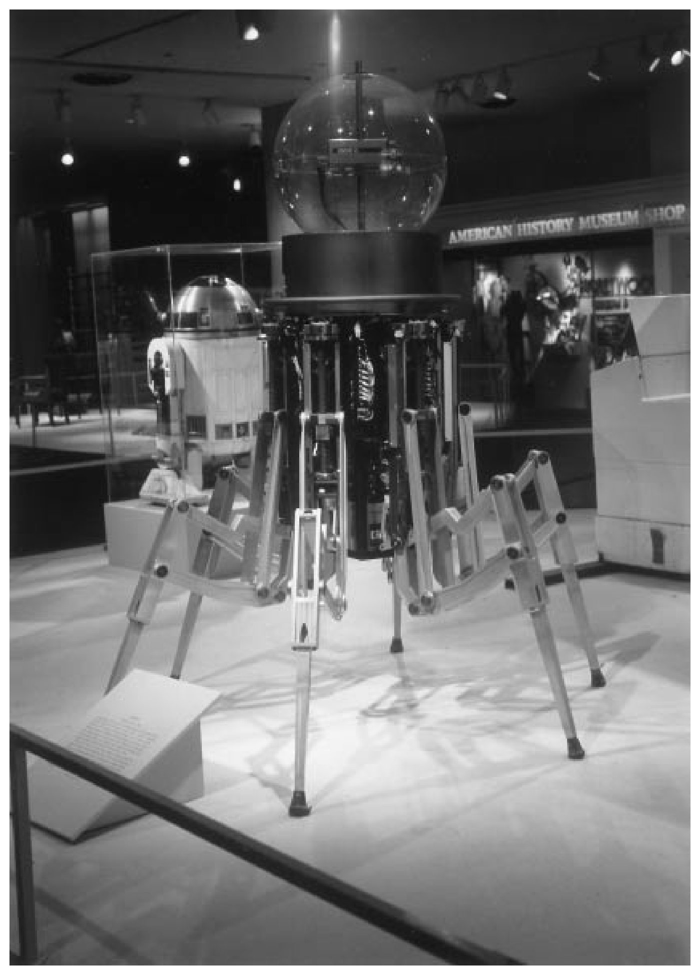

Figure 10. Odex I, Odetics' first walking robot, is part of the Smithsonian Institution's permanent collection of technological artifacts. Courtesy of Odetics, Inc., Anaheim, CA.

Figure 11. The TCS 90 Library management machine. Courtesy of Odetics Broadcast.

nate unexploded bombs, carry out mining operations on the ocean floor, and explore for natural resources such as oil and gas. NASA's lunar orbiters were robot photographers of the 1960s. Lunar surveyors were robot spacecraft that landed on moon before humans. The Mars Pathfinder mission successfully exploited the capabilities of *Sojourner,* which included a six-wheeled robotic car. Two decades before the *Sojourner* were the Viking Landers that had touched down on Mars. These robots took photographs, studied the weather, and examined the soil on the Red Planet in 1976.

Robots have been popular characters in science fiction stories and movies for a long time, and the movie *Star Wars* made R2-D2 and C-3PO household names. In contrast to

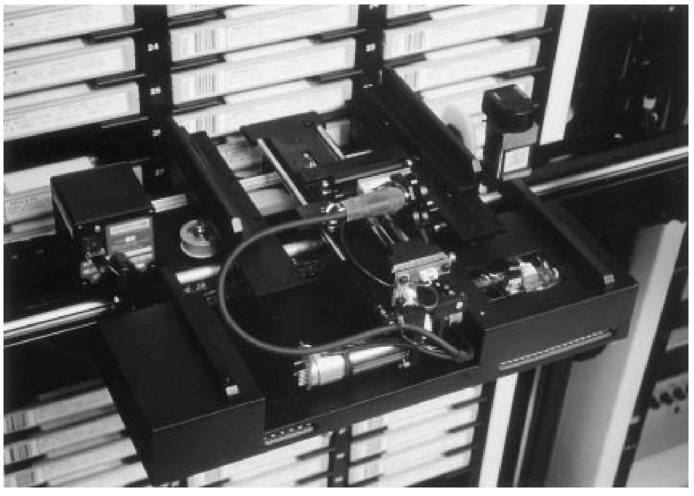

Figure 12. A close-up view of the robotic arm. Courtesy of Odetics Broadcast.

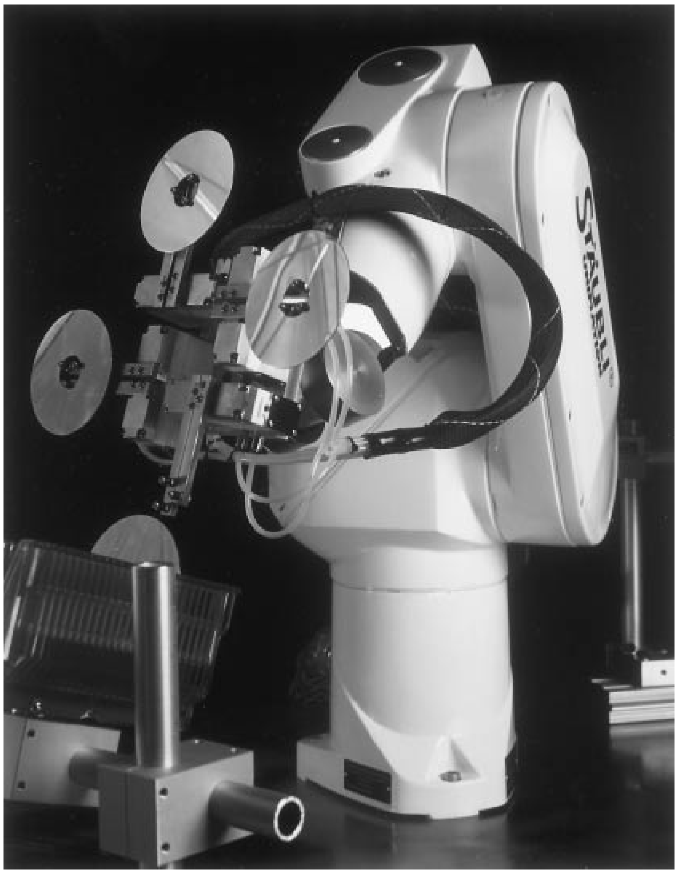

Figure 13. Wafer handling in a clean room. Courtesy of Stäubli Corporation, Duncan, SC.

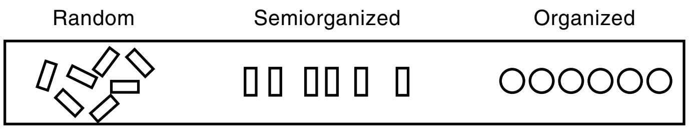

Figure 14. Sophisticated vision systems, such as the Adeptmotion servo system, incorporate industry standard motion and vision packages to control and guide flexible robotic machines. Courtesy of Technistar Corporation, Longmont, CO.

these fictitious robots, some real-world robots have incorporated revolutionary ideas. The walking robot that can climb stairs on six legs is an example. Such robots have attained historical fame and have become a part of the Smithsonian Institution's permanent collection of technological artifacts. Figure 10 shows Odex I at the Smithsonian Institution in Washington DC (R2-D2 can also be seen in the background).

Broadcast television industry widely uses robotic data cartridge handling systems. The TCS 90 Cart Machine, shown in Fig. 11, is a library management machine manufactured by Odetics Broadcast. The TCS 90 automatically stores, retrieves, and televises commercials news spots and other programs. A close-up view of this type of automatic storage retrieval system is shown in Fig. 12. This specific video cart machine uses a robotic data cartridge handling system that acts like an arm of a robot and automatically switches videocassettes during on-air television broadcast.

Robotics makers are exploring numerous areas where automation may have great impact. For example, integrated circuit manufacture requires specially designed clean rooms. Industrial robots have had a major influence in this area. Figure 13 shows a Stäubli Unimation robot in a clean room application, that of wafer handling.

Gasoline dispensing, garbage collection, household vacuuming, fast-food preparation, household cleaning, and hospital support are some of the applications robotics is ready to explore in the 21st century. Many major corporations in the food and beverage industry, such as General Mills, Nabisco, and Kraft Foods, are planning to invest heavily in robotics-based automation. Specially designed suction-cup gripper mechanisms can transfer prepackaged bakery goods from a conveyor for case loading. High-speed robotic pick-and-place packaging machines, such as the Galileo, developed by TechniStar Corporation, can transfer as many as five hundred items per minute. These machines have been praised as a breakthrough solution for higher production and cost efficiency in final product packaging. Galileo uses TechniStar's patented Dynamic Acquisition and Placement (DAP) technology. The creation of a DAP work cell is ideal for applications involving items on a moving conveyor belt that have random position and orientation (Fig. 14). The system uses high-speed AdeptOne or AdeptThree SCARA robots in conjunction with the Adept XGS-II High-Resolution (509 × 481 pixels) Vision System along with an MC 68020 vision processor. This flexible robotic machine can pick products randomly positioned and oriented from a continuously moving flat-belt in-feed conveyor and place them into cartons, trays, or an in-feed/outfeed conveyor. Figure 15 shows a robotic packaging system, designed by TechniStar Corporation of Longmont, CO, that can pick up a dozen loaves of bread at a time from a conveyor for case loading. Robot-guided water-jet cutting (also called hydrodynamic machining) systems are gaining popularity in a variety of applications. Food products, composite materials, wood, plastic, rubber, leather, and brick can be cleanly and efficiently cut using water-jet machining equipment. An example of a robot-guided water-jet cutting machine by Stäubli is given in Fig. 16.

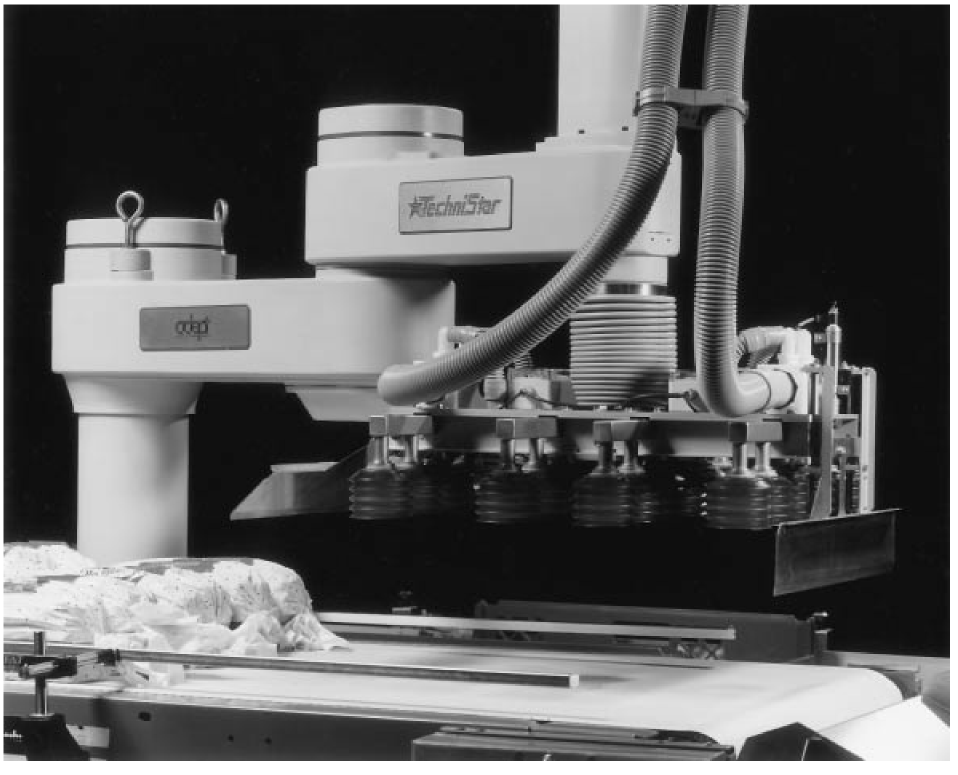

Figure 15. A robotic packaging application designed by Technistar uses an AdeptOne robot to grab a dozen loaves of bread at a time. Courtesy of Technistar Corporation, Longmont, CO.

Figure 16. Stäubli waterjet cutting system setup. Courtesy of Stäubli Corporation, Duncan, SC.

Figure 17. Stäubli Unimation RX 130 robot in a compound angle deburring operation. Courtesy of Stäubli Corporation, Duncan, SC.

Deburring and flash removal from castings and forgings involves tedious manual labor and is therefore an expensive part of a manufacturing process. Burrs are thin ridges that develop along the edges of a workpiece from machining operations, sheet metal shearing, and trimming of forgings, and castings. Burrs may reduce fatigue life of components and cause problems in assembly operations. Cost reduction in deburring operations has been successfully accomplished through the use of specially equipped robots in conjunction with programmable controllers. An example of compound angle deburring using an RX 130 Stäubli Unimation robot is given in Fig. 17.

Reading List

G. Beni and S. Hackwood, *Recent Advances in Robotics,* New York: Wiley, 1985.

P. I. Corke, *Visual Control of Robots,* Taunton, England: Research Studies Press, 1996.

W. H. Cubberly and R. Bakerjian, eds., *Tool and Manufacturing Engineers Handbook,* Dearborn, MI: Society of Manufacturing Engineers, 1989.

R. C. Dorf, *Concise International Encyclopedia of Robotics,* Ann Arbor, MI: Robotics Industries Association, 1990.

J. F. Engelberger, *Robotics in Service,* Ann Arbor, MI: Robotics Industries Association, 1989.

H. R. Everett, *Sensors for Mobile Robots,* Wellesley, MA: A. K. Peters Limited, 1995.

W. B. Gevarter, *Intelligent Machines,* Englewood Cliffs, NJ: Prentice-Hall, 1990.

B. K. Paul Horn, *Robot Vision,* Cambridge, MA: The MIT Press, 1988.

J. Hoshizaki and E. Bopp, *Robot Applications Design Manual,* New York: Wiley, 1990.

V. D. Hunt, *Understanding Robotics,* Ann Arbor, MI: Robotics Industries Association, 1990.

S. Kalpakjian, *Manufacturing Processes for Engineering Materials,* Menlo Park, CA: Addison Wesley Longman, 1997.

S. Y. Nof, *Handbook of Industrial Robotics,* New York: Wiley, 1985.

O. Omidvar, Ed., *Neural Systems for Robotics,* San Diego, CA: Academic, 1997.

L. A. Payne and M. A. Toomajian, *Vision for Inspection,* Barrington, IL: *Proc. Control Eng. Conf.,* 1987.

Robotics World, Winchester, MA: Douglas Publications, 1994–1997.

M. E. Rosheim, *Robot Wrist Actuators,* New York: Wiley, 1989.

M. E. Rosheim, *Robot Evolution,* New York: Wiley, 1994.

B.-Z. Sandler, *Robotics,* Englewood Cliffs, NJ: Prentice-Hall, 1991.

M. Shahinpoor, *A Robot Engineering Textbook,* New York: Harper and Row, 1987.

A. C. Staugaard, Jr., *Robotics and A.I.,* Englewood Cliffs, NJ: Prentice-Hall, 1987.

A. M. S. Zalzala and A. S. Morris, *Neural Networks for Robotic Control,* New York: Simon and Schuster International Group, 1996.

Internet Information

There are dozens of other web sites not mentioned here, and each manufacturing company has its own web site. Readers are encouraged to visit the numerous sites.

1. Robotics: Frequently Asked Questions [FAQ] http://www.rokoh.gen.u-tokyo.ac.jp/information/robotics.faq
2. Internet Robotics Information: http://www.cs.indiana.edu/robotics/world.html
3. What companies sell or build robots? http://www.frc.ri.cmu.edu/robotics-faq/8.html
4. The Utah/MIT Dexterous Hand: http://piglet.cs.umass.edu:4321/p50/utah-mit-hand.html
5. NASA Space Telerobotics Program: http://ranier.oact.hq.nasa.gov/Telerobotics_page/internetrobots.html
6. European Robotics Network [ERNET]: http://deis58.cineca.it/ernet/ernetbook/index.html
7. John M Hollerbach: Professor of Computer Science: http://www.cs.utah.edu/~jmh/

MYSORE NARAYANAN
Miami University

INDUSTRIAL ROBOTS. See ROBOTS.
INDUSTRY, CEMENT. See CEMENT INDUSTRY.
INFERENCES. See COGNITIVE SYSTEMS.
INFERENCE, UNCERTAIN. See PROBABILISTIC LOGIC.
INFINITE-DIMENSIONAL SYSTEMS. See DISTRIBUTED PARAMETER SYSTEMS; CONTROL OF PDES.
INFINITE IMPULSE RESPONSE FILTERS. See IIR FILTERS.
INFORMATICS IN HEALTHCARE. See MEDICAL INFORMATION SYSTEMS.
INFORMATION DESIGN. See DOCUMENT AND INFORMATION DESIGN.
INFORMATION FUSION. See DATA FUSION.
INFORMATION MANAGEMENT. See DATABASES.
INFORMATION MANAGEMENT, PERSONAL. See PERSONAL INFORMATION MANAGEMENT SYSTEMS.