# 3

# Robot Components and Operation

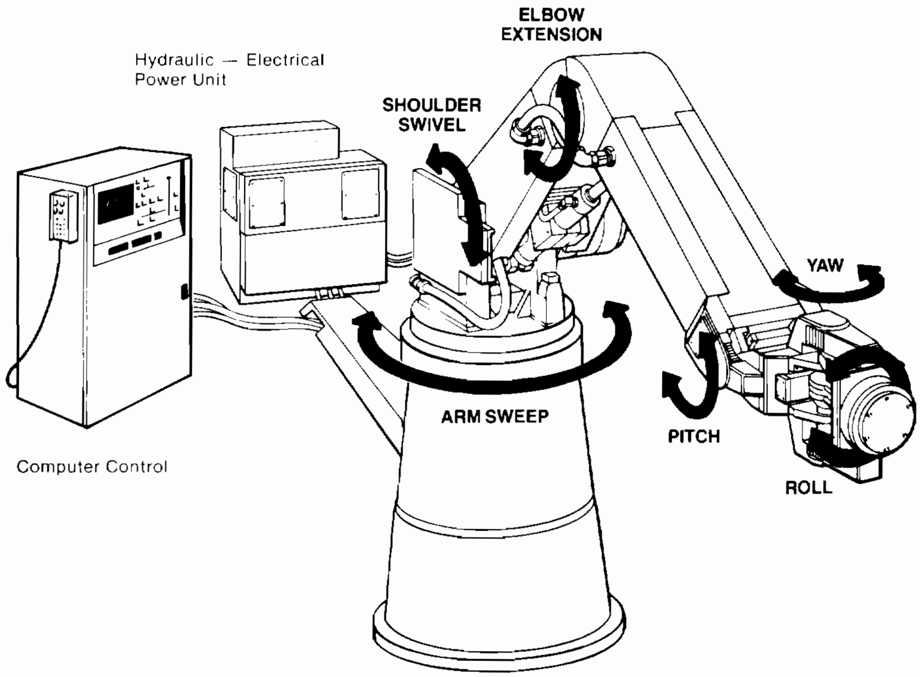
## 3.1 Basic Components

Industrial robots of today come in a variety of sizes, shapes, and capabilities. All have three basic components: a manipulator, a computer controller, and a power source, as shown in Figure 3–1. This illustration shows a modern industrial robot with a humanlike or anthropomorphic manipulator arm, a microcomputer controller, and a power source, which consists of both electric and hydraulic components. The manipulator arm moves tools or material to do the work. The arm shown has a load capacity of 225 pounds and can reach 13 feet. The controller provides the sequence of control signals to the manipulator and provides for interface to sensors, such as switches and cameras, to determine the motion the robot performs. The power source, which is usually electric, hydraulic, or pneumatic, provides the energy for the robot motions. In space, solar or nuclear power sources may be required. As yet, no hydrocarbon-powered (which we humans are) robots have been suggested, except in science fiction.

To use, program, or design an industrial robot, we must understand how they move and manipulate objects.

### *Manipulators*

Since we live in a three-dimensional world, the general robot must be able to reach a point in space. Such points are described by coordinates. The robot may move forward and backward, to the left and right, and up and down. This may be accomplished in several ways. The simplest conceptual form moves independently, although concurrently, in three mutually perpendicular directions in a manner named after the famous French mathematician, René Descartes, who first developed this form of defining a point in space. This is the Cartesian, rectilinear, rectangular coordinate, or (x,y,z)-geometry robot shown in Figure 3–2a. The first coordinate, x, might represent left and right



CINCINNATI MILACRON T³ ROBOT SYSTEM

**Figure 3–1.** An industrial robot consists of three major components: a manipulator arm, a controller, and a power source. The 6 degrees of freedom—arm sweep, shoulder swivel, elbow extension, wrist pitch, yaw, and roll—are sufficient to place a tool in any position and orientation in the robot's work space. (Courtesy of Cincinnati Milacron.)

motion; the second, y, may describe forward and backward motion; the third, z, generally is used to depict up-and-down motion. The advantage of this design form is that motions in one direction can be made independently of the other two. Also, equal increments of motion may be achieved in all axes by using identical actuators (electric, hydraulic, or pneumatic motors). In general, the longer the arm, the less its stiffness. The locus or path of points that can be reached by a robot is called its work space or volume. The work volume of a Cartesian robot is a cube, so that any work performed by the robot must only involve motions inside this space. The work envelope of a robot is the outline of the work volume region. For a cubic work volume, the work envelope when viewed from either the top or side appears as a square. An actual Cartesian robot is shown in Figure 3–3. It also uses linear motions to move from one point to another.

Rotation of the manipulator about some axis gives the robot a simple method for moving around in a plane. Robots that have one rotational capability or degree of freedom and two translational (linear) degrees of freedom are called cylindrical coordinate robots. A degree of freedom is simply a variable motion. The first coordinate

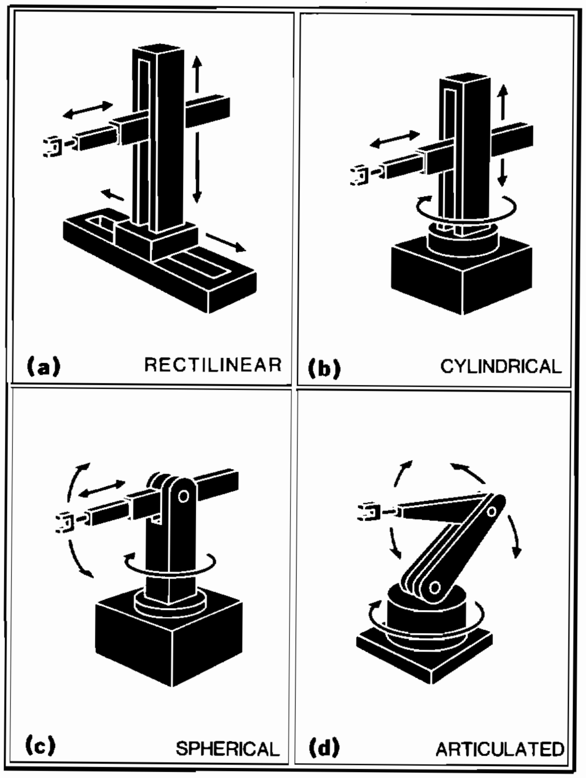


**Figure 3–2.** The four basic types of robots are described by their axes of motion. (a) A rectangular or Cartesian robot manipulator has three linear axes of motion and a cubic-shaped work volume. (b) A cylindrical or post-type robot has two linear motions and one rotary motion. The work volume of this robot has a cylindrical shape with the central core removed to accommodate the robot base and perhaps a pie-shaped section removed to provide for the backward extension of the arm. (c) A spherical or polar coordinate robot has one linear motion and two rotary motions. The work volume is shaped like a section of a sphere with upper and lower limits imposed by the angular rotations of the arm. A central core of the work volume is omitted to accommodate the robot base. A pie-shaped section may also be omitted to accommodate the rearward motion of the arm or to provide a safe operating position for the operator. (d) A jointed or anthropomorphic (humanlike) robot that uses three rotary motions. The work volume shape is spherical when viewed from the side and cylindrical when viewed from the top, with scallops on the inside limits of motion. (Courtesy of Cincinnati Milacron.)

describes the angle of base rotation, perhaps about the up-down, or z, axis. The second coordinate may correspond to a radial, or in-out, motion at whatever angle the robot is positioned. The final coordinate again corresponds to the up-down, or z position. The cylindrical coordinate robot shown in Figure 3–2b can reach any point in a cylindrical volume of space, although a central portion of the space must be devoted to the robot,

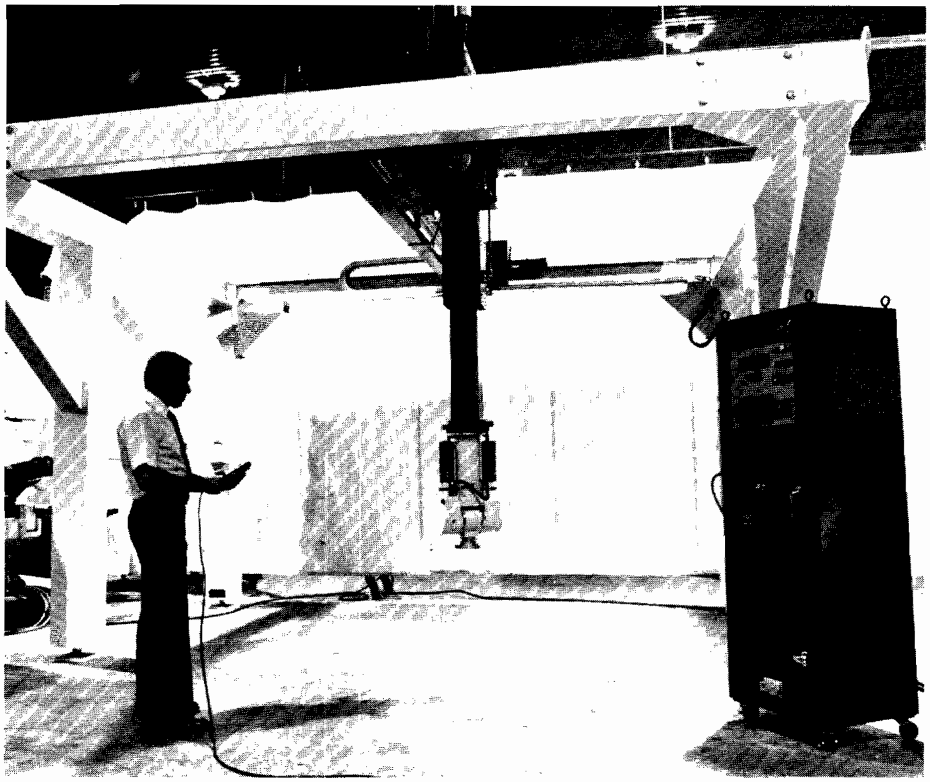


**Figure 3–3** A Cartesian robot developed by GCA Corporation. (Courtesy of GCA, St. Paul, Minnesota.)

and limits to the full rotation may also be imposed. Its rotational ability gives it the advantage of moving rapidly to a point in the z plane of rotation. An actual cylindrical coordinate robot is shown in Figure 3–4. The resolution of a cylindrical robot is not usually equal in its three axes of motion. The resolution of the base rotation is expressed in terms of an angular measurement, and the linear axes' resolution is expressed in terms of linear increments.

The spherical coordinate robot, shown in Figure 3–2c, reaches any point in space through one linear and two angular motions. The first motion corresponds to a base rotation about a vertical axis. The second motion corresponds to an elbow rotation. The third motion corresponds to a radial, or in-out, translation. The two rotations can point the robot in any direction and permit the third motion to go directly to a specified point. The points that can be reached by the spherical coordinate robot include the volume of a globe or sphere. An actual spherical coordinate robot is shown in Figure 3–5.

The anthropomorphic or jointed-arm robot shown in Figure 3–2d uses three rotations to get to any point in space. This design is similar to the human arm, which has

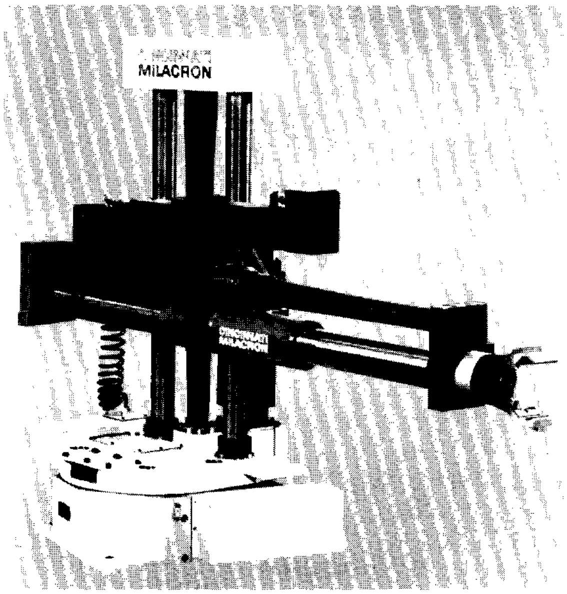


**Figure 3–4** A cylindrical coordinate robot developed by Cincinnati Milacron, Model T3 363. (Courtesy of Cincinnati Milacron.)

two links—the shoulder and the elbow—and positions the wrist by rotating the base about the z axis, then rotation of the shoulder, and finally rotation of the elbow. In the jointed-arm robot, the first rotation is about the base and is a rotation about the z axis. The second shoulder rotation is a rotation about a horizontal axis. The final motion is a rotation of the elbow, which may be a rotation about a horizontal axis, but the axis may be at any position in space determined by the base and shoulder rotations. For the jointed-arm robot, the work envelope when looked at from the top of the robot is circular. When looked at from the side, the envelope has a circular outer surface; however, the inner surface has scallops due to the limits of the joints. An actual anthropomorphic robot is shown in Figure 3–6. The jointed-arm design can move at high speeds in various directions and has a greater variety of angles of approach to a given point.

The Cartesian robot has a cube-shaped work volume. The cylindrical robot has a cylindrical work volume. The spherical robot has a spherically shaped work volume. The anthropomorphic robot has a somewhat spherically shaped work volume with scallops due to the joint constraints, as shown in Figure 3–7. Each practical robot has fixed limits of motion so that the actual work volume is usually less than the theoretical volume. For example, some space must be left out of the work volume for the robot manipulator, since no two solid objects can occupy the same space simultaneously. However, each design has found wide application.

It is interesting to compare the jointed-arm robot to the human arm. First, we have a

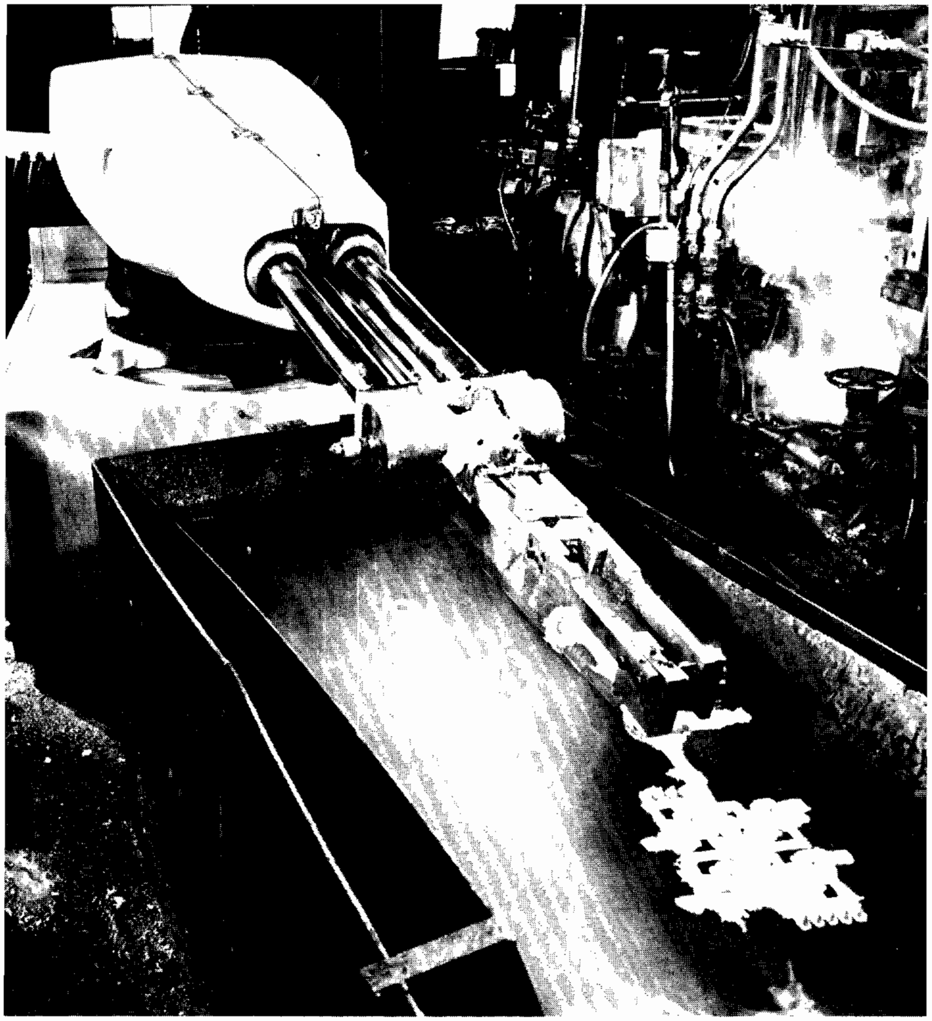


**Figure 3–5.** A Unimate spherical coordinate robot. (Courtesy of Joseph F. Engleberger.)

mobile base through the use of our legs, which may be used to position our body at any accessible point in space. Next, we have 3 degrees of rotation more at our waist, which might be used to orient the shoulder in any direction. These extra or redundant degrees of freedom give dexterity to the mobile human over the single base rotation of the robot. At the shoulder, which we may compare to the industrial robot shoulder, we have a very unique ball-and-socket joint. Instead of a single rotational degree of freedom, the human shoulder can rotate in three different ways. It can rotate up and down about a horizontal axis, which we may call pitch. It can rotate forward and backward about a vertical axis,

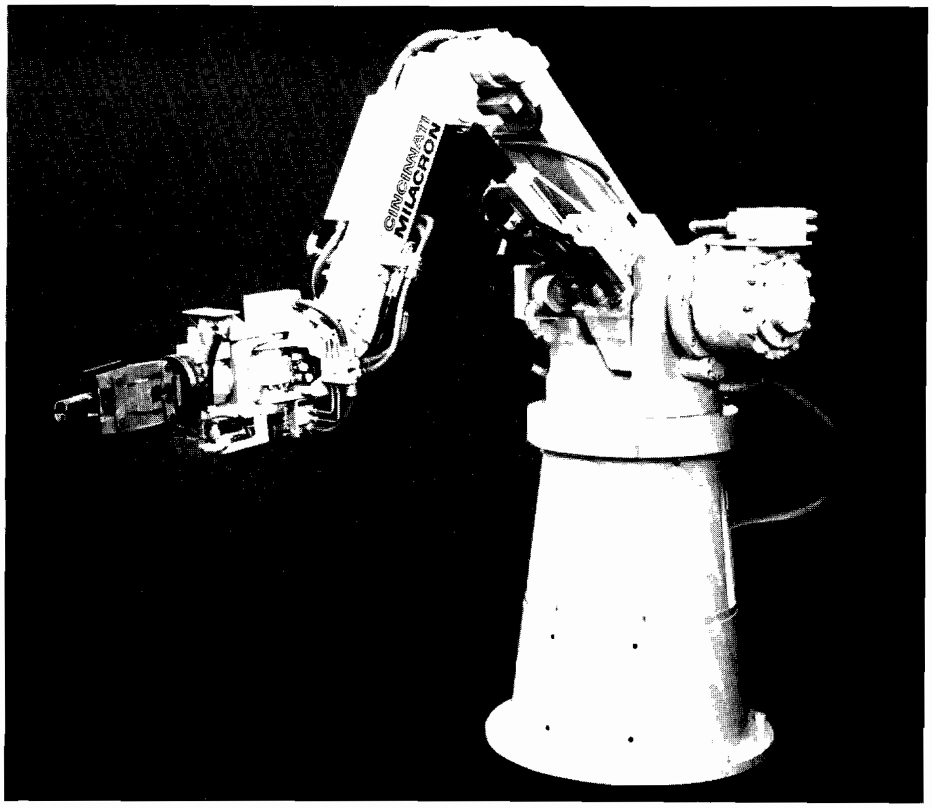


**Figure 3–6.** An anthropomorphic robot. (Courtesy of Cincinnati Milacron.)

which we may call yaw. Finally, it can roll about an axis along the straightened arm. Now, let's consider the elbow rotation with the human in a sitting position. The human elbow can rotate about a horizontal axis, a vertical axis, and about the axis of the forearm, achieving pitch, yaw, and roll actions. These extra degrees of freedom in the human arm are redundant, since only three are needed to position the wrist at any point in our work space. They give humans many different ways to position the wrist in space, aid in avoiding collisions, and improve the ability to reach into constrained spaces. You may want to try the following experiment. Close your fist, and keep the wrist joint rigid. Pick any point in space, say, an object on a table in front of you within your reach. Now, explore the many ways you can move your hand toward that point. An infinite variety of pathways can be used. This fascinating versatility of the human has not yet been built into our industrial robots. Perhaps the most basic reason is cost. Each degree of freedom requires an actuator, power source, and control mechanism. Another reason is simply that we do not yet have the mathematical sophistication to solve the equations of motion for such a complicated mechanism as the

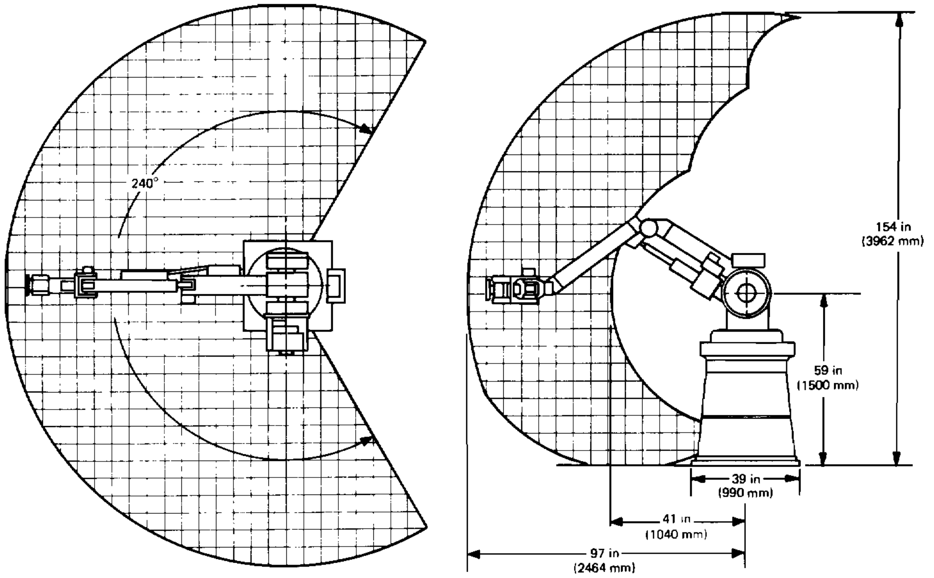


**Figure 3–7.** The work volume of a jointed-arm robot. (Courtesy of Cincinnati Milacron.)

human arm, nor do we have the computer power to make the control calculations at a nearly human speed. Furthermore, no one has yet designed a remotely actuated ball joint, such as that in the human shoulder. Fundamental and applied research are needed in the basic mathematics required for the control, in high-speed computation, and in electromechanical design before we can fully understand or duplicate the human arm. In the meantime, it is a tribute to robot designers and engineers that they have developed designs and practical industrial robots that perform so well.

The arm may be driven or actuated directly with the actuator located at the joint, or remotely with the actuator located at the base and a transmission used to transmit power to the joint. For an anthropomorphic design, 3 rotary degrees of freedom are required. The base can often be directly driven, since its actuator can be located in the base itself, and therefore not add to the weight and inertia of the manipulator. The shoulder actuator may also be located in or near the base. The elbow actuator may require careful design to avoid adding significant inertia to the base. Piston and cylinder, ball screws, gear drives, or other remote drives are often used to minimize the weight and inertia of the arm.

A new form of robot has recently been developed. Its design is somewhat like the links in our spine or of the vertebrae in a snake. This robot is called the active cord mechanism (ACT) by its developer, Professor Y. Umetani, of Tokyo University. The "spine" design provides a very flexible motion characteristic that would even permit it to move through a pipelike space.

Mobility may be considered a separate attribute of the robot manipulator. Mobile robots perform useful tasks by moving themselves and perhaps a payload through various programmed motions. This class of robots may include wheeled, tracked, or leg-type robots.

### *Wrists*

Thus far, we have described the robot arm's 3 degrees of freedom that permit it to position a tool at any point in three-dimensional space within its work volume. To perform useful work, it must also be able to position a tool in any possible orientation. This requires a wrist, which in general requires 3 degrees more of rotational freedom for tool orientation.

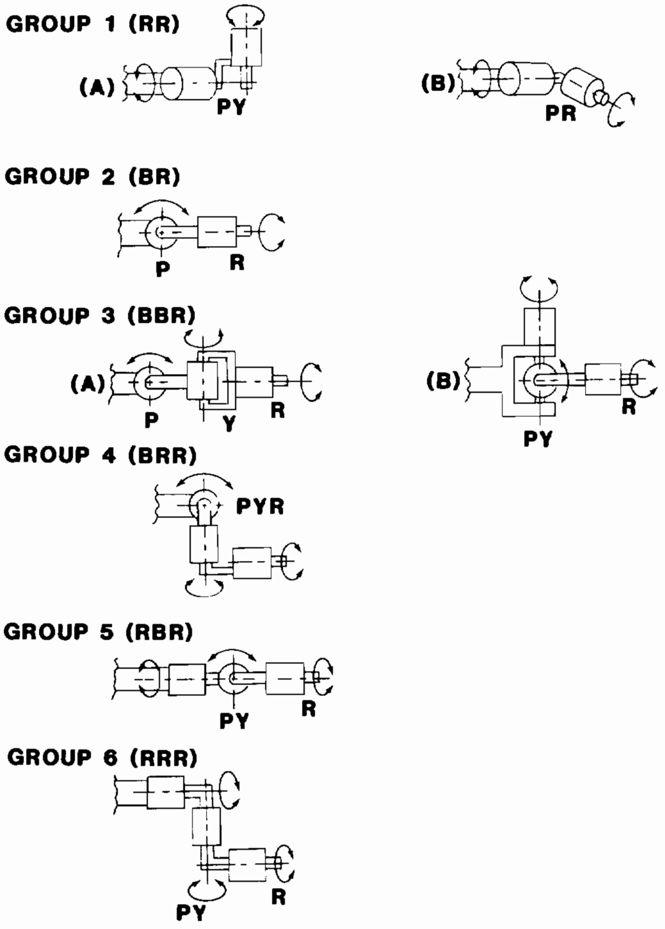
Wrists may be designed with various degrees of freedom and in various configurations. Stackhouse (1979) developed an interesting classification for robot wrists based upon the type and sequence of rotations used to obtain the three rotary motions. Three rotations are required to orient a tool or part in any desired manner. To appreciate this, suppose you are working with a regular screwdriver with a blade that is thick in one dimension and thin in the other. To orient the screwdriver requires a pitch rotation up and down about a horizontal axis to provide the first angle of orientation. Another rotation, yaw, around another horizontal axis is required for the second. Finally, to align the blade of the screwdriver requires a final rotation, a roll, which is a rotation about the axis of the screwdriver. These three angular rotations would also orient a tool, such as a gripper, a wrench, or a welding gun.

In Stackhouse's classification, a distinction is made between a bending rotation and a roll rotation. In the screwdriver example, the pitch and yaw rotations would be classified as bends, which are rotations about an axis perpendicular to the longitudinal axis of the link or tool. The final rotation is defined as a roll, which is a rotation about the link or tool axis. The difference in these rotations is that a bend motion is restricted from full 360-degree rotation by its link, but a roll rotation could theoretically rotate all the way around. We may also define the rotations from the workpiece or tool action. A pitch is a rotation about a horizontal axis. In an airplane, pitch causes the nose of the plane to move down or up. Yaw is a rotation about a vertical axis. In the airplane, a yaw motion moves the nose of the plane to the left or right. Finally, a roll is a rotation about the axis of the link. In the airplane, a roll motion turns the plane about its own axis. With these definitions in mind, let's consider various wrist designs that have 1, 2, or 3 degrees of freedom.

A variety of wrist actions are shown in Figure 3–8. Wrists with 1 degree of freedom could involve either a bend or a roll. However, we will see that on almost all industrial robots, the final rotation is a roll. Wrists with 2 degrees of freedom are more practical, because some robots, such as those used for spray painting, may need only 2 degrees of freedom to point a spray device in a given direction. These present two possibilities. Let's call group 1 wrists those that have two rolls. Two-roll wrists would have two separate links, each link capable of rotating about its longitudinal link axis. Consider the following two designs. In one design, which we will call type A, the axes of the two links intersect at a point that is offset from the physical point of contact. In type B, the intersection and the point of contact are coincidental.

| Group | Wrist Axes | Wrist Orientations of Payload |
|---|---|---|
| 1 | Roll-Roll | Pitch & Yaw or Pitch & Roll |
| 2 | Bend-Roll | Pitch & Roll |
| 3 | Bend-Bend-Roll | Pitch, Yaw, & Roll |
| 4 | Bend-Roll-Roll | Pitch, Yaw, & Roll |
| 5 | Roll-Bend-Roll | Pitch, Yaw, & Roll |
| 6 | Roll-Roll-Roll | Pitch, Yaw, & Roll |

(Note: By indexing the wrists in each group by 90° about the longitudinal axis of the arm, the pitch and yaw axes of orientation will become yaw and pitch axes, respectively.)



SCHEMATICS OF WRIST CONFIGURATIONS

**Figure 3–8.** A classification of wrist designs by the sequence, from the arm, of the rotations used in the wrist. Note that each wrist ends with a roll action. This is typical of manipulative wrists. Other wrist designs may be used for special applications, such as camera or other sensor mounts. (Courtesy of Cincinnati Milacron.)

Group 2 wrists are the other type of two-roll wrists, but in these designs, a bend is followed by a roll. The Microbot uses this type of design.

For wrists with 3 degrees of freedom, there are four possible design groups, each of which ends with a roll action. Group 3 wrists are of the bend-bend-roll variety. These implement pitch, yaw, and roll actions as seen from the manipulator arm. Type A has separate axis locations for the pitch and yaw motions. Type B has intersecting axes for the pitch and yaw actions.

The next wrist design, group 4, has a bend followed by two roll actions. Group 5 designs have a roll-bend-roll action. Group 6 wrists have three roll actions. Two design variations are possible within this group. Type A covers those in which the roll axes are not coaxial, and type B covers those in which the roll axes are coaxial. An example of this type of wrist is the Cincinnati Milacron design of its patented, three-roll wrist, used on its T3 746 robots.

The wrist may be driven directly with the actuator located at the joint or remotely with the drive power transferred from the base with chain drives, rigid links, or other mechanisms. The directly driven design can generally supply greater strength but adds to the weight and inertia of the manipulator. The remotely driven wrist reduces the inertia of the manipulator but adds to the complexity of the design since a transmission is required.

We have now considered the basic robot manipulator design that implements 6 degrees of freedom—3 that enable it to position a tool at any point in three-dimensional space, and 3 orientation angles, which permit it to position a tool in any orientation. Interestingly, almost all industrial robots have a roll action as the last motion, so that such motions as those required to turn a screwdriver can be accommodated. This design is different from the human arm, which implements its main roll capabilities in the elbow and shoulder.

The human arm has several more than the 6 degrees of freedom found on today's industrial robots. The design and use of these redundant degrees of freedom is an exciting topic for further research.

Let's look at some examples of commercial wrist designs. The Cincinnati Milacron T3 wrist is shown in Figure 3–9. This wrist is a group 3 design with two bend motions followed by a roll action. This wrist is moved by hydraulic actuators located near the rotational joints. Its initial design permitted it to lift a 100-pound load located 10 inches from its faceplate. This design permits great lifting capacity; however, it is directly rather than remotely driven. That is, the actuators are located at the joint action locations. This adds weight to the arm and makes the wrist rather bulky since the wrist size also includes the actuators.

A Unimate 4000 wrist design is shown in Figure 3–10. This is a group 4 design with a bend, roll, and roll action. The wrist is capable of lifting a 175-pound load and providing 3500 inch-pounds of torque for its first bend action, 2800 inch-pounds of torque about the first roll axis, and 2300 inch pounds of torque about the final roll axis. This wrist is also remotely driven and contains an ingenious set of gear trains in the wrist.

A schematic of the Renault robot wrist is shown in Figure 3–11. This wrist is a group 5 design since it has a roll, bend, roll configuration. This wrist is remotely driven

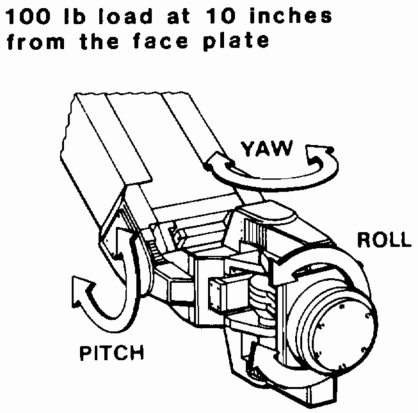


**Figure 3–9.** An example of a bend-bend-roll or group 3 wrist used on the Cincinnati Milacron T3 robot. The wrist is directly driven by the hydraulic actuators located on the wrist. (Courtesy of Cincinnati Milacron.)

by three actuators that transmit the drive force through a gear train, shown in the illustration, to achieve the pitch, yaw, and roll motions.

As a final example, let's consider the Cincinnati Milacron three-roll wrist shown in Figure 3–12a. This wrist fits into the group 6 category with three consecutive roll actions and with all three roll axes intersecting at one point. This patented, unique design was

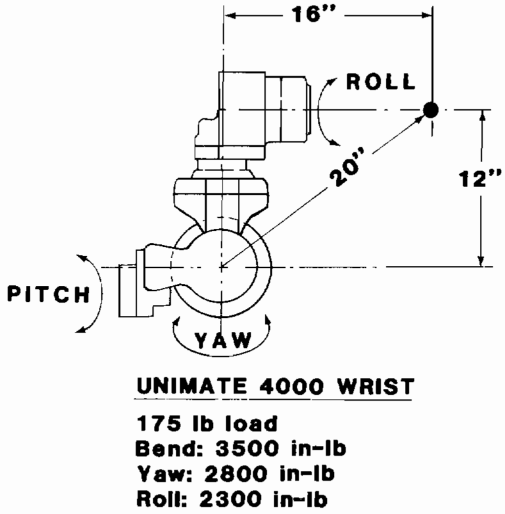


**Figure 3–10.** An example of a bend-roll-roll or group 4 wrist design used on the Unimation/Westinghouse 4000 series robot. (Courtesy of Joseph F. Engleberger.)

**RENAULT ROBOT WRIST**

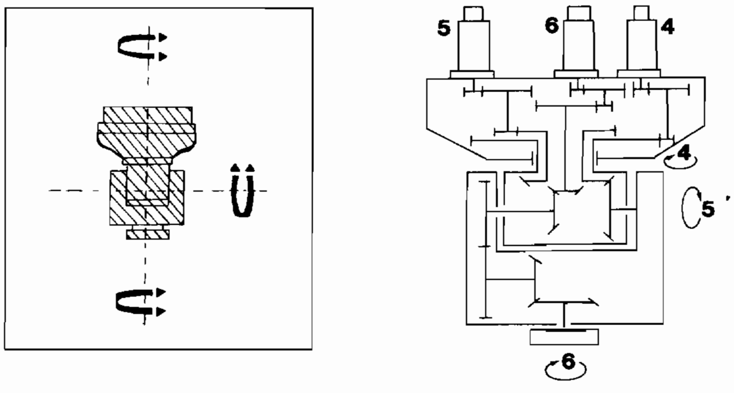


**Figure 3–11.** An example of a roll-bend-roll or group 5 wrist design used on a Renault robot. The wrist is remotely driven by actuators that activate a gear train located in the wrist.

reportedly conceived on a Saturday while Ted Stackhouse, an engineer at Cincinnati Milacron, was working in his basement. He looked up at the ductwork for his heating system and noted that the axes of the bent ductwork were coincident and realized that a robot wrist could be built using the same offset. The wrist also includes a uniquely simple gear train that could be remotely driven by three concentric torque tubes to provide the remote actuation for the three roll motions, as shown in Figure 3–12b. An outer torque tube drives the first roll, an middle torque drives the second roll, and an inner torque tube drives the final roll.

### *End Effectors*

With a clear idea of the arm and wrist geometries that provide the general robot with the ability to reach any point in space with any orientation, it is now time to consider the "business end," or end effector, of the robot.

Robot end effectors come in great variety to provide versatility. Basically, end effectors can be divided into two types—grippers and process tooling. Grippers may be two- or more fingered devices designed to grasp an object or tool in a manner similar to the human hand and fingers. Process tooling may be any useful device, such as a spot-welding torch, a spray-painting gun, a vacuum suction cup, or a set of interchangeable tools.

Grippers may be designed as physical constraint or as friction devices. A physical constraint device might work like a spatula that slides under an object to enable one to lift it. A frictional device depends upon the frictional force between two materials to provide the gripping force. When you put your hand under an object to lift it, you are using the physical constraint principal. When you grasp an object with your fingers to lift it, you

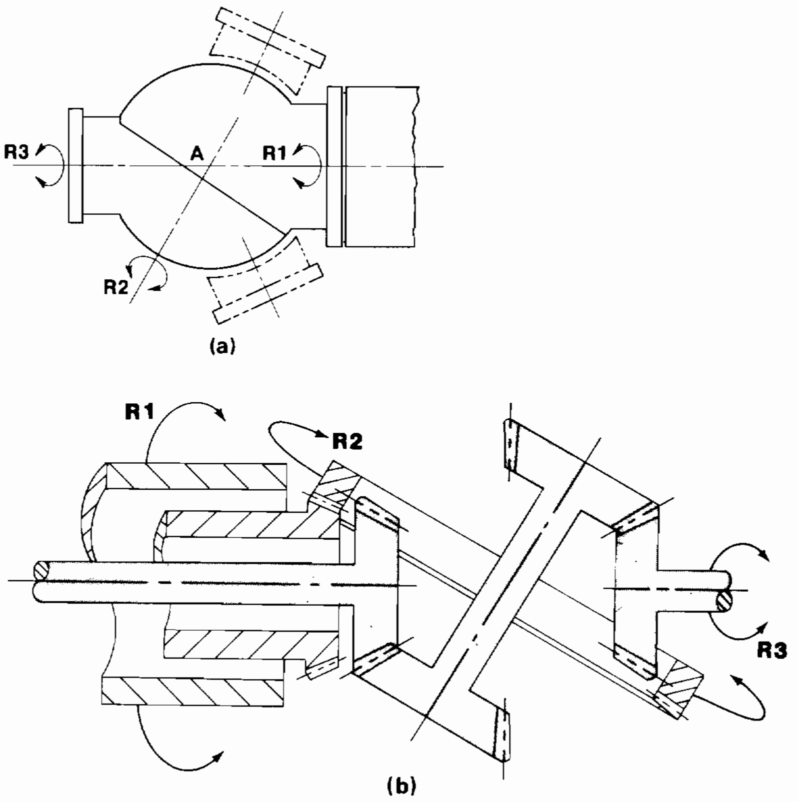


**Figure 3–12.** (a) An example of a roll-roll-roll or group 6 wrist used on the Cincinnati Milacron robot. The wrist actions are remotely driven by concentric torque tubes that power a gear train located in the wrist. (b) The wrist includes a unique, simple gear train. The gear train and torque tubes are shown here. (Courtesy of Cincinnati Milacron.)

are relying on the frictional force between the skin and object material to permit you to lift it.

When you lift an object using the constraint principle, it may appear that the only force you must overcome is the weight of the object. However, if you move the object, dynamic forces must also be overcome. Suppose you accelerate an object from a resting state at a rate equal to the acceleration of gravity. This is the rate at which an object falls in a vacuum. To get an idea of this acceleration, just drop a small steel ball. It will fall 16 feet in the first second. When you accelerate the object upward at this rate, you must not only overcome the static force, which is equal to its weight, but also overcome a dynamic force equal to its weight. The dynamic force equals the product of mass times acceleration. (The mass is equal to the weight divided by the acceleration of gravity. When this is multiplied by the acceleration of gravity, the result is simply the weight.) The total force to move the object in this example is equal to the sum of the static and dynamic forces, which is twice the weight of the object.

When you lift an object upward by gripping the object from its sides using frictional forces, only a fraction, given by the coefficient of friction, of the sideways or horizontal normal force is available to overcome the static and dynamic forces acting vertically. For example, if the coefficient of friction is 0.2, then a horizontal normal force equal to five times the weight is required to lift the object. (The required force equals the coefficient of friction divided by the vertical force.) Generally, the softer the material, the greater its coefficient of friction, and the more nearly equal the normal force will be to the vertical force. Again, moving the object would require a compensation for the dynamic force. To move an object upward at the acceleration of gravity always requires a normal force greater than its weight. If the coefficient of friction were 0.2, then a normal force five times its weight on each side would be required to accelerate the object. The total force required to lift and move the object would now be 10 times its weight. For example, if a 100-pound object were used, a normal force of 1000 pounds would be required. This same difference between constrained and frictional forces for gripping objects may partially explain why so many of our useful implements have handles on them.

Several examples of gripper designs are shown in Figure 3–13. The simplest design is shown in Figure 3–13a and is actuated by a linear actuator that pulls or pushes the two drive linkages that cause the gripping linkages to rotate and close on an object. The maximum clamping force, the size of the opening, and the moving speed of the gripper fingers depend directly on the location of the rotation centers. A four-linkage mechanism is shown in Figure 3–13b. The advantage of this design is that the fingers move in a parallel motion. This design is suitable for gripping box-shaped components. For handling soft objects, a design such as that shown in Figure 3–13c is appropriate. This frictional-type gripper has bellows on each side that are inflated to grasp the object. A dual gripper that can grasp either the inside or outside diameter of a part is shown in Figure 3–13d. A variation of this design for longer rectangular or cylindrical objects is shown in Figure 3–13e. Various commercial designs are shown in Figure 3–13f, including suction cups in different arrangements. The Skinner hand is shown in Figure 3–13g. This three-fingered hand, with 3 degrees of freedom for each finger, has 9 degrees of freedom and consequently much greater gripping flexibility than a two-fingered gripper. Finally, electromagnetic grippers are shown in Figure 3–13h. This great variety of gripper designs shows the flexibility that can be achieved in using robots for many applications. Also note that the multifingered hand is the best example yet developed of a universal gripper.

Process tooling refers to the general class of special end effectors that may be attached to the robot wrist. A spot-welding gun can be attached to the robot wrist to place a series of welds on flat or curved surfaces. Generally, a 3-degree-of-freedom wrist is required because of the dexterity required for maneuvering the gun. An arc-welding torch is another widely used end effector. The robot can position the welding torch for a single straight or curved run or use a weaving pattern for wider welds. Ladles are also used for applications in which the robot must scoop up and pour molten metal into a casting. Spray-painting guns are also commonly used by industrial robots. In some cases

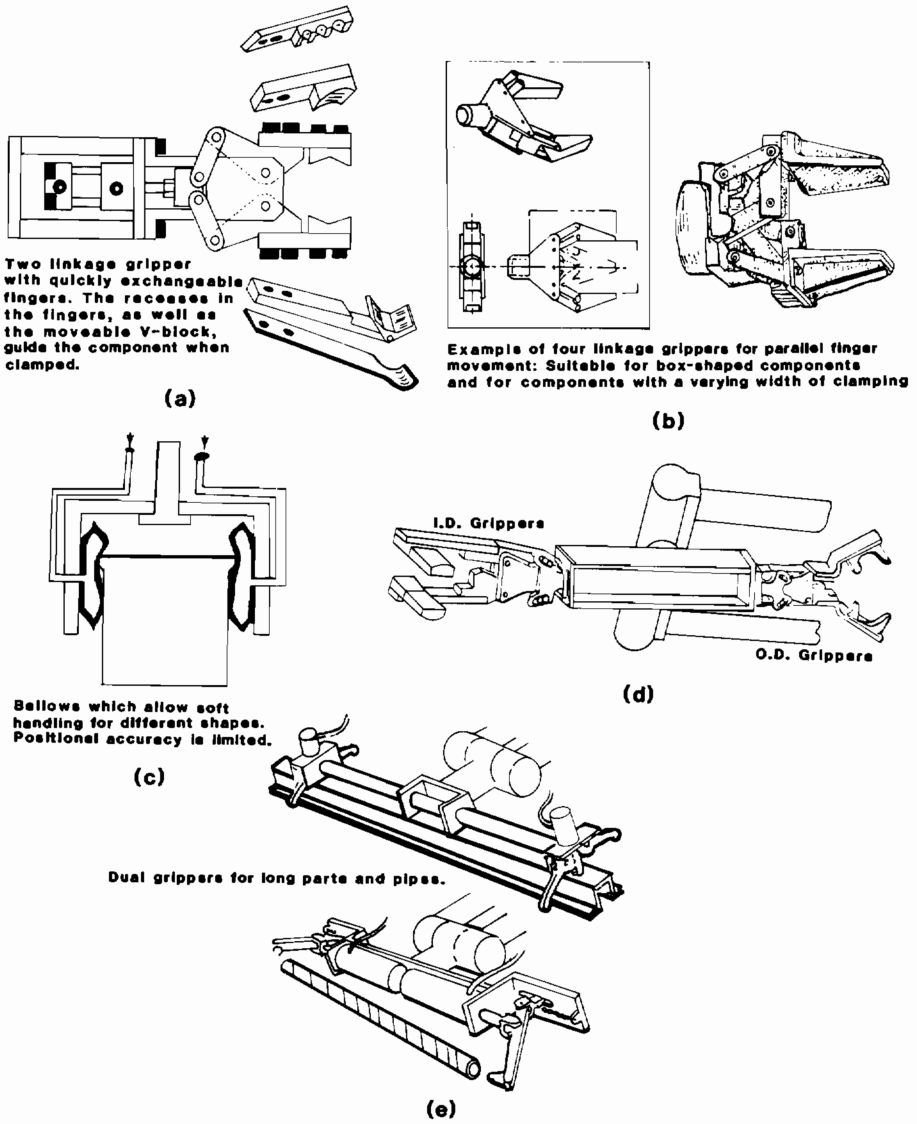
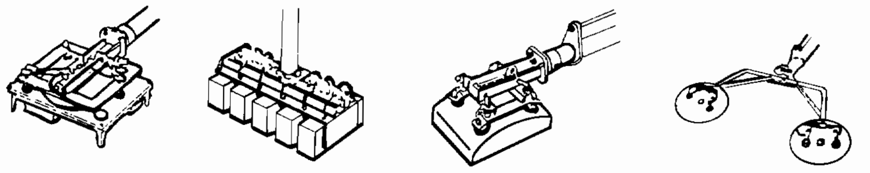
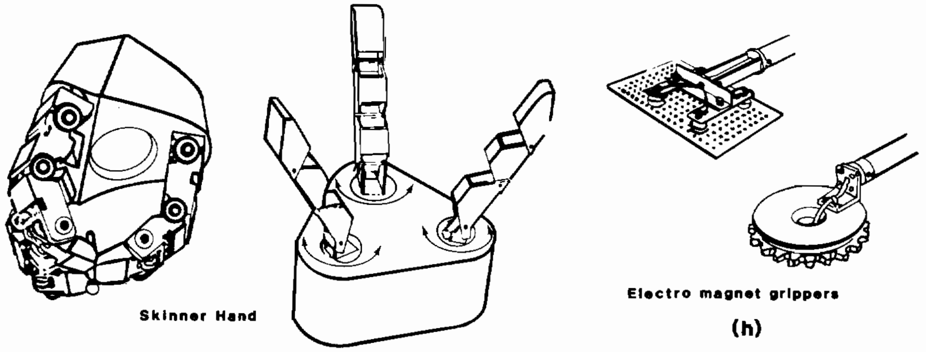


**Figure 3–13.** Various types of end effectors used on industrial robots. (a) A rotary or two-linkage gripper designed for interchangeable fingers. The linear motion of the drive mechanism causes the gripper linkages to rotate and open and close the gripper. The recesses in the fingers, as well as the movable V-block, guide the component when clamped. (b) An example of a four-linkage gripper design that provides for parallel finger movement. This gripper action is suitable for box-shaped components and for components requiring a variable width for clamping. (c) A bellows gripper that permits soft handling of objects of various shapes. The positional accuracy of such a design is limited. (d) A rotatable gripper designed to grasp either the inside or outside diameter of an object. (e) Elongated gripper designs suitable for grasping long objects from either the inside or outside diameters. (f) Various types of vacuum suction cups (Shinko, Japan.) (g) The Skinner hand, a three-fingered gripper that has 12 degrees of freedom. (h) Two forms of electromagnetic grippers. (Courtesy of Joseph F. Engelberger.)



Suction cups in different arrangements (Shinko, Japan)

(f)



Skinner Hand

(g)

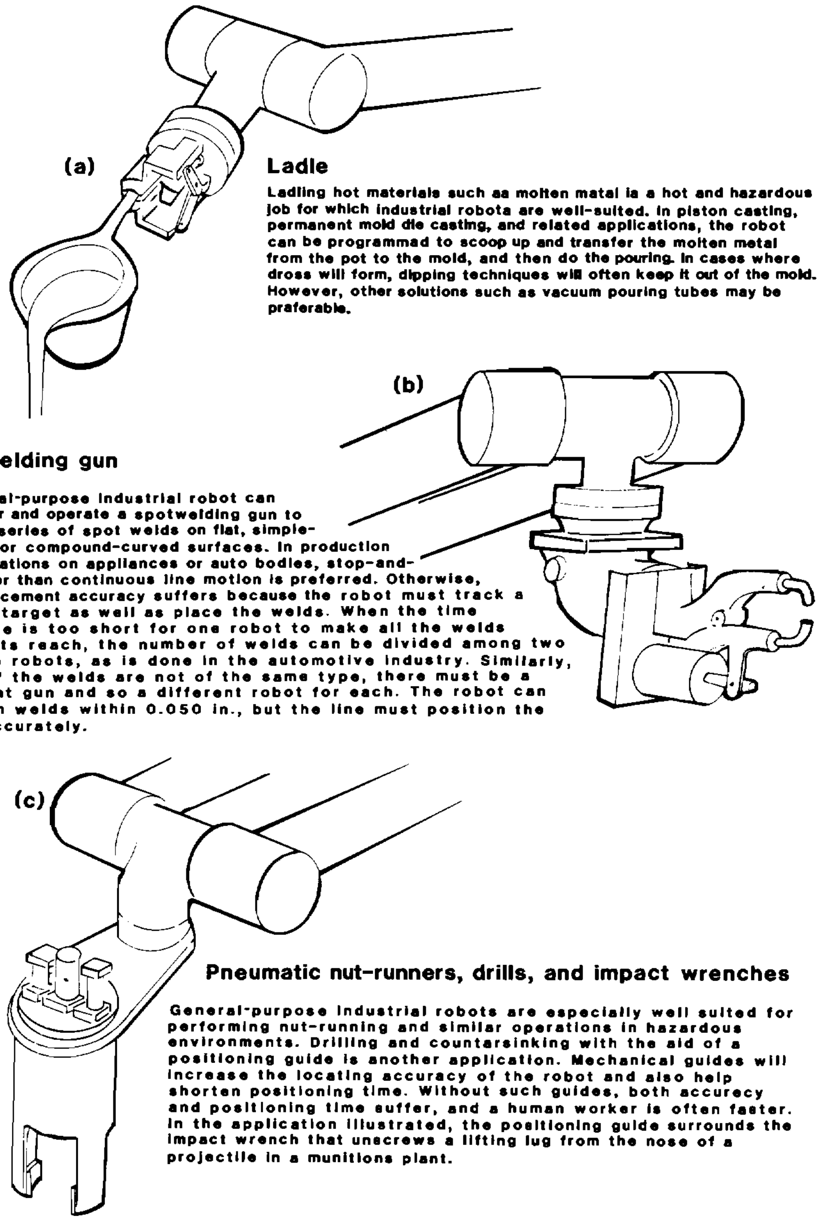
Electro magnet grippers

(h)

**Figure 3–13** (continued)

only 2 degrees of freedom may be required of the robot wrist for spray painting. The robot can spray parts with compound curved surfaces. Grinders, routers, or sanders are also easily attached to a robot wrist. A large class of assembly tools, such as drills, screwdrivers, and wrenches, can be used by the robot. In some cases these tools are automatically interchangeable by the robot.

A variety of process tools is shown in Figure 3–14. These tools were developed by Unimation for the many applications of their industrial robots. A tool for ladling hot materials, such as molten metal, is shown in Figure 3–14a. This type of tool is used in casting applications. A spot-welding gun is shown in Figure 3–14b. The welding gun consists of electrodes that, when positioned by the robot, are energized to melt the materials to form a joint. Tools, such as impact wrenches, similar to those used to remove the nuts from automobile tire lugs may also be used for robotic applications. One such example is shown in Figure 3–14c. Other tools, such as drills, screwdrivers, and cutting tools, can also be attached to the robot wrist. A tool called a stud-welding head is shown in Figure 3–14d. Studs are fed through a tube and welded in place. An arc-welding torch is shown in Figure 3–14e. Arc welding is an important industrial application not only because it removes a human from a hazardous environment but also because it provides improved weld consistency and quality. The industrial robot can also manipulate a tool like the heating torch shown in Figure 3–14f. A tool for grinding is shown in Figure 3–14g. Grinding, edge routing, or sanding can be readily accomplished with an industrial robot with the appropriate tooling. Spray painting or adhesive



**Ladle**

Ladling hot materials such as molten metal is a hot and hazardous job for which industrial robots are well-suited. In piston casting, permanent mold die casting, and related applications, the robot can be programmed to scoop up and transfer the molten metal from the pot to the mold, and then do the pouring. In cases where dross will form, dipping techniques will often keep it out of the mold. However, other solutions such as vacuum pouring tubes may be preferable.

**Spotwelding gun**

A general-purpose industrial robot can maneuver and operate a spotwelding gun to place a series of spot welds on flat, simple-curved, or compound-curved surfaces. In production line operations on appliances or auto bodies, stop-and-go rather than continuous line motion is preferred. Otherwise, weld placement accuracy suffers because the robot must track a moving target as well as place the welds. When the time available is too short for one robot to make all the welds within its reach, the number of welds can be divided among two or more robots, as is done in the automotive industry. Similarly, if all of the welds are not of the same type, there must be a different gun and so a different robot for each. The robot can position welds within 0.050 in., but the line must position the work accurately.

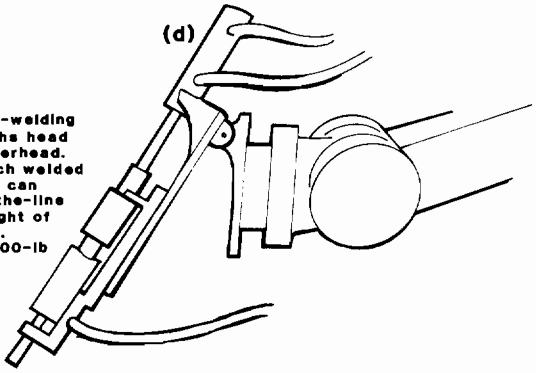
**Pneumatic nut-runners, drills, and impact wrenches**

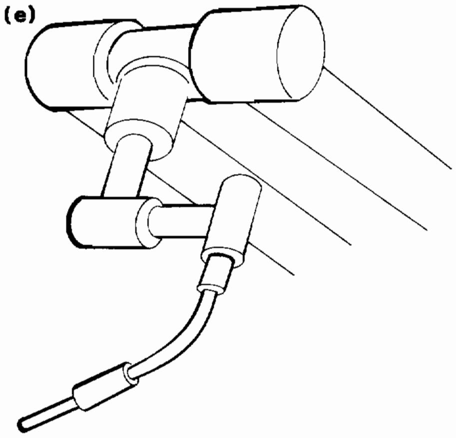
General-purpose industrial robots are especially well suited for performing nut-running and similar operations in hazardous environments. Drilling and countersinking with the aid of a positioning guide is another application. Mechanical guides will increase the locating accuracy of the robot and also help shorten positioning time. Without such guides, both accuracy and positioning time suffer, and a human worker is often faster. In the application illustrated, the positioning guide surrounds the impact wrench that unscrews a lifting lug from the nose of a projectile in a munitions plant.

**Figure 3–14.** Various types of process tools. (a) Ladle for pouring hot materials, such as molten metal, into a mold. (b) Spot-welding gun used to place a series of welds to join two materials. (c) Pneumatic impact wrench that was used for unscrewing a lifting lug from the nose of a projectile in a munitions plant. (d) Stud-welding head. (e) Arc-welding torch. (f) Heating torch used to bake foundry molds. (g) Grinder used for removing rough edges from castings. (h) Spray-painting gun. (i) Changeable tools can be used with the industrial robot. In the application shown, spot- and arc-welding guns may to changed using the holding device. (Courtesy of Joseph F. Engelberger.)

## Stud-welding head

Equipping an industrial robot with a stud-welding head is also practical. Studs are fed to the head from a tubular feeder suspended from overhead. One caution concerns accuracy with which welded studs can be located. An industrial robot can position a stud within 0.050 in., but on-the-line work positioning must be exact. The weight of the head is rarely a significant limitation. Stud-welding heads are well within the 100-lb capacity of standard robots.





## Inert gas arc welding torch

Arc welding with a robot-held torch is another application in which an industrial robot can take over from a man. The welds can be single or multiple-pass. The most effective use is for running simple-curved and compound-curved joints, as well as running multiple short welds at different angles and on various planes. Maximum workpiece size is limited by the robot's reach, unless the robot is mounted on rails. Where the angle at which the gun is held must change continuously or intermittently, the industrial robot is a good solution. But long welds on large, flat plates or sheets are best handled by a welding machine designed for that purpose. In addition to welding for fabrication purposes, wear-resistant surfaces and edges can be prepared by laying down a weld bead of tough, durable alloy. And the robot will handle a flame cutting torch with equal facility.

## Heating torch

The industrial robot can also manipulate a heating torch to bake out foundry molds by playing the torch over the surface, letting the flame linger where more heat input is needed. Fuel is saved because heat is applied directly, and the bakeout is faster than it would be if the molds were conveyed through a gas-fired oven.

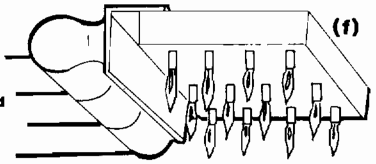
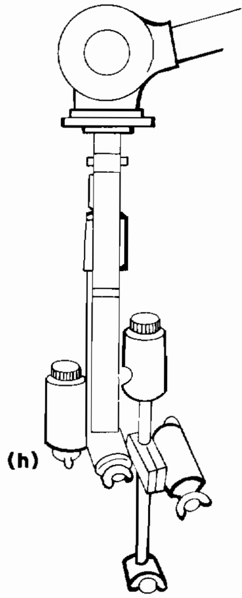
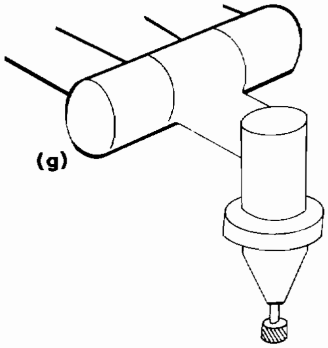


**Figure 3–14** (continued)



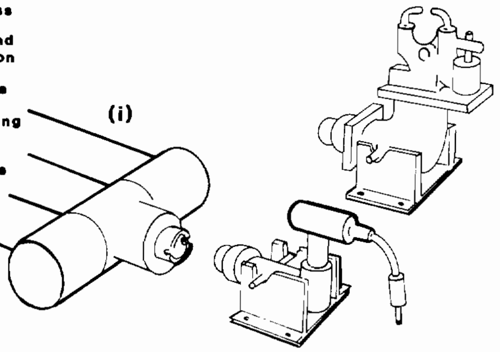


## Routers, sanders and grinders

A routing head, grinder, belt sander,or disc sander can be mounted readily on the wrist of an industrial robot. Thus equipped, the robot can rout workpiece edges, remove flash from plastic parts, and do rough snagging of castings. For finer work, in which a specific path must be followed, the tool must be guided by a template. The template is a substitute for the visual-and sometimes tactile- control that a human worker would exercise. In such a case, the overall accuracy achieved depends upon how accurately the workpiece is positioned relative to the template. Usually, the part is automatically delivered to a holding fixture on which the template is mounted.

## Spray gun

Ability of the industrial robot to do multipass spraying with controlled velocity fits it for automated application of primers, paints, and ceramic or glass frits, as well as application of masking agents used before plating. For short or medium-length production runs, the industrial robot would often be a better choice than a special-purpose setup requiring a lengthy changeover procedure for each different part. Also, the robot can spray parts with compound curvatures and multiple surfaces. The initial investment in an industrial robot is higher than for most conventional automatic spraying systems. When the cost of frequent changeovers is considered, the initial investment assumes less importance. Industrial robots can be furnished to meet intrinsically safe standards for installation in solvent-laden, explosive atmospheres.



## Tool changing

A single industrial robot can also handle several tools sequentially, with an automatic tool-changing operation programmed into the robot's memory. The tools can be of different types or sizes, permitting multiple operations on the same workpiece. To remove a tool, the robot lowers the tool into a cradle that retains the snap-in tool as the robot pulls its wrist away. The process is reversed to pick up another tool.

**Figure 3–14** (continued)

placement can be applied by a tool such as that shown in Figure 3–14h. The device shown has two containers that may be used to paint in two different colors. Finally, an example of tool changing is shown in Figure 3–14i. Obviously, the variety of process tools that can be connected to the industrial robot is limited only by the applications required.

**Compliant End Effectors.** A special end effector that is neither a gripper nor a process tool but rather a device that fits between the robot wrist and end effector for special assembly applications is the remote center compliant (RCC) device. This device was developed at the Charles Stark Draper Laboratory of Cambridge, Massachusetts and is now commercially available. In effect, the RCC is a springy wrist attachment that permits parts to be mated together. The design permits the frictional forces encountered when putting a peg in a hole to rotate or translate the peg to fit the hole. The two errors that can be encountered in parts mating are a translational error when the part is not centered over the hole and a rotational error when the part is not aligned with the hole. The RCC device consists of two linkage mechanisms, each of which reduces one of the error types. The two mechanisms and an actual RCC device are shown in Figure 3–15. The rectangular linkage mechanism causes a translation in response to frictional forces. The trapezoidal portion produces a rotation about a remote center point, which aligns the part. In the commercial version both mechanisms fit together to produce a rugged, compliant design. Other devices for assembly are also available. For example, engineers at the Kawasaki laboratories in Japan can put together complex parts, such as motors and gearboxes, using high-precision feedback, cleverly designed grippers, and compliant fixtures. Also, an active RCC device has been constructed in which the center may be changed.

### *Control Units*

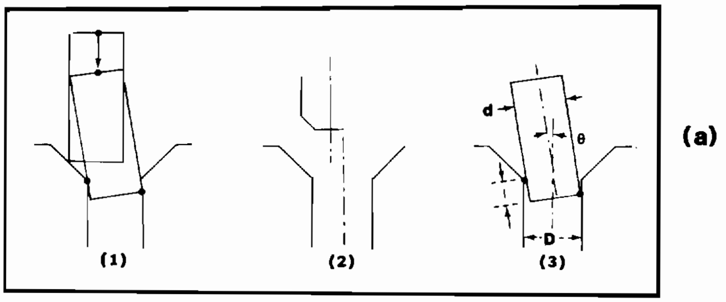
The arm, wrist, and end effector compose the main moving portion of a robot. However, a controller and power source are also required. A controller may be as simple as a sequencer with a series of adjustable mechanical stops or as complicated as a hierarchical array of computers. The modern controller must contain memory to permit storage of programs and data, drive elements for each of the robot's degrees of freedom, and interface elements to permit the response to external signals. The robot can be programmed to accurately follow a path from point to point or a continuous path.

The modern programmable controller used with an industrial robot is a special microprocessor equipped with easily interfaced circuits for connections to external devices, a special programming language, and an industrial-quality enclosure. Methods of control are more fully described in Sections 3.2, 3.3, and 3.4.

### *Power Units*

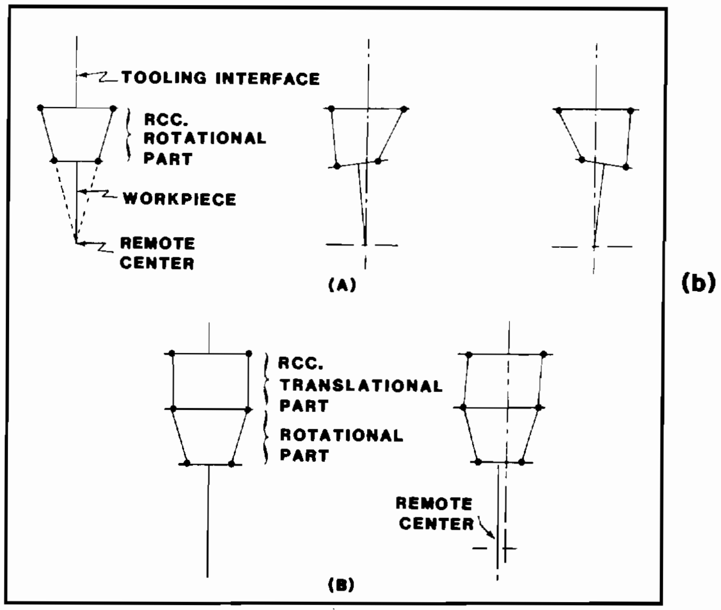
A power unit is required to move the robot and payload through the desired motion. A hydraulic power source is generally used for lifting heavy weights or in a possibly

**Problems in Small Parts Mating**



**As part slides down chamfer (1) it acquires angular error if it is held at the top. Chamfer of peg falls within chamfer of hole (2). Only one chamfer on peg or hole is necessary. Defining terms for analysis of two point contact (3).**

**Remote Center Compliance (RCC) Device**



**Sketches in (A) show two-dimensional representation of rotational part of RCC. Translational part allows workpiece to translate without rotating (B).**

**Figure 3–15.** Problems in assembling small components can be overcome using the principle of remote center compliance. (a) Positioning errors result in an offset of the part from the hole. Orientation errors result in angular offset. (b) Design of a passive compliant device that uses only frictional forces to overcome both positional and orientational errors. The trapezoidal four-bar linkage causes the part to rotate about a remote center and align the part with respect to the hole. The rectangular four-bar linkage translates the part to overcome positional errors. (c) A schematic of a practical implementation that includes both compliant mechanisms in a compact arrangement. (d) A commercial remote center compliance device in a rugged compact design. (Courtesy of the Charles Stark Draper Laboratory, Inc., Cambridge, Massachusetts.)

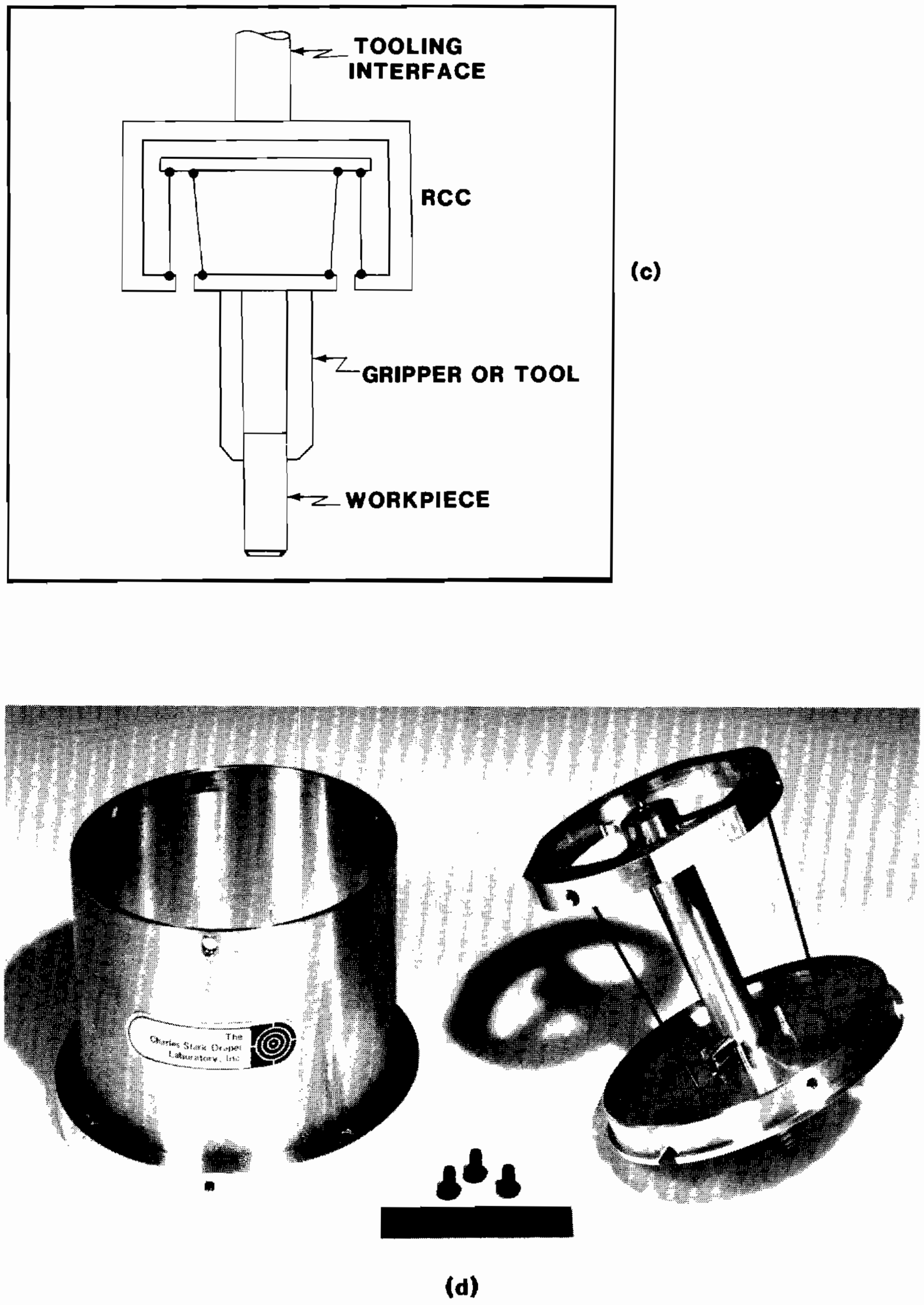


Figure 3–15 (continued)

explosive environment, such as in spray painting. An electric-drive robot may be used in a medium-weight application for which high accuracy is required. A pneumatic source has often been used for simple pick-and-place robots, especially in factory environments that have a readily available compressed air supply. A typical hydraulic power system is shown in Figure 3–16. In operation,.the pump generates a flow at a given pressure. An accumulator unit is used to dampen any changes in the pressure due to loading or other factors, such as temperature changes. The fluid flows through a load, such as an actuator valve, and back through a cooler into a reservoir, where it is filtered and recycled. Hydraulic actuators can provide power to lift very heavy loads and provide smooth operation. Spray-painting robots, such as the DeVilbiss/Trallfa TR-4500 shown in Figure 3–17, typically use hydraulic power for these reasons and to avoid any explosive hazard that might be caused by an electric motor.

Many of the newer robots are using electric power in such applications as welding, in which there is no spark hazard. An example of an electrically powered robot is shown in Figure 3–18. Direct current motors may be designed to meet a wide range of power requirements and are relatively inexpensive and reliable.

Pneumatically powered robots have an industrial advantage because air power lines are usually as common in factories as are electrical lines in a home. Therefore, these robots can be installed without a separate power source by direct connection to the existing pneumatic plant power. Pneumatic action is especially popular for nonservo robots. An example of a pneumatically powered robot is shown in Figure 3–19.

## 3.2 Operation of Industrial Robots

We have just briefly considered the mechanical aspects of the industrial robot, including the manipulator, control unit, and power source. We will now consider the operation of the robot. In general, control systems may be divided into two types, commonly called open-loop or closed-loop systems. Both are used in industrial robots. An example of an open-loop system is a stepper motor in which the control signals directly position the motor without feedback. Two types of closed-loop systems are used. These two types are called nonservo and servo. Each uses a feedback signal.

In an open-loop system, the input is applied and the output behaves in accordance with the characteristics of the system. An example of such a system would be the heating of a house by a fireplace. The input to the system is the fuel put into the fireplace, and the output is the temperature of the house at some point in time. The output temperature is determined by the amount of fuel burned, the outside temperature, the wind velocity, the amount of insulation in the house, and other factors. In contrast, a closed-loop control for a house might be one that uses a thermostat with a desired temperature setting and a thermometer. If the house temperature is less than the desired temperature, the furnace is turned on until the temperature reaches the desired value. The cycle of operation is closed because the temperature of the house acts through the thermostat to operate the furnace that heats the house and produces the desired temperature.

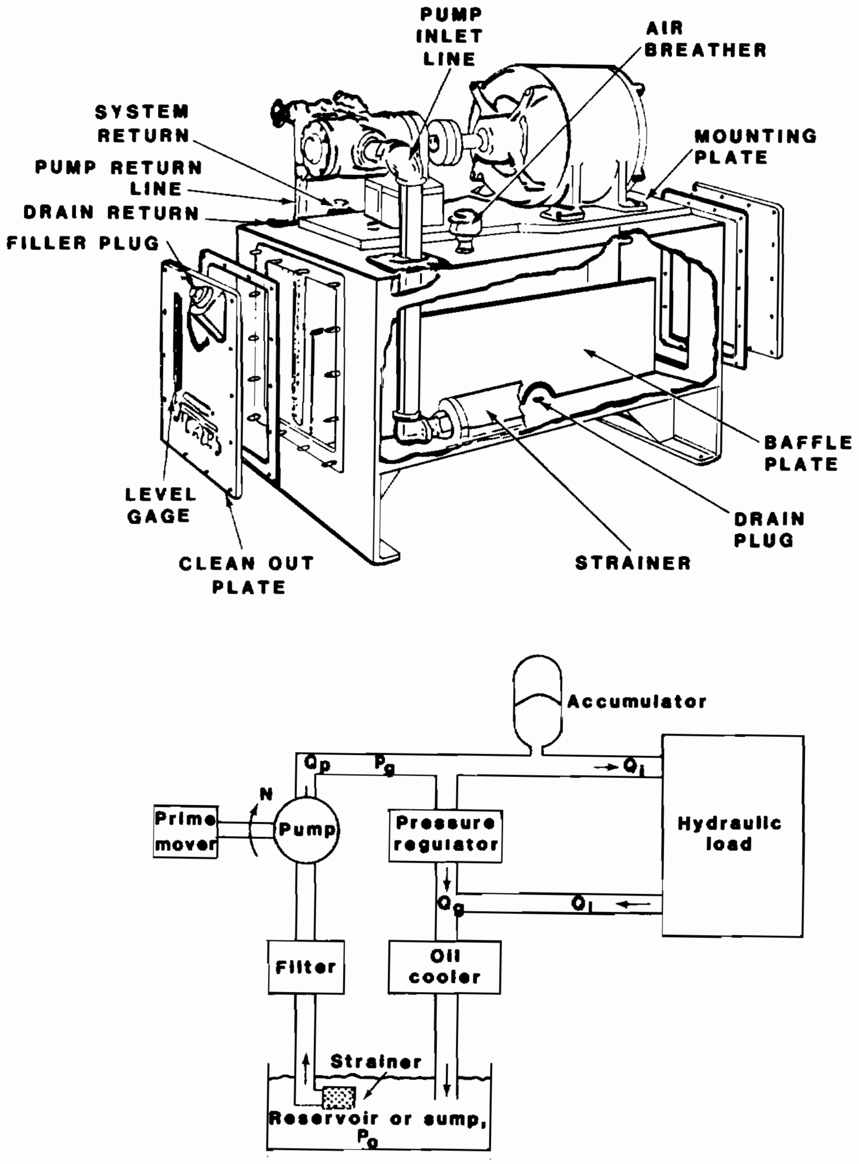


**Figure 3–16.** A hydraulic power supply. (a) Physical unit. (b) Flow diagram of the hydraulic unit. (Adapted from Herb Merritt, *Hydraulic Control Systems*. Reprinted by permission of John Wiley & Sons, Inc.)

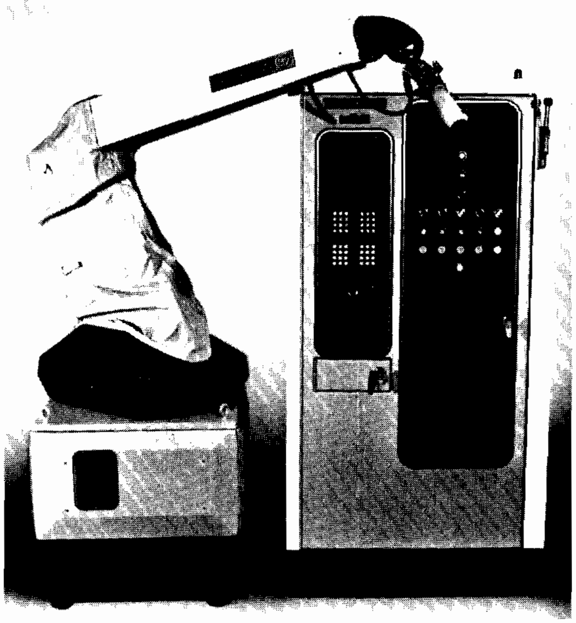


**Figure 3–17.** The DeVilbiss/Trallfa TR-4500 spray-finishing robot uses a hydraulic power system. (Courtesy of DeVilbiss Co., Toledo, Ohio.)

The word *servo* refers to a continuous-position controlling device. A nonservo robot may use a limit switch to indicate that the robot has reached the desired or end position. A servo system provides continuous positioning information along the path of the robot's movement.

Open and closed loop may also be used in reference to the overall robot manipulator. Five different classes of robot controllers are shown in the block diagrams in Figure 3–20. The first, shown in Figure 3–20a, is an open-loop axis controller that uses no feedback signals. The second, shown in Figure 3–20b, is called a nonservo controller and receives only on-off feedback signals. This type is in common use today and consists of an overall open-loop control, but local closed-loop joint controls. The third type, shown in Figure 3–20c, uses servo motors and feedback for each axis and is called a servo controller. This popular type uses local environment sensors that sense position and velocity to provide feedback information. The fourth type, shown in Figure 3–20d, is a more intelligent control with sensors in both the local and global environments to provide an overall feedback control. This type of control has not yet been implemented on an industrial robot. The fifth type, shown in Figure 3–20e, is an intelligent closed-loop control in which both local and global sensors are used to create and modify the strategy of the robot. This type is also currently in the research stage of development.

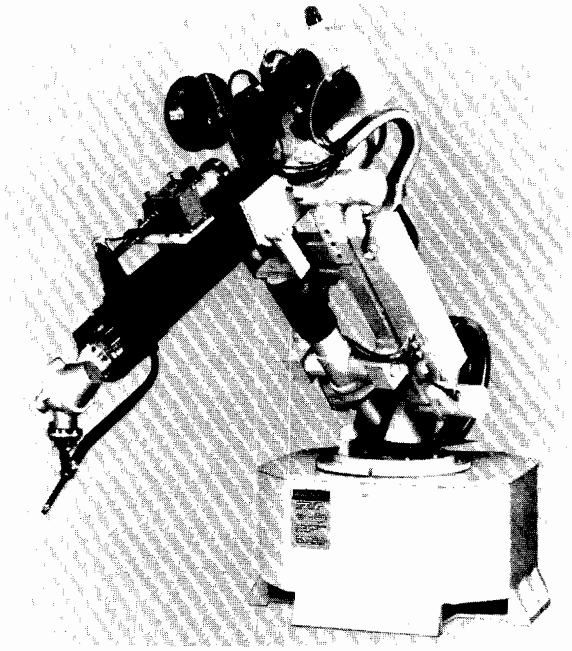


**Figure 3–18.** The Cincinnati Milacron T3 726 electric-drive robot with arc-welding torch. (Courtesy of Cincinnati Milacron.)

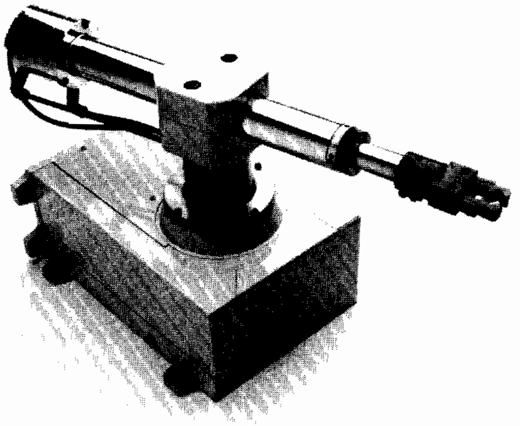
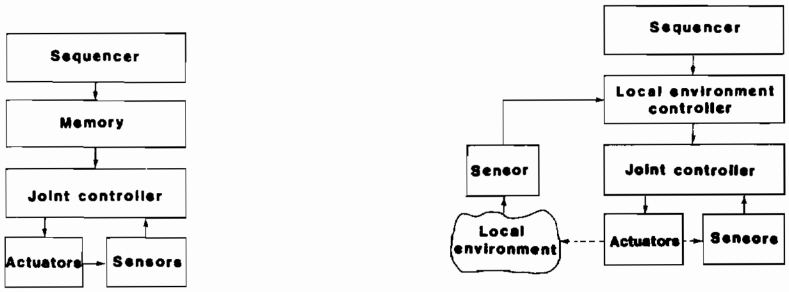


**Figure 3–19.** The Seiko Model 700 pneumatically powered industrial robot. (Courtesy of Seiko Instruments USA, Inc., Torrance, California.)

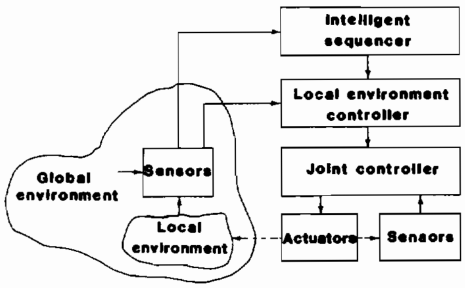
(a) Open-loop controller.

(b) Non-servo controller.



(c) Servo controller-sequencer, memory, and local control relationships for a typical robot.

(d) Closed-loop local controller, which uses sensors to dynamically modify the control strategy.



(e) Intelligent closed-loop controller, which uses local and global sensors to create as well as modify the local and global strategy.

**Figure 3–20.** Five classes of robot controllers. (a) Open-loop controller in which drive signals are sent to actuators but no feedback is used. An example of this type of control is the stepper motor actuators used on the Microbot MiniMover. Servo motors may also be used in this manner. (b) Bang-bang, off-on, or nonservo control in which drive signals are sent to the actuators but a return signal is sent back to the drive motors when the desired position is reached. Nonservo robots, such as the Seiko, use this simple form of feedback. (c) Servo control in which drive signals sent to the actuator are compared with measured signals from the axis to control the motion of the axis. (d) Closed-loop local controller that controls all axes in a coordinated manner. This type of control has not yet been implemented in an industrial robot because of computational complexity. (e) Intelligent closed-loop control in which the local and global sensors are used to create and modify the robot strategy and motion. (Adapted with permission from *Engineering Intelligent Systems: Concepts, Theory and Applications,* by Robert M. Glorioso and Fernando C. Colon Osorio, Jr., Copyright by Digital Press/Digital Equipment Corp., Bedford, Massachusetts, 1980.)

### *Nonservo Robot Operation*

The operation of a nonservo robot might be as follows for the control of a single axis. A controller is used to initiate signals to the control valve for the axis motion. The control valve opens, admitting air or oil to the actuator, which would be either pneumatic or hydraulic. The actuator starts the robot axis moving. The valve remains open, and the member continues to move until it is physically restrained by contact with an end stop. A limit switch placed at the end stop is used to signal the end of travel back to the controller, which then commands the control valve to close. If the controller is a sequencer or device capable of sending a sequence of control signals, it then indexes to the next step, and the controller again provides an output signal. These signals may go to the actuators on the robot manipulator or to external devices, such as the gripper. The process is repeated until the entire sequence of steps is completed.

Some features of this design are that the manipulator's members move until the limits of travel or end stops are reached. The number of stopping positions for each axis is at least two, providing the starting and stopping positions. It is possible to have intermediate stopping positions; however, there is a practical limit to the number of these that can be installed. This type of robot is thus limited in the number of positions in space that can be reached. If a six-axis robot has only start and end stops for each axis, then $2^6$, or 64, positions can be reached. To soften the shock upon reaching a stop, a shock absorber or additional valving may be used to provide deceleration. The sequencer may be programmed and conditionally modified through the use of external sensors. However, the sequence for this class of robots is usually restricted to the performance of a single program, such as that required to pick up an object at a fixed location and place it at a given location.

Several characteristics make the nonservo robot ideal for certain tasks. One such characteristic is the relatively high speeds achievable, since a control valve can provide the full flow of air or oil to the actuator. Manual speed adjustment may be provided by regulating this flow. These robots are also relatively low in cost, simple to operate, set up, and maintain, offer excellent repeatability, and have high reliability. They have been mainly used in materials-handling tasks for investment casting, die casting, conveyor unloading, palletizing, multiple parts handling, machine loading, and injection molding. A typical nonservo robot is shown in Figure 3–21. The dual-gripper design would permit the robot to load and unload a machine tool without having to rotate completely. The control loop of a nonservo robot is shown in Figure 3–22a. Note that the nonservo robot is limited to situations requiring little adaptability.

As an example of the operation of machine loading and unloading, let's consider the Prab Model FA robot installation at Eaton Corporation in Marshall, Michigan. In this application, the part to be machined is a 20-pound malleable iron casting used for a locking differential for a three-quarter-ton truck. It is a back-breaking job for humans to move 12 tons of parts per shift, and the resulting operator fatigue can lead to a decline in productivity and possible quality problems. It was decided to group three drilling and boring machines into a compact work cell designed to include a centrally located Prab Model FA cylindrical coordinate robot.

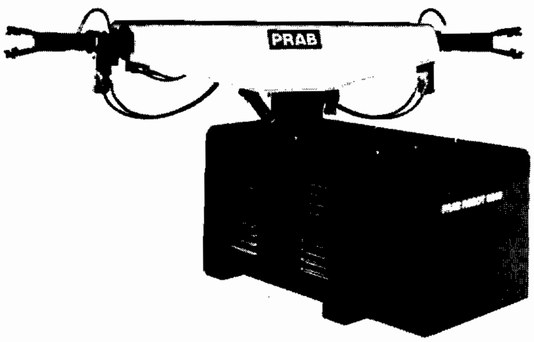


**Figure 3–21.** A nonservo controlled Prab robot, which is effectively used for many pick-and-place operations and is characterized by excellent repeatability and modest cost. Two arms, capable of working independently, qualify the new Prab Model 6200 robot for high-speed parts-transfer jobs, especially in the metal stamping press room. With five to nine axes of motion and ±0.008 inch repeatability, the Prab Model 6200 handles payloads weighing from a few ounces to 70 pounds with end-of-arm grippers. (Courtesy of Prab Robots, Inc., Kalamazoo, Michigan.)

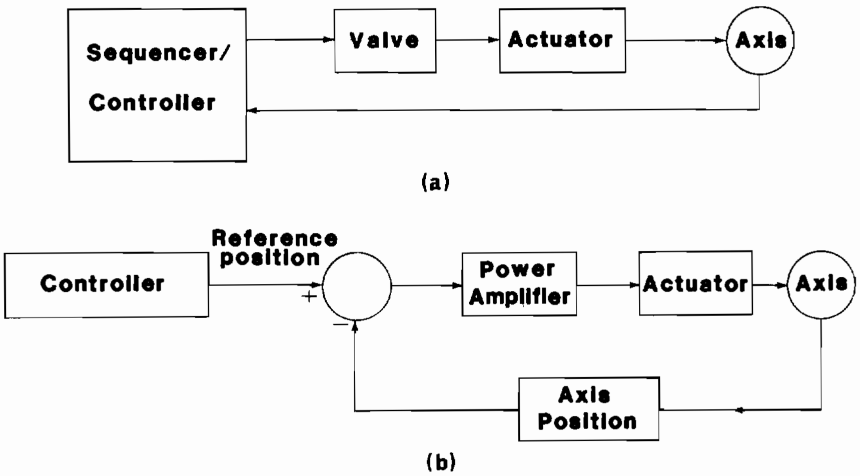


**Figure 3–22.** (a) The control loop for a nonservo robot. The controller or sequencer sends a drive signal to a valve that drives the actuator. When the axis reaches the desired position, a signal is sent back to close the valve. A characteristic of this type of control is that the robot can stop only at positions in which stops have been set. (b) The control loop of a servo robot. The controller sends a reference desired position. This desired position is compared with the actual position as measured by sensors, such as a shaft encoder and tachometer, where the error signal is used to drive the actuator through the power amplifier. When the error signal is zero, the actuator stops.

This example of a work cell is illustrative of the type of processes that may be included in the factory of the future. The operation of the cell is as follows. A pair of bell-shaped housings arrive at the work cell on an indexing conveyor precisely oriented on a fixtured pallet for the robot to pick up. Photoelectric cells are used to communicate to the robot that the parts are in position and ready to pick up. The machines are designed to accept two housings at a time. Therefore, the robot's gripper is designed to pick up and simultaneously move two parts through the three machines. The machines perform a drill-bore-drill operation. The first machine performs a drilling operation, and the second performs a boring operation. Both these machines require the parts to be oriented end to end, with the housing sides exposed for machining. The third machine performs a drilling operation requiring the parts to be oriented side by side. The dual grippers mounted on a rotary cylinder attached to the robot arm are programmed to accomplish this positioning. Following this last operation, the robot moves the parts to an unloading fixture on a simple outgoing belt conveyer. The robot is sequenced from unloading the third machine back to the incoming conveyor because the machine fixtures must be emptied before another pair of parts can be loaded. The robot performs a sequence of 49 steps to complete this cycle.

### *Servo Operation*

A basic servo-controlled system receives its reference position signal from the sequence controller. The axis position measurement device also provides a feedback signal proportional to its current location. The difference between the desired and current position is called the error signal. This signal is converted to the proper form and applied to the actuator. If there is a large difference, a large signal is applied to the actuator and it moves quickly. If the error signal is zero, no signal is applied to the actuator, since it is at the desired location. With proper design, the action of this feedback is very smooth and reliable.

The operation of a more modern controller will now be described. Upon start of execution, the controller addresses the memory location of the first command position and also reads the actual position of the axis from the position-measuring device. The desired and actual position signals are subtracted to form an error signal. The error signal is then amplified and converted to a velocity signal. The actual velocity signal is read from a velocity-measuring device, such as a tachometer. The difference between the desired and actual velocities is used as another error signal. This velocity error is fed to a compensation network, which serves to keep the controlled motion stable. The output of this network is amplified and used to control the actuating device that moves the robot arm. The position and velocity feedback signals are linked directly to the robot axis. Industrial examples of the use of servo-controlled robots are shown in Figure 3–23.

As the actuators move the manipulator's axis, the feedback signals are compared with the desired position data, generating new error signals that are used to command the robot. This process continues until the error signals are effectively reduced to zero, and the axes come to rest at the desired position. The controller then addresses the next memory location and responds appropriately until the entire sequence or program has

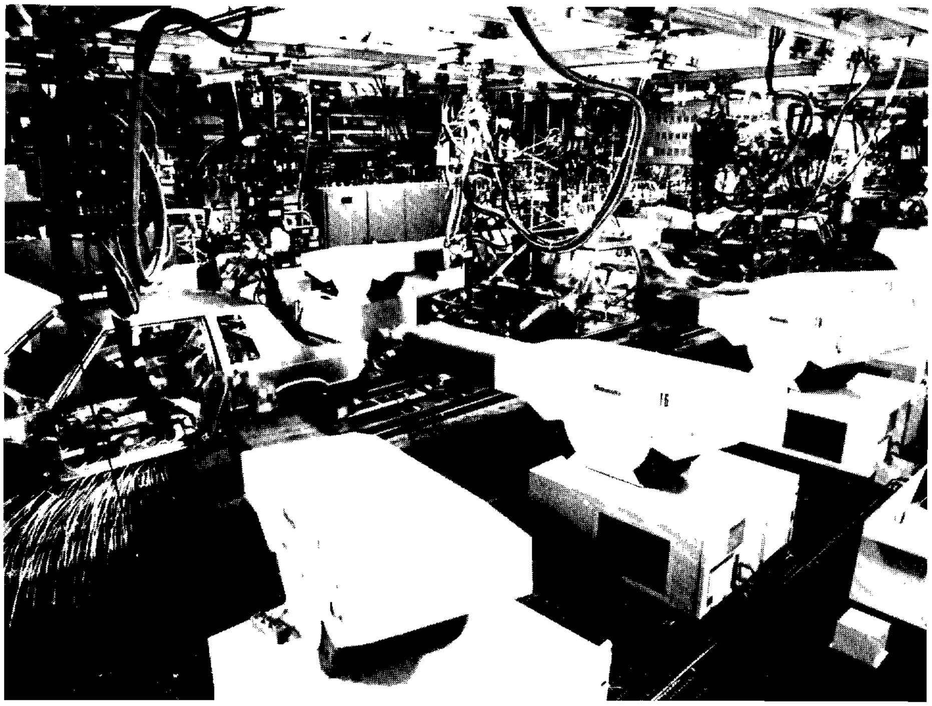


**Figure 3–23.** Examples of servo-controlled Unimate robots. A characteristic of this type of control is that the robot can be commanded to stop at any point in its work volume. (Courtesy of Joseph F. Engelberger.)

been executed. A simple control loop for a servo-controlled robot is shown in Figure 3–22b.

One of the main features of the servo-controlled robot is its versatility. It can move to any point within its limit of travel. It is also possible to control the velocity, acceleration, and deceleration between program points. With many systems, one can specify the travel velocity between points, which permits dexterous movements. The repeatability can be varied by changing the magnitude of the error signal, which is considered "zero." This feature may be used to permit the robot to round off a path between control points. Servo control systems have been used for hydraulic-, electric-, and, more recently, pneumatic-powered systems.

Programming may be accomplished either by a teach pendant, which permits the manual insertion of program points, or by external control for off-line programming. Either the output of the feedback position devices or the location of the end effector may be stored in the memory of the controller computer. The memory capacity of this computer is usually sufficient to store thousands of program points.

The characteristics of a servo-controlled robot may be observed in the smooth motions with control of speed and acceleration. This permits the controlled movement of heavy loads or delicate operations for sophisticated tasks. Since the servo robot can be positioned at any point within its working envelope, it has maximum resolution. Furthermore, most computer controllers permit the storage of main programs, as well as macros or subroutines, and permit program transfer based on tool conditions or external signals. Because of their complexity, servo-controlled robots may be more expensive than nonservo-controlled robots; however, the greater flexibility permits them to accomplish a greater variety of tasks.

## 3.3 Methods of Motion Control

The control of the path of movement of the robot can be accomplished in several ways. Four popular methods are called continuous path, point-to-point, joint interpolated, and controlled path motion. These will now be described.

### *Continuous Path Motion*

Continuous path control is illustrated in Figure 3–24 and is the most popular method for spray-painting robots. To program this motion, the operator, either by directly moving the robot or by using a teaching arm or pendant, leads the robot through the desired path. The controller records the robot position at a fixed time increment. The time increment may be variable within a range from 5 to 80 points per second. If the operator moves slowly, the recorded points will be close together, and if fast motion is used, widely spaced points will result. Some editing capabilities may also be available to permit correction of errors. Programming the continuous path motion sometimes requires considerable operator skill. It has been recommended, for instance, that the programming be done by the best operator on his or her best day.

The actual path of the robot between the control points may not be a straight line, since it is a function of the actuator response action in the fixed time increments. The programmed points must be stored, and cassette tapes or floppy disks may be used to store several thousand points. An example of this kind of painting robot was the Japanese robot at the 1982 World's Fair exhibit, which used different programs to paint various figures for sightseers to take home as souvenirs. An interesting point about this robot is that the robot arm vibrated at its stop points, which made the pictures come out differently each time. Such vibration would be undesirable for extreme precision.

### *Point-to-Point Operation*

The point-to-point programming method consists of moving the robot arm to each point using joysticks or push buttons to move the axes individually during teaching. At the desired location, a program button is pushed that stores the position information of that point, as shown in Figure 3–25. Points can be inserted at either closely or widely spaced intervals. In the standard point-to-point control, in playback or automated operation, all

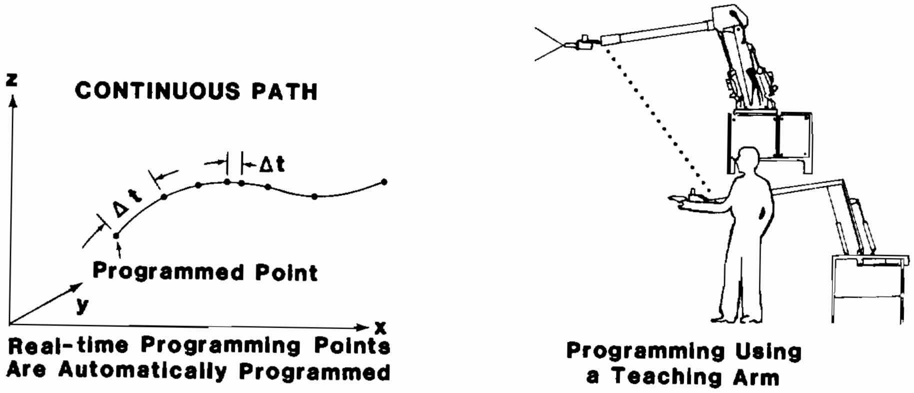


**Figure 3–24.** Continuous path motion as used, for example, on a spray-painting robot. During the programming stage, actuator control points are read and stored continuously or at discrete time intervals. If points are stored at discrete time intervals, the distance between points may vary. Upon playback the robot moves through the stored points in a point-to-point manner. (Adapted from R. E. Hohn, "Application Flexibility of a Computer Controlled Industrial Robot," MR76-603, 1976. Reprinted by permission of the Society of Manufacturing Engineers, Dearborn, Michigan.)

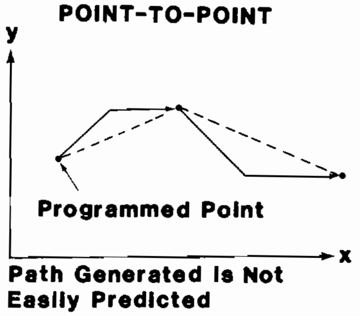


**Figure 3–25.** Point-to-point control. During programming, the actuator positions at selected points are stored. Upon playback, the robot moves through the programmed points. Motion between the points may be made in a coordinated manner by adjusting the velocity so that all axis motions end at the same time. (Adapted from R. E. Hohn, "Application Flexibility of a Computer Controlled Industrial Robot," MR76-603, 1976. Reprinted by permission of the Society of Manufacturing Engineers, Dearborn, Michigan.)

axes move at the maximum rate in a rather uncoordinated manner called the "race" mode. Whichever axis has the smallest distance to move will reach its position first, then wait for the others. This results in a path between points that cannot be easily predicted. Consider the following table, which is an example of the joint motions for a rotary axis robot with a fixed velocity of 10 degrees per second.

| Joint | Amount of rotation (deg) | Speed (deg/sec) | Time (sec) |
|---|---|---|---|
| 1 | 40 | 10 | 4 |
| 2 | 80 | 10 | 8 |
| 3 | 20 | 10 | 2 |
| 4 | 60 | 10 | 6 |
| 5 | 40 | 10 | 4 |
| 6 | 100 | 10 | 10 |

Note that joint 3 will reach its desired position in only 2 seconds but joint 6 will not be at the desired location for 10 seconds. The resulting motion may appear somewhat awkward.

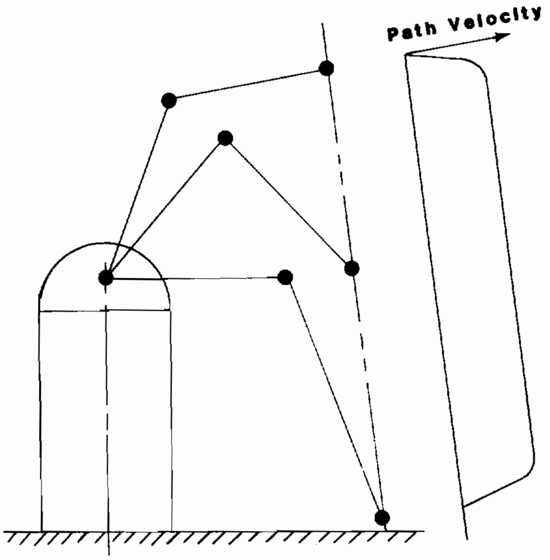
### *Joint Interpolated Motion*

Modified point-to-point or joint interpolated motion is designed to provide smoother motion. The points are programmed in a manner similar to the previous method. However, on automated playback, the velocity of each axis is adjusted. In this "proportional" mode, the axis that has the furthest to go, goes at maximum velocity. The other axes go at proportionally slower speeds. The following table clarifies this. Note that all axes reach their final position at the same time. The action is more coordinated than in the "race" mode; however, it is still not easy to predict the path.

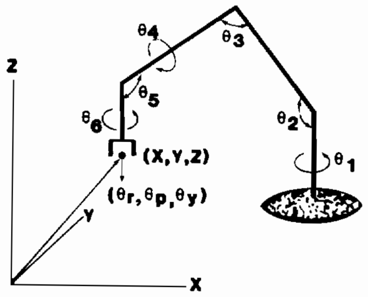
| Joint | Amount of rotation (deg) | Speed (deg/sec) | Time (sec) |
|---|---|---|---|
| 1 | 40 | 4 | 10 |
| 2 | 80 | 8 | 10 |
| 3 | 20 | 2 | 10 |
| 4 | 60 | 6 | 10 |
| 5 | 40 | 4 | 10 |
| 6 | 100 | 10 | 10 |

### *Controlled Path Motion*

Controlled path motion is still programmed at discrete points. However, the motion between points is a controlled path, such as a straight line, as shown in Figure 3–26. Intermediate points are computed so that a straight line path may be followed. This involves an internal computation between the commanded world coordinates of the robot and the joint angle coordinates. For example, the points programmed may be



| TIME (ms) | HAND POSITION & ORIENTATION | | | | | | OR | JOINT ANGLE | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | X | Y | Z | ROLL | PITCH | YAW | | $\theta_1$ | $\theta_2$ | $\theta_3$ | $\theta_4$ | $\theta_5$ | $\theta_6$ |
| 5 | 10 | 2 | 3 | 10° | 20° | 30° | | 10° | 35° | 70° | 92° | 18° | 36° |
| 10 | 12 | 2 | 3 | 11° | 20° | 31° | | 11° | 34° | 70° | 90° | 18° | 36° |
| ⋮ | | | | | | | | | | | | | ⋮ |



**Two alternate ways of representing the path of a robot**

**Figure 3–26.** Controlled path motion. This type of motion ensures that the robot follows a straight line between programmed points. An interpolation between programmed points is required to supply intermediate control points. This operation requires a computer capable of computing transformations between joint angles and hand position and orientation. The velocity and acceleration may also be controlled. (Adapted from R. E. Hohn, "Application Flexibility of a Computer Controlled Industrial Robot," MR76-603, 1976. Reprinted with permission of the Society of Manufacturing Engineers, Dearborn, Michigan.)

stored in either joint angles or world coordinates. However, for interpolation of intermediate points, the simplest computation is done in world coordinates. The command signals must again be in joint coordinates. This leads to the coordinate transformations (Huston and Kelly, 1982). These computations may be made either off-line and stored for playback by the robot, or computed on-line. The on-line computation provides the greatest flexibility of robot control. A vivid demonstration of the straight-line motion is shown in Figure 3–27. A ruler may be placed along the path of the end tool in this illustration to show the precision.

## 3.4 Hierarchy of Control for Robots

The overall control of a robot is a complex problem consisting of strategy development, path planning, sensory information integration, position commands, and drive signals. One method of simplifying this problem is to break it into levels of a hierarchy. In the hierarchy, items or tasks that are grouped together at a low level remain grouped through the higher levels. A family hierarchy with parents and children is a familiar example. A web or network in which there is more than one path to a particular mode is a more complex example.

The hierarchical control strategy for robots is described by Barbera (1977). He

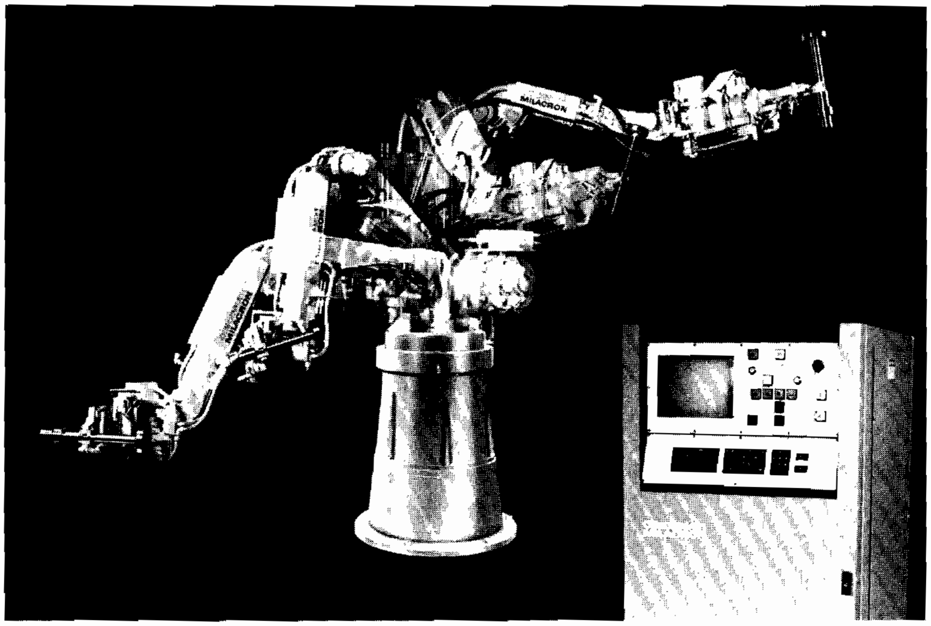


**Figure 3–27.** A Cincinnati Milacron T3 robot in a vivid demonstration of straight-line, controlled path motion. (Courtesy of Cincinnati Milacron.)

starts with a first-level control that receives joint position commands and sends drive signals to the robot's joint actuators. These first-level control loops often have feedback from position and velocity indicators to ensure that the joint motion is controlled and stable. In implementation, the first-level controller may be an analog, digital, or hybrid circuit. Stability, speed, and repeatability are key design specifications.

The second level control receives as input such commands as MOVE TO (X,Y,Z) and interprets this global command into individual joint position commands. These are then sent to the first-level control. If the command GRASP OBJECT is sent, then tactile or force feedback from the end effector may be sent to the second-level controller to verify that a grasp has been accomplished. Proximity sensors may also be used to alter the approach speed of the gripper. The interpretative nature of the second- and higher level controls often dictates a digital controller for implementation. The ability to interface with external sensors and interpret commands are characteristics of the second-level control.

The third-level control divides or parses higher level commands into individually required actions for the second level control. For example, the command MOVE TO (X,Y,Z) AT VELOCITY 30 INCHES/SECOND, DECELERATE AT 12 INCHES FROM OBJECT, GRASP UNTIL FORCE EQUALS 1 POUND must be divided into motion commands, positioning commands, and grasping commands. Feedback from joint positions and velocity sensors, proximity sensors, and tactile force sensors is needed to execute the command.

Higher levels of control may also be developed. Each higher level takes more complex task commands and higher level sensory information and develops commands for the lower level controllers. For example, in executing the previous command, the position and orientation of the object being grasped must be known. This information may be determined by a vision sensor. If more than one type of object is available, then the part identity must be established. Also, the relation of the part to the other objects and its surroundings must be determined. If the object is covered by other objects, then these obstructing objects must be removed before the part can be grasped.

Higher levels of control are needed for positioning commands. If there are obstacles in the environment, a strategy for avoiding them must be developed. If a path has been specified, it must be checked to see if it can actually be followed. If a path has not been specified, one must be determined. Even higher levels of control, which could take a single command like BUILD A CAR from a human and develop all the required lower level commands, can be envisioned; however, a great deal of research is needed before such a system can be implemented. An illustration of a hierarchy of control is shown in Figure 3–28.

## 3.5 Line Tracking with Industrial Robots

The assembly line is a control concept in existing and planned future factories. It characterizes the division of a task into subtasks, such as the material processing required to transform a given raw material into a finished product. The stationary

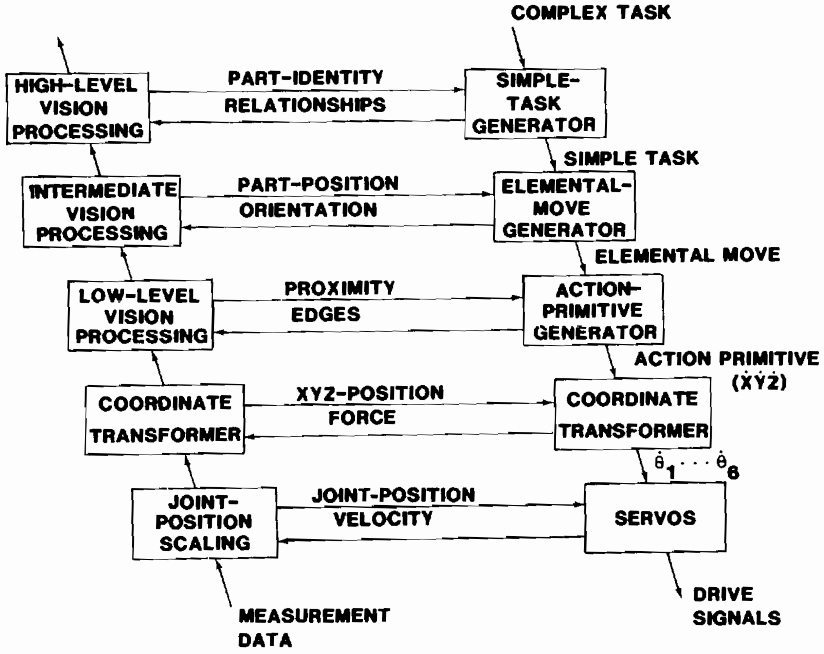


**Figure 3–28.** The hierarchy of control for servo robots. A complex task at the top of the hierarchy is divided into simple tasks, the simple tasks into elemental moves required to complete the task, and the elemental moves into primitive action commands in a world coordinate system. These coordinate commands are transformed into robot joint commands; the joint commands then become the drive signals for the robot actuators. The sensors required to accomplish each level of task accurately are shown on the left. Actuator joint positions and velocity are required by the servos. Overall measurement of position and force may be desired for the coordinate transformer. Low-level visual processing to determine position or proximity may be needed by the action generator. Higher level visual or tactile sensing may be required to determine the position and orientation of the workpiece. Very high level computer vision may be required to determine the position of obstacles, to permit path planning, and to react to unusual events in the environment. (Adapted from James S. Albus, *Brains, Behavior and Robotics,* 1981. Reprinted by permission of BYTE/McGraw-Hill.)

industrial robot is integrated into the assembly line by line tracking. Line tracking is the ability of a machine to carry out operations on parts mounted on a continually moving conveyor. Without line tracking, expensive, high-speed, and often heavy-duty shuttle systems must be installed and maintained. These shuttle systems take parts from the main conveyor to a location for processing, then return them to the main line. If the processing time is too long or the process robot too limited, a shuttle system is required. However, a robot with line-tracking capability can eliminate this nonproductive shuttle operation and reduce the part cycle time.

Industrial robots may be used for line tracking in two ways. In the moving-base line-tracking system, the robot is mounted on a traverse base. Generally, this method gives the robot a longer time to work on a given part, but requires an expensive traverse system. The second method is stationary-base line tracking. This method gives the robot access to a larger portion of the object and eliminates the need for the traverse system. Special considerations are required with line tracking. In the simplest case, a position resolver is attached to the conveyor and calibrated, and a part in the range switch is installed. Teach programming is then performed on a stationary part. This taught program can then be executed on the moving part, even at variable speeds.

## 3.6 Modular Robots

How is a robot built? Most industrial robots are custom-built to the specifications of the buyer. However, one other method is to use modular components and assemble the type of robot desired. Mack Corporation supplies nine basic components that can be combined to build a 6-degree-of-freedom Cartesian robot. The nine basic components are the grippers, adapters, x-axis, y-axis, and z-axis transporters, roll, pitch, and yaw rotators, and position incrementers, as shown in Figure 3–29.

The grippers are provided in four sizes in two- and three-finger configurations for

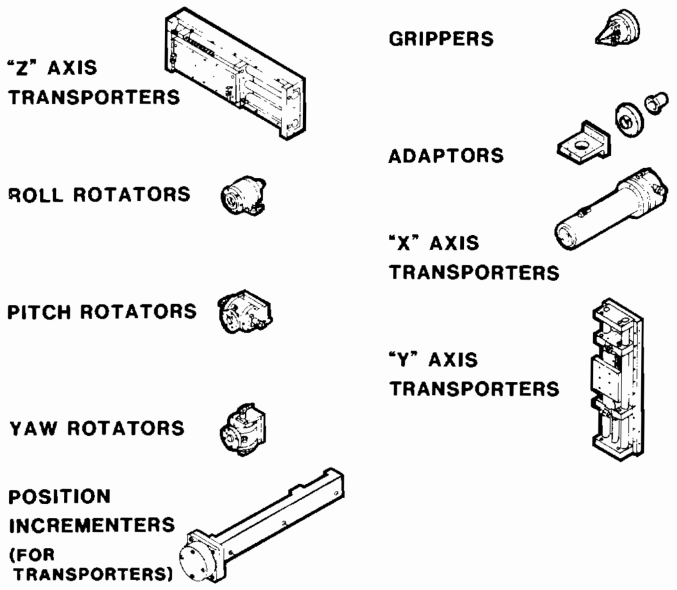


**Figure 3–29.** Basic components of the Mack Corporation modular robotic system. The components may be concatenated to form a variety of different Cartesian robot designs. These robot components are powered by pneumatic or electric sources. The maximum load capacity is 5 pounds. The resulting manipulator, when combined with a power system and controller, can make a complete robot system custom-designed to an application. (Courtesy of Mack Corporation, Flagstaff, Arizona.)

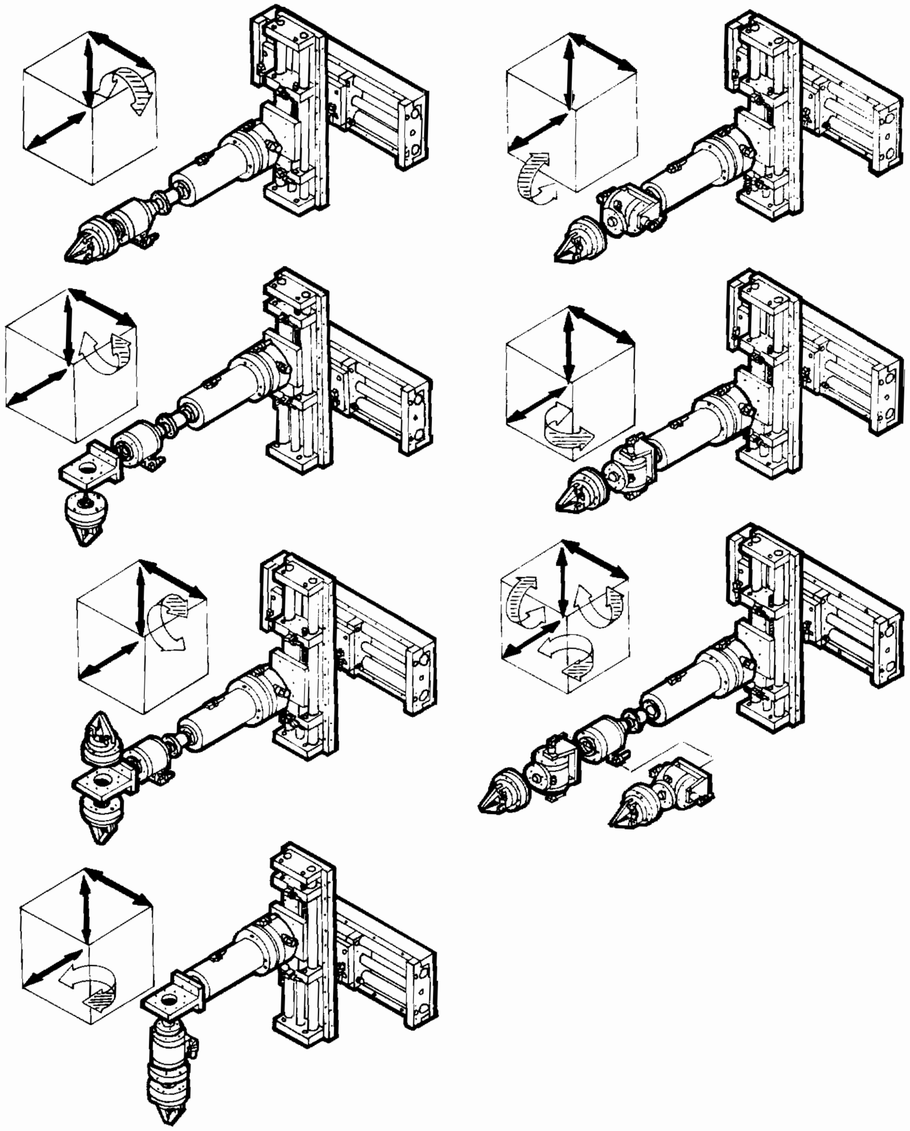


**Figure 3–30.** Combinations of the Mack components to produce a variety of robot designs. (Courtesy of Mack Corporation, Flagstaff, Arizona.)

external or internal gripping, as well as soft blank fingers that can be easily modified for special shapes. The smallest size is about twice as large as a thimble and the largest about the size of a human hand. All units operate on the principle of a double-acting cylinder controlled through a simple four-way valve circuit. Fluid pressure opens or closes the fingers. Maximum operating pressure is 150 pounds per square inch (psi) in either hydraulic or pneumatic service. However, most applications use plant air at 80 psi for a reliable source of fluid power. At 80 psi, a pinch force between 5 and 50 pounds may be developed, depending on the model size.

The gripper may be mounted in several orientations. Perhaps the simplest is to mount the gripper in line with the first desired motion. This mounting is facilitated by the various adapters. The transporters are the next elements to consider. The x-axis transporter is an air cylinder that provides straight-line motion. Special features include adjustable travel stops and pistons keyed against rotation. The x-axis transporter may also be combined with y- and z-axis transporters. These transporters may also be powered with plant air and may be controlled by simple air logic, or by programmable controllers or computers when more sophistication is required. Rotators are also key components in the modular system. The rotators are nonservo, air-operated, vane-actuated units with a choice of 90- or 180-degree rotations in roll, pitch, and yaw. Adjustable stops provide close control over the angular positions.

Many different designs can be constructed from the basic components, as shown in Figure 3–30. Combinations of the various components can provide a 6-degree-of-freedom, rectangular robot with a payload of 5 pounds and nonservo operation. Controllers are also provided. However, it should be noted that the modular robot components described here are for a fixed-sequence, nonservo positioner.

## Questions

1. What is the number of degrees of freedom required to position a robot manipulator at any point in three-dimensional space?
2. What is the work volume of a cylindrical robot?
3. A computer controller is essential in industrial robots for obtaining what controlled path motion?
4. In the hierarchical control strategy for a servo industrial robot, what is the function of the first-level control?
5. What are the four commonly used industrial robot configurations?
6. In assembly-line tracking with industrial robots, two methods were discussed. What were they?