ROBOTS

A robot is a mechanical device that can perform certain operations automatically. The technical definition of the term *robot* or *robotics* varies. What Americans may call a complex mechanical manipulator may be referred to as a robot in Japan. In 1979, the Robot Institute of America defined a robot as "a reprogrammable multifunctional manipulator to move materials, parts, tools or specialized devices through various programmed motions for accomplishing a variety of tasks."

A simple robot may have three degrees of freedom, in the x, y, and z directions. In an industrial setting, such a robot may transfer an object from one point to another and may be referred to as *pick-and-place robot.* Figure 1 depicts a simple robot equipped with soft grippers. Such a robot does not offer any trajectory control. However, an intelligent robot may have several servomotors that receive feedback from sensors that gather information from the workplace environment. Thus, the robot can be programmed to make certain decisions contingent on the feedback information received.

Most robots are either floor- or machine-mounted. Floor-mounted robots are best suited for machine loading (and unloading) applications. For example, a floor-mounted, pedestal robot can retrieve a raw, unfinished part from a conveyor and deliver it to a lathe for purposes of machining. A machine-mounted robot, on the other hand, is dedicated to a single machine. Therefore, such a robot can be designed with fewer degrees of freedom. Machine-mounted robots are also used to retrofit existing machinery.

ROBOT SELECTION AND IMPLEMENTATION

The selection of a robot for a specified application mainly depends on its dynamic properties. Since the design of a robot is very complex, the engineer normally devotes great attention to a set of features the robot is supposed to offer. Automated systems that use robots perform operations that generally fall into one of the following three categories:

1. Pick and place
2. Processing and assembly
3. Special purpose

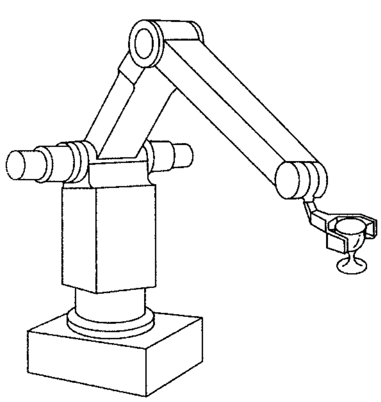

Figure 1. Robot equipped with soft grippers.

In particular, emphasis is placed on the following characteristics:

1. *Accuracy and Resolution.* Resolution is indicative of the smallest incremental motion the robot is capable of delivering within its work envelope. The engineer expresses it in terms of tolerance limits, so as to make it possible to accomplish tasks such as accurate tool positioning and precise object orientation.
2. *Repeatability of Operation.* Once it is trained, a robot is expected to continue to *repeat* the "taught" operation indefinitely, with consistent accuracy and resolution. Obviously, this is an essential characteristic to guarantee uniform product quality.
3. *Stability in Performance.* A robot is expected to be consistent in its operation, free from vibrations or oscillations. Vibration-free tool-mounting hardware and object grippers are some of the important features that reduce wear and tear and ensure reliable precision.
4. *Compliance of the Manipulator.* Compliance in a robot manipulator permits *mechanical float* in the tool with respect to the tool mounting frame. Compliant motion is essential to allow for the inherent inaccuracies in the robot control system. It also provides for the margin of error the real world demands. Compliance corrects errors in assembly operations that arise from misalignment.

Successful implementation of robotics has become indispensable in certain industrial situations that pose adverse conditions. Examples of adverse conditions are:

1. High temperatures such as new boilers or furnaces
2. Dusty, dirty, and greasy surroundings
3. Hazardous conditions such as heavy vibrations, toxic substances, or corrosive chemicals
4. Fire-prone environmental conditions or potentially explosive situations
5. Inaccessibility, as in deep sea searches or planetary explorations

HISTORICAL PERSPECTIVE

In 1923, the Czech playwright Karel Čapek used the word *robot* (Czech for worker) in his play *Rossum's Universal Robots.* In the 1940s the science-fiction writer Isaac Asimov used the word *robotics.* George DeVol and Joseph Engleberger developed the first industrial robot in the late 1950s. Engleberger was the founder of Unimation, and is also called the "father of robotics." Unimation manufactured the PUMA (programmable universal machine for assembly) for many years. These PUMA robots can still be found in many industries and universities. Unimation was later acquired by Westinghouse; it is now owned by Stäubli of Switzerland and called Stäubli Unimation Limited.

During the sixties, industrial use of robots began to gain prominence. Presently there are more than a hundred major companies that manufacture robots and associated equipment. (See the section Web Site Addresses at the end of this article.) The early robots had limited capabilities and were designed to deal with situations that required specific applications, such as moving a heavy load of caustic chemical. During the seventies, heavy emphasis on factory automation resulted in the increased use of robots on the shop floor for a variety of operations such as spot welding and spray painting. During the eighties and nineties, sophisticated robots coupled with cameras were able to "see." This resulted in the birth of *robotic vision systems.*

Some robots with a limited amount of artificial intelligence and expert systems have started to take over specialized seam welding tasks, precision assembly jobs, inspection, and quality control operations. The use of these robots has resulted in improved quality, minimized waste, increased productivity, and reduced production costs.

By some estimates, about 50% of the world robot population is centered in Japan. The United States and western Europe share approximately 20% each. The rest of the world accounts for only 10%. The total value of existing robots exceeds $10 billion. However, these figures are only approximate, in part because of the different ways to define "robot." Also, the robot population is continuously changing, not only in any country, but also in any factory or industry. Many other countries, recognizing the importance of robots for the quality of manufactured goods, are also adopting them for automation. There are substantial government support and subsidies for this process in certain countries.

Panasonic, for example, developed Pana Robo, the industry's first exclusive welding robot. By integrating an artificially intelligent and inverter-controlled 350 A welding power supply into the robot controller, the need for an interface box was eliminated. This is noteworthy because Pana Robo has resulted in a 20% reduction in controller installation space and an almost 50% reduction in floor space compared to the conventional systems. In addition, the teaching time has been reduced 20% by using capacitance-type distance sensors. These sensors are located on the top of the torch, and they detect distance to the welding line and the torch posture. This information is fed to the robot, so that the robot can automatically follow the welding line and concurrently activate the teaching process.

High-speed touch sensing enables the robot to reduce tact time and to adjust itself even through inaccurate work is supplied or the work is not properly clamped. Touch sensing and shifting of programs can be done in three dimensions. By weaving the tip of the welding torch, an *arc sensor unit* can recognize the work, sense deviations, and adjust the welding line in order to get good welding results. A *supersmall spin arc sensor system* rapidly rotates the welding tip itself. As a result, it shortens the arc sensing cycle and improves the welding bead. In addition it disperses arc pressure and heat evenly. High-speed and excellent-quality weld tracking on plates as thin as 1.6 mm can be achieved, and speeds of up to 2 m/min have been realized. Figure 2 represents an automotive arc welding application (courtesy of American Robot).

The first generation of robots required precise positioning of the workpieces because they were "dumb" robots that could not "see." Specific arrangements were made to ensure that the robots were appropriately located and oriented in relation to nearby machines and personnel. At each selected location the product or the workpiece had to be positioned with very good accuracy. The robots were then "taught" to perform a chosen task by a human being using a *teach pendant.* The resulting motions were subsequently stored in the robot's memory, and the robot executed the "taught" operation repeatedly with good accuracy. These first-generation robots helped increase productivity and manufactured goods with consistent quality. In addition they relieved the human operator from boring, repetitive tasks and dangerous environments. Nevertheless, automation engineers envisioned much more sophisticated systems, and this led to the development of the second generation of robots.

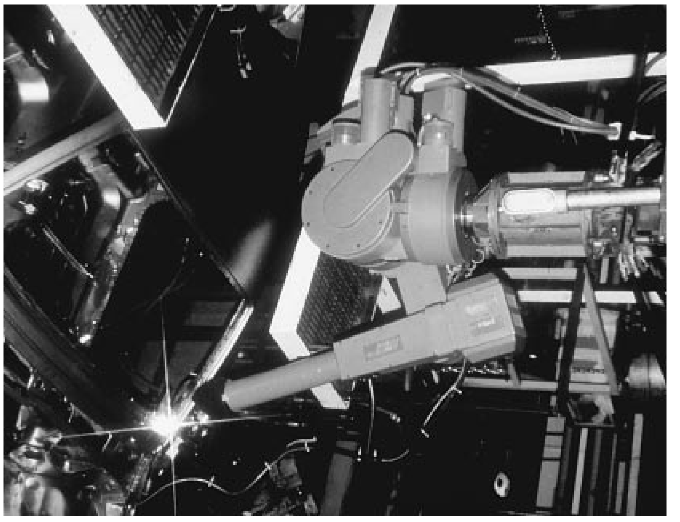

Figure 2. Automotive arc welding application. An overhead-mounted MERLIN® robot performs seam welding on an auto body. Courtesy of American Robot Corporation.

The second generation of robots utilized programmable controllers and computers to perform operations that helped with industrial automation. These robots, integrated with vision, force, torque, proximity and tactile sensors, helped pave the way for the factory of the future. These robots were capable of adapting to the specific needs of the work environment. The operator was provided with a variety of programming tools that could help the robot to work effectively with the surrounding machine tools and personnel.

The third generation of robots is equipped with advanced sensors and can be interfaced with other computers on the manufacturing assembly line. Extensive use of closed-loop feedback control systems in these modern robots has provided automation engineers with a variety of unique and sophisticated features. Sensing elements can change the input to modify the process being controlled based on the information received from the output. For example, when interfaced with vision systems and tactile, force, and torque sensors, these *intelligent robots* can retrieve workpieces positioned at random. Further, they can inspect them for defects, reject the defective components, and perform precision assembly operations. They can also perform a final inspection of the assembled part prior to product packaging and shipping.

Robotics is a booming industry and is a billion-dollar business in North America alone. It 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 economical performance of certain jobs and processes such as high-quality spot welding. It is almost impossible for human beings to perform the precision welding or soldering operations demanded by the current electronics industry, which depends on microminiaturization. Ergonomic

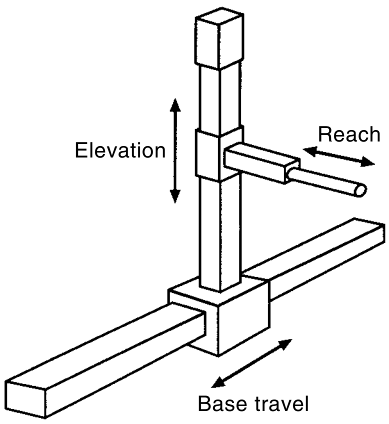

Figure 3. Robot operation based on rectangular coordinates. Linear motion in three different directions is possible.

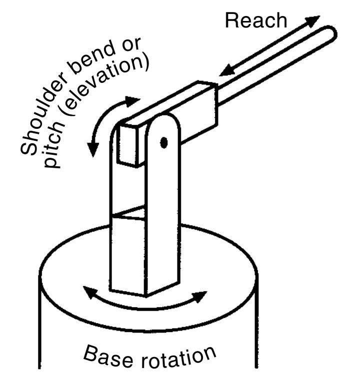

Figure 5. Robot operation based on spherical coordinates. Linear motion in one and rotary (or partial rotary) motion in two directions are possible.

problems have been eliminated by the successful implementation of robots in certain assembly operations.

ROBOT CLASSIFICATION

Coordinate Geometry

A robot may be classified according to the coordinate geometry within which it operates.

Rectangular. The first three joints of the mechanical manipulator are capable of linear motion in the x, y, and z directions (Fig. 3).

Cylindrical. The first joint is capable of rotational motion in a horizontal xz plane over 360°. The other two joints provide linear motion in the x and y directions (Fig. 4).

Spherical. The first joint is capable of rotational motion in a horizontal xz plane over 360°. The second joint is capable of rotational motion in a horizontal xy plane over 180° or less. The third joint provides linear motion in the x direction (Fig. 5).

Articulated. The three joints provide either full or partial rotational motion in three different planes: xy, yz, and xz (Fig. 6).

Control System

A robot may also be classified according to the control system employed: for example, non-servo-controlled and servo-controlled. A robot may work in an open-loop configuration or in a closed-loop configuration.

Open Loop. These robots are called pick-and-place robots or limited sequence robots. They basically procure an object from a given location, transport it to a different location within its reach, and place it there. For example, an open-loop robot can pick up a small package from an incoming chute and place it on a conveyor belt. These are basically non-servo-controlled robots that move at a constant speed along a predetermined path between two points. A limit switch is necessary to bring the robot to a halt after the specified trajectory is traced and the robot has reached its destination.

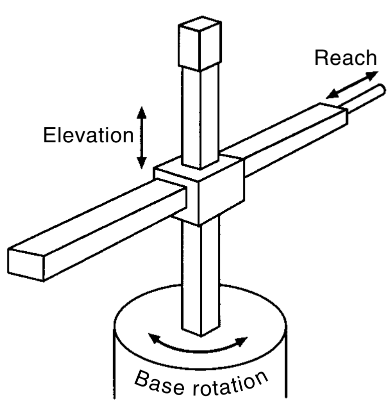

Figure 4. Robot operation based on cylindrical coordinates. Linear motion in two directions is possible.

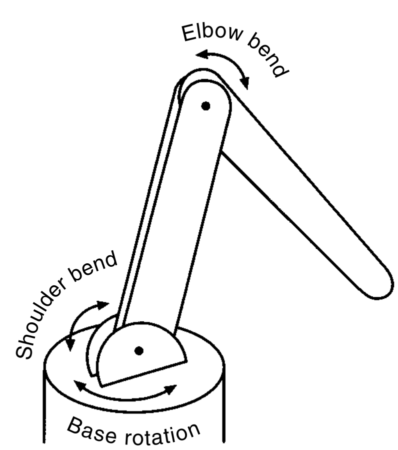

Figure 6. Robot equipped with articulated joints. Rotary (or partial rotary) motion in all three directions is possible.

These robots can perform pick-and-place operations at high speeds, with reliable repeatability.

Closed Loop. This type of servo-controlled robot systems utilizes position feedback measurement techniques and is very popular with factory automation engineers. Error signals are generated, amplified, and fed back to servomotors. These signals facilitate required corrections in the robot program, till the error signals are effectively reduced to zero. Machine vision systems, encoders, potentiometers, tachometers, and several other position and displacement measuring devices help these robots adapt to a *flexible manufacturing environment*. Robot programming and the associated electronic hardware play a vital role in the execution of command signals.

Programming Schemes

A robot may also be classified according to the programming schemes employed.

Teach Pendant. A hand-held device called a *teach pendant* is used to “teach” the robot the trajectories it should follow. Once this is accomplished and the information is stored in its memory, the robot will perform this “taught” operation again and again, with good, repeatable accuracy. Pick-and-place robots and robots that perform simple jobs such as spot welding utilize a teach pendant.

Low-Level Programming. Special, simple robot programming languages help the user to input the required coordinate information along with other simple instructions that control the movement of the robot arms, elbows, or grippers. This helps the user to be creative in providing information to the robots and is a step up from the teach pendant system. Robots that carry out operations in a work-cell environment utilize some sort of low-level programming language.

High-Level Programming. Modern programming languages, which are expanding every day, help in creating a flexible manufacturing environment. Full use of computer control and arithmetic and logic functions provides the programmer with unlimited capabilities. Techniques such as feedback control systems are employed to provide the robot with instructions to modify and correct its path or operation on the basis of information received from sensors or machine vision.

Type of Power

Robots are sometimes classified according to the way they are powered: for example, hydraulic, pneumatic, or electric.

Robots driven with hydraulic power need special hydraulic servo valves, analog resolver units, encoders, and feedback control systems. There are several aspects that make such robots attractive. They are strong and operate at high speeds. They are also simple in construction and operation. Electric sparks, which appear when the contacts of a relay or a circuit breaker are opened or closed, are absent in hydraulic robots, which makes them attractive in applications where explosion is a hazard. Automation engineers are likely to select hydraulic (or pneumatic) robots for specific applications such as spray painting of automobiles. In comparison with electrical manipulators, hydraulic actuators are capable of transporting heavy loads. However, there are some limitations posed by these types of robots. For example, it is necessary to maintain separate hydraulic pumps and other ancillary equipment in addition to electrical power. Another problem is posed by leakage of fluids such as oil. Further, hydraulic hammer may pose a problem in certain cases by introducing oscillations. Hydraulic robots are large, requiring a lot of valuable floor space. They are also very noisy. Their installation and maintenance costs are high.

Pneumatically driven robots have relatively low operating and maintenance costs, but they are mainly suitable as pick-and-place robots, because they offer only limited sequence control. They also suffer from poor repeatability. Their position control is not reliable, due to the compressibility of air. Therefore, they normally operate in the open-loop mode. These simple robots are not capable of meeting the needs of modern industry or the demands of the quality-conscious customer. Their accuracy is inadequate for producing high-quality goods at low cost with minimized waste.

Developments in the area of modern feedback control systems, stepper motors, and servomotors have made electrically powered robots the automation engineer’s preferred choice. Electrically powered robots are clean and leakproof. These do not need separate hydraulic or pneumatic power sources. This results in cost savings in capital investment and installed machinery. They conserve floor space and contribute to a reduction to the overall noise level on the shop floor. These robots incorporate a variety of electronic circuitry such as analog-to-digital converters (ADCs) and digital-to-analog converters (DACs), current amplifiers, voltage amplifiers, power amplifiers, stepper motors, servomotors, transducers, and optical encoders. The recent advances in electronics, microprocessors, programmable controllers, and computer interfacing have made these types of robots extremely popular with automation engineers.

Electrically driven robots are less expensive and are easy to design, control, and maintain. They can perform with very good precision and offer the excellent repeatability needed for present-day industry. They have the ability to operate at a variety of speeds. However, in some cases they may not be as fast as hydraulic systems, because many electric robots utilize dc stepping motors. Also, the payload capacity is considered to be less than for the other two systems. In the low and moderate load ranges, however, electric motors provide the largest variety of design choices. They are also very efficient and offer desirable torque–speed characteristics. They can deliver peak power at high speeds and can quickly accelerate or decelerate the payload. However, electric motors offer only rotary motion, and in many cases there is need for converting this rotary motion into linear, translatory motion. This necessitates additional components and equipment.

Artificial intelligence and expert systems have opened up new horizons and have helped in strengthening the communication between robots and human beings. The design engineer can systematically collect, organize, and sort out all the data that are relevant to the robot environment using different sensors. The gathered information and the stored knowledge can then be used to generate an ideal solution to the problem at hand. An intelligent robot offers a variety of design features and is capable of deciding and determining its goal, based upon the data it retrieves. Further, it will take appropriate action by effecting necessary modifications to its planned actions. The intelligent robot, therefore, needs to possess large amounts of computer memory to store its knowledge base—possibly a CAD database.

One of the major problems faced by the modern manufacturing engineers was the transition from *fixed* or *hard* automation to *flexible* automation. Electrically driven robots offered an excellent way to overcome this obstacle. Development of microstepping techniques, skillful use of computer interfacing, and appropriate use of programmable *controllers* have provided the design engineers with a variety of tools that has enabled the creation of a "factory of the future" based on the principles of *flexible manufacturing systems.*

Uses

Robots are sometimes classified according to their intended uses.

Industrial Robots for Materials Handling. These pick-and-place robots are simple devices and may cost less than $25,000. They relieve human beings of monotonous jobs. Figure 7 shows a machine for loading and unloading plastic measuring cups with an L. R. Mate robot from FANUC Robotics. These simple robots can handle hazardous materials and work in dangerous environments.

Dedicated, Single-Purpose Robots. These industrial robots may cost up to $50,000. They are custom-designed to meet a specific need and to accomplish a given task. Examples include spot-welding robots, screw-fastening robots, and automobile paint-spraying robots. Figure 8 shows automotive spray painting with a P-200 robot system from FANUC Robotics.

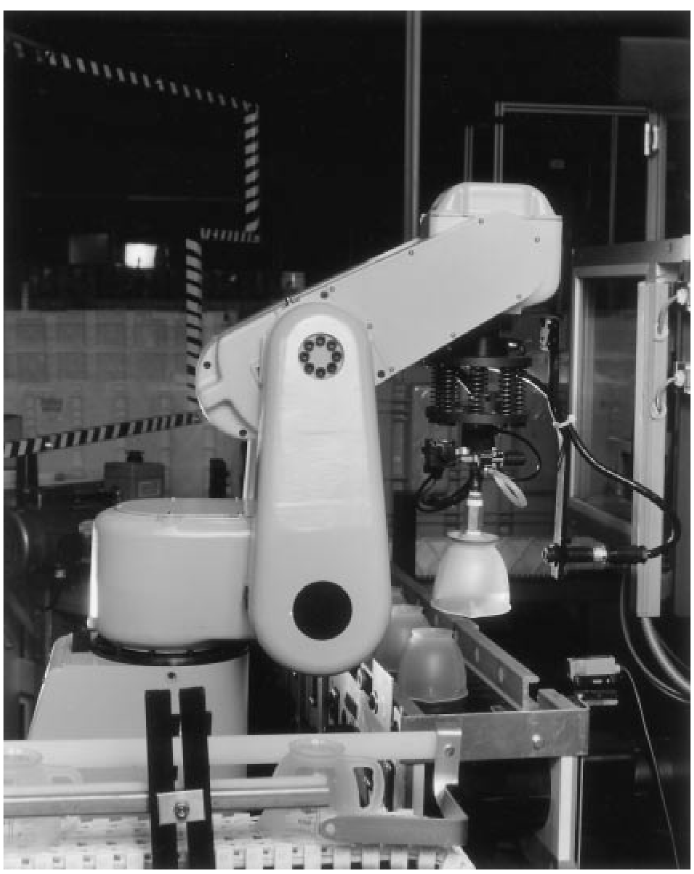

Figure 7. Machine loading and unloading of plastic measuring cups with an L. R. Mate robot. Courtesy of FANUC Robotics North America, Inc.

Multifunctional and Multipurpose Robots. These are the top-of-the line industrial robots and are very expensive. They are normally used in conjunction with a programmable controller. They are capable of handling a variety of tasks, from simple materials handling to complex assembly operations. Skillful use of programming enables the engineer to perform different operations, utilizing the same robot, but different end effectors and grippers. Figure 9 shows the robotic assembly of a valve body housing with a FANUC Robotics A-520 i robot.

Manipulators, actuators, end effectors, and grippers have been studied, modified, and customized in a number of ways to meet the specific needs of a given application task. The Utah–MIT Dexterous Hand Project had a specific goal to achieve. They successfully created a robot hand that had the same dexterity as the human hand. The hand has three fingers and a thumb. The thumb and all three fingers have four degrees of freedom. The Utah–MIT dexterous hand has been used in conjunction with robots, such as the GE P350 robot. This robot, with its hand, has been used for a variety of reaching and grasping experiments. For example, it can be used to plan an obstacle-avoiding course for pick-and-place operations. Another example is deducing the shape of a chosen object utilizing the information obtained from finger contact. During the early 1980s several other successful attempts were made to develop and build a robotic hand that was similar to a human hand. The Hitachi three-fingered robotic gripper, the Salisbury hand, and the Caporali–Shahinpoor hand are noteworthy.

Some other companies specialize in designing robot legs instead of robot hands. For example, Odetics of Anaheim, California, have developed several walking robots. These are specially designed for use in hazardous areas. The Odex I, II, and III, shown in Fig. 10, can move through tight and congested work spaces, adjust height and width, and negotiate stairs and other obstacles. Odex II incorporates full-force reflection feedback in the articulator (leg) assemblies for use on soft or giving surfaces, as is shown in Fig. 11.

A typical robot might be specified as follows: It has a 1.5-m reach and a 15-kg payload capacity. It has repeatability to 0.05 mm. The arm tip velocity is 1 m/s. Typical applications include palletizing, packaging-parts feeding, and machine loading. In addition, the robot may be used in inspection and quality control applications, with certain modifications. The robot has six degrees of motion as follows:

Waist rotation, 320°
Shoulder rotation, 325°
Flange rotation, 530°
Elbow rotation, 300°
Wrist bend, 210°
Wrist rotation, 310°

Special Purpose Robots

Robots are sometimes specifically designed to accomplish a designated task. These are classified as *special purpose robots.*

Figure 8. Automotive spray painting with P-200 robot system. Courtesy of FANUC Robotics North America, Inc.

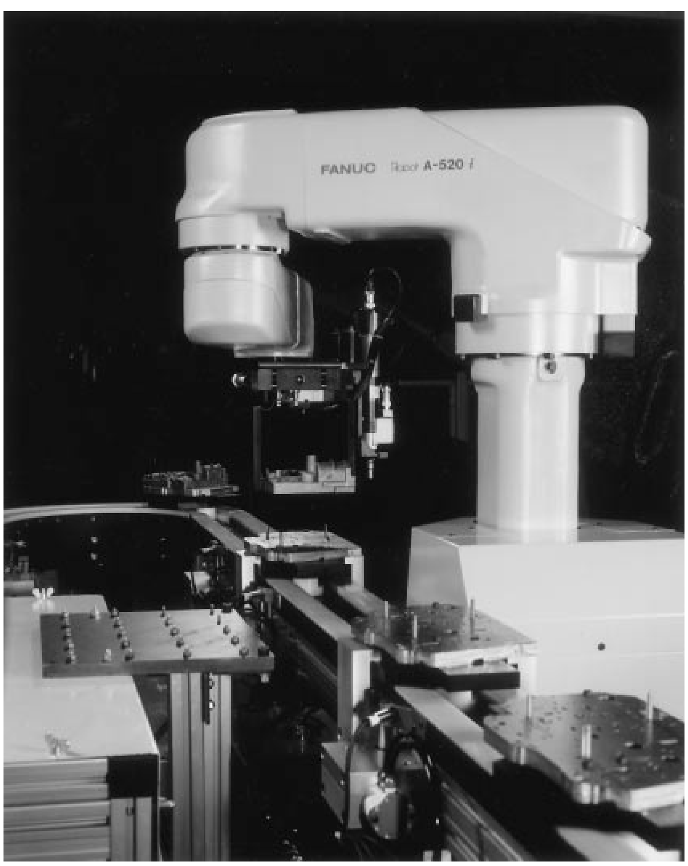

Figure 9. Robotic assembly of a valve body housing with A-520 i robot. Courtesy of FANUC Robotics North America, Inc.

Although most robots are stationary, some applications require *mobile robots.* These are industrial robots that can be moved under command. This movement is normally in the x, y, and z directions and is in addition to the five or six degrees of freedom the robot already possesses. For example, linear mobility in one direction can be accomplished by mounting the robot on rails, carriage guides, or gantry devices. Area mobility can be achieved by using an *XY* table, bridge crane, or *XY* gantry fixtures. Suitably designed lifting devices in addition to *XY* gantry or bridge cranes can provide robots with space mobility in all three directions.

Mobile robots are best suited for exploring unknown environments. Such a robot must possess adequate intelligence to detect and overcome obstacles encountered in its path. An executable path for the mobile robot can be mapped utilizing feedback information from visual, ultrasonic, or infrared sensors and cameras mounted on the robot itself. Mobile robots are wheeled, legged, or tracked. Control of a tracked robot is the easiest, and control of a legged robot is more difficult than control of a wheeled robot. Stability of the entire manipulator, ground contact of the legs, and position orientation are some of the important feedback information a legged robot needs to procure for efficient operation. With these data the manipulator adjustments can be activated appropriately so that the joined linkages cause the robot to walk.

Thing is a small, twelve-degree-of-freedom, four-legged walking robot that was built in the Laboratory for Perpetual Robotics at the University of Massachusetts, Amherst. Thing uses its joint torque and position sensors to acquire information about the terrain. It uses infrared sensors to discover large obstacles in its environment and navigate around them using harmonic path planning. The laboratory used a distributed control approach to legged locomotion that constructs be-

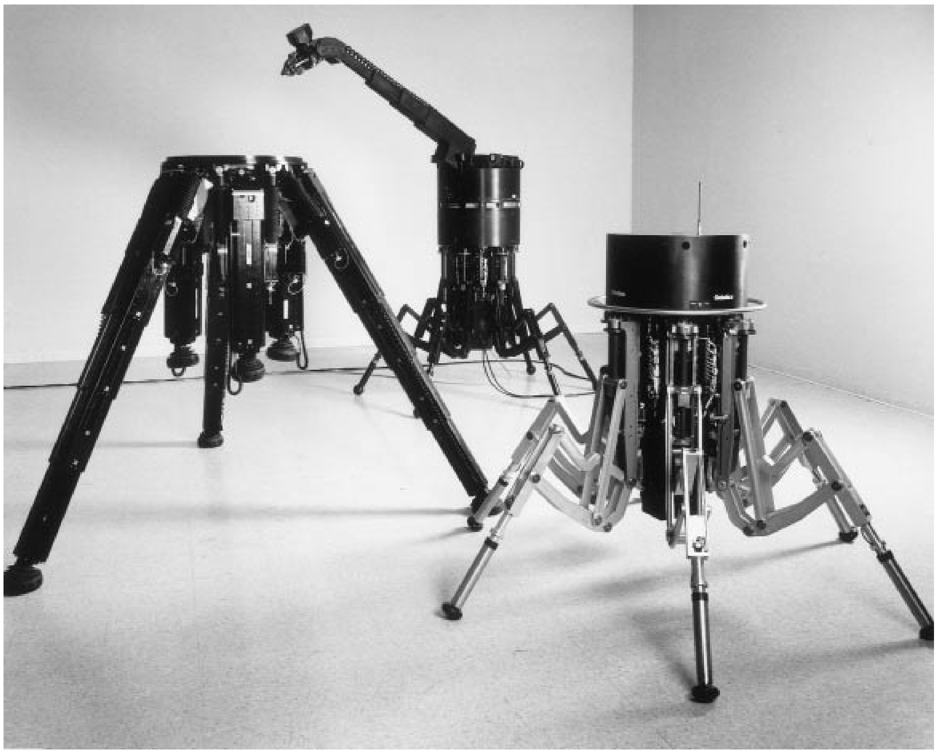

Figure 10. Odex I, II, and III can move through tight and congested work spaces. Courtesy of Odetics, Anaheim, CA.

Figure 11. Odex II incorporates full-force reflection feedback in the articulator leg assemblies. Courtesy of Odetics, Anaheim, CA.

havior online by activating combinations of reusable feedback control laws drawn from a control basis. In addition, the device independent of the control basis allows its generalization not only over task domains, but also over different hardware platforms. Coordinating multiple effectors to maintain stability and mobility is a central issue in both legged systems and multifingered hands. Odetics's pioneer robot, Odex I, was designed to work in hazardous environments or locations inaccessible to conventional wheeled or tracked vehicles. The 170-kg (370 lb) robot, shown in Fig. 12, walks on six legs and is maneuvered using a remote joystick control unit. It uses video cameras for transmitting imagery to a remote human operator.

Unmanned exploration of deep sea, planetary surface, or outer space sometimes requires robots to follow certain tracks or move on wheels or walk. These mobile robots are capable of adapting themselves to nonstructured and unknown environments. However, this necessitates the use of several sophisticated techniques, because the robot needs several input parameters. To start with, the initial position of the robot may be unknown. In addition, the path of the mobile robot must be free from obstacles. Skillful use of ultrasonic, vision, force, tactile, and proximity sensors helps in obtaining information about the robot's surrounding environment.

Sojourner is the first robotic rover ever sent to another planet (Fig. 13). Launched December 4, 1996, aboard the Mars Pathfinder, it is remotely controlled from earth and cost about $25 million. It landed on July 4, 1997 and began exploring the surface of Mars. Sojourner is solar powered with backup batteries. It runs on six wheels, and each wheel is independently suspended and rotated. This "robotic car" is approximately 60 × 60 × 30 cm (2 × 2 × 1 ft) and weighs

Figure 12. Odex I uses video cameras for transmitting imagery to a remote human operator. Courtesy of Odetics, Anaheim, CA.

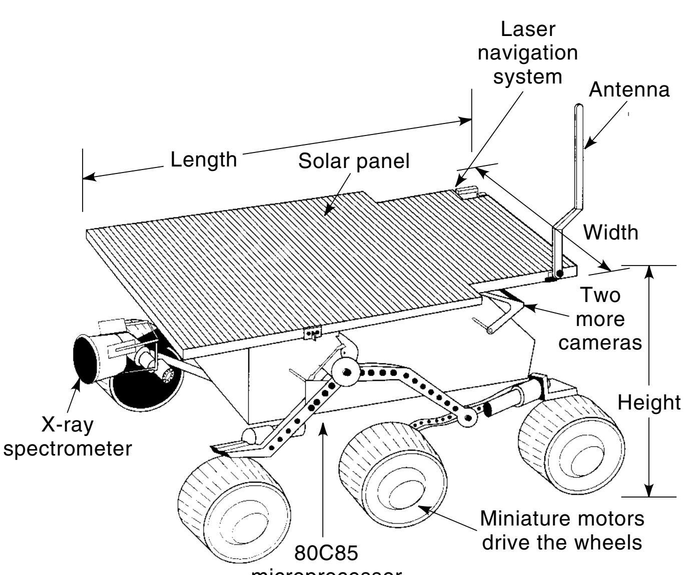

Figure 13. Artist's sketch of Sojourner robotic rover (Mars Pathfinder Mission).

about 10 kg (23 lb). It can travel at speeds of up to 1 cm/s (2 ft/min) and is equipped with three cameras, an X-ray spectrometer, and other instruments. It can photograph geologically interesting rocks, conduct a chemical analysis of the selected rocks, and relay the data back to earth. Sojourner is an excellent example of robotic vehicles used in planetary explorations.

GLOSSARY

AI. An *artificial intelligence* system takes action based on certain information and *reasoning.* The mechanism should provide tools to respond to expected as well as unexpected situations and conditions that might arise in an industrial environment. Computer-aided machine vision systems and a variety of sensors help in creating *expert systems* that can make decisions and take actions appropriately. An intelligent robot may be capable of obtaining a perception of the environmental surroundings using a sophisticated system of feedback control systems. It may then make certain decisions based on certain rules and draw conclusions. These decisions may include problem solving and self-programming to perform the necessary actions dictated by the situation on hand. An intelligent robot is also called a *sensory-controlled robot.*

AGV. *Automated guided vehicles* are widely used to transport materials, tools, and parts over long distances in a manufacturing assembly plant or a factory. AGVs are also known as *robot carts.* Wires embedded in the factory shop floor guide carts via predetermined paths to appropriate locations. These routes and paths are changeable simply by reprogramming. Facilities that utilize principles of *flexible manufacturing systems* (FMS) utilize AGVs for transporting and changing complete tool magazines. AGVs can handle loads of as much as 10,000 kg (20,000 lb). In principle, the robot cart has virtually an unlimited traveling range within the confines of the plant.

Android. A robot that resembles a human being.

Anthropomorphic. A robot is called *anthropomorphic* if it mimics a human arm. This necessitates that the robot be equipped with all rotary joints that facilitate motions in several directions. Such a robot is also called a jointed-arm robot.

Cycle time. The time required completing a given operation from start to finish. Knowledge of the cycle time is essential to determine and specify the production rate of an industrial robot.

Encoder. A transducer that converts linear or rotational position data into digital data.

End effector. The hand of the robot: a device that is fastened to the tip (free end) of a robotic manipulator for performing the designated task. The end effector may be a simple gripper that can grasp objects. It may be a mechanical clamp that can hold a welding torch or a paint-spraying gun. It may be a vacuum suction cup designed to procure the windshield of an automobile. Certain production applications may need scoops and ladles as end effectors. A number of end effectors may be mounted on a *turret* to facilitate quick and automatic change during a particular operation. This change can be accomplished using sensors integrated in the tooling.

Gantry robots. Also called *overhead robots,* gantry robots are best suited for moving workpieces from one machine to another. Mounted near the ceiling of the factory, these robots can travel at high speeds, covering the length and breadth of the factory. They can provide a high degree of accuracy as well. In addition to parts loading, they can be used for such jobs as cleaning up or vacuuming.

Link. A mechanism that permits the transmission of motion between joints or between a joint and an end effector. A link of a manipulator plays a vital role in defining and determining its coordinate system in space.

LISP. A high-level computer language developed at the Massachusetts Institute of Technology. The name derives from "list processing." It is a useful tool in the development of AI systems for robots.

Manipulator. A mechanism for grasping, moving, locating, or inserting an object. Robotic manipulators normally consist of arms, links, and segments joined together in some suitable fashion so that they can slide, rotate, move, retract, or extend relative to each other. These actions usually possess several degrees of freedom. A *manual manipulator* is controlled by an operator. The tool is manipulated into the appropriate position for welding, machining, or assembling operations. However, nowadays a programmable controller or a computer has replaced the manual manipulator in most cases. A *mechanical manipulator* is a mechanical device that resembles a human arm and a human hand. Basic three-dimensional geometry dictates that three values are necessary to specify a point in space. In addition, three angles are required to specify an orientation. Therefore, a complete manipulator must possess six joints. The study of the relationship between the applied torque and the resultant motion is called *manipulator dynamics.* It has two formulations. The *Lagrangian formulation* is in terms of the Lagrangian function L, defined as the difference between the total kinetic energy and the potential energy of the manipulator. The *Newton–Euler formulation* uses an iterative form to evaluate the velocities and accelerations.

MOBOT.

1. Abbreviation for *mobile robot,* an industrial robot that possesses one, two, or three degrees of freedom in addition to its standard six axes of freedom. This enables it to exhibit linear mobility or area mobility or space mobility.
2. Abbreviation for *modular robot.* In a modular robot, the controls, joints, arms, wrists, grippers, and other associated hardware are all designed as independent "building blocks." Each module is designed with its own drive unit, power lines, and communication lines. A supervisory control system oversees the entire operation, and a variety of modules may be combined to provide the engineer the desired kinematics best suited for a specified application. MOBOT was the trade name of the Mobot Corporation of San Diego.

Off line. Devices that do not exercise direct control and operate independently of the peripheral equipment are said to be *off line.* Off-line programming of robots is beneficial in that it leads to a dramatic reduction in robot down time. Besides, the programmer need not work under adverse or hazardous conditions. A single programming scheme for an assortment of robot configurations and designs is made possible by using off-line programming. The robot program may be developed without using the robot itself. Later on, the developed program can be downloaded to the robot controller for achieving the desired trajectories and operations. Complex tasks such as integration with existing CAD/CAM systems can be simplified using techniques of off-line programming.

Optimization. Robot optimization seeks to maximize the safety of personnel and equipment, as well as productivity and the quality of work performed. It seeks to minimize the amount of waste and scrap, the total production cost for the task, the time required to perform a single task or produce one unit, the amount of effort involved, and the amount of energy required for a specific job—all without sacrificing safety. *Robot ergonomics* studies the relevant aspects for optimal use of robots in actual working environments, including workplace design, performance characteristics, methodologies, instrumentation, and measurement techniques.

Payload. The maximum weight a robot can handle. The robot should be able to carry out its normal operations safely and effectively while its grippers are carrying or transporting the specified weight.

Pitch. The angular displacement of a moving joint, describing the ability of a robot arm joint to bend. The joint normally moves in a direction that is perpendicular to the line of motion. Further, it is in the same plane as the top side of the body.

Pixel. Abbreviation for *picture cell.* One pixel is one sensor element of a digital picture. A pixel is also known as a *photoelement* or *photosite.*

PUMA. General Motors Corporation developed a *programmable universal machine for assembly* to be used in conjunction with an articulated robot. Unimation Inc., presently known as Stäubli-Unimation of Switzerland, later marketed this commercially.

Roll. The rotational displacement of a joint around its principal axis: a parameter of the wrist of the robot, where the end effector or gripper is located. The roll describes the ability to rotate around a joint. It is also called the *Twist.*

RPL. Robot Programming Language, developed by SRI International of Menlo Park, California. RPL is based on LISP and is extremely useful in designing manufacturing systems that consist not only of robots, but also of sensors, manipulators, CNC machines, and other auxiliary equipment. RPL has helped in the effective utilization of techniques such as machine vision, sensor-activated feedback control mechanisms, and touch-sensor-based gripper operation and other sophisticated systems.

SCARA. Selective compliance robotic arm for assembly. A very popular configuration designed and developed by the engineers at Yamamachi University in Japan. Useful in assembly operations such as the insertion of printed circuit boards and integrated circuit parts.

Sensors. Devices that enable a robot to monitor, interpret, and react to its environment. The robot may get sensory inputs from limit switches, transducers, machine vision systems, tactile sensors, and other instruments or measuring devices. A transducer detects a physical phenomenon, such as an increase in temperature or a decrease in pressure, and relays the data to a feedback control system. Internal sensors provide information about a robot joint's position, velocity, and acceleration, wrist forces, gripper forces, etc. External sensors provide information about the robot's geometrical po-

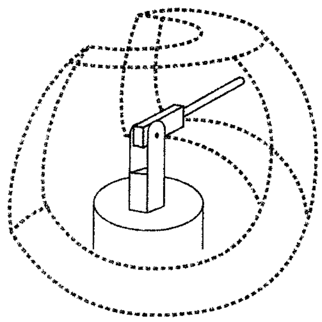

Figure 14. Work envelope of a robot with spherical coordinates.

sitioning, and about the orientation of workpieces and other objects. An external sensor enables one to modify the actions of the robot using a signal that is independent of the robot's internal design. A sensor-controlled robot is also known as an *intelligent robot.*

Tilt. The orientation of a view of a tool or an object with respect to a chosen reference frame. The view can be obtained using a video camera.

Work envelope. The contour of all the points that represent the maximum reach of the robot end effector tool in all three dimensions—in other words, that volume in space that the robot can touch with a tool mounted at the tip of its arm. This is also called the *operating envelope* of the robot. Knowledge of it is essential from the point of view of safety. In many cases, a *light curtain* may disconnect power to the robot if an operator enters the robot work envelope. Examples are shown in Figs. 14 and 15.

Wrist. The arm of the robot is joined to its hand using a *wrist* joint. The wrist permits the orientation of the tool relative to the workpiece. It normally consists of a set of joints that allow rotation of the end effector.

Yaw. The angular displacement of a moving joint, describing the ability of a robot arm joint to move in an angular fashion. The joint normally moves in a direction that is perpendicular to the line of motion. Further, it is perpendicular to the top side of the body.

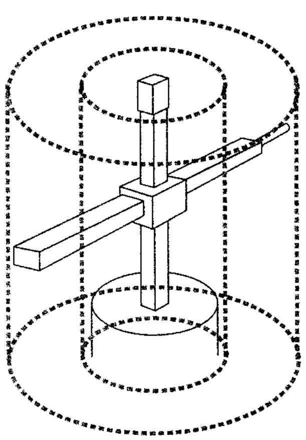

Figure 15. Work envelope of a robot with cylindrical coordinates.

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Web Site Addresses

Given below is a partial list of web sites. There are dozens of other web sites, and each manufacturing company has its own.

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

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ROBOT SELECTION EXPERT DECISION SYSTEM.

See EXPERT DECISION SYSTEM FOR ROBOT SELECTION.

ROBOTS. See INDUSTRIAL ROBOTS; MECHATRONICS; MOBILE ROBOTS.