Module -5

Processing Operations, Assembly & Inspection: Spot welding, continuous arc welding, spray coating, other processing operations using robots. Assembly and robotic assembly automation, parts presentation methods, assembly operations, compliance and remote center compliance (RCC) device, assembly system configurations, designing for robotic assembly, inspection automation. [Textbook-1]

Autonomous Mobile Robots: Introduction, Planning &Navigation: Introduction, basic control scheme for mobile robots (only basic understanding of perception, localization, path planning & motion control). [Textbook-3]

In addition to parts-handling applications, there is a large class of applications in which the robot actually performs work on the part. This work almost always requires that the robot's end effector is a tool rather than a gripper. Accordingly, the use of a tool to perform work is a distinguishing characteristic of this group of applications. The type of tool depends on the processing operation that is performed. We divide the processing operations that are performed by a robot into the following categories for purposes of organizing this chapter:

1. Spot welding
2. Continuous arc welding
3. Spray coating
4. Other processing operations

The two welding categories represent important application areas for robots. Spot welding is probably the single most common application for industrial robots in the United States today because they are widely used in automobile body assembly lines to weld the frames and panels together. Arc welding is an application that is expected to grow in use as we develop the technology required for using robots in this process. Spray coating usually means spray painting, an operation that is accompanied by an unhealthy work environment for humans, and therefore represents a good opportunity for robots. We use the term "spray coating" to indicate that there are additional applications beyond painting for a robot to spray a substance onto a surface. The final category in the listing above is a miscellaneous applications area. It includes certain machining operations, polishing, deburring, and other processing operations. These operations are usually, but not always, characterized by the use of a rotating spindle by the robot. We discuss the four categories of operations and how robots are used to accomplish these operations in the following sections.

5a.1 SPOT WELDING

As the term suggests, spot welding is a process in which two sheet metal parts are fused together at localized points by passing a large electric current through the parts where the weld is to be made. The fusion is accomplished at relatively low voltage levels by using two copper (or copper alloy) electrodes to squeeze the parts together at the contact points and apply the current to the weld area. The electric current results in sufficient heat in the contact area to fuse the two metal parts, hence producing the weld.

The two electrodes have the general shape of a pincer. With the two halves of the pincer open, the electrodes are positioned at the point where the parts are to be fused. Prior clamping or fixturing of the parts is usually required to hold the pieces together for the process. The two electrodes are squeezed together against the mating parts, and the current is applied to cause heating and welding of the contacting surfaces. Then the electrodes are opened and allowed to cool for the next weld. A water circulation system is often used to accelerate the cooling of the electrodes. The actual welding portion of the sequence typically requires less than a second. Therefore, the rates of production in spot welding are largely dependent on the time required for positioning of the welding electrodes and the parts relative to each other. Another factor that affects production rate is the wear of the electrodes. Because of the heat involved in the process, the tips of the electrodes gradually lose their shape and build up a carbon deposit which affects their electric resistance. Both of these effects reduce the quality of the welds made. Therefore, the electrode tips must periodically be dressed to remove the deposits and restore the desired shape.

Spot welding has traditionally been performed manually by either of two methods. The first method uses a spot-welding machine in which the parts are inserted between the pair of electrodes that are maintained in a fixed position. This method is normally used for relatively small parts that can be easily handled.

The second method involves manipulating a portable spot-welding gun into position relative to the parts. This would be used for larger work such as automobile bodies. The word "portable" is perhaps an exaggeration. The welding gun consists of the pair of electrodes and a frame to open and close the electrodes. In addition, large electrical cables are used to deliver the current to the electrodes from a control panel located near the workstation. The welding gun with cables attached is quite heavy and can easily exceed 100 lb in weight. To assist the operator in manipulating the gun, the apparatus is suspended from an overhead hoist system. Even with this assistance, the spot-welding gun represents a heavy mass and is difficult to manipulate by a human worker at the high rates of production desired on a car body assembly line. There are often problems with the consistency of the welded products made on such a manual line as a consequence of this difficulty.

5a.1.1 Robots in Spot Welding

As a result of these difficulties, robots have been employed with great success on this type of production line to perform some or all of the spot-welding operations. A welding gun is attached as the end effector to each robot's wrist, and the robot is programmed to perform a sequence of welds on the product as it arrives at the workstation. Some robot spot-welding lines operate with several dozen robots all programmed to perform different welding cycles on the product. Today, the automobile manufacturers make extensive use of robots for spot welding. In 1980 it was reported3 that there were 1200 robots used in this application. Figure 14-1 shows an overview of an automobile body assembly line in which robots are used to perform the spot-welding operations. Figure 14-2 shows a close-up of a spot-welding gun mounted on a Cincinnati Milacron T3 robot performing its task inside the car body.

The robots used in spot welding must possess certain capabilities and features to perform the process. First, the robot must be relatively large. It must have sufficient payload capacity to readily manipulate the welding gun for the application. The work volume must be adequate for the size of the product. The robot must be able to position and orient the welding gun in places on the product that might be difficult to access. This might result in the need for an increased number of degrees of freedom. The controller memory must have enough capacity to accomplish the many positioning steps required for the spot-welding cycle. In some applications, the welding line is designed to produce several different models of the product. Accordingly, the robot must be able to switch from one programmed welding sequence to another as the models change. For welding lines in which there are multiple robots, programmable controllers are used to keep track of the different models at the various welding stations and to download the programs to the robots at individual workstations as needed.

The benefits that result from automation of the spot-welding process by means of robots are improved product quality, operator safety, and better control over the production operation. Improved quality is in the form of more consistent welds and better repeatability in the location of the welds. Even robots with relatively unimpressive repeatability specifications are able to locate the spot welds more accurately than human operators. Improved safety results simply because the human is removed from a work environment where there are hazards from electrical shocks and burns. The use of robots to automate the spot-welding process should also result in improvements in areas such as production scheduling and in-process inventory control. The maintenance of the robots and the welding equipment becomes an important factor in the successful operation of an automated spot-welding production line.

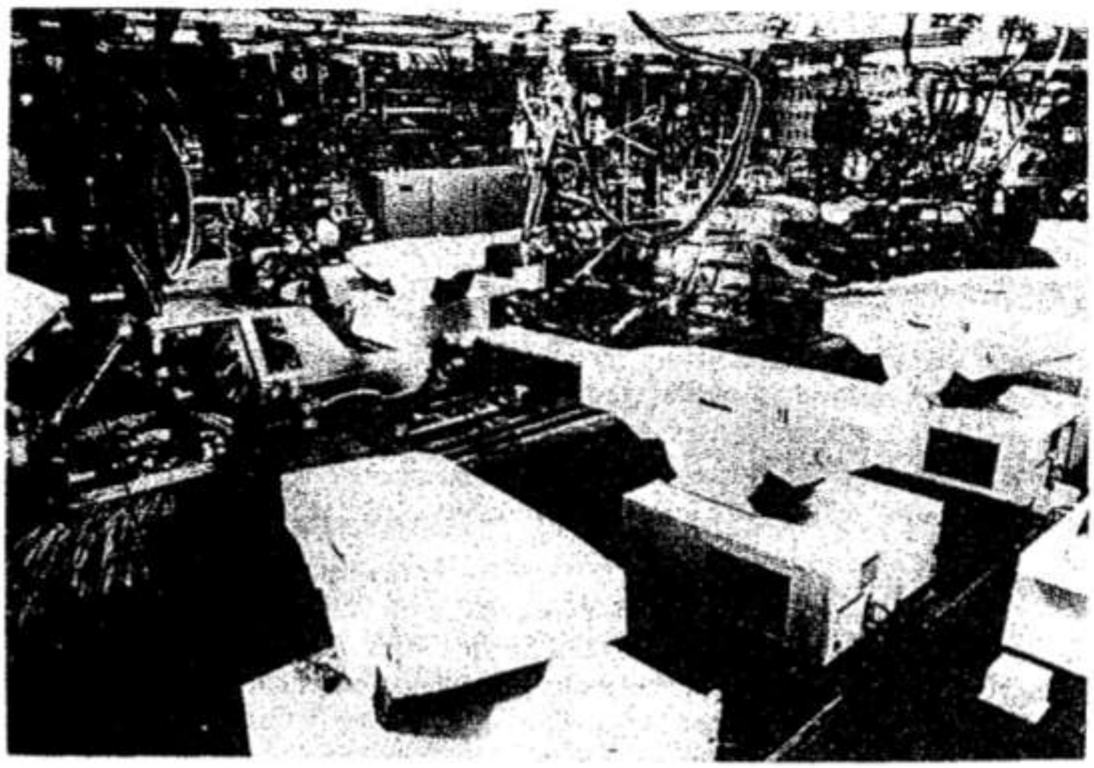

Figure 14-1 Robots performing spot welding operations on an automobile assembly line. (Photo courtesy of Unimation Inc., a Westinghouse Company)

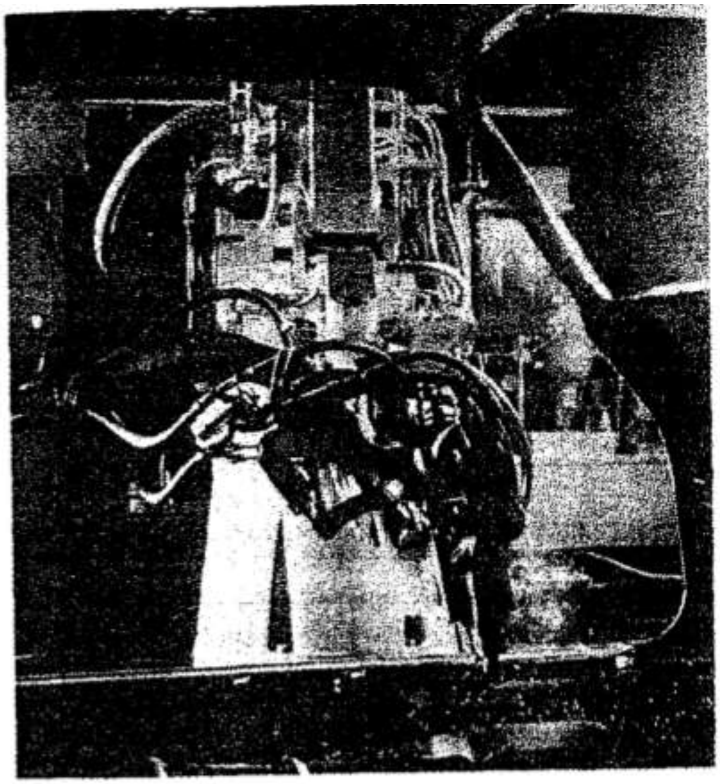

Figure 14-2 Close-up of a Cincinnati Milacron T3 robot performing a spot welding operation inside the car body. (Photo courtesy of Cincinnati Milacron)

5a. 2 CONTINUOUS ARC WELDING

Arc welding is a continuous welding process as opposed to spot welding which might be called a discontinuous process. Continuous arc welding is used to make long welded joints in which an airtight seal is often required between the two pieces of metal being joined. The process uses an electrode in the form of a rod or wire of metal to supply the high electric current needed for establishing the arc. Currents are typically 100 to 300 A at voltages of 10 to 30 V. The arc between the welding rod and the metal parts to be joined produces temperatures that are sufficiently high to form a pool of molten metal to fuse the two pieces together. The electrode can also be used to contribute to the molten pool, depending on the type of welding process.

Arc welding is usually performed by a skilled human worker who is often assisted by a person called a fitter. The purpose of the fitter is to organize the work and to fixture the parts for the welder. The working conditions of the welder are typically unpleasant and hazardous. The arc from the welding process emits ultraviolet radiation which is injurious to human vision. As a result, welders are required to wear eye protection in the form of a welding helmet with a dark window. This dark window filters out the dangerous radiation, but it is so dark that the welder is virtually blind while wearing the helmet except when the arc is struck. Other aspects of the process are also hazardous. The high temperatures created in arc welding and the resulting molten metals are inherently dangerous. The high electrical current used to create the arc is also unsafe. Sparks and smoke are generated during the process and these are a potential threat to the operator.

There are a variety of arc-welding processes, and the reader is referred to the available manufacturing process texts for more details than we can include here. For robot applications, two types of arc welding seem the most practical: gas metal arc welding (GMAW) and gas tungsten arc welding (GTAW). GMA welding (also called MIG welding for metal inert gas welding) involves the use of a welding wire made of the same or similar metals as the parts being joined. The welding wire serves as the electrode in the arc-welding process. The wire is continuously fed from a coil and contributes to the molten metal pool used in the fusion process. GMA welding is typically used for welding steel. In GTA welding (also called TIG welding for tungsten inert gas welding), a tungsten rod is used as the electrode to establish the arc. The melting point of tungsten is relatively high, and therefore the electrode does not melt during the fusion process. If filler metal must be added to the weld, it must be added separately from the electrode. The GTA process is typically used for welding aluminum, copper, and stainless steel. In both GMA and GTA welding, inert gases such as helium or argon are used to surround the immediate vicinity of the welding arc to protect the fused surfaces from oxidation.

5a. 2.1 Problems for Robots in Arc Welding

Because of the hazards for human workers in continuous arc welding, it is logical to consider industrial robots for the process. However, there are significant technical and economic problems encountered in applying robots to arc welding. Continuous arc welding is commonly used in the fabrication industries where products consisting of many components are made in low quantities. It is difficult to justify automation of any form in these circumstances. A related problem is that arc welding is often performed in confined areas that are difficult to access, such as the insides of tanks, pressure vessels, and ship hulls. Humans can position themselves into these areas more readily than robots.

One of the most difficult technical problems for welding robots is the presence of variations in the components that are to be welded. These variations are manifested in two forms. One is the variation in the dimensions of the parts in a batch production job. This type of dimensional variation means that the arc-welding path to be followed will change slightly from part to part. The second variation is in the edges and surfaces to be welded together. Instead of being straight and regular, the edges are typically irregular. This causes variations in the gap between the parts and other problems in the way the pieces mate together prior to the welding process. Human welders are able to compensate for both of these variations by changing certain parameters in the welding process (e.g., adjusting the welding path, changing the speed at which the joint is traversed, depositing more filler metal where the gap is large, etc.). Industrial robots do not possess the sensing capabilities, skills, and judgment of human welders to make these compensations. There are two approaches to compensate for these variations and irregularities in robot welding applications:

1. Correct the upstream production operations so that the variations are reduced to the point where they do not create a problem in the robot welding process.
2. Provide the robot with sensors to monitor the variations in the welding process and the control logic to compensate for part variations and weld gap irregularities.

Correction of the production operations that deliver parts to the arc-welding process is an attractive alternative because it tends to contribute to the overall quality of the product, and because it simplifies the welding robot project. The potential disadvantage of this approach is that it is likely to increase the cost of manufacturing the individual components because their dimensions must be held to closer tolerances. The second approach represents an area of intensive research and development activity in robotics.

Features of the Welding Robot

An industrial robot that performs arc welding must possess certain features and capabilities. Some of the technical considerations in arc-welding applications are discussed in the following:

1. **Work volume and degrees of freedom**. The robot's work volume must be large enough for the sizes of the parts to be welded. A sufficient allowance must be made for manipulation of the welding torch. Also, if two part holders are included in the workstation, the robot must have adequate reach to perform the motion cycle at both holders. Five or six degrees of freedom are generally required for arc-welding robots. The number is influenced by the characteristics of the welding job and the motion capabilities of the parts manipulator. If the parts manipulator has 2

degrees of freedom, this tends to reduce the requirement on the number of degrees of freedom possessed by the robot.

2. **Motion control system.** Continuous-path control is required for arc welding. The robot must be capable of a smooth continuous motion in order to maintain uniformity of the welding seam. In addition, the welding cycle requires a dwell at the beginning of the movement in order to establish the welding puddle, and a dwell at the end of the movement to terminate the weld.
3. **Precision of motion.** The accuracy and repeatability of the robot determines to a large extent the quality of the welding job. The precision requirements of welding jobs vary according to size and industry practice, and these requirements should be defined by each individual user before selecting the most appropriate robot.
4. **Interface with other systems**. The robot must be provided with sufficient input/output and control capabilities to work with the other equipment in the cell. These other pieces of equipment are the welding unit and the parts positioners. The cell controller must coordinate the speed and path of the robot with the operation of the parts manipulator and the welding parameters such as wire feed rate and power level.
5. **Programming**. Programming the robot for continuous arc welding must be considered carefully. To facilitate the input of the program for welding paths with irregular shapes, it is convenient to use the walkthrough method in which the robot wrist is physically moved through its motion path. For straight welding paths, the robot should possess the capability for linear interpolation between two points in space. This permits the programmer to define the beginning and end points of the path and the robot is capable of computing the straight line trajectory between the points.

Some welding applications require the robot to follow a weave pattern (back and forth motion across the welding seam) during the operation. Other applications require a series of passes along the same path, but each pass must be slightly offset from the previous one to allow for the welding bead that was laid down in the previous pass. Both of these requirements are generally associated with large welding jobs where the amount of material to be added is greater than what can be applied normally during a single welding pass. Robots intended specifically for arc welding are often provided with features to facilitate the programming of weave patterns and multiple welding passes.

5a.2.2 Sensors in Robotic Arc Welding

At present, a wide variety of arc-welding sensors are either commercially available or under development in various research and development laboratories.

The robotic arc-welding sensor systems considered here are all designed to track the welding seam and provide information to the robot controller to help guide the welding path. The approaches used for this purpose divide into two basic categories: contact and noncontact sensors.

5a.2.2.1 Contact arc-welding sensors: Contact arc-welding sensors make use of a mechanical tactile probe (some of the probe systems would better be described as electromechanical) to touch the sides of the groove ahead of the welding torch and to feed back position data so that course corrections can be made by the robot controller. Some systems use a separate control unit designed to interpret the probe sensor measurements and transmit the data to the robot controller. To accomplish the position measurements, the probe must be oscillated from one side of the groove to the other by the sensor system. The nature of the operation of these sensor systems limits their application to certain weld geometries in which the side-to-side motion of the probe permits it to make contact with the edges or surfaces that are to be welded. Some of the weld geometries in this category include butt welds that have grooved joints, lap joints, and fillet welds. Figure 14-4 shows a diagram which depicts the operation of the contact arc welding sensor and several of the types of joints in which it can be used.

Another limitation of the contact arc weld sensor is that the probe must be maintained in the proper position ahead of the welding torch, and this makes these systems most effective on welds that are long and straight. These kinds of arc-welding applications do not make full use of most robots' capabilities for more complex path control

5a.2.2.2 Noncontact arc-welding sensors: The second basic type of sensor system used to track the welding seam uses no tactile measurements. A variety of sensor schemes have been explored in this category, but our discussions will concentrate on arc-sensing systems and vision-based systems since these are the approaches used more in today's commercial systems.

Arc-sensing systems (sometimes called "through-the-arc" systems) rely on measurements taken of the arc itself, in the form of either electric current (in constant-voltage welding) or voltage (in constant-current welding). In order to interpret these signals, they must be varied during the arc-welding process. This is accomplished by causing the arc to weave back and forth across the joint as it moves down the path. The side-to-side motion along the joint can be achieved by programming the robot to perform the weave pattern, or by means of a servo system that attaches to the robot wrist and determines the position of the torch, or by other mechanisms. The weaving motion permits the electrical signals to be interpreted in terms of vertical and cross-seam position of the torch. The controller performs an adaptive positioning of the torch as it moves forward along the joint centerline so that the proper path trajectory can be maintained. As irregular edges are encountered along the weld path, the control system compensates by regulating either the arc length (for constant-current systems) or the distance between the torch tip and the work surface (for constant-voltage systems). Operation of the typical through the-arc seam tracking system is illustrated in Fig. 14-5.

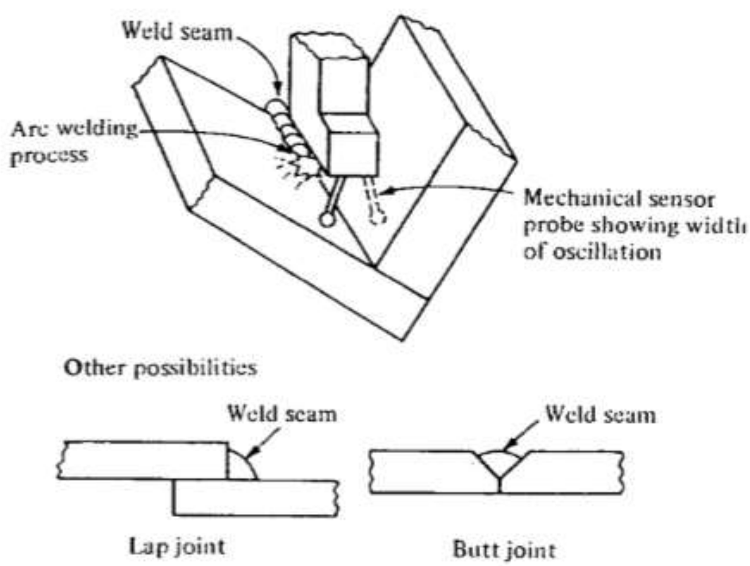

Figure 14-4 Diagram depicting the operation of the contact arc welding sensor and several of the types of joints in which it can be used.

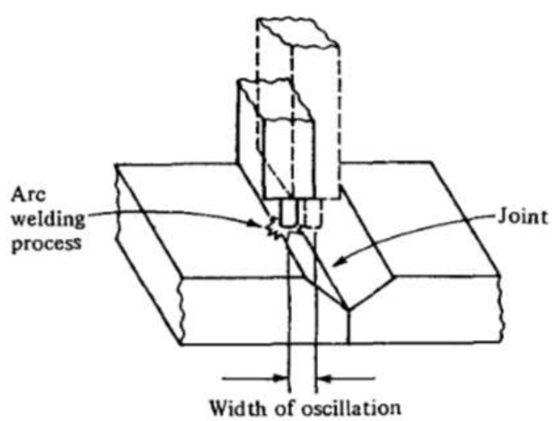

Figure 14-5 Operation of a typical "through-the-arc" seam tracking sensor system, depicting oscillation from side to side in the welding groove.

Vision-based systems represent a promising technology for tracking the seam in arc-welding operations. These systems utilize a vision camera mounted on the robot near the welding torch to view the weld path. In some cases the camera is an integral component of the welding head. Highly structured light is usually required for the camera sensors to function reliably.

There are two approaches used with vision sensors for arc welding: two-pass systems and single-pass systems. In both types, the robot must be programmed for the welding path before the operation begins.

In the two-pass systems, the vision camera takes a preliminary pass over the seam before the welding operation begins. As indicated above, the robot must be programmed for the particular seam path before either pass is taken. Then the two passes are taken automatically by the robot. In the first pass, light is projected onto the seam and the camera scans the joint at high speed (speeds up to 1 m/s are claimed), checking for deviations from the anticipated seam path. These deviations are analyzed by the controller and remembered for the second pass. During the second pass, in which the welding process is performed, the controller makes adjustments in the seam path to correct for the deviations detected in the first pass. The first pass requires only about l0 percent of the time for the welding pass, and the advantage gained by using two passes is that the vision system can see a clean view of the welding path on the preliminary scanning pass, absent of the smoke and intense brightness encountered during actual welding.

In the single-pass system, the vision camera is aimed at the welding seam just ahead of the torch. Deviations from the programmed seam location are detected and corrections are made in the weld path. The obvious advantage of the single-pass systems, compared to the two-pass systems, is that time is saved by eliminating the need for a second pass along the weld path. Another advantage is that the single-pass systems are able to compensate for thermal distortions in the weld path caused by the welding process.

Examples of commercial vision systems in the single-pass category are the Robovision II from Automatix Inc., and WeldYision from General Electric. In the Automatix system, the camera is focused about 4 cm in front of the weld. The observed image is analyzed to extract the location of the center of the seam, the seam width, and the distance of the seam from the camera. In the General Electric system, the vision sensor is incorporated into the design of the welding torch. The image observed by the camera includes the weld puddle and the seam ahead of it. By analyzing both the weld puddle and the seam, the controller is able to make adjustments in the process to automatically track the seam.

5a.2.2.3 Advantages and Benefits of Robot Arc Welding

A robot arc-welding cell for batch production has the potential for achieving a number of advantages over a similar manual operation. These advantages include the following:

1. Higher productivity
2. Improved safety and quality-of-work life
3. Greater quality of product
4. Process rationalization

The productivity of a manual arc-welding operation is characteristically quite low. The productivity is often measured by the "arc-on" time. This gives the proportion of time during the shift that the welding process is occurring, and therefore production is taking place. Typical values of arc-on time range between 10 and 30 percent. The lower value corresponds to one-of-a-kind welding jobs, and the higher value corresponds to batch type production. One of the reasons why the arc-on time is low in manual welding is the fatigue factor. The hand-eye, coordination required and the generally uncomfortable working environment tend to be tiring to the human welder and frequent rest periods must be taken. With robot welding cells for batch production, a 50 to 70 percent arc-on time can be realized. There are several factors that contribute to the increased arc-on time when robots are used in batch production. Certainly one factor is the elimination of the fatigue factor. Robots do not experience fatigue in the sense that human workers do. A robot can continue to operate during the entire shift without the need for periodic rest breaks. Another contributing factor is the presence of two parts positioners in the cell. The robot can be performing the welding operation at one positioner while the human operator is unloading the previous assembly and loading new components at the other positioner.

Improved safety and quality-of-work environment result from removing the human operator from an uncomfortable, fatiguing, and potentially dangerous work situation. As described above, the welding environment contains a number of serious hazards for human beings.

Greater product quality in robot arc welding results from the capability of the robot to perform the welding cycle with greater accuracy and repeatability than its human counterpart.

This translates into a more consistent welding seam, one that is free of the start-and-stop buildup of filler metal in the seam that is characteristic of many welds accomplished by human welders.

The term process rationalization refers to the systematic organization of the work and the material flow in the factory. The design and installation of a robot welding cell forces the user company to consider such issues as the delivery of materials to the cell, the methods required to perform the welding process, the design of the fixtures, and the problems of production and inventory control related to the operation of the cell. Typically, these issues are not adequately addressed when the company relies on human welding stations.

5a.3 SPRAY COATING

Most products manufactured from metallic materials require some form of painted finish before delivery to the customer. The technology for applying these finishes varies in complexity from simple manual methods to highly sophisticated automatic techniques. We divide the common industrial coating methods into two categories:

1. Immersion and flow-coating methods
2. Spray-coating methods

Immersion and flow-coating methods are generally considered to be low-technology methods of applying paint to the product. Immersion involves simply dipping the part or product into a tank of liquid paint. When the object is removed, the excess paint drains back into the tank. The tanks used in the process can range in size from 1 or 2 gallons for small objects to thousands of gallons for large fabricated metal products. Closely related to immersion is the flow-painting method. Instead of dipping the parts into the tank, they are positioned above the tank and a stream of paint is directed to flow over the object. Both of these methods are relatively inefficient in terms of the amount of paint deposited onto the object. Although dipping and flow coating· are relatively simple processes, the methods for delivering the product to the painting operation may involve considerable mechanization. For example, conveyor systems are often used in high production to carry the parts down into the dipping tanks to apply the coating.

A more advanced immersion method is **electrodeposition**. This is a process in which a conductive object (the part or product) is given a negative electrical charge and dipped into a water suspension containing particles of paint. The paint particles are given a positive electrical charge, and consequently they are attracted to the negatively charged object (the cathode). The electrodeposition coating method is a highly sophisticated technique and requires close control over the process parameters (e.g., current, voltage, concentration of paint in suspension) in order to ensure the success of the operation. Its advantage is that it does not waste nearly as much paint as conventional immersion methods.

The second major category of industrial painting is spray coating. This method involves the use of spray guns to apply the paint or other coating to the object. Spray painting is typically accomplished by human workers who manually direct the spray at the object so as to cover the desired areas. The paint spray systems come in various designs, including conventional air spray, airless spray, and electrostatic spray. The conventional air spray uses compressed air mixed with the paint to atomize it into a high velocity stream. The stream of air and paint is directed through a nozzle at the object to be painted. The airless spray does not use compressed air. Instead the liquid paint flows under high fluid pressure through a nozzle. This causes the liquid to break up into fine droplets due to the sudden decrease in pressure in front of the nozzle.

The electrostatic spray method makes use of either conventional air spray or airless spray guns. The feature which distinguishes the electrostatic method is that the object to be sprayed is electrically grounded and the paint droplets are given a negative electrical charge to cause the paint to adhere to the object better. The spray-coating methods, when accomplished manually, result in many health hazards to the human operators. These hazards includes :

Fumes and mist in the air. These result naturally from the spraying operation. Not all of the paint droplets become attached to the surface of the object. Some remain suspended in the atmosphere of the spray painting booth. To protect the human operators, ventilation systems must be installed in the booth and protective clothing and breathing masks must be worn. Even with this protection, the environment is uncomfortable and sometimes toxic for humans.

Noise from the nozzle. The spray gun nozzle produces a loud shrill noise. Prolonged exposure by humans can result in hearing impairments.

Fire hazards. Flammable paint, atomized into a fine mist and mixed with air, can result in flash fires in the spray painting booths.

Potential cancer hazards. Certain of the ingredients used in modern paints are believed to be carcinogenic, with potentially unsafe health consequences to humans

Robots in Spray Coating

Because of these hazards to humans, the use of industrial robots has developed as an alternative means of performing spray-coating operations. Spray-coating operations to which robots have been applied include painting of car bodies, engines, and other components in the automotive industry, spraying of paint and sound absorbing coatings on appliances, application of porcelain coatings in bathroom fixtures, and spray staining of wood products. Some of the applications have consisted of a stand-alone robot spraying a stationary workpart that has been positioned in a paint booth by a human worker. However, these applications are generally less successful because they rely heavily on the human worker and the utilization of the robot is relatively low.

In most robot spray-coating applications, the robots are usually part of a system that includes a conveyor for presenting the parts to the robot, and a spray booth for shielding the spraying operation from the factory environment. Figure 14-7 illustrates a robot spray painting a part. When a conveyor-robot system is used, the operation of the robot and the conveyor must be closely synchronized. In the case of an intermittent (irregular/discontinuous) conveyor system, interlocks are used to coordinate the start and finish of the robot program with the movement of the conveyor. With a continuously moving conveyor, some form of baseline tracking system is required in order to synchronize the robot's motions with the movement of the conveyor. Another feature of many robot spray-coating applications is that the system must be designed to process a variety of part styles, each with its own unique configuration. This is usually accomplished by providing the workcell with a parts identification system. Once the part has been properly identified, the robot can then apply the correct spray cycle for that part

In general, the requirements of the robot for spray-coating applications are the following:

1. Continuous-path control. In order to emulate the smooth movement of a human spray paint operator, the robot must possess many degrees of freedom in its manipulator and it must have continuous path capability.
2. Hydraulic drive. Hydraulic drive is preferred over electric or pneumatic drive in spray-painting applications. In electric drive there is danger that a spark in the electric motor system may ignite the paint fumes in the spray booth environment. The motions generated in pneumatic drive are generally too jerky to be suitable for spray-coating applications.

3. Manual leadthrough programming. In most spray-coating applications, the most convenient method of teaching the robot involves leadthrough programming in which the robot arm is manually pulled through the desired motion pattern by a human operator who is skilled in the techniques of spray painting. During the programming procedure, a "teach arm" which is light and maneuverable, is often substituted for the actual robot arm, which tends to be heavy and difficult to manipulate smoothly.
4. Multiple program storage. The need for multiple program storage arises in paint production lines in which more than one part style are presented to the robot for spraying. The capability to quickly access the program for the current- part is a requirement for these lines. Either the robot itself must have sufficient memory for the programs required or it must be interfaced to the cell controller (computer or programmable controller) for random access to this memory capacity.

In robot spray-coating operations, the spray gun is the robot's end effector. Control over the operation of the spray gun system must be accomplished by the robot during program execution. In addition to on-off control over the spray gun nozzle, some of the important process variables that must be regulated during the spray cycle include paint How rate, fluid and/or air pressure, and atomization. These variables are regulated through the output interlock functions of the robot controller. The operation of the interlock functions is established during the programming procedure. Other parameters that must be controlled during the spray-coating process are related to the coating fluid (e.g., the paint). Viscosity, specific gravity, temperature, and other characteristics of the fluid must be maintained at consistent levels in order for the results of the finishing operation to be acceptable.

Another requirement for consistent quality in the finishing operation is that the spray gun must be periodically cleaned. This can be accomplished without significant loss of production time by programming a cleaning cycle into the workcell operation at regular intervals. The cleaning operation takes only a few seconds to complete and consists of the robot placing the spray nozzle under cleaning jets which spray solvent into the nozzle opening. Incorporating the cleaning operation into the work cycle should be planned to minimize the impact on the productive portion of the cycle.

Benefits of Robot Spray Coating

Use of robots to perform spray-finishing operations provide a number of important advantages. These advantages include:

1. Removal of operators from hazardous environment 2. Lower energy consumption 3. Consistency of finish 4. Reduced coating material usage 5. Greater productivity

Removing the human workers from the kinds of hazards which characterize the manual spray-finishing environment (i.e., fumes, fire hazards, etc.) is a significant health benefit of using robots. Also, because humans are not in the spray booth, the ventilation requirements are reduced below the levels needed when humans are present. Therefore less energy is needed to control the environment. Other advantages include better quality and fewer rejects. Because the robot performs the same spraying cycle on every workpart, the quality of the finishing job is more consistent compared to a human worker. As an added benefit, the amount of paint required to coat the parts is typically reduced by 10 to 50 percent when robots are used. These various features of the robot spray-coating cell result in substantial labor savings and improved productivity in the process.

Example 14-1 An example of a modern high-technology robotic spraypainting cell design is presented in a paper by Akeel. 1 The cell design is the result of the development efforts of the General Motors Manufacturing Staff directed at the problem of automating the paint shops in an automobile production plant. A typical paint cell for producing 60 jobs per hour consists of eight robots (four pairs, each pair servicing the two sides of the automobile) and is illustrated in Fig. 14-8. Other features of the cell include:

A machine vision system for identifying the body style so that the proper robot program can be used.

Backup robots so that if one of the production robots breaks down, they can be quickly replaced by the backups. An overhead crane system serves to replace the robots when needed.

Automatic two-axis door openers so that the internal surfaces of the car can be sprayed.

Supervisory computer control of the cell, including a backup computer that is operated in parallel with the primary system. The backup can he switched into service should the primary computer fail.

The individual painting robots (GM calls them paint spray machines) are seven-axis manipulators that are operated under computer control. The supervisory computer communicates the correct work cycles to the individual machines on the line. Each spray paint machine is equipped with two spray guns especially designed by GM engineers for automatic operation in the cell. Each spray gun is provided with its own paint supply system so that one system can be in the process of being changed over (purged, cleaned, and refilled with the next paint) while the other system is in production. The parallel paint supply lines are contained inside the manipulator arm.

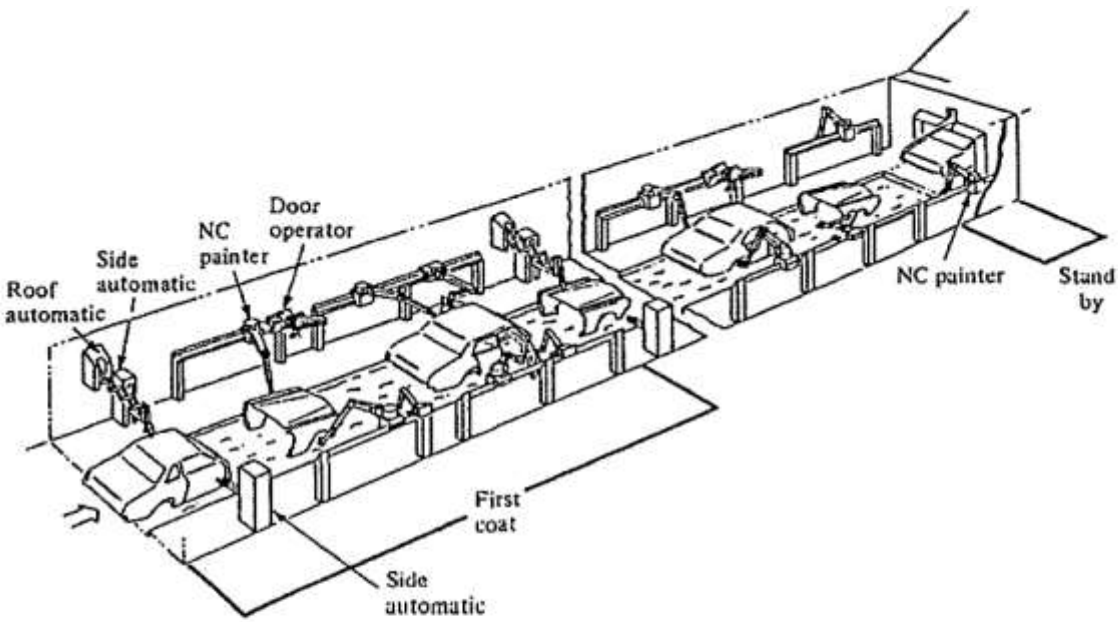

Figure 14-8 Typical configuration of GM paint spray cell. (Reprinted with permission from Akeel

5a.4 OTHER PROCESSING OPERATIONS USING ROBOTS

In addition to spot welding, arc welding, and spray coating, there are a number of other robot applications which utilize some form of specialized tool as the

Drilling, routing, and other machining operations

Grinding, polishing, dehurring, wire brushing, and similar operations

Riveting

Waterjet cutting

Laser drilling and cutting

We are excluding from this category applications in assembly, inspection, and nonmanufacturing operations which might employ a tool as end effector. From the preceding list, it can be seen that a typical end effector in this category is a powered spindle attached to the robot's wrist. The spindle is used to rotate a tool such as a drill or grinding wheel. The purpose of the robot is to position the rotating tool against a stationary workpart in order to accomplish the desired processing operation. In the other examples given in the above list (riveting, waterjet cutting, and laser operations), the end effector is not a powered spindle, but the job of the robot is still to position the tool relative to the part. Requirements of these applications vary, but one of the inherent disadvantages of robots in some of these operations is their relative lack of accuracy as compared to a regular machine tool. Small robots tend to be more accurate than large robots, but large robots are more likely to possess the strength and rigidity necessary to withstand the forces involved to hold the powered spindle against the part during the process. Figure 14-9 shows a PUMA 500 robot performing a wire brush deburring operation.

Figure 14-9 PUMA 500 robot performing a wire brush operation to deburr a workpart. (Photo courtesy of Unimation Inc.)

Example 14-2 This example resulted from an Air Force ICAM (Integrated Computer-Aided Manufacturing) sponsored project 4 and represents an important project in the development of processing applications. The application involves drilling and routing operations of different aircraft components. The components are various sheet metal fuselage panels for the F-16 fighter aircraft which is fabricated by General Dynamics Corporation in Fort Worth, Texas. A diagram of the cell concept is illustrated in Fig. 14-10. The principal components of the cell are the robot and a part fixture. The robot used in the application is a Cincinnati Milacron T3 robot which has a repeatability of + or - 0.050 in and a relatively large work envelope. The application requirement was that the robot should be able to reach over a 3 by 4 ft part area. The fixture has two positions so that the robot can be processing one part while loading and unloading is being accomplished at the opposite position. A human worker performs the loading and unloading tasks. The cell works in a batch production mode and was first placed in operation in October, l979. Some of the important features about this robot application are:

Supervisory computer control to coordinate the activities of the robot and the part fixture

Multiple program storage so that the robot executes the correct program on each different fuselage component.

Automatic workpart identification system employing an optical character reader to recognize which part is to be processed next. This allows the correct program to be called from multiple program storage.

Automatic tool changing of drills and routing tools. A tool rack is used to hold the different tools required in the sequence of processing operations. The robot is programmed to select the proper tool for the particular operation to be performed.

Templates are used to define hole patterns and router paths. Also, compliant end effectors are used to permit the tools to line up with the templates. These measures were adopted in order to overcome the inherent accuracy and repeatability limitations of the T3 robot.

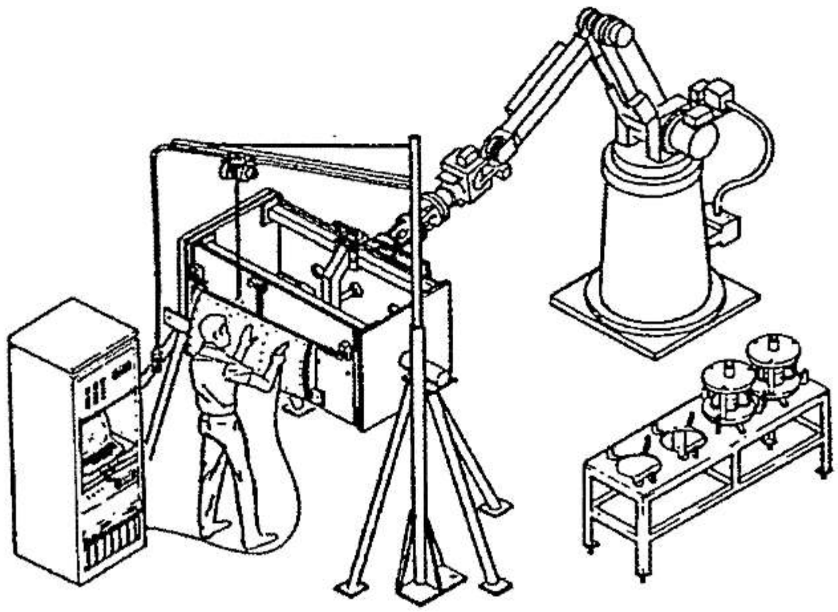

Figure 14-10 Diagram of the drilling and routing cell developed under Air Force ICAM sponsorship. (Reprinted with permission from Golden et al. [4])

Example 14-3 A more recent application, similar to the one described in Example 14-2, is the installation at Grumman Aerospace Corp. The robot cell is used to accomplish light machining of complex contour sheet metal parts for aircraft skins and other components. An ASEA IRB-60 robot performs routing, trimming, and drilling of the aircraft parts. The workcell consists of the robot mounted on a linear track system (this is a mobile robot cell), the part holders, tool-changing module, and cell controller. The cell layout is illustrated in Fig. 14-11. The track system provides approximately 20 ft of linear movement for the robot. This dramatically increases the robot's work volume.

The tool-changing module is shown in Fig. 14-12. Several air-powered drilling and routing tools are used as the robot's end effector. Human operators load the parts into the fixtures and notify the cell controller which parts are to be processed.

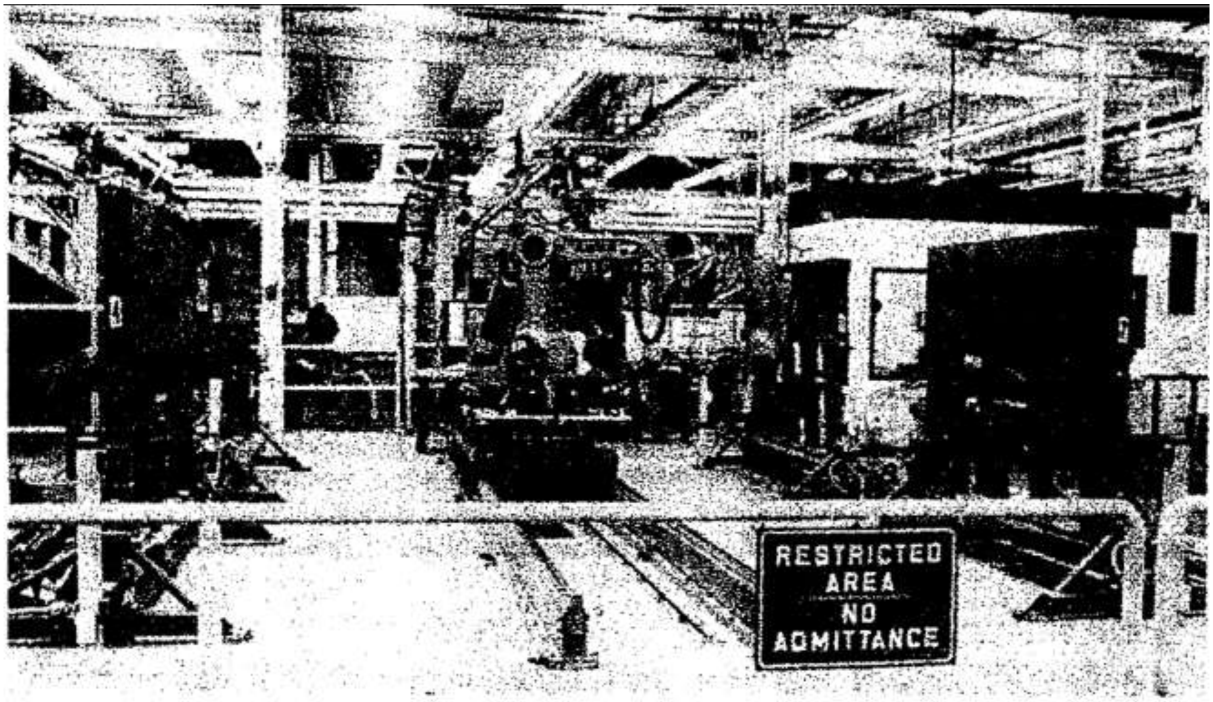

Figure 14-11 Cell layout for Example 14-3. (Photo courtesy of Grumman Aerospace Corp.)

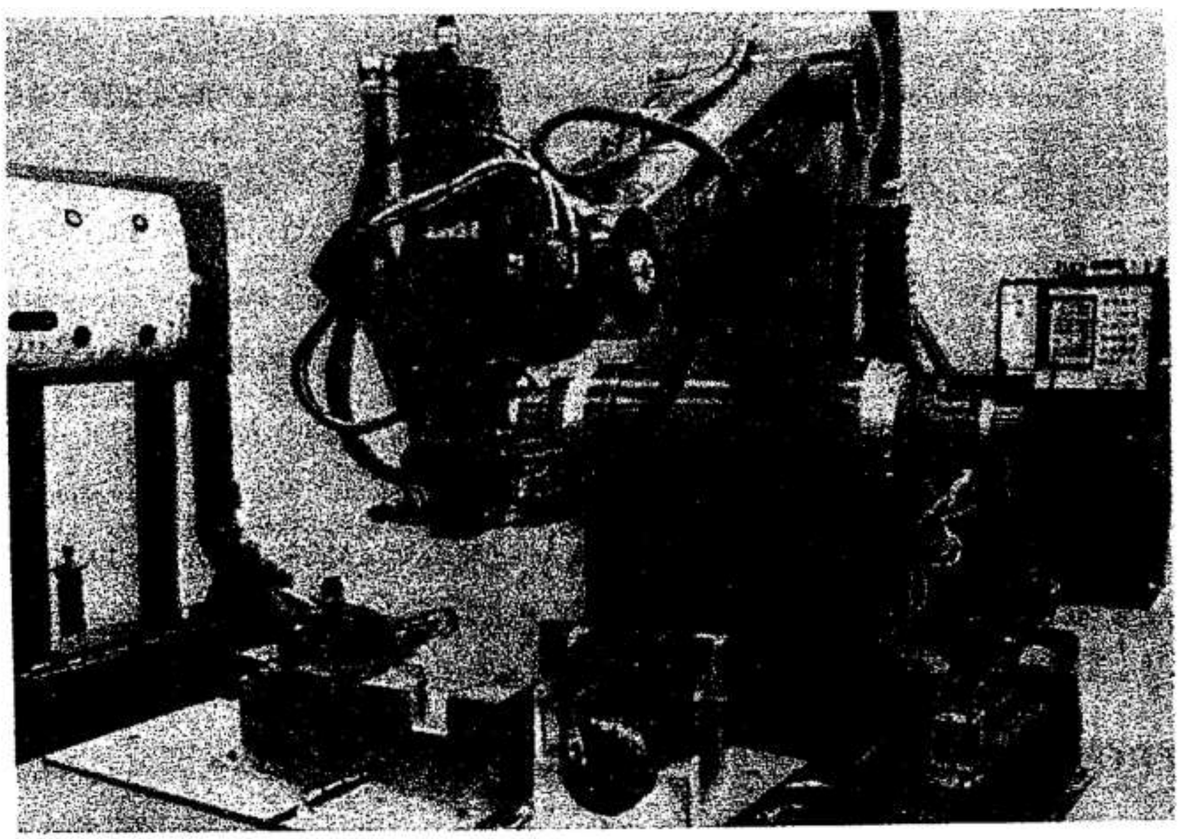

Figure 14-12 Tool-change set up for Example 14-3. (Photo courtesy of Grumman Aerospace Corp.)

5a.5 ASSEMBLY AND ROBOTIC ASSEMBLY AUTOMATION

The term assembly is defined here to mean the fitting together of two or more discrete parts to form a new subassembly. The process usually consists of the sequential addition of components to a base part or existing subassembly to create a more complex subassembly or a complete product. As such, assembly operations involve a considerable amount of handling and orienting of parts to mate them together properly. The difference between assembly tasks and other material-handling tasks is that value is added to the product through the assembly operation. Also, there are often interactions that take place between the two parts being assembled, between the gripper and the part, and between other elements of the workcell. When parts are fastened together (called parts joining), there are often additional interactions with the medium used to join the components (e.g., adhesive). All of these potential interactions can make assembly operations considerably more complex compared to the simpler task of moving a part from one location to another.

There are a variety of assembly processes used in industry today. These include mechanical fastening operations (using screws, nuts, bolts, rivets, swaging, etc.), welding, brazing, and bonding by adhesives. Some of these processes are more adaptable to automatic assembly. We will discuss the various assembly methods in more detail in a later section. It was mentioned in the introduction that assembly operations can be performed manually, or by high-speed automatic assembly machines, or by robots and other programmable systems. In addition, combinations of these techniques can be used in the design of an assembly system for a particular application.

In our coverage of the application of robotics to assembly, we will d1v1de the subject into three areas as suggested by the preceding discussion:

Parts presentation methods

Assembly tasks

Assembly cell designs

The following four sections will examine these three areas and some of the particular problems associated with them. We also present a discussion of a major development project devoted to the application of robots to assembly called the Adaptable-Programmable Assembly System (APAS). Our discussion of assembly will conclude with a section devoted to the topic of product design for automated assembly.

5a.6 PARTS PRESENTATION METHODS

In order for a robot to perform an assembly task, the part that is to be assembled must be presented to the robot. There are several ways to accomplish this presentation function, involving various levels of structure in the workplace:

Parts located within a specific area (parts not positioned or oriented)

Parts located at a known position (parts not oriented)

Parts located in a known position and orientation

In the first case, the robot is required to use some form of sensory input to guide it to the part location and to pick up the part. A vision system could be used as the sensory input system for this purpose. In the second case, the robot would know where to go to get the part, but would then have to solve the orientation problem. This might require the robot to perform an additional handling operation to orient the part. The third way of presenting the part to the robot (known position and orientation) is the most common method currently used, and is in fact the method used in automatic assembly that precedes the advent of robotics. This approach requires the least effort from the robot and sensor system, but it places the largest requirement on the parts feeding system.

Bowl Feeders

Bowl feeders are the most commonly used devices for feeding and orienting small parts in automated assembly operations. They are made by numerous companies and have been used to feed everything from delicate electronic parts to rugged metal castings. A bowl feeder consists of two main components: the bowl and the vibrating base. A track rising in a spiral up the sides of the bowl is used to deliver parts in the bottom of the bowl to an outlet point. This track is commonly located on the inside of the bowl. A typical bowl feeder is shown in Fig. 15-1.

The base of the bowl feeder is constructed of leaf springs and an oscillating electromagnet which causes the bowl and track to vibrate. The vibratory motion causes the parts to be driven up the spiral track until they reach the outlet point.

As the parts are driven up the track and approach the outlet point, they are oriented randomly and must be placed in the proper orientation for delivery out of the bowl feeder. This can be done by either of two methods, called selection and orientation. Selection (sometimes called passive orientation) involves taking parts that are not properly oriented and rejecting them from the track back into the bottom of the bowl, thus permitting parts that are properly oriented to pass through to the outlet point. Orientation involves taking parts that are not oriented properly and physically reorienting them as desired. Both methods are usually accomplished by means of a series of obstacles located along the track. These obstacles allow the parts to pass through only if they meet certain orientation criteria. In the case of part reorientation, obstacles or other mechanisms are used to physically change the orientation of the part as it moves along the track. Some of the techniques that are used in selection and orientation devices are pictured in Fig. 15-2. By providing a sufficient number of obstacles along the track, we can ensure that only parts that possess the desired orientation will successfully reach the outlet point.

Parts exiting the bowl feeder usually travel down a track or chute to some type of holding fixture. This fixture is located at an elevation which is below the outlet point of the bowl feeder so that gravity can be used to deliver the parts from the outlet to the holding fixture. The fixture is isolated from the vibration of the bowl feeder so the robot or other device that retrieves the part will not have to contend with the problems of a vibrating or moving target. The holding fixture maintains the desired position and orientation of the part until it is removed for the assembly operation. If a robot is to perform the assembly operation, the fixture must be designed with enough clearance for the robot gripper to grasp the part.

Another issue that must be addressed is the "back pressure" caused by the parts along the track leading to the holding fixture. Back pressure is the result of two forces: the force imparted on the parts by vibration in the track, and the force generated by the weight of all the parts in the track ahead of the fixture.

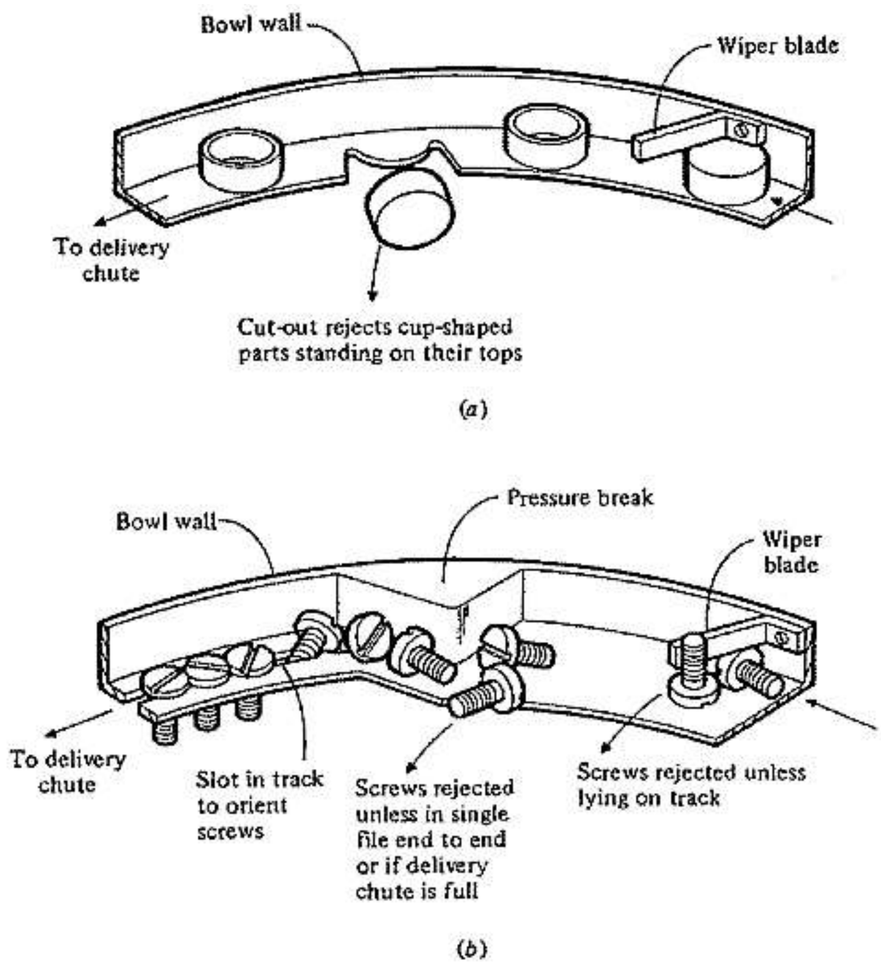

Figure 15-2 Part selection and orientation methods used in vibratory bowl feeders.
(a) Selection and orientation of cup-shaped parts
(b) selection and orientation of screws. (Reprinted with permission from Boothroyd and Redford)

If the back pressure is large enough, it can inhibit the robot from successfully removing the part from the fixture. The following relation describes when the robot will be unable to remove a part from the fixture:

$$u_f F_g < u_p[F_b + n W(\sin \theta)]$$

where u_f = coefficient of friction between the gripper and the part

F_g = gripping force of the gripper

u_p = coefficient of friction between the parts in the track

F_b = back pressure force due to track vibration

n = number of parts in the track leading up to the fixture

W = weight of each part

θ= angle that the track makes with the horizontal (the angle is assumed constant in the portion of the track containing parts leading to the fixture)

There are several ways to limit the back pressure at the holding fixture. The first is to turn off the vibration of the bowl whenever there are a large enough number of parts in the track that the back pressure would reach an undesirable level. On-off control of the bowl operation can easily be accomplished by providing a sensor in the track that detects the presence of the parts. A simple limit switch can be used for this purpose. When parts back up along the track to the point where the sensor is located, the bowl would be turned off. By properly positioning the sensor, the back pressure can be controlled to allow smooth pickup of parts by the robot from the holding fixture. A second way to reduce the back pressure is to make the angle of the track leading into the fixture relatively small. The risk here is that the parts will not properly slide down the track. A third way is to use an "escapement" device at the end of the track to individually place the parts into the holding fixture. This avoids the weight of many parts stacked against each other in the track. Figure 15-3 illustrates a number of escapement devices.

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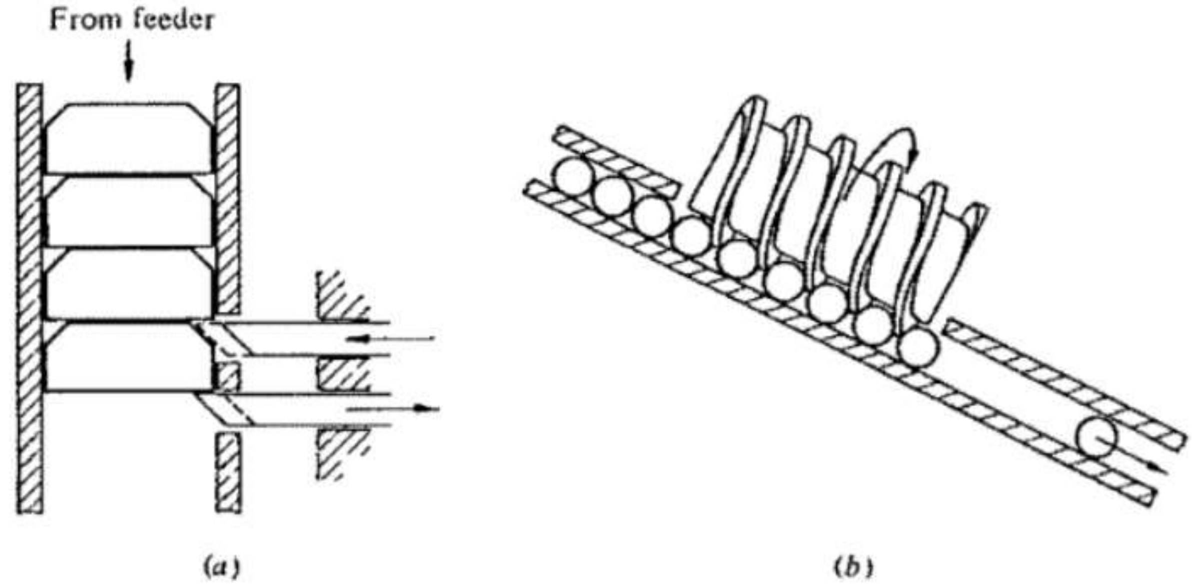

Figure 15-3 Several types of escapement devices used in automated assembly. (a) Linear motion escapement device for disk-shaped parts, (b) worm escapement device. (Reprinted with permission from Boothroyd and Redford)

Magazine Feeders

Bowl feeders are generally used to handle parts that are received at the workstation in bulk. Parts supplied in bulk are randomly oriented and one of the functions served by the bowl feeder is to deliver the parts to the track in proper orientation. An alternative to the use of a bowl feeder is to receive the parts at the workstation in a preoriented orderly fashion. The use of magazine feeders is one technique in which preoriented parts can be received at the workstation. Of course, this does not eliminate the problem of orienting and loading the parts; it simply transfers the problem away from the workstation. The most convenient way to load parts into the magazine in a proper orientation is to perform the loading operation as an integral element of the production process that makes the parts. What makes this possible is that the parts come out of the production process already oriented. For example, in a sheet metal stamping operation, the parts always come out of the press in the same way. It is therefore possible to load the stamped parts one on top of the next in the same orientation, into some kind of tube or other container. This container would constitute the magazine. The tube filled with parts could subsequently be attached to a mechanism (e.g., an escapement) designed to withdraw the parts and present them to the assembly workhead or the robot.

On the other hand, if the parts cannot be loaded into the magazine directly from the production operation and must be loaded instead manually, then the parts magazine loses much of its appeal. One of the disadvantages associated with the use of a parts magazine is that it typically holds fewer parts than a bowl feeder. Consequently, it must be replaced and refilled more frequently requiring a greater level of human attention at the workstation.

Trays and Pallets

Sometimes it is too expensive to use bowl feeders or parts magazines. In those cases, trays or pallets can be used. A specific advantage of using trays, pallets, and other similar storage containers is that they can be used for a variety of different part geometries. Bowl feeders and magazines must usually be custom engineered for a particular part configuration. However, there are certain conditions that generally must be satisfied in using trays and pallets in robotics. Namely, the parts must be located in known positions and orientations with respect to certain reference points on the device, usually the edges of the containers. This allows the trays to be registered correctly at the workstation and for the robot to be programmed to go to the known positions in the trays to retrieve the parts.

If the cycle time of the operation is relatively long, and the tray capacity is large, then the trays could be presented to the workstation by a human operator as required. If the cycle rate is fast, and a more automated operation is desirable, then some type of materials handling system must be devised to present the trays to the workstation automatically. In either case, an issue of great importance in the design of this type of container system (in robotics or any other form of automation) is that the containers must be positioned accurately at the workstation and the parts must be positioned precisely in the containers. If different part styles use the same basic container and material handling system, the information system supporting the operation must be sophisticated enough to handle the differences.

The alternative to the approach of precise part location is for the parts to be randomly oriented in the trays, and for the robot to perform some kind of "bin-picking" procedure in order to pick out the parts one at a time.

5a.7 ASSEMBLY OPERATIONS

Assembly operations can be divided into two basic categories: Parts mating and parts joining. In parts mating, two (or more) parts are brought into contact with each other. In parts joining, two (or more) parts are mated and then additional steps are taken to ensure that the parts will maintain their relationship with each other. In this section we discuss a number of assembly tasks that fall into these two categories, along with their implications for a robot system's capabilities.

Parts Mating The variety of parts mating operations include the following assembly situations:

1. **Peg-in-hole**. This operation involves the insertion of one part (the peg) into another part (the hole). It represents the most common assembly task. Peg-in-hole tasks can be divided into two types: the round peg-in-hole and the square peg-in-hole. The two types are illustrated in Fig. 15-4. With the round peg-in-hole, the robot needs only 5 degrees of freedom to insert the peg since there is no requirement to align the peg about its own axis. With the square peg-in-hole case, a full 6 degrees of freedom are needed in order to mate the corners of the square peg with the corners of the hole.
2. **Hole-on-peg**. This is a variation of the peg-in-hole task. Similar problems exist in defining the degrees of freedom needed to execute the mating of the two parts. A typical example of the hole-on-peg task would be the placement of a bearing or gear onto a shaft.
3. **Multiple peg-in-hole**. This is another variation on case 1 except that one part has multiple pegs and the other part has corresponding multiple holes. Consequently, •he assembly task always requires the ability of the assembly system to orient the parts in all directions. An example would be the assembly of a microelectronic chip module with multiple pins into a circuit card with corresponding holes, as illustrated in Fig. 15-5. This example represents a common assembly problem in the electronics industry.
4. **Stacking.** In this type of assembly, several components are placed one on top of the next, with no pins or other devices for locating the parts relative to each other. In a subsequent assembly operation, the group of parts would he joined together. An example of the stacking assembly operation would he a motor armature or a transformer in which the individual laminations are stacked.

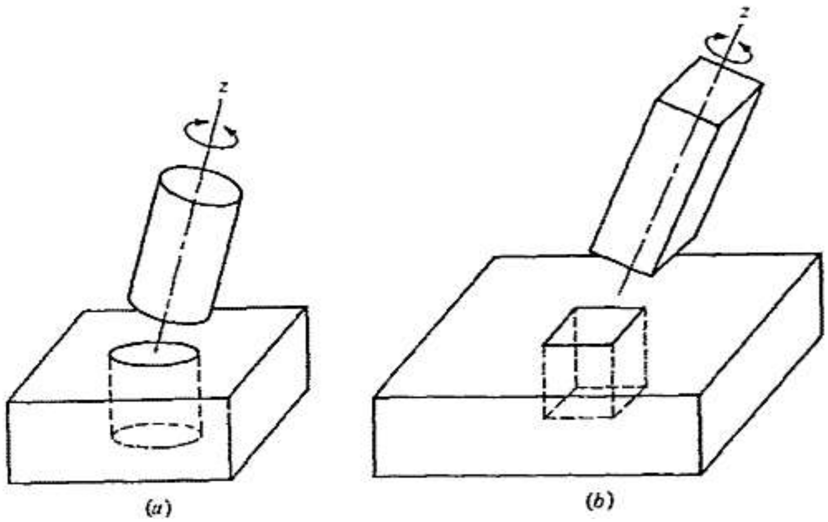

Figure 15-4 Two types of peg-in-hole assembly tasks. (a) round peg-in-hole and (b) square peg-in-hole-orientation about z-axis required.

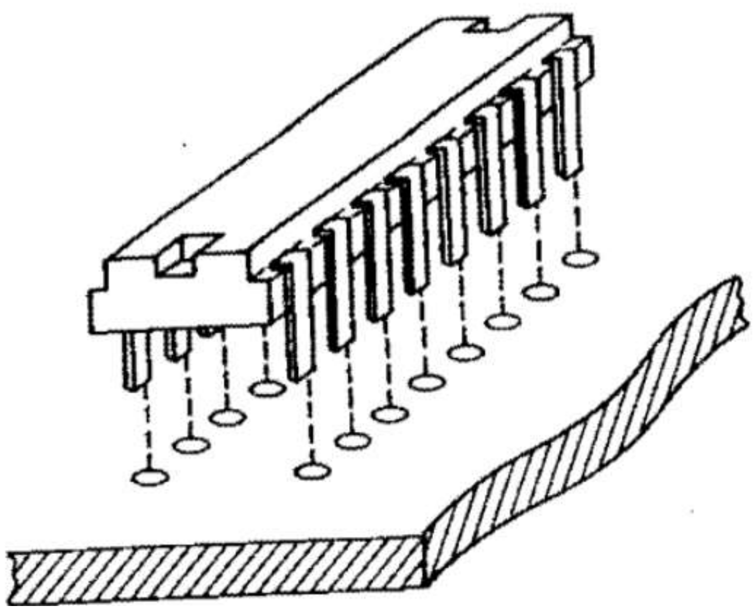

Figure 15-5 Multiple peg-in-hole assembly task: insertion of a semiconductor chip module into a circuit card

Parts-Joining Tasks

In parts joining, not only must the two (or more) components be mated, but also some type of fastening procedure is required to hold the parts together. The possible joining operations include the following:

1. Fastening screws. The use of screws is a very common method of joining parts together in manual assembly. Self-tapping screws are often used and this eliminates the need to perform the extra operation of tapping the threaded hole in the mating part. There are two ways in which a robot can perform the screw-fastening operation: it can drive the screw by advancing and simultaneously rotating its wrist, or it can manipulate a special end effector consisting of a power screwdriver. Power screwdrivers are available that not only drive the screws but also feed them automatically to the bit. Figure 15-6 shows a power screwdriver that can be attached to a robot wrist. Screw fastening without the aid of a power screwdriver turns out to be a relatively difficult task for a robot because of the complexity of the motions involved to rotate the screw and advance it into the hole at the same time. Also, when a screw is to be fastened into a threaded hole (in other words, a self-tapping screw is not used), there is the possibility for binding to occur between the screw threads if the mating hole threads are not properly aligned.
2. Retainers. Retainers can take a number of alternative configurations. They can be pins inserted through several parts in order to maintain the relationship among the parts. Another form of retainer is a ring that clamps onto one part to establish its relationship with another part. Common ring retainers are snap rings and C-rings.
3. Press fits. This is another variation of the peg-in-hole task except that the parts to be mated have an interference fit. This simply means that the peg is slightly larger than the hole into which it is to be inserted. Press-fitted parts can form a very strong assembly. However, a substantial force is required to accomplish the insertion operation. In most force-fit operations, the robot will not be able to provide the necessary force to press the parts together, and therefore the application will be designed so that the robot loads the parts into a power press which performs the actual press-fitting operation.
4. Snap fits. This joining technique has features of both the retainer and the press-fitting methods. A snap fit involves the joining of two parts in which the mating elements of the parts possess a temporary interference that only occurs during the joining process. When the parts are pressed together, one (or both) of the parts elastically deforms to accommodate the interference, then catches into the mating element of the part. The parts are usually designed so that a slight interference fit exists between the two parts even after they are snapped together. Figure 15-7 illustrates the snap fit assembly. This joining

method turns out to be an ideal method for automatic assembly methods including robotics.

5. Welding and related joining methods. Continuous arc welding and spot welding are two common welding operations used to joint parts together. We have discussed these two joining techniques in the preceding chapter. In addition there are other similar joining techniques requiring heat energy that are used in assembly operations. These include brazing, soldering. And ultrasonic welding. All of these joining methods can he implemented by means of robots.
6. Adhesives. Glue and similar adhesives can be applied to join parts together by using a dispenser to lay down a bead of the adhesive along a defined path (for a robot, the motion cycle is similar to arc welding) or at a series of points (similar to spot welding). In most applications the adhesive dispenser is attached to the robot's wrist, while in other cases the robot manipulates the part and presents it to the dispenser.
7. Crimping. The term crimping, in the context of assembly, refers to the process of deforming a portion of one part (often a sheet metal part) to fasten it to another part. A common example of crimping is when an electrical connector is crimped (squeezed) onto a wire. To perform a crimping process, the robot requires a special tool or pressing device attached to its wrist. Staking operations and riveting operations are similar to crimping in that they involve deformation of one part to attach it to another. Staking usually refers to the use of metal tabs on one part that are bent over the joining part. Riveting involves specially designed fasteners (screws without threads) whose ends are flattened over the joining part.
8. Sewing. Although not typically considered as a robot application, this is a common joining technique for soft, flexible parts (e.g .. cloth, leather).

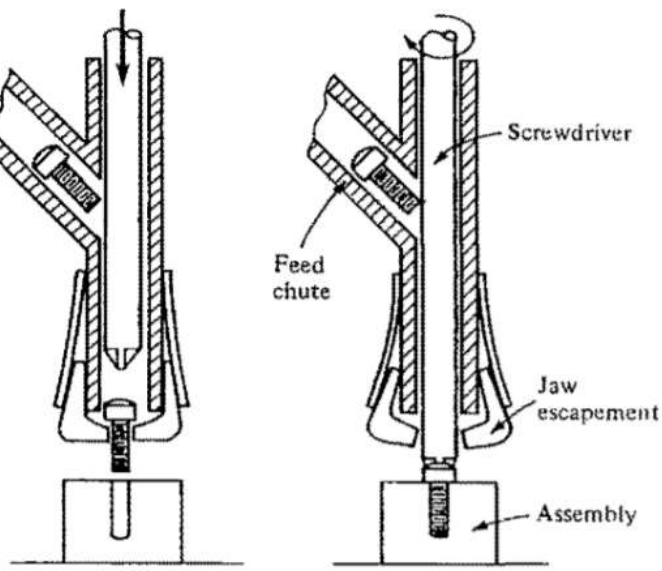

Figure 15-6 Operation of a power screwdriver. (Reprinted with permission from Boothroyd and Redford))

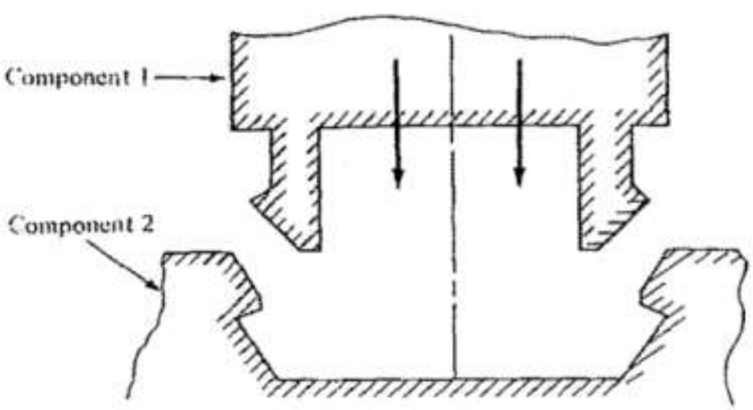

Figure 15-7 Snap fit assembly showing cross-section of tab-hook configuration for two mating parts.

5a.8 COMPLIANCE AND THE REMOTE CENTER COMPLIANCE (RCC) DEVICE

Let us examine the peg-in-hole assembly task and consider the potential problems that are encountered during insertion. When a peg is inserted into a hole there are two possible positioning errors for the peg: a lateral position error and an angular error. These possibilities are illustrated in Fig. 15-8. When the parts are chamfered and there is a position error small enough to allow insertion to begin, it is still likely that an angular error will result during chamfer crossing as the peg rotates about the grip point at the top of the peg. Figure 15-9 shows how this problem can occur. The angular error allowable on the peg is a function of the clearance of the hole and the depth of the insertion. That is, the deeper the part is inserted into the hole, the less angular error can be tolerated; likewise, the smaller the clearance between the parts and the hole, the smaller the angular error. If the angular error is greater than the tolerable error, the parts will wedge into place much in the same way that a dresser drawer gets wedged when it becomes cocked in the drawer side. Conceptually, what must be done to perform a successful peg-in-hole insertion task is to correct for the lateral and angular errors during assembly. A common solution to the problem makes use of the Remote Center Compliance device.

The Remote Center Compliance device, or RCC, was developed during research on assembly at the Charles Stark Draper Laboratory in Cambridge, Massachusetts. Today, RCC products are commercially available and one such product is pictured in Fig. 15-10. The RCC device is typically mounted between the wrist of the robot and its gripper. Figure 15-11 shows a mechanical gripper attached to the RCC device.

The RCC device is capable of accommodating the lateral errors and angular errors encountered in an insertion operation and in other tasks requiring limited compliance. In the peg-in-hole insertion process, the RCC operates as though the part (peg) were being pulled into the hole by the tip, rather than being pushed from the top. The action is accomplished as illustrated in Fig. 15-12.7 Parts (a) and (b) of the figure show the accommodation of the lateral forces. Suppose there is a lateral error in position between the peg and the hole as shown in part (a). Because of the chamfer on the hole, the error will cause a lateral force on the peg. This force causes the RCC to translate the peg so that it can be inserted into the hole. Next, consider the possibility of an angular error. Suppose the axis of the hole is not parallel with the axis of the peg. The peg will enter the hole (assuming the necessary lateral compliance occurs), but its leading edge will contact one side of the hole, while the edge of the hole will contact the other side of the shaft as shown m Fig. 15-12(c). This will cause a moment on the peg. The RCC will accommodate the moment by means of a rotation about the compliant center as illustrated in part (d) of the figure.

RCCs are typically constructed using elastomer springs rather than the mechanical linkages shown in Fig. 15-12. This has resulted in designs that are simple, small, and lightweight. The parameters to be considered when selecting a remote center compliance device include the following:

Remote center distance. This is also called the center of compliance dimension. It is the distance between the RCC bottom surface and the compliant center of the RCC device. The compliant center (also called the elastic center) is the point about which the forces acting on the object being inserted are minimum. The remote center distance should be selected on the basis of the length of the part and the gripper.

Axial force capacity. This is the maximum force in the axial direction which the RCC device is designed to withstand and still function properly.

Compressive stiffness. This is also called the axial stiffness. It is the force per unit distance or spring constant required to compress the RCC device in the direction of insertion. Generally, the compressive stiffness is relatively high to allow for press fitting of parts together.

Lateral stiffness. This is the spring constant relating to the force required to deflect the RCC laterally (perpendicular to the direction of insertion). This parameter should be determined according to the stiffness of the robot and the delicacy of the parts being assembled.

Angular stiffness. This is also called the cocking stiffness. It is the rotational spring constant that relates to the force required to rotate the part about the elastic center by a certain amount.

Torsional stiffness. This is the torsional spring constant which relates to the moment required to rotate the part about the axis of insertion. This parameter becomes important when the insertion task requires orientation relative to the axis of insertion.

Other parameters to be considered in the specification of the remote center compliance device are the maximum allowable lateral and angular errors. These errors are generally determined by the relative size of the product and by its design (e.g., design of the chamfers). They must be sufficiently large to compensate for errors in the workcell due to parts, robot, and fixturing.

A second approach to provide compliance would be to measure the forces and moments encountered by the part and to servo the robot to compensate for these forces. Also, the Instrumented Remote Center Compliance (IRCC) device is a possible approach to this type of problem. The IRCC is an RCC device that has been instrumented to measure deflections. These deflections provide an indication of the forces and moments being applied to the wrist. Whereas most force sensors are very rigid and deflect very little under load, the IRCC is compliant in certain directions. This permits high-speed part insertion owing to the compliance of the RCC while allowing monitoring and data collection of forces during operation of the system.

Finally, a third approach to provide compliance for assembly tasks is the class of robot manipulators known by the acronym SCARA robots, for Selective Compliance Arm for Robotic Assembly. SCARA robots are horizontally articulated manipulators with a vertical insertion axis at the wrist end. The SCARA type robot was illustrated in Fig. 2-8. The arm is very stiff in the vertical direction, but is relatively compliant laterally. This is very convenient for a variety of assembly tasks in which components are stacked from the vertical direction.

5a.9 ASSEMBLY SYSTEM CONFIGURATIONS

There are two basic configurations of assembly systems, a single workstation, and a series of workstations (an assembly line). Combinations of these two basic types are also possible. For example, it is sometimes advantageous to design a series configuration with certain stations in parallel. The following subsections will cover the various possibilities.

Single-Workstation Assembly

In this configuration all of the parts which are required to complete the desired assembly are presented to the operator or robot at a single workstation. All of the parts mating and joining tasks for the assembly are accomplished at the single workstation. In manual assembly, this configuration is generally used for low-volume products (e.g., custom-engineered machinery). In robotic assembly, the conditions warranting the use of this configuration are different from those for manual assembly. A single-station robotic assembly system would typically be used for low- and medium-volume work in which there were a limited number of assembly tasks and parts to be handled. This means that the product is of low to medium complexity. The features and problems of this configuration are illustrated by means of an example.

Example 15-1 The workcell is illustrated in Fig. 15-13 and is designed to assemble an electric motor consisting of the following components: rear endbell, front endbell, rotor, stator, two brushes, two bearings, two screws. There are many alternative ways to define the assembly sequence. In this example, we will begin with the procedure shown in Table 15-1. Some of the problems of robotic assembly become apparent in the sequence. Can the robot handle all of the different shaped parts? Can it reach all of the points on the assembly? It is quite possible that a single gripper will be inadequate to perform all of the handling and assembly tasks. For example, the robot will probably have to use a special powered screwdriver in order to accomplish the screw-fastening operations. It is also likely that the subassembly will have to be repositioned at some point during the assembly sequence. In our analysis of the work cycle, we will assume that one gripper can be designed to handle the rotor, stator, endbells, and completed motor. It will also be assumed that the same gripper can be used to retrieve and grasp a powered screwdriver to perform the screw-fastening operations. A second gripper will be designed to handle the screws, brush holders, and bearings. We will assume that the RTM method is used to analyze the work cycle and to define the following element times for certain general categories of tasks shown in Table 15-1:

Assembly task	8 s
Gripper change	12 s
Reorientation of work	7 s
Tool cycle (screwdriver and press)	4 s

Given these times and the gripper limitations, the sequence of operations and the corresponding element times would be as shown in Table 15-2. The total assembly time is 234 s. If it were possible to design a single gripper to handle all of the different part configurations in the assembly sequence, then a total of 96 s (elements 2, 4, 7, 9, 11, 13, 18, and 20) could be saved, thus reducing the cycle time to 138 s. If the powered screwdriver could somehow be built into the gripper design, and the screwdriver could be designed to feed the screws as part of its process rather than merely drive them, then an additional 48 s (elements 12, 14, 15, and 16) could be saved. This would decrease the cycle time to 90 s. The production rate of the assembly workstation can be determined from the cycle time analysis. Using the 234-s cycle time the production.

Table 15-1 Sequence of steps to assemble electric motor of Example 15-1

1. Place rear endbell into fixture
2. Set first bearing into endbell
3. Set rotor into bearing–endbell
4. Set stator around armature
5. Set second bearing on top of rotor shaft
6. Set front endbell over bearing–rotor–stator
7. Insert first screw
8. Insert second screw
9. Drive both screws
10. Insert first brush holder
11. Insert second brush holder
12. Press both brush holders
13. Off-load completed motor

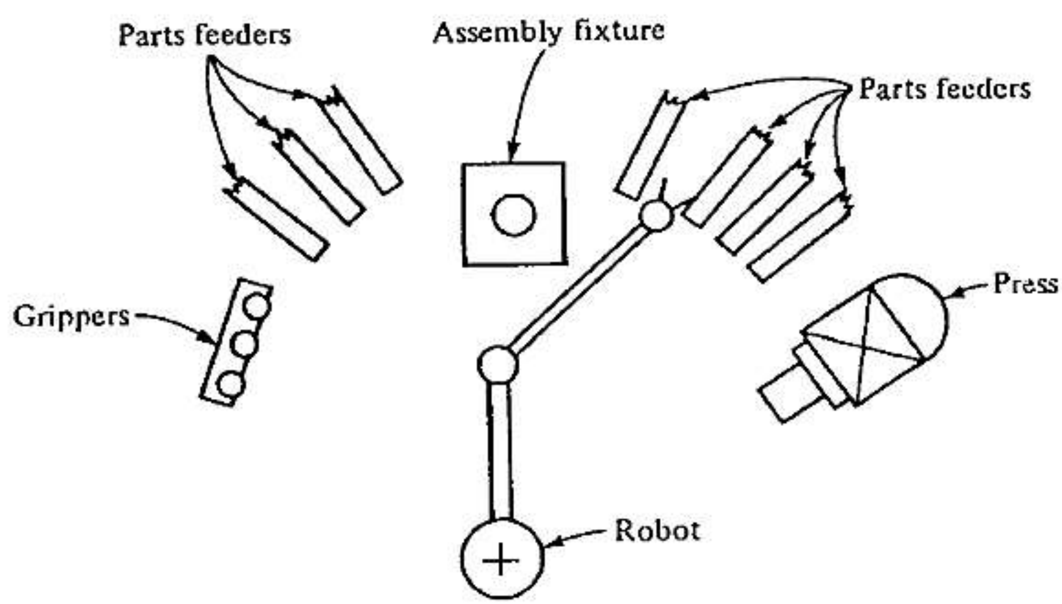

Figure 15-13 Single station robotic workcell for Example 15-1

Table 15-2 Sequence of assembly steps for robot in Example 15-1

Step	Time, s
1. Load first endbell (gripper 1)	8
2. Change gripper	12
3. Install bearing (gripper 2)	8
4. Change gripper	12
5. Install rotor (gripper 1)	8
6. Install stator (gripper 1)	8
7. Change gripper	12
8. Install bearing (gripper 2)	8
9. Change gripper	12
10. Install endbell (gripper 1)	8
11. Change gripper	12
12. Install two screws (gripper 2)	16
13. Change gripper	12
14. Retrieve screwdriver (gripper 1)	12
15. Drive two screws (gripper 1)	8
16. Replace screwdriver (gripper 1)	12
17. Reorient motor (gripper 1)	7
18. Change gripper	12
19. Install two brush holders (gripper 2)	16
20. Change gripper	12
21. Load motor into press (gripper 1)	8
22. Cycle press	4
23. Unload motor (gripper 1)	7
Total	234

rate would be

$$R = 60/234$$

$$= 0.2564 \text{ motors/min or } 15.38 \text{ motors/hour}$$

If the 106-s cycle time is used (assuming the improvements in the work cycle could be made), the production rate would be increased to

$$R = 3600/90 = 40.0 \text{ motors/hour}$$

It is obvious that changing grippers can become a time-consuming portion of the cycle. The reader should also note that reorienting parts (in the example there was a need to reorient the motor in element 17) results in lost time. This can often be avoided by designing a workholding fixture which presents the assembly to the robot in a proper orientation. Several conclusions can be drawn from this example about single-station assembly cells. First, the single-workstation configuration is not very fast, even for assemblies of relatively low complexity (a total of 10 components in our example). Second, other things being equal, the production rate of the cell is inversely proportional to the number of parts in the assembly. Also, it is reasonable to infer, and experience bears this out, that the more parts that must be assembled by the system, the less reliable it will be. Third, a larger number of distinct parts that must be assembled will present a more difficult problem to the designer of the gripper and other tooling (e.g., workholding fixture). In the case of the gripper, either the design must be more complicated to handle the variety of different parts; or the gripper must be instrumented with sensors (usually tactile sensing) to accommodate the part differences; or a tool-changing mechanism must be devised for exchanging the various specialized grippers and other end effector tooling. The single-workstation assembly system possesses one attractive merit, and that is it requires the least capital expense for low-volume automated production of the alternatives in robotics.

5a.10 DESIGNING FOR ROBOTIC ASSEMBLY

Certain assembly tasks are more difficult for a robot to perform than others. If possible, this difficulty factor should be considered in the design of the product. As an example, for a robot to accomplish the screw-fastening operation without the use of an automatic screwdriver is difficult. Even with a powered device to perform the operation, the process of turning the screw into the part requires time. If the objective of using a threaded fastener is to allow for subsequent disassembly (e.g., for service of the product), then the use of screws may be an appropriate design decision. However, if the particular assembly or subassembly is designed to be permanent, then perhaps a better choice than screw fastening would be a press-fit or adhesive bonding of the parts.

Another consideration in the design of an assembly is the direction in which the parts are to be added in the assembly operation. If the parts can all be added without reorienting the partially completed subassembly, then time and money can be saved. On the other hand, if the subassembly requires many reorientations, then handling time is being spent without adding any real value. Similarly, if all the components can be added along the same axis direction, a robot with fewer degrees of freedom can perform the assembly tasks. This suggests that stacking of parts during the construction of an assembly is advantageous.

Today's robots are typically one-armed machines. Coordination of more than one arm at a time is difficult with current control technology. Interpreting this limitation in terms of limitations on the assembly process, an automated mating or joining operation should require the robot to handle no more than one part at a time. Assemblies that require the robot to manipulate two parts simultaneously or to maintain the relationship between two parts while adding a third may require a significant amount of fixturing. The solution to these problems is to design the parts so that they maintain their relationships with each other by designing such features into the components as locating bosses grooves, and other mating elements.

In order to facilitate automatic assembly, it is often appropriate to add certain features to the components. For example, breaking edges and corners on parts, and adding chamfers to the holes will make it easier to accomplish part insertion tasks. These design features added to the components will minimize the robot's accuracy requirements and should allow faster operating cycles. Also, the design of distinct alignment features into the parts, or purposely making an otherwise symmetric part into an asymmetric part, makes it easier to feed and mate the parts in the proper orientation. These added part features will probably necessitate extra processing operations which may increase manufacturing costs of the components. The increases in part costs must be justified by corresponding reductions in assembly costs.

5a.11 INSPECTION AUTOMATION

Inspection is a quality control operation that involves the checking of parts, assemblies, or products for conformance to certain criteria generally specified by the design engineering department. The inspection function is commonly done for incoming raw materials at various stages of the production process, and at the completion of manufacturing prior to shipping the product: Testing is another quality control operation often associated with inspection. The distinction between the two terms is that testing normally involves the functional aspects of the product, such as testing to ensure that the product operates properly, fatigue testing, environmental testing, and similar procedures. Inspection is limited to checking the product m relation to nonfunctional design standards. For example, a mechanical component would be inspected to verify the physical dimensions (e.g., length, diameter, etc.) that have been established by the design engineer.

This section will consider how robotics can be used to perform inspection operations. It turns out that fully automated manufacturing systems have a significant need for inspection to be incorporated as part of the production operation. We encountered this need in our discussion of the APAS project. While automation may reduce inconsistency and errors in manufacturing, it also removes the sensory capabilities and judgment that the human operator can bring to the production process. These capabilities (or some of them, at feast) must somehow be replaced in fully automated production operations.

Robotics can be used to accomplish inspection or testing operations for mechanical dimensions and other physical characteristics, and product function and performance. Generally the robot must work with other pieces of equipment in order to perform the operations. Examples include machine vision systems, robot manipulated inspection and/or testing equipment, and robot loading and unloading operation with automatic test equipment. The following subsections will discuss these three categories of robotic inspection systems.

5a.12.1 Vision Inspection Systems

Machine vision can also be used to implement a robotic inspection system. Typical robotic vision systems are capable of analyzing two-dimensional scenes by extracting certain features from the images. Examples of inspection tasks carried out by this procedure include dimensional accuracy, surface finish, and completeness and correctness of an assembly or product. The robot's role in the inspection process would be either to present the parts to the vision system in the proper position and orientation, or to manipulate the vision system over the portions of the parts or assemblies that must be inspected.

In the design of a machine vision inspection system, there are a number of factors that must be considered in order for the system to operate reliably. These factors include:

The required resolution of the vision camera

The field-of-view of the camera relative to the ob1ect being inspected

Any special lighting requirements

The required throughput of the inspection system

A representative example of a machine vision inspection system will illustrate this robotic application.

> **Example 15-4** Inspection of a PCB provides a good example of a potential vision system application. The robot is used to present the PCB to the vision system in the proper position. If the board is relatively large or there is a need to inspect both sides of the board, the robot would be used to reposition as needed. The PCB consists of a number of electronic components mounted on an epoxy board. The process of fabricating the assembly is complex and there are many opportunities for error. Yet the nature of the product makes it difficult to inspect by human eye.

There are a number of features of the board assembly that would be of interest to the manufacturer. These include:

The size of the epoxy board and the location of certain mounting holes The number and location of the electronic components on the board The identification of the components on the board

For instance, the PCB may consist of an epoxy board measuring 250 by 450 nm, with a certain number of integrated circuit modules and other components each with its own unique identification (size, color, and part number). The vision inspection system would be programmed to perform the following operations:

1. Check the dimensions of the circuit board to ensure that it is within specification.
2. Search for the components mounted on the board and count them to verify that the correct quantity are present.
3. Identify the components by type to make certain that the correct component was located in the designated position on the board.

5a.12.2 Robot-Manipulated Inspection or Test Equipment

This method of robotic inspection involves the robot moving an inspection or testing device around the part or product. An example would be for a robot to manipulate an electronic inspection probe or a laser probe along the surface of the object to be measured. As long as the accuracy of the measurement is not required to exceed the repeatability of the robot, the approach is feasible.

> **Example 15-5** Manual methods of inspecting a car body often involve building fixture large enough to surround the body, and measuring the desired dimensions

on the body relative to gauge points on the fixture. Since robots are capable of positioning an end effector to precise locations in space, the car body dimensions can be measured relative to the robot's coordinate system. There are a number of examples in the automotive industry where robots are used to inspect certain dimensions on car bodies.

In one application reported for one of the Ford Motor Company assembly plants[8] , four Cincinnati Milacron T3 robots perform a series of dimensional checks on automobile bodies at the rate of five or six bodies per hour. This compared with the previous manual inspection method in which only one or two inspections were completed each shift. The robots manipulate electromechanical probes to make approximately 150 dimensional checks around windshield, door, and window openings. At a General Motors plant, an application was developed in which several robots were fitted with laser-ranging equipment. As the automobile body passed through the robotic inspection station, the laser gauges were positioned at critical locations around the car body and measurements were taken. Using this system, GM was able to test every car body that came down the line, rather than one per shift using the traditional manual techniques.

5a.11.3 Robot-Loaded Test Equipment

The third application area in robotic inspection is loading and unloading inspection and testing equipment. This application is very similar to machine tool loading/unloading. There are various types of inspection and testing equipment that can be loaded by a robot. These include mechanical, electrical, and pneumatic gauges, and functional testing devices,

A robotic inspection application would logically be incorporated into the manufacturing method. The robot would be used to unload the finished part from the production machine and to load it into an inspection gauge which would determine if the part was acceptable. If the part were within tolerance, it would be passed to the next step in the production process. If it did not meet the tolerance specification, the part would be rejected.

Taking this inspection system one logical step further, the robotic system would act as a feedback control system by making adjustments for tool wear and other sources of variation in the metal cutting process. The automatic inspection system would be programmed to determine not only whether the parts were within tolerance, but also to perform a trend analysis and to input this information into the machine tool control system so that compensating adjustments could be made to the tool path.

Functional testing is commonly used in the electronics industry. The quality and performance of the product cannot be determined by visual inspection alone. Accordingly, the parts must be loaded into functional testers which measure the response of the system to certain controlled inputs. For example, if a voltage is placed across the coil of a relay, one would expect the contacts to close and the resistance of the contacts to decrease. A tester can be built to perform this kind of performance test. A more elaborate functional tester can be designed to test the response of all the circuits in a printed circuit board.

Example 15-6 Figure 15-24 shows a robot cell for testing printed circuit board. The PC boards are presented to the robot in a tote bin. The robot unloads the board from the tote bin and places it in one of the available testers. It then signals the tester to perform the test. When tester completes the functional testing, it informs the robot and indicates whether the board has passed the testing procedure. The robot then sorts the PCB accordingly into the appropriate output tote bins.

5a.12.4 Integrating Inspection into the Manufacturing Process

As we have discussed earlier in this chapter, inspection is a vital component of the automated assembly process. This is true not only in assembly but also in other automated manufacturing methods as well. As the human operator is removed from the workstation, the function of checking the work must be taken over by other means. One of the features of a robotic workcell is that the inspection can usually be added for a nominal capital cost. The inspection process can often be accomplished on the finished part at the same time as the production process is working on the next part. Therefore the added time to inspect can be minimized. It is likely that the automated factory of the future will be characterized by a very high level of integration between the manufacturing process and the inspection process. The earlier that a defect is discovered in the automated manufacturing process, the less expensive the part repair or scrap will be. In fact, automatic part inspection may even eliminate certain breakdowns in the production equipment due to jamming of the parts or similar failures.

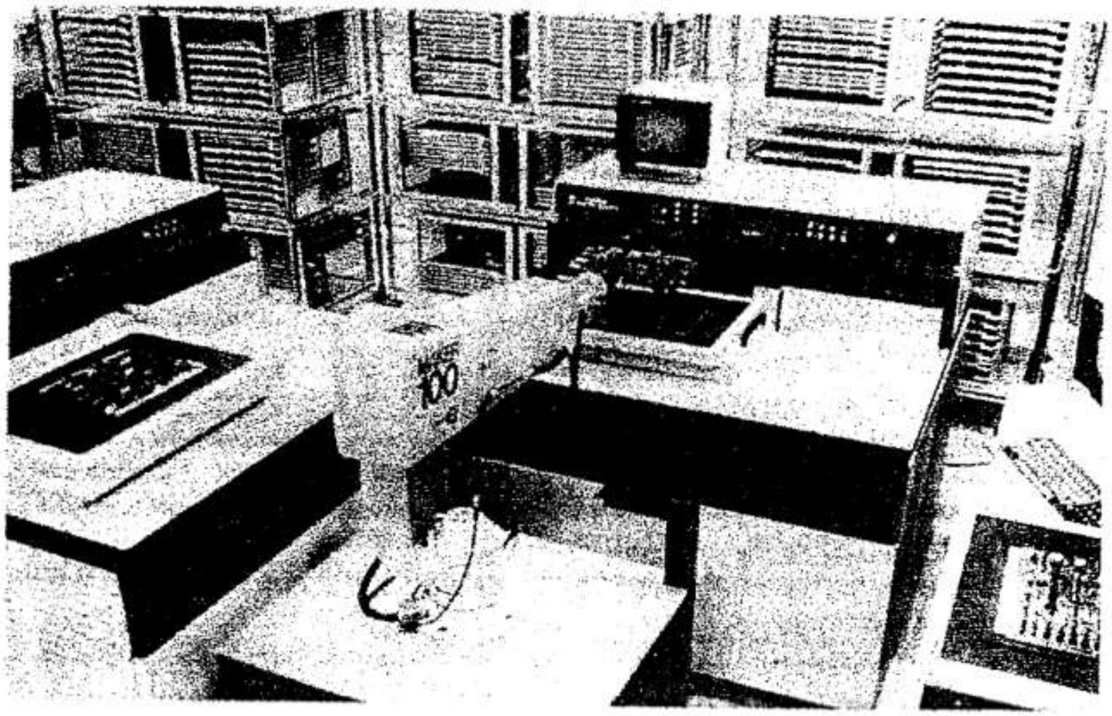

Figure 15-24 Automatic test cell of Example 15-6. (Photo courtesy of United States Robots, subsidiary of Square D Company}

5b) Autonomous Mobile Robots: Introduction, Planning & Navigation:

5b.1 Introduction

5b.2 Basic control scheme for mobile robots

5b.2.1 Perception

One of the most important tasks of an autonomous system of any kind is to acquire knowledge about its environment. This is done by taking measurements using various sensors and then extracting meaningful information from those measurements,

In this chapter we present the most common sensors used in mobile robots and then discuss strategies for extracting information from the sensors.

Sensors for Mobile Robots

A wide variety of sensors is used in mobile robots (figure 4.1). Some sensors are used to measure simple values such as the internal temperature of a robot's electronics or the rotational speed of the motors. Other more sophisticated sensors can be used to acquire information about the robot's environment or even to measure directly a robot's global position.

Here we focus primarily on sensors used to extract information about the robot's environment. Because a mobile robot moves around, it will frequently encounter unforeseen environmental characteristics, and therefore such sensing is particularly critical. We begin with a functional classification· of sensors. Then, after presenting basic tools for describing a sensor's performance, we proceed to describe selected sensors in detail.

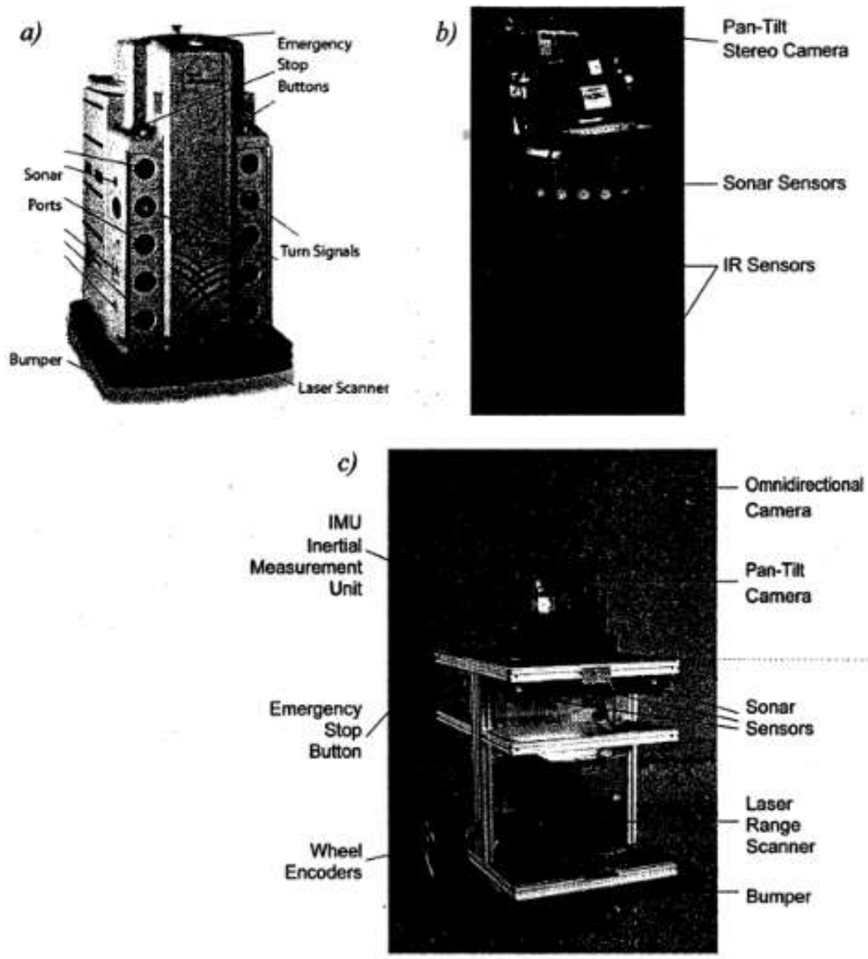

Figure 4.1
Examples of robots with multisensor systems: (a) **HelpMate** from Transition Research Corporation; (b) B21 from Real World Interface; (c) BIBA Robot, **Blue**Botics SA.

1. Sensor classification

We classify sensors using two important functional axes: *proprioceptive/exteroceptive* and *passive/active.*

Proprioceptive sensors measure values interna l to the system (robot), for example, motor speed, wheel load, robot arm joint angles, and battery voltage.

Exteroceptive sensors acquire information from the robot's environment, for example, distance measurements, light intensity, and sound amplitude. Hence exteroceptive sensor measurements are interpreted by the robot in order to extract meaningful environmental features.

Passive sensors measure ambient environmental energy entering the sensor. Examples of passive sensors include temperature probes, microphones, and CCD or CMOS cameras.

Active sensors emit energy into the environment, then measure the environmental reaction. Because active sensors can manage. more controlled interactions with the environment, they often achieve superior performance; However, active sensing introduces several risks: the outbound energy may affect the very characteristics that the sensor is attempting to' measure. Furthermore, an active sensor may suffer from interference between its signal and those beyond its control. For example, signals emitted by other nearby robots, or similar sensors on the same robot, may influence the resulting measurements. Examples of active sensors include wheel quadrature encoders, ultrasonic sensors, and laser range finders.

Table 4.1 provides a classification of the most useful sensors for mobile robot applications. The most interesting sensors are discussed in this chapter. The sensor classes in table 4.1 are arranged in ascending order of complexity and descending order of technological maturity. Tactile sensors and proprioceptive sensors are critical to virtually all mobile robots and are well understood and easily implemented. Commercial quadrature encoders, for example, may be purchased as part of a gear-motor assembly used in a mobile robot. At the other extreme, visual interpretation by means of one or more CCD/CMOS cameras provides a broad array of potential functionalities, from obstacle avoidance and localization to human face recognition. However, commercially available sensor units that provide visual functionalities are only now beginning to emerge.

2. **Characterizing sensor performance**

The sensors we describe in this chapter vary greatly in their performance characteristics. Some sensors provide extreme accuracy in well-controlled laboratory settings but are overcome with error when subjected to real-world environmental variations. Other sensors provide narrow, high-precision data in a wide variety of settings.

Basic sensor response ratings

A number of sensor characteristics can be rated quantitatively in a laboratory setting. Such performance ratings will necessarily be best-case scenarios when the sensor is placed on real-world robot, but are nevertheless useful.

Dynamic range is used to measure the spread between the lower and upper limits of input values to the sensor while maintaining normal sensor operation. Formally, the dynamic range is the ratio of the maximum input value to the minimum measurable input value. Because this raw ratio can be unwieldy, it is usually measured in decibels, which are computed as ten times the common logarithm of the dynamic range. However, there is potential confusion in the calculation of decibels, which are meant to measure the ratio between powers, such as watts or horsepower. Suppose your sensor measures motor current and can register values from a minimum of l mA to 20 mA. The dynamic range of this current sensor is defined as

$$10 \cdot \log\left[\frac{20}{0.001}\right] = 43 \text{ dB} . \tag{4.1}$$

Now suppose you have a voltage sensor that measures the voltage of your robot's battery, measuring any value from 1 mV to 20 V. Voltage is not a unit of power, but the square of voltage is proportional to power. Therefore, we use 20 instead of 10:

$$20 \cdot \log\left[\frac{20}{0.001}\right] = 86 \text{ dB} . \tag{4.2}$$

Range is also an important rating in mobile robot applications because often robot sensors operate in environments where they are frequently exposed to input values beyond their working range. In such cases, it is critical to understand how the sensor will respond. For example, art optical rangefinder will have a minimum operating range and can thus provide spurious data when measurements are taken with the object closer than that minimum.

Resolution is the minimum difference between two values that can be detected by a sensor. Usually, the lower limit of the dynamic range of a sensor is equal to its resolution.

However, in the case of digital sensors, this is not necessarily so. For example, suppose that you have a sensor that measures voltage, performs an analog-to-digital (A/D) conversion, and outputs the converted value as an 8-bit number linearly corresponding to between 0 and 5V . If this sensor is truly linear, then it has 2^8-1 total output values, or a resolution of

5 V(255) = 20 mV

Linearity is an important measure governing the behavior of the sensor's output signal as the input signal varies. A linear response indicates that if two inputs x and y result in the two outputs $f(x)$ and $f(y)$, then for any values a and b, $f(ax+ by) = af(x) + bf(y)$. This means that a plot of the sensor's input/output response is simply a straight line.

Bandwidth or **frequency** is used to measure the speed with which a sensor can provide a stream of readings. Formally, the number of measurements per second is defined as the sensor's frequency in **hertz**. Because of the dynamics of moving through their environment, mobile robots often are limited in maximum speed by the bandwidth of their obstacle detection sensors.

Thus, increasing the bandwidth of ranging and vision sensors has been a high priority goal in the robotics community.

Table 4.1
Classification of sensors used in mobile robotics applications

General classification (typical use)	Sensor Sensor System	PC or EC	A or P
Tactile sensors (detection of physical contact or closeness; security switches)	Contact switches, bumpers Optical barriers Noncontact proximity sensors	EC EC EC	P A A
Wheel/motor sensors (wheel/motor speed and position)	Brush encoders Potentiometers Synchros, resolvers Optical encoders Magnetic encoders Inductive encoders Capacitive encoders	PC PC PC PC PC PC PC	P P A A A A A
Heading sensors (orientation of the robot in relation to a fixed reference frame)	Compass Gyroscopes Inclinometers	EC PC EC	P P A/P
Acceleration sensor	Accelerometer	PC	P
Ground beacons (localization in a fixed reference frame)	GPS Active optical or RF beacons Active ultrasonic beacons Reflective beacons	EC EC EC EC	A A A A
Active ranging (reflectivity, time-of-flight, and geometric triangulation)	Reflectivity sensors Ultrasonic sensor Laser rangefinder Optical triangulation (1D) Structured light (2D)	EC EC EC EC EC	A A A A A
Motion/speed sensors (speed relative to fixed or moving objects)	Doppler radar Doppler sound	EC EC	A A
Vision sensors (visual ranging, whole-image analysis, segmentation, object recognition)	CCD/CMOS camera(s) Visual ranging packages Object tracking packages	EC	P

A, active; P, passive; P/A, passive/active; PC, proprioceptive; EC, exteroceptive.

5b.2.2 Localization

Navigation is one of the most challenging competences required of a mobile robot. Success in navigation requires success at the four building blocks of navigation: ***perception*** (the robot must interpret its sensors to extract meaningful data); ***localization*** (the robot must determine its position in the environment, Figure 5.1); ***cognition*** (the robot must decide how to act to achieve its goals); and ***motion control*** (the robot must modulate its motor outputs to achieve the desired trajectory).

Of these four components (Figure 5.2), localization has received the greatest research attention in the past decade, and as 'a result, significant advances have been made on this front.

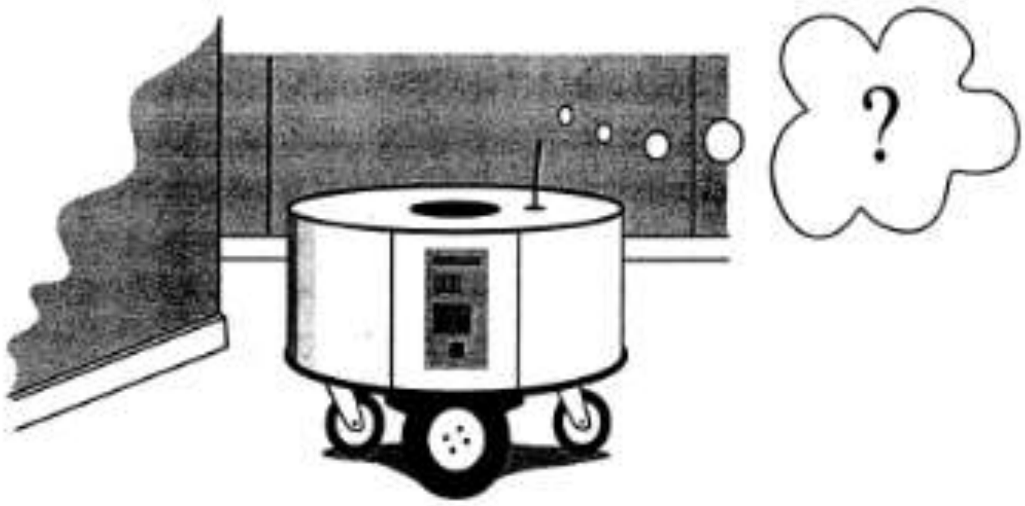

Figure 5.1
Where am I?

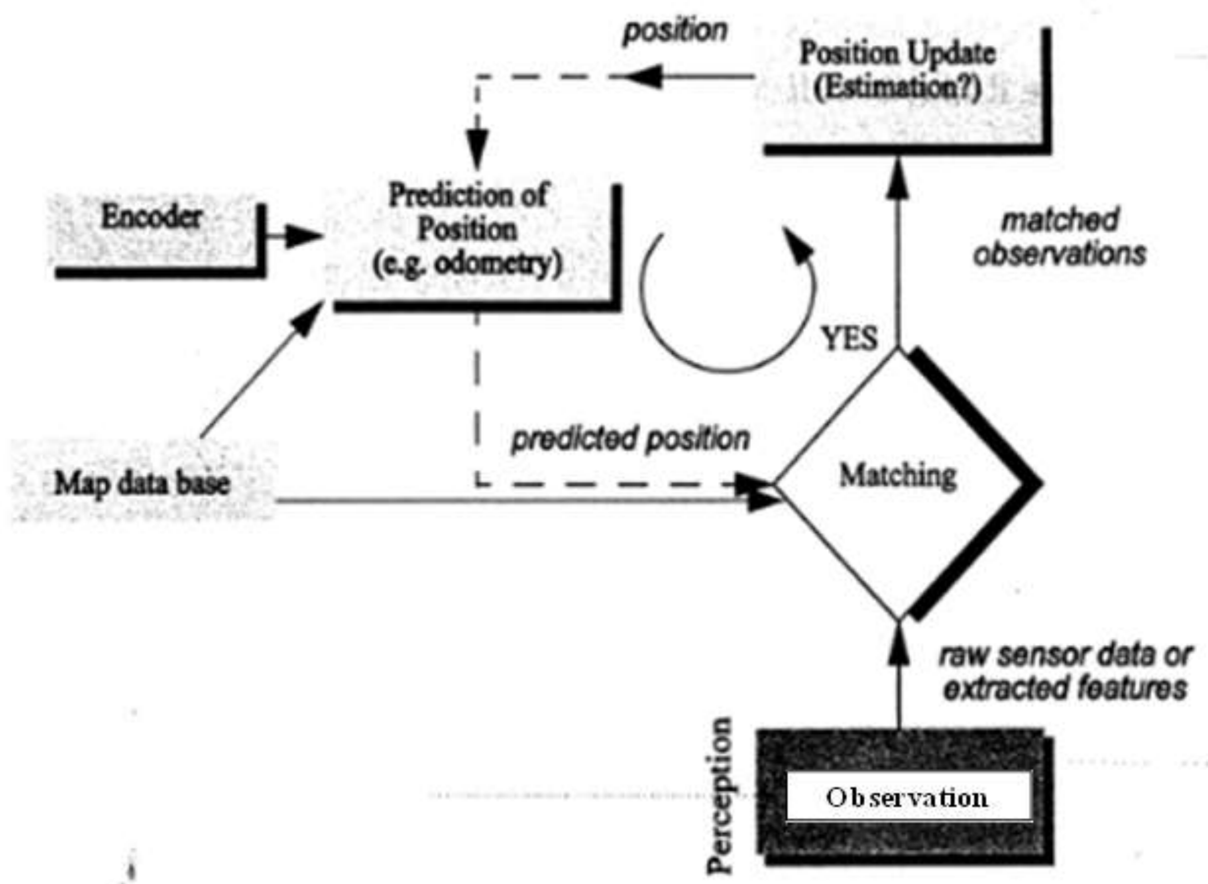

Figure 5.2
General schematic for mobile robot localization.

The Challenge of Localization: Noise and Aliasing

If one could attach an accurate GPS (global positioning system) sensor to a mobile robot, much of the localization problem would be obviated. The GPS would inform the robot of its exact position, indoors and outdoors, so that the answer to the question, "Where am I?" would always be immediately available. Unfortunately, such a sensor is not currently practical. The existing GPS network provides accuracy to within several meters, which is unacceptable for localizing human-scale mobile robots as well as miniature mobile robots such as desk robots and the body-navigating nanorobots of the future. Furthermore, GPS technologies cannot function indoors or in obstructed areas and are thus limited in their workspace.

But, looking beyond the limitations of GPS, localization implies more than knowing one's absolute position in the Earth's reference frame. Consider a robot that is interacting with humans. This robot may need to identify its absolute position, but its relative position with respect to target humans is equally important. Its localization task can include identifying humans using its sensor array, then computing its relative position to the humans. Furthermore, during the ***cognition*** step a robot will select a strategy for achieving its goals. If it intends to reach a particular location, then localization may not be enough. The robot may need to acquire or build an environmental model, a ***map***, that aids it in planning a path to the goal. Once again, localization means more than simply determining an absolute pose in space; it means building a map, then identifying the robot's position relative to that map.

Clearly, the robot's sensors and effectors play an integral role in all these forms of localization. It is because of the inaccuracy and incompleteness of these sensors and effectors that localization poses difficult challenges. This section identifies important aspects of this sensor and effector suboptimality.

To Localize or Not to Localize: Localization-Based Navigation Versus Programmed Solutions

Figure 5.6 depicts a standard indoor environment that a mobile robot navigates. Suppose that the mobile robot in question must deliver messages between two specific rooms in this environment: rooms *A* and *B.* In creating a navigation system it is clear that the mobile robot will need sensors and a motion control system. Sensors are absolutely required to avoid hitting moving obstacles such as humans, and some motion control system is required so that the robot can deliberately move.

It i s less evident, however, whether or not this mobile robot will require a *localization system.* Localization may seem mandatory in order to navigate successfully between the two rooms. It is through localizing on a map, after all, that the robot can hope to recover its position and detect when it has arrived at the goal location. It is true that, at the least, the robot must have a way of detecting the goal location. However, explicit localization with reference to a map is not the only strategy that qualifies as a goal detector.

An alternative, espoused by the behavior-based community, suggests that, since sensors and effectors are noisy and information limited, one should avoid creating a geometric map for localization. Instead, this community suggests designing sets of behaviors that together result in the desired robot motion. Fundamentally, this approach avoids explicit reasoning about localization and position, and thus generally avoids explicit path planning as well.

This technique is based on a belief that there exists a procedural solution to the particular navigation problem at hand. For example, in Figure 5.6, the behavioralist approach to navigating from room *A* to room *B* might be to design a left-wall following behavior and a detector for room *B* that is triggered by some unique queue in room *B*, such as the color of the carpet. Then the robot can reach room *B* by engaging the left-wall follower with the room *B* detector as the termination condition for the program.

The architecture of this solution to a specific navigation problem is shown in Figure 5.7. The key advantage of this method is that, when possible, it may be implemented very quickly for a single environment with a small number of goal positions. It suffers from some disadvantages, however. First, the method does not directly scale to other environments or to larger environments. Often, the navigation code is location-specific, and the same degree of coding and debugging is required to move the robot to a new environment.

Second, the underlying procedures, such as *left-wall-follow,* must be carefully designed to produce the desired behavior. This task may be time-consuming and is heavily dependent on the specific robot hardware and environmental characteristics.

Third, a behavior-based system may have multiple active behaviors at any one time. Even when individual behaviors are tuned to optimize performance, this fusion and rapid switching between multiple behaviors can negate that fine-tuning. Often, the addition of each new incremental behavior forces the robot designer to retune all of the existing behaviors again to ensure that the new interactions with the freshly introduced behavior are all stable.

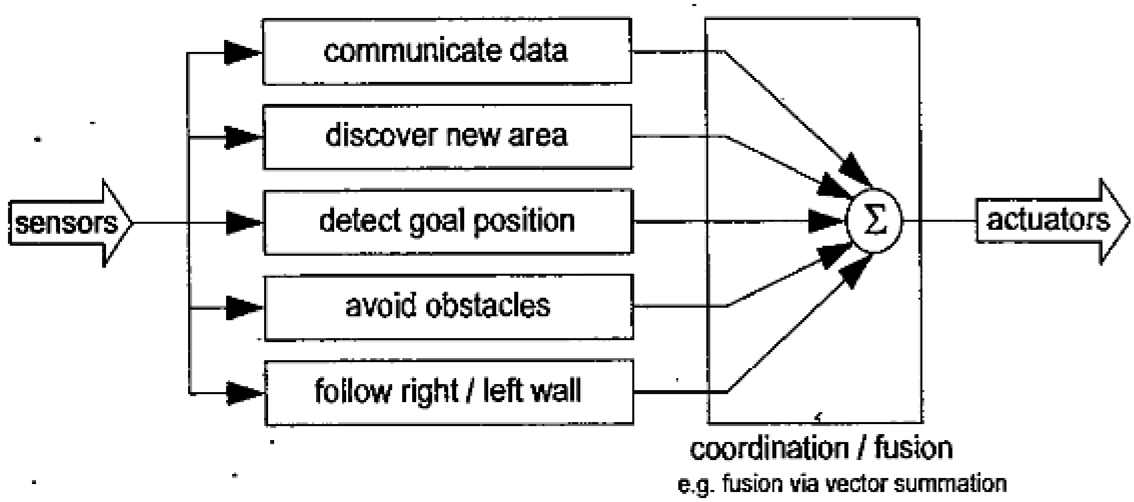

Figure 5.7
An architecture for behavior-based navigation.

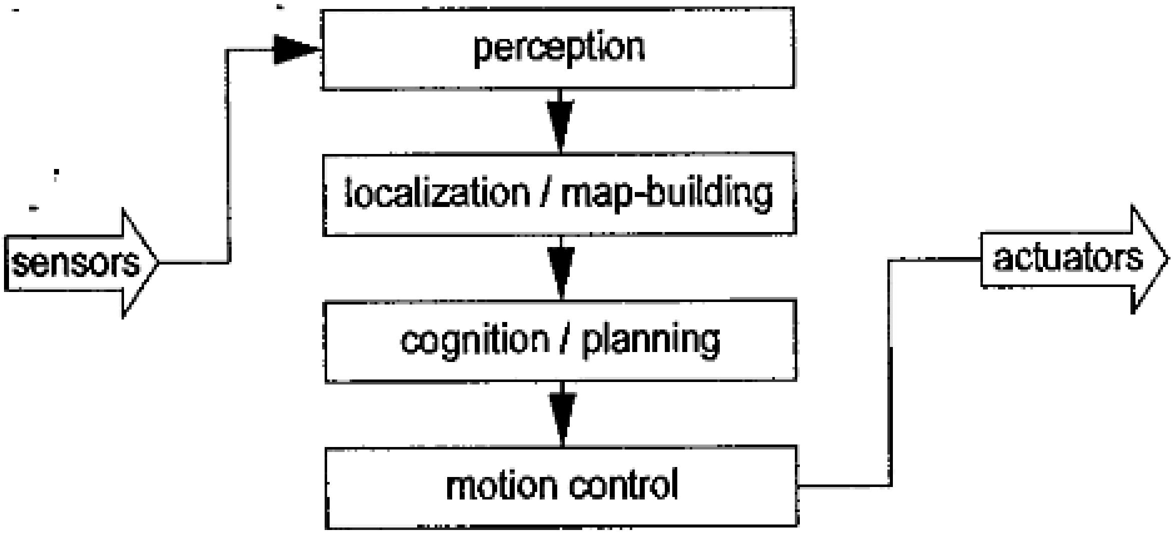

Figure 5.8
An architecture for map-based (or model-based) navigation.

In contrast to the behavior-based approach, the map-based approach includes both *localization* and *cognition* modules (see Figure 5.8). In map-based navigation, the robot explicitly attempts to localize by collecting sensor data, then updating some belief about its position with respect to a map of the environment. The key advantages of the map-based approach for navigation are as follows:

- The explicit, map-based concept of position makes the system's belief about position transparently available to the human operators.
- The existence of the map itself represents a medium for communication between human and robot: the human can simply give the robot a new map if the robot goes to a new environment.
- The map, if created by the robot, can be used by humans as well, achieving two uses.

The map-based approach will require more up-front development effort to create a navigating mobile robot. The hope is that the development effort results in an architecture that can successfully map and navigate a variety of environments, thereby amortizing the upfront design cost over time.

Of course the key risk of the map-based approach is that an internal representation, rather than the real world itself, is being constructed and *trusted* by the robot. If that model diverges from reality (i.e. , if the map is wrong), then the robot's behavior may be undesirable, even if the raw sensor values of the robot are only transiently incorrect.

In the remainder of this chapter, we focus on a discussion of map-based approaches and, specifically, the localization component of these techniques. These approaches are particularly appropriate for study given their significant recent successes in enabling mobile robots to navigate a variety of environments, from academic research buildings, to factory floors, and to museums around the world.

5b.2.3 Path planning & Motion control

Even before the advent of affordable mobile robots, the field of path planning was heavily studied because of its applications in the area of industrial manipulator robotics. Interestingly, the path-planning problem for a manipulator with, for instance, six degrees of freedom is far more complex than that of a differential-drive robot operating in a flat environment. Therefore, although we can take inspiration from the techniques invented for manipulation, the path-planning algorithms used by mobile robots tend to be simpler approximations owing to the greatly reduced degrees of freedom. Furthermore, industrial robots often operate at the fastest possible speed because of the economic impact of high throughput on a factory line. So, the dynamics and not just the kinematics of their motions are significant, further complicating path planning and execution. In contrast, a number of mobile robots operate at such low speeds that dynamics are rarely considered during path planning, further simplifying the mobile robot instantiation of the problem.