CHAPTER 47
ROBOTS AND SMART MACHINES

Kenneth J. Waldron, Ph.D.
Professor of Mechanical Engineering
The Ohio State University

47.1 INTRODUCTION

47.1.1 Elements of a Robot System

In recent years, the so-called industrial robot has become a familiar feature of manufacturing plants. This class of machines is, of course, only a part of a much more diverse family of devices characterized by large numbers of degrees of freedom and intelligent controllers. Industrial robots are, however, by far the most numerous, visible, and economically important group of devices in this family. For this reason, much of the material in this chapter is directed at industrial robot design, although an attempt is made to place them in an overall context of intelligent mechanical systems.

Figure 47.1 indicates the hardware subsystems present in a generalized industrial robot system. The manipulator usually has six independently actuated joints, because a body which moves freely in space has six degrees of freedom. Consequently, if the "hand" of the manipulator is to be placed in an arbitrary position and orientation within the manipulator's reach, then the mechanism must have six degrees of freedom. Nevertheless, some industrial robots on the market have as few as four or as many as seven degrees of freedom. Some types of tasks do not require the full six degrees of freedom and can be handled by four- or five-degree-of-freedom robots.

Because the joints usually are not capable of complete rotation but can move only over a restricted angular range, additional degrees of freedom beyond the basic six are often useful for demanding manipulative operations. The joints may be actu-

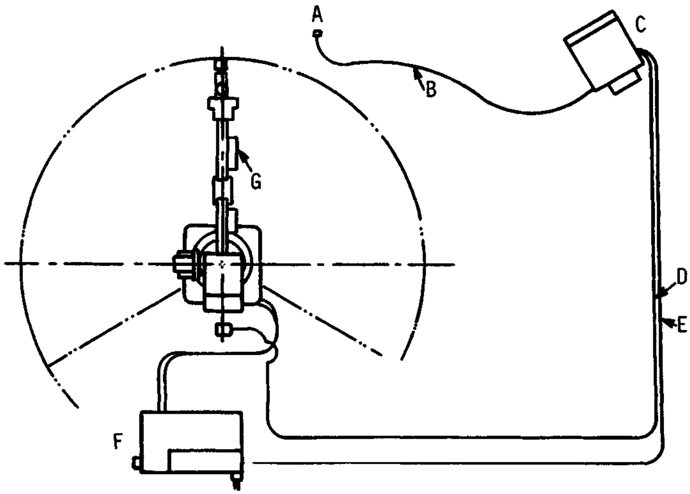

FIGURE 47.1 Components of a generalized industrial robot system: A, teach pendant; B, control to pendant (flexible conduit); C, control cabinet; D, robot to control (flexible conduit); E, power supply to control (flexible conduits); F, power supply; G, industrial robot.

ated electrically, hydraulically, or pneumatically. Each joint is equipped with a position sensor that furnishes the input signal to a servo controller, which positions the joint in response to commands from the central controller.

The hand of the manipulator takes a wide variety of forms depending on the operations for which it is being used. Most often it is a special-purpose tool such as a spot welder, a shielded-arc electrode, a paint sprayer, or a rotary drill. For manipulative or transfer operations it is often a simple gripper, consisting of two jaws which close as a vise on the workpiece.

The power supply varies considerably with the type of actuation used but is always present in some form. High-quality servo systems require well-regulated power regardless of the type of system. Hydraulic systems usually have relatively large and complex power supplies because conversion from electric to hydraulic power is performed locally.

The central controller is a mini- or microcomputer or, more accurately, is a set of software resident in that computer which translates a stored program to a series of position commands to the joint servo controllers to repetitiously generate a series of motions. The controller usually includes permanently stored monitor and operating system firmware. The latter includes a system for programming the machine and may include capability for writing and reading to tape cassettes or floppy disks. This latter capability permits long-term storage and reuse of programs. It also permits a program generated on one machine to be used on other similar machines.

The teach pendant, or programming box, is used in many robots, particularly those of the so-called point-to-point type. The operator uses controls on the teach pendant to place the robot in a series of positions. These positions are recorded and form the data used by the operating program. Additional programming information may be entered by command buttons or by keyboard entry of instructions. Thus, if the robot gripper is to be moved to a specified position and close at that position during the operating cycle, the operator must move the manipulator, using the teach pendant controls, until the gripper is in the desired position. Then the operator enters a command to close the gripper by means of the keyboard and pushes a button on the teach pendant, causing the positions of the joints to be recorded.

Modes of programming and operating industrial robots vary considerably with the class of functions for which each robot is designed. These are discussed further in Sec. 47.2.

47.1.2 Use of the Word *Robot*

The word *robot* has come to be used in a variety of different senses. Its use in naming the rather restricted class of devices introduced above and called *industrial robots* is at variance with the general English use of the word and, indeed, with its technical use outside the industrial robot industry. In common use, a robot is a device which mimics some of or all the characteristics of autonomous intelligence, locomotion, and manipulation found in human beings. In earlier technical use, as in the space program, for example, a robot device was one with a certain amount of local information-processing capability which could execute quite complex operations in response to relatively infrequent supervisory commands. This use was often applied to devices which had no manipulatory or locomotory function at all.

The essential feature of an industrial robot is that it is a *flexibly reprogrammable mechanical device* capable of performing a wide variety of functions. Industrial robots are devices built to perform relatively complex, but nevertheless highly repetitive, operations. They differ from purely mechanical devices, such as cam mechanisms, which also perform complex repetitive operations, in that the constraints which cause them to perform determinate motions are provided by digital data lists via an active actuation system rather than by kinematic constraints. In fact, from the point of view of mechanical design, the definition of the industrial robot is excessively restrictive. It excludes teleoperators (remote handling devices) and more general devices which more closely approach the general concept of a robot.

47.1.3 Externally Constrained Mechanisms

A more useful definition, from the point of view of mechanical design, is that a robot is an *externally constrained mechanism*. An externally constrained mechanism is one which has a relatively large number of degrees of freedom and which performs deterministic motions because additional constraints are provided by means of an active system which interfaces with the mechanism. The active system can be a set of servo actuators controlled by a computer, as in an industrial robot. It can also be an operator manipulating a control harness which is part of the mechanism, as in the case of a passive teleoperator. Many intermediate combinations are also found.

Figure 47.2 shows a purely mechanical teleoperator designed for the handling of radioactive materials. The master and slave arms are kinematically identical, and motion is transmitted between them by means of linkages. The device has six degrees of freedom. The external constraints are provided directly by the operator acting on the master.

The space shuttle manipulator arm is an example of a very sophisticated teleoperator. The operator's movements are not mechanically transmitted to the slave manipulator, as in the device of Fig. 47.2. The master controller geometry, in fact, bears no resemblance to the arm geometry. The controller movements are trans-

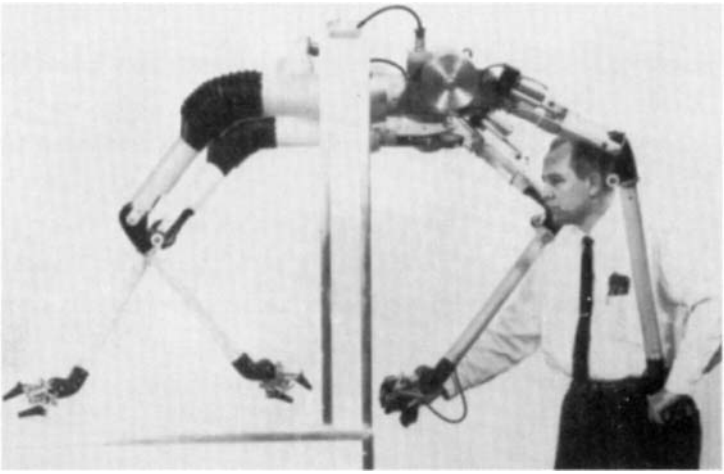

FIGURE 47.2 Mechanical teleoperator system for handling nuclear materials. The motion is transferred by linkages and cables. (*Sargent Industries.*)

formed in a computer to commands to a set of servo actuators which move the arm. Despite being a teleoperator, or master-slave mechanism, this device has a high level of machine intelligence. This is needed not only to transform the movements of the controller to movements of the geometrically dissimilar arm, but also to apply sophisticated control techniques to obtain smooth, stable motion from the highly compliant arm. The device is a teleoperator because the ultimate source of the external constraints is the movements of the operator acting on the controller in real time.

Figure 47.3 shows a typical industrial robot. It has six degrees of freedom. In the operational mode, it is moved by servo actuators in response to commands from a minicomputer which reads a stored list of operator commands. Thus, the essential difference between it and the teleoperator is that although the movement commands still originate from an operator, the operator is not interacting with the device in real time during its normal operation. The important point, then, is that this distinction has little impact on the mechanical design of the devices. They belong to the same class for this purpose.

As larger and larger amounts of processing power are placed on these devices, the distinctions made above among teleoperators, industrial robots, more general robots, and other related devices tend to blur. Figure 47.4 is a scale model of a device which, while very definitely an externally constrained mechanism, fits none of the above categories. It is a vehicle for use in rough terrain conditions. In rugged conditions, legs have significant mechanical advantages over wheels or tracks. It is, however, very much more difficult to actuate the legs efficiently while maintaining the adaptability characteristic of an externally constrained mechanism. The device has a high level of onboard data processing power, allowing it to automatically coordinate the movements of the leg actuators in response to information about the terrain in front of the device received from an optical scanning system, information about the leg loading received from force sensors in the "ankles," and information about the positions of returning legs relative to the ground received from proximity sensors. The operator commands direction and speed but, when cruising, does not directly influence leg movements. This device is certainly not a robot, since it has an opera-

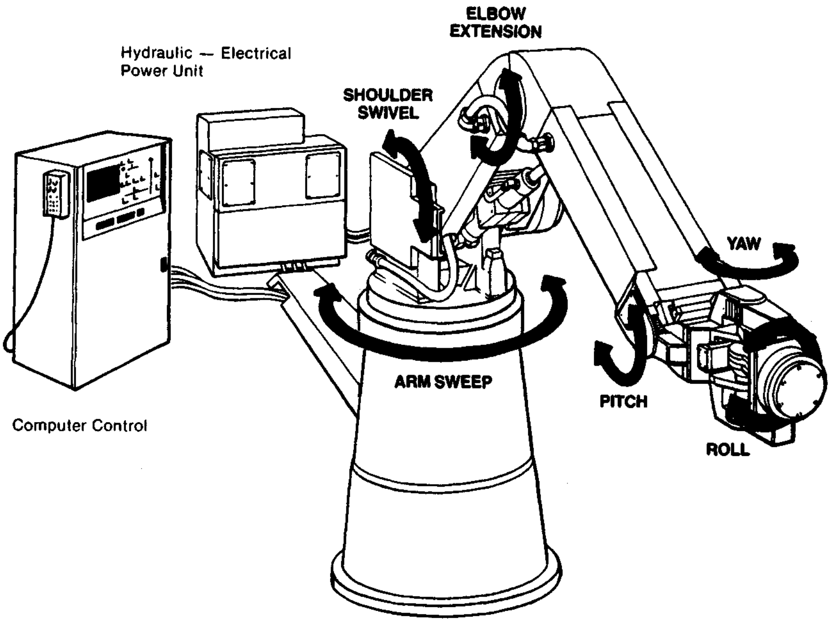

FIGURE 47.3 Drawing of an industrial robot indicating the degrees of freedom. (*Cincinnati Milacron.*)

tor on board. Although the operator is the source of some of the information used to provide external constraint, she or he is not the sole source of that information. Thus, it is not a teleoperator either. Nevertheless, the technology used is similar to that used in robots and advanced teleoperators. Once again, the concept of an externally constrained mechanism highlights the essential relationship between the characteristics of these devices.

FIGURE 47.4 The adaptive suspension vehicle (1/10-scale model). This is a vehicle for transportation in very rough terrain conditions which uses legged locomotion. (*The Ohio State University.*)

47.2 DESIGN AND FUNCTION

Turning again now to the restricted class of industrial robots, we realize that although they are flexibly programmable to perform an infinite variety of movements, by no means are they designed as universal tools. Industrial robots are designed with specific types of application in mind, and this fact very strongly influences the design of both hardware and software [47.1].

Figure 47.5 shows a robot well suited to one of the earliest industrial robot applications: spot welding. In this application, fairly high accuracy and repeatability are needed at the weld positions. However, when the robot moves between those positions, the path of the tool is usually of little concern. Therefore, a very simple and fast coordination algorithm operating in joint coordinates might be used. In this type of operation, each joint is independently commanded to move to its next position, producing an uncoordinated motion. Since the tool is heavy and good repeatability is required, the structure and actuation system must be both strong and stiff.

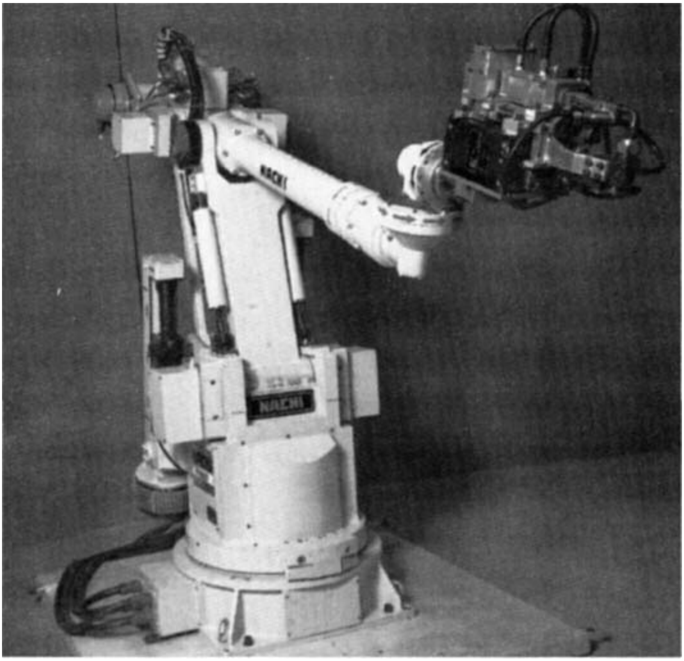

FIGURE 47.5 Heavy-duty industrial robot equipped for spot welding. This is called the NACHI Robot 8000 Series. [*C. Itoh & Co. (America)*.]

A robot suited to seam welding is one of the most important current applications in economic terms. Such robots usually have only five degrees of freedom. Since the tool is a rotationally symmetric electrode, a sixth degree of freedom is unnecessary. Arc-welding robots are, however, used often in conjunction with programmable work tables which, in principle, provide one or two additional degrees of freedom. The use of sliding joints for the first three degrees of freedom is favored in many arc-welding robot designs, even though it leads to a very large structure, because it simplifies the generation of accurate straight lines. These are frequently necessary in the welding of seams. One reason for using programmable tables is to line up the seam to be welded with one of the manipulator slides. Since an arc welder must accurately generate straight lines and curves and must closely control the orientation of the welding head, the type of software suggested above for the spot welder would be quite unsuitable. A relatively sophisticated coordination algorithm based on resolved motion rate control would be preferable. The robot would still be a point-to-point robot. That is, only discrete positions would be taught by the operator. The machine would automatically generate its path between those positions.

When robots are used for spray painting, the loads are light and great accuracy and repeatability are not necessary. Thus, spray-painting robots are often relatively lightly built. The explosive environment in which they operate mandates great care in the use of electric motors. Remote actuation systems, permitting better protection of the motors, are often used. Pneumatic or hydraulic actuation systems may be used to eliminate potential spark sources.

Spray-painting robots are usually taught in a *continuous-path* mode. The operator moves the device through the motion to be taught in real time. Joint positions are sampled at equal time intervals. In playback operation, a simple interpolation algorithm is used between the sampled positions to generate a smooth motion. For this type of algorithm, the geometry of the robot is unimportant. In fact, the computer does not even know what the robot "looks like." Consequently, quite complex geometries are sometimes used for spray-painting robots.

Figure 47.6 shows a robot designed for assembly operations. Actually, the tasks involved in robot assembly are quite diverse. Correspondingly, so-called assembly robots vary from very simple "pick and place" devices up to the most sophisticated

FIGURE 47.6 Robot suitable for assembly operations. Orthogonal slide arrangement gives uniform positioning accuracy and is well adapted to planar transport of parts and unidirectional insertion. Large range of motion in wrist and force-sensing gripper gives good dexterity.

units presently available. Assembly robots tend to be relatively small and geometrically adapted, as in Fig. 47.6, to vertical movements and large movements in the horizontal plane. They may have fewer than six degrees of freedom since many assemblies are designed for all parts to be added from a single direction. The more sophisticated units have more general geometries, sometimes even more than six degrees of freedom, and force sensing in the gripper.

47.3 STRUCTURAL DESIGN

47.3.1 Structural Characteristics

The unique characteristics of externally constrained mechanisms lead to structural design problems which, while certainly not unique to this class of mechanisms, are otherwise relatively uncommon. Most externally coordinated mechanisms have sequential chains of members and joints fixed to a base at one end and loaded at the other. Structurally, this is a cantilever beam, but one which changes geometry.

The overriding structural design constraint for most industrial robots is accuracy and repeatability. For the present generation of industrial robots, which operate without endpoint feedback, this implies high stiffness. Many current-generation robots consequently have massive structures even though their rated load capacity is very modest.

There is a second reason for the importance of stiffness. The servo actuation systems used to operate the joints can be a source of excitation of structural vibration. This is particularly true of the digital servo controllers, which are becoming increasingly popular. The frequency of the update cycle becomes a source of vibration excitation. A rule of thumb in robot design is that the lowest natural frequency of free structural vibrations should be at least 3 to 4 times the servo bandwidth and preferably rather more.

The irregular movements of the manipulator itself also excite vibrations. However, these are transient in nature. If not damped out quickly enough, they may cause problems in fine manipulation operations.

47.3.2 Impact of Mode of Sensing and Control

The need for great stiffness to obtain sufficient accuracy is a consequence of the type of position control used. Since only the joint positions are read and hand position is inferred from them indirectly, errors resulting from the behavior of the intervening structure must be avoided. If, however, hand position relative to the workpiece can be measured directly, a completely different structural design philosophy can be used. Figures 47.7 and 47.8 show two machines which illustrate this point very well. Both are externally constrained mechanisms. The first is a manipulator designed to be used as a self-help device by a quadriplegic (a person wholly or partially paralyzed from the neck down because of a spinal injury). It uses computer coordination to generate coordinated movements from very restricted operator inputs. The operator may be capable of providing only two-degree-of-freedom control movements. For the present purpose, however, the important point is that *endpoint feedback* is available to this device by means of the operator's vision. Despite the fact that the arm is lightly built and quite compliant, there is no problem with accurate positioning.

FIGURE 47.7 Manipulator for use by quadriplegic. This device is a teleoperator which operates from very limited inputs and achieves good accuracy despite light, compliant structure and drive because operator's vision provides endpoint feedback. (*Jean Vertut, CEA, Saclay, France.*)

The second device, shown in Fig. 47.8, is a prototype of an industrial robot designed for shearing sheep. Although it is hydraulically actuated, it is also relatively lightly built and is quite compliant. It has eight degrees of freedom. Seven of these move the member carrying the cutter approximately in a series of passes over a computer model of the sheep's body. The remaining joint is a sliding joint which is maintained approximately normal to the surface of the sheep's body and which carries the clippers. It is equipped with a fast, accurate servo actuation system. A contact sensor, which operates by measuring the electric resistance between the clippers and the body of the sheep, and capacitative proximity sensors provide information about the distance of the clippers from the sheep's skin which is used by the sliding-joint servo controller to maintain a constant distance between clippers and skin. Again, the use of direct measurement of the position of the tool relative to the workpiece removes the need for a massive, stiff structure and for fast, accurate response in most joints.

47.3.3 Selection of Structural Sections

Since, in the present generation of industrial robots, strength is unimportant and the lowest vibrational natural frequencies are important, hollow structural sections with

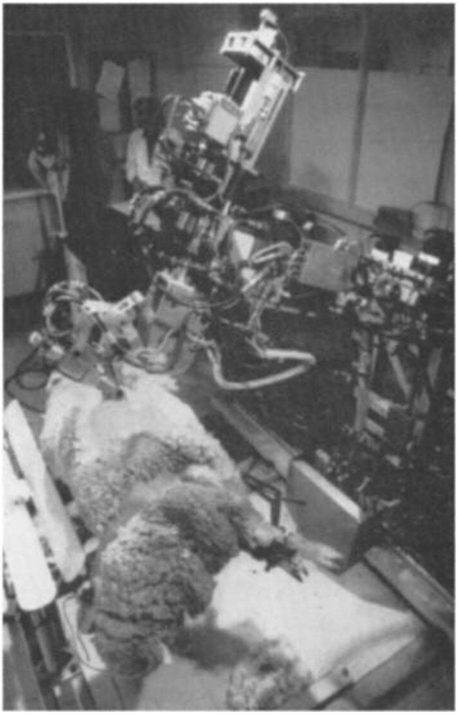

FIGURE 47.8 Prototype sheep-shearing robot. High performance is achieved by means of endpoint feedback from resistive and capacitative sensors mounted in clippers. Robot structure is compliant and has low response except for RAM, which is maintained normal to body of sheep and which responds rapidly. (*Automated Sheep Shearing Project, University of Western Australia, Nedlands.*)

a high degree of symmetry tend to be used. Square sections are particularly popular. Selection of an adequate structural section is not necessarily sufficient to attain adequate stiffness. The compliances of the servo actuators are usually at least comparable to those of the structural members. Because of the complexity of the structure and the mass distribution resulting from the locations of the relatively massive actuators, it is really necessary to use numerical design analysis tools both for determining static deflection and for estimating vibration modes and frequencies. The position in which the arm is fully extended in the horizontal direction with a mass whose weight corresponds to full load lumped at the gripper can usually be regarded as the worst case for both types of analysis.

Even when good structural analysis packages are used, the problem is far from straightforward. Modeling of the manipulator as a solid cantilever with appropriate mass distribution, followed by finite-element analysis, does not usually yield good results for dynamic behavior because of joint compliance. If the joint compliances are high enough for structural compliance to be neglected, better results can be obtained by using one of the mechanism analysis packages which model the members as rigid and the joints as damped springs.

No matter how well the system is modeled, the free-vibration frequencies must be treated with caution. Although vibrational modes can be accurately predicted by good numerical models, modal frequencies are notoriously difficult to estimate accurately. The designer should be prepared to use prototype testing with appropriate adjustments to the structural design to ensure adequate structural performance.

47.3.4 Material Selection

Since strength is not usually a consideration, the materials used in robot construction are quite conventional. The choice is usually based on ease of manufacture. Low-carbon steel has been used in many designs. Some reduction in weight, without losing stiffness and with consequent improvement in vibrational performance, can be achieved by using aluminum. Extruded aluminum tube sections are a convenient structural choice. Glass-fiber-reinforced composites are attractive for the same reason and are appearing in some of the newer designs. Because bending stiffness is the primary requirement, the reinforcing fibers should be laid at a low angle to the section axis. Relatively large tube diameters, or side dimensions for prismatic tubes, with thin walls must be used for the same reason.

Parallel Structures. As has been noted, the current generation of industrial robots uses series chain structures almost exclusively. There is no basic reason why manipulators must be constructed in this way. The Stewart platform shown in Fig. 47.9 is, equally, a six-degree-of-freedom externally constrained mechanism but has a parallel actuation geometry rather than a series geometry. The Stewart platform has been widely used in aircraft simulators and similar devices, as shown in Fig. 47.10. It functions in a simulator in a very similar manner to an industrial robot. The Stewart platform's vibrational and load-carrying capabilities are certainly superior to those achievable by a comparable series structure. Its motion range is more limited. Nevertheless, it does indicate that there may be something to be gained by thoughtful use of parallel actuation geometries.

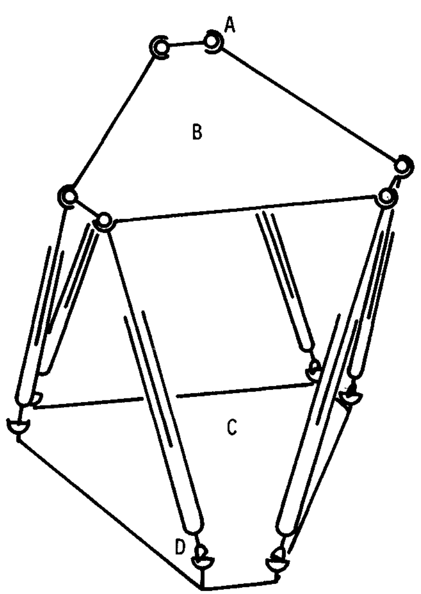

FIGURE 47.9 Schematic drawing of the Stewart platform. A, ball-and-socket joint; B, movable platform; C, fixed base; D, Hooke joint. The movable platform is supported on six legs.

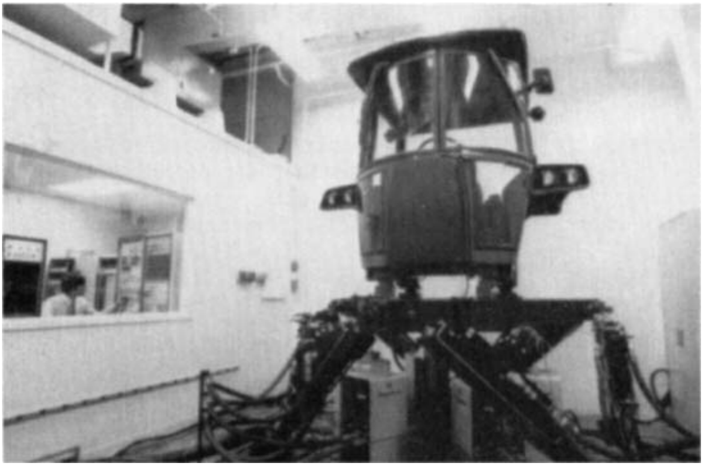

FIGURE 47.10 Stewart platform used to simulate six-degree-of-freedom movement of tractor cab. (*Deere & Company.*)

47.4 ACTUATION AND POWER TRANSMISSION SYSTEMS

47.4.1 Requirements

To date, three different power transmission media have been used in industrial robots: electric, hydraulic, and pneumatic. In each case, there is considerable variety in possible system configurations.

The mechanical requirements for actuators used in robots include high force-to-weight ratio for linear actuators, or torque-to-weight ratio for rotary actuators. This requirement results from the necessity to mount at least some of the actuators outboard on the arm. Joint rates are comparatively low. A typical robot with a maximum reach of about 2 meters (m) will have a maximum hand velocity of the order of 800 inches per minute (in/min) [250 millimeters per second (mm/s)]. This requires a joint rate at the shoulder of 0.2 radian per second (rad/s) or about 2 revolutions per minute (r/min) maximum. Of course, any actuation system used must be capable of being smoothly controlled with at least moderately fast dynamic response.

Electric systems are widely used in industrial robot systems, although, at the present state of the art, their capabilities for providing adequate torque-to-weight ratio with good dynamic response are quite marginal. The other advantages of electric systems include lower cost than hydraulics; compact, silent, and inexpensive power supplies; cleanliness; and ease of routing transmission lines. Because electric systems have trouble meeting the high torque-to-weight requirements of robotic applications, there is a strong trend to use high-technology servomotors. Pancake motors and, more recently, rare-earth motors are very widely used despite their relatively high cost. Rare-earth motors offer an improvement in torque-to-weight ratio by a factor of 2 to 3 over conventional permanent-magnet motors. Current rare-earth designs tend to be long, slender cylinders which present considerable packaging problems to the robot designer. Pancake motors, while not offering such high performance, are short axially with relatively large diameter, as their name implies. This configuration usually presents fewer packaging problems. Other types of electric actuator, such as stepping motors, which might otherwise seem attractive, at present cannot approach the torque-to-weight ratios necessary for robot applications.

Another consequence of the somewhat marginal torque-to-weight performance of electric systems is that they are limited in load-carrying capacity. In the present environment, in which most robot applications are low-load applications, this is not a serious handicap. However, as robot applications diversify, a role for heavy-duty robots will develop. In fact, "heavy-duty" robots have been on the market for a long time. At present *heavy duty* might be defined as anything over a payload of about 150 pounds (lb) [70 kilograms (kg)]. It is no surprise that hydraulic systems dominate this end of the market.

47.4.2 Electric Systems

Electric motors have very low intrinsic torque-to-weight ratios. In compensation, they are capable of operating at very high speeds. Thus, the torque of the motor can be matched to that needed at the joint by means of a speed-reducing and torque-increasing mechanical transmission. Another important feature of electric motors as actuators is that they are highly inefficient at low speeds under load. In particular, they do not hold stationary position well under load. Thus, it is usually advisable to provide solenoid-actuated brakes in electric systems for use when the joint is to hold stationary position. For both these reasons, electric actuators must always be used with mechanical transmissions.

Selection of Transmission. The necessity of a transmission as an electric actuator brings with it a number of problems. Use of very high speed-reduction ratios (which is, in principle, a solution to the torque-to-weight ratio problem) results in very high reflected armature inertias, as viewed from the joint. This results, in turn, in sluggish dynamic response. In addition, because of the discontinuous nature of robot movements, the substantial amounts of kinetic energy which a motor armature stores while running at high speed must be dissipated regularly, usually by conversion to heat. This results in increased system power demand and potential heat-dissipation problems.

Therefore, the selection of transmission ratio and actuator operating speed is a compromise between the increased torque-to-weight ratio achievable with high reduction ratios and the dynamic response and power dissipation problems caused by use of those ratios. Obviously, the actuator and transmission components must be selected or designed on a system basis. The primary design constraint on the system is dynamic response. The torque-to-weight ratio should be maximized consistent with meeting the dynamic response specifications.

The problems just discussed are not the only ones which result from use of a mechanical transmission. The compliance and backlash of the transmission present additional problems. Compliance in the transmission also degrades dynamic response. Thus, this fact should also be considered when the actuation and transmission system is designed to meet specified dynamic response goals. Backlash is often a far more troublesome problem. If joint position is used as the controlled variable of the joint servo system, backlash can lead to instability because the motor position and velocity cannot be inferred from the corresponding joint variables. Use of high reduction ratios exacerbates the problem. Of course, controlling motor shaft position and velocity directly removes this problem, but it introduces errors in joint position. In some successful designs, gravitational loading is used to eliminate backlash during normal operation.

The requirements of low backlash and compliance, relatively high output torque, and large speed reduction in a compact, lightweight package have resulted in wide use of several types of transmission which, while certainly not unknown in other types of mechanical systems, might be regarded as exotic. Harmonic drives, for example, which use a flexible splined intermediate member, have been used in several designs. Their advantages are a large speed-reduction capability in a single stage, with consequent light weight and compactness, and backlash-free operation. Disadvantages are relatively high compliance, a consequence of the flexible spline member, and only modest mechanical efficiency—of the order of 70 percent. Harmonic drives are usually supplied as a set of unpackaged components. They require considerable care in the design of mountings of the drive components and of the support bearings of the input and output shafts to ensure good service life.

Cycloidal drives, now on the market in several types, offer one-stage reduction ratios similar to those of harmonic drives with lower compliance and higher mechanical efficiency. However, robot applications tend to come in at the bottom end of the size range for cycloidal drives, and so they tend to be relatively large and heavy. Nevertheless, they are an attractive alternative in situations in which their weight can be handled.

Gear trains have also been used, both in conventional multistage configurations and in epicyclic trains. Since three or four reductions may be needed to achieve an adequate overall ratio, straight trains tend to be bulky. Backlash may be minimized by use of high-quality, accurately cut gears. It is not usually practical to spring-load multiple-stage gear trains. Gears are a viable option inboard where bulk and weight are not problems. Larger gears than are needed to carry the torque may be used to reduce compliance.

The epicyclic gear heads supplied as matched units by some manufacturers of servomotors tend to have inadequate torque capacity for robot applications. Custom design and manufacture of high-ratio, low-backlash, epicyclic trains is difficult and expensive. Nevertheless, epicyclic speed reducers are capable of filling robot transmission requirements.

The usual low-cost option for large-reduction-ratio transmission, worm gears, is not popular in robot applications. The relatively high backlash and low mechanical efficiency of worm gears are the main reasons. The noncoaxial geometry imposed by a worm reduction often creates packaging problems, which are an important consideration in outboard locations. One feature of worm gear sets is attractive. They can be designed to be self-locking, thus removing the need for brakes.

One of the most elegant solutions to the problem of obtaining a large speed reduction in a compact, lightweight package without backlash and with low compliance is obtained by the use of a ball screw. Ball screws are easily spring-loaded to eliminate backlash by using a preloaded double nut. They have high mechanical efficiency. When a rotary joint is powered in this manner, the system effectively has two speed-reduction stages. The first is in the conversion from rotary to linear motion via the screw. The second is in the conversion from linear back to rotary motion via a lever arm. The result is a very compact and efficient high-ratio reduction. Of course, the lever arm introduces a nonlinear relationship between joint position and motor position and limits the maximum joint rotation range to about 150°. The nonlinearity is of little importance provided the servo system operates on joint position and its time derivatives rather than motor position. The restricted rotational range is adequate for about half of the joints in a typical industrial robot geometry. Comparatively speaking, ball-screw drives are very stiff.

Band mechanisms have also been used in several externally constrained mechanisms. They have been particularly successful in teleoperators for remote handling of nuclear materials. Speed reduction is achieved by means of a block-and-tackle arrangement with metal tape used instead of cable. Figure 47.11 shows the very sophisticated band drives used in a servo-operated teleoperator. Those used in the manipulator of Figure 47.7 are of similar type. Band drives, although very compliant, allow transmission of power from actuators located inboard to the outboard joints. This has the advantage of allowing a lightweight, slender structure. It also allows better shielding of motors during operation in flammable environments such as in spray painting.

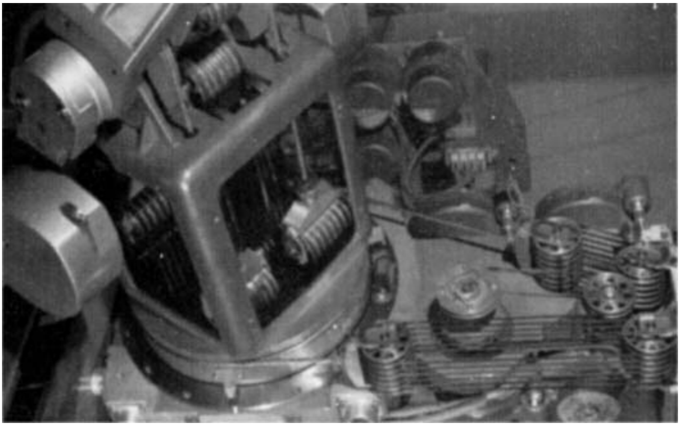

FIGURE 47.11 Band drives used in a servo teleoperator for handling nuclear materials. Speed reduction is achieved by use of block-and-tackle sets. *(Jean Vertut, CEA, Saclay, France.)*

Roller-chain drives can also be used to transmit power outboard from actuators mounted inboard. They are much stiffer than band mechanisms. However, it is not possible to use roller chain in block-and-tackle mechanisms, so the direct speed reduction obtainable is very limited. Thus, a speed reducer must be placed between the motor and the drive sprocket of the chain transmission.

Power Control Systems. Many electric actuation systems use conventional variable-armature-resistance servomotor control. However, the advent of solid-state power-switching devices such as silicon controlled rectifiers (SCRs) has allowed the introduction of phase control and similar modulation techniques. These operate by applying a train of voltage pulses of controllably variable width to the motor. Effectively, the motor responds to the average voltage of this pulse train. These schemes offer substantial improvements in efficiency and, correspondingly, reductions in heat dissipation because they operate on a nondissipative principle. Motor efficiencies in the range from 70 to 90 percent become feasible.

48.4.3 Hydraulic Systems

Hydraulic actuators have the advantage of very high force-to-weight ratio. This allows direct drive of the joints without any intervening transmission. Pressure-regulated, parallel hydraulic circuits perform best at low joint rates and large loads. Hydraulic actuators hold fixed position well under load. Therefore, brakes are not needed. They are worst at high joint rates and low loads. Under those circumstances, large amounts of energy are converted to heat at the control valves. This is the reverse to the pattern of electric drives, which perform best at high joint rates and low loads and worst at low joint rates and high loads. Neither pattern is optimum for manipulator service since a typical operational cycle will include periods both of slow motion or holding position and of rapid motion.

The disadvantages of hydraulic systems are the need for a large, expensive, and noisy power supply; the high cost of servo valves; and the dirt created by oil leaks.

Hydraulic actuators may be linear actuators (hydraulic cylinders), rotary actuators capable of less than 1 revolution (fixed-vane actuators), or rotary actuators capable of continuous rotation (hydraulic motors). Hydraulic cylinders usually give lighter-weight actuation systems than rotary actuators for the same joint torque and motion requirements. However, as was mentioned in relation to ball-screw drives, any crank-type linear-to-rotary drive gives a nonlinear relationship between actuator displacement and joint rotation and is limited to about 150° of joint rotation. Fixed-vane actuators are also lighter than hydraulic motors. The nonlinearity does not cause problems if the control variables of the servo system are joint position and its derivatives, rather than actuator position.

Dynamic response is improved both by locating servo valves so as to minimize the line lengths between them and the actuators they serve and by minimizing actuator volume consistent with load capacity specifications. In particular, connections from the valve to the actuator should be hard-walled tube, not flexible hose. Increasing system operating pressure allows use of smaller actuators. However, since most industrial robot actuators are relatively lightly loaded and losses in small hydraulic actuators are relatively high, moderate supply pressures [1000 to 2000 pounds per square inch (psi)] are favored to permit use of reasonably large actuators.

Cooling Requirements. In the technology used at present, the actuators are on parallel branches of the circuit. A pressure-regulated supply is used, and the actuators exhaust to a reservoir. A four-way servo control valve acts across both the inlet and the exhaust lines of each actuator. In this configuration, the difference between the pressure drop from supply to reservoir and that needed across the actuator to balance the load is made up by the pressure drops across the two sides of the control valve. Mechanical energy is converted to heat at the valve at a rate which is the product of the flow rate and the sum of the valve pressure drops. Thus, at low loads and high joint rates, large quantities of energy are converted to heat. The heat is carried off in the hydraulic oil. The reservoir and possibly an oil cooler must be sized to allow this heat to be dissipated without undue rise in the oil temperature at the pump inlet. The oil temperature can build up very rapidly if there is insufficient cooling. Excessive temperatures result in breakdown of the oil and damage to the circuit components, particularly the expensive valves. Use of a variable-displacement pump with a pressure-sensing servo loop, instead of the wasteful technique of regulating pressure by a relief valve, helps this situation considerably. Of course, relief valves must be included for safety, but they should remain closed in normal operation.

47.4.4 Pneumatic Systems

Pneumatic actuation is quite extensively used in simple pick-and-place devices with three or four degrees of freedom. These can hardly be called industrial robots, since the control logic needed is minimal. Attempts to power five or six degrees of freedom, and to use rotary inboard joints to achieve reasonably large working volumes from a compact device, quickly run into problems resulting from the high compliance and low force-to-weight ratios of pneumatic actuators. These can be overcome by the use of high-speed air motors. However, as with electric actuators, this requires a mechanical transmission, with its attendant problems.

The components used in pneumatic actuation and control are quite similar to those used in hydraulic systems. However, pneumatic systems are usually supplied from a central compressor rather than from a local power supply, as is used for hydraulic systems. This is practicable by virtue of the much lower viscosity of air as compared to hydraulic fluid.

Pneumatic systems will continue to be important in automated light manufacturing, particularly in simple transfer devices which are lightly loaded and require only a few degrees of freedom. They are also attractive in functions such as spray painting in which special environmental conditions make electric systems less attractive. However, primarily because of the compliance problem, electric or hydraulic systems are more suited to most industrial robot applications.

47.5 SENSING SYSTEMS

47.5.1 Requirements

Although sophisticated robot sensors are under laboratory development, the only sensors used on most industrial robots are joint position sensors. A number of different types of rotary position sensors are available, and several have been used on robots.

A rather wide variation in the accuracy required during the sensing of position at the different joints of a manipulator is usual. A typical industrial robot with a reach of 6 feet (ft) (1.8 m) will be designed to achieve repeatability within 0.05 in (1.3 mm). This requires a resolution at the shoulder joints of 0.0007 rad (2.4 minutes of arc), or 1/9048 revolution. If a digital readout is used, a resolution of 16 384, or 2^{14}, divisions per revolution is needed. At the wrist, the distance to the hand reference point may be 1 ft or less. Thus, the resolution needed is 0.0042 rad (14.3 minutes of arc), or 1/1508 revolution. A digital resolution of 2048, or 2^{11}, divisions per revolution is adequate. Thus, although quite high resolution is needed at the wrist, it is still substantially less than that at the shoulder.

Few position sensors can read 14 bits (2^{14} divisions) per revolution directly. A sensor with lower resolution can be geared up so that it completes several revolutions per joint revolution. Of course, backlash must be avoided during this time. Since the sensor does not load the gear train, it is simple to remove backlash by use of spring-loaded gears. Many electric systems use position sensing on the motor shaft, which accomplishes the same objective.

When gearing up is used to increase resolution in this manner, it is always necessary to start the system from a "home," or reference, position. Otherwise, if the system is started from an arbitrary position, there is no way of knowing how many complete revolutions the sensor has performed since leaving the reference position. This is the reason that many industrial robots must be placed in a home position before automatic operation is begun.

In addition to having high resolution, robot joint position sensors must be highly reliable, since they must read accurately and without noise over many service hours of continuous movement. For this reason, sensors with electric-brush contact, such as potentiometers or commutator-type encoders, should not be used. Several types of position sensor are available which require no mechanical contact and which, for this reason, are much more reliable.

47.5.2 Encoders

Encoders are position sensors which read out in digital form. There are two basic types: incremental encoders and absolute encoders. Absolute encoders read out a binary number which uniquely identifies the joint position within the resolution of the device. Incremental encoders are much simpler devices. Basically, they are pulse generators, generating a voltage pulse every time the joint moves through an angle equal to the encoder resolution. It is necessary for the computer to count the pulses to determine position. Actually, two outputs phase-shifted relative to each other are used. Otherwise, it would be impossible to determine the direction of rotation. Of course, pulses counted during reverse motion must be subtracted from the total which indicates joint position.

Incremental encoders present an additional problem. It is necessary to provide a zero reference position from which to begin the count. This can be done by means of a home position in the same way as with absolute sensors in a multiturn mode. However, it is necessary that joint position be referenced much more accurately for incremental encoders. When multiturn absolute sensors are used, it is necessary only that each joint sensor be on its initial revolution when the manipulator is placed in the home position. Precise location is not required. When incremental encoders are used, each joint must be located to within the resolution of the encoder.

Absolute encoder types available include optical and electromagnetic types as well as the commutator type mentioned earlier as being unsuitable. They are available at accuracies ranging from 6 to 22 bits per revolution (bits/r). High-accuracy encoders are expensive and require great care in mounting. Another consideration is the length of the binary word which the computer can conveniently handle. Since the microprocessors most popular in current new designs use a 16-bit word length, and since 16 bits/r is adequate accuracy, there is little incentive to go to higher accuracies. When 8-bit word length microprocessors are used, gearing up an inexpensive 8-bit/r encoder may be an economically attractive alternative to the use of an expensive 16-bit encoder with the additional complication of reading and manipulating the encoder output as two 8-bit words.

Encoders do not usually read out in natural binary code. Rather, they read out in a binary code known as *gray code*. Figure 47.12 shows the natural binary and gray code representations of the numbers 0 through 15. The reason for using gray code is that only one binary digit changes between any two adjacent gray code divisions. This is not true of natural binary code, and so the use of natural binary code can lead to large errors at the interface between divisions since, because of mechanical or electronic misalignment, the changes in some digits will be sensed momentarily earlier than those of others. Thus, in changing 7 to 8 in natural binary, if the change in the most significant digit is sensed after that of the other three digits, the output may go from 7 to 0 before going to 8. Gray code eliminates that problem. Gray code can be converted to natural binary by applying a logical exclusive-OR operation with the previously converted digit to each binary digit in turn, starting with the most significant digit. An exclusive-OR operation outputs 0 if the digits compared are like and 1 if they are unlike. It is possible to write simple and efficient microprocessor assembly-language routines to perform this conversion.

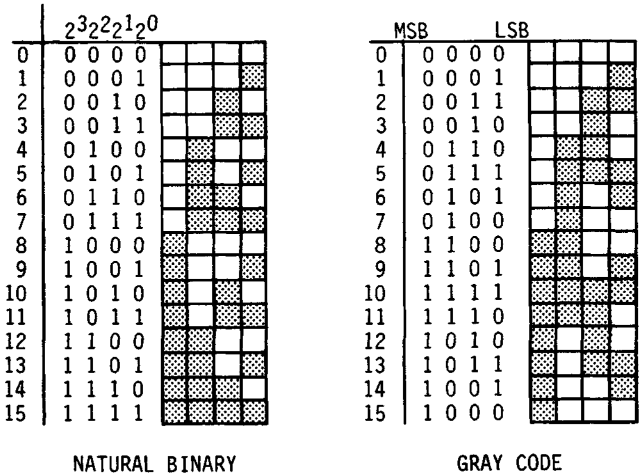

FIGURE 47.12 Comparison of natural binary and gray code representation of numbers 0 through 15. Gray code avoids generation of errors at the transition between divisions.

47.5.3 Resolvers

Resolvers are small, alternating-current (ac), rotating electromagnetic machines related to synchros and linear variable-differential transformers. Figure 47.13 is a schematic diagram showing the two rotor and two stator windings. In both cases, the two windings are arranged to act orthogonally to each other. For simple angle measurement, only one stator winding is excited; the other is short-circuited. If the rotor is at angle θ from its null position, the amplitudes of the alternating electromotive forces excited in the two rotor coils are proportional to sin θ and cos θ, respectively. High-accuracy resolvers are typically designed for 26-volt (V) maximum excitation voltage at 400 hertz (Hz) and have open-circuit output voltage from 0 to 26 V. Resolvers are available with resolution ranging from 6 to 16 bits/r. They are attractive because they do not have mechanical contact and they produce a readily usable analog output voltage.

47.5.4 Force Sensors

Some form of force sensing is highly desirable when grippers are used. The sensor might be simply a contact sensor which indicates whether a workpiece is in the gripper. Such a sensor is easily arranged by mounting a leaf spring along the gripping surface with its free end bearing on a microswitch. By suitably designing the compliance of the spring and cementing strain gauges to it, a readout of gripping pressure is obtained. This is desirable when fragile workpieces are handled. Sensors which will not only measure contact pressure but also locate the point of contact are being developed with solid-state electronic technology. The technology necessary to measure all six components of tool load by means of load cells mounted in either the wrist or the base has been well proved in the laboratory but has not yet found its way into industrial service.

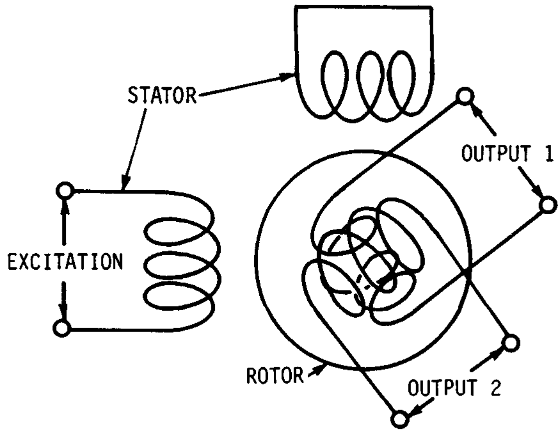

FIGURE 47.13 Schematic drawing of resolver windings. One stator winding is excited at high frequency. Amplitude of electromotive force excited in rotor windings is sinusoidally related to rotor angle.

47.5.5 Robot Vision Systems

Most robot vision systems are based on television camera technology, using either conventional vidicon-tube cameras or array cameras. Constructing a three-dimensional computer model of an object seen in two or three views by television cameras is difficult, is fraught with ambiguity, and requires time-consuming computation. Thus this is not attempted in industrial service. By using highly structured environments, taking advantage of known workpiece geometries, and possibly using structured light sources, it is possible to detect orientations of parts and command a robot to pick them up at the correct position and with the gripper correctly aligned with the part. It is also possible to pick out one type of part from a mixture of several different types. Vidicon-tube cameras give best resolution, but at relatively low frame rates. Array cameras use arrays of photodiodes formed by using integrated-circuit techniques. They are very compact and rugged and read out faster. The best array cameras presently available split a square viewing area into a 512-by-512 array of pixels. This approaches the resolution of an ordinary television set.

47.5.6 Proximity Sensors

Proximity sensing using optical or acoustic techniques is useful when a robot tool is brought into contact with a workpiece. Since the robot is designed to be very stiff and the workpiece is usually quite rigid, the contact force between them builds very rapidly when the robot contacts the workpiece with finite velocity. Even if force sensing is used, the contact force may build to damaging levels before the system can respond. Proximity sensors are short-range, noncontact sensors which allow fine control of tool velocity shortly before contact to avoid severe impacts. Optical systems based on triangulation or simply the intensity of light reflected off the workpiece have been tested. Ultrasonic rangefinders using a sonar-type principle offer an alternative technology.