CHAPTER 5 Robot End Effectors

5.0 OBJECTIVES

After studying this chapter, the reader should:

1. Be acquainted with the types of end effectors
2. Understand standard, special, and other types of grippers
3. Be familiar with gripper selection, design, and force analysis
4. Recognize process tools and their classifications
5. Be able to define compliance systems and their applications
6. Be able to analyze multiple and complex end-effector systems

5.1 TYPES OF END EFFECTORS

Industrial robots today come in a variety of sizes, shapes, and capabilities. However, all have four basic components: a manipulator, an end effector (which is part of the manipulator), a computer controller, and a power supply, as shown in Figure 5.1.1.

The manipulator is a mechanism consisting of several segments or arms and composed of three sections, as shown in Figure 5.1.2:

- The major linkages
- The minor linkages (wrist components)
- The end effector (gripper or tool)

The major linkages are the set of joint-link pairs that out-position the manipulator in space. Usually, they consist of the first three sets (counting from the base of the robot). The minor linkages are those joints and links associated with the fine positioning of the end effector. They provide the ability to orient the tool-mounting plate and subsequently the end effector once the major linkages get it close to the desired position.

The end effector, which is mounted on the tool plate, is a device used to make intentional contact with an object or to produce the robot's final effect on its surroundings by performing a particular task.

The end effector may be a tool that does a function such as welding or drilling, or it may be some type of gripper if the robot's task is to pick up parts and transfer them to another location. A gripper may be a simple pneumatically controlled device that opens and closes or a more complex servo-controlled unit capable of exerting specified forces or of measuring the part within its grasp.

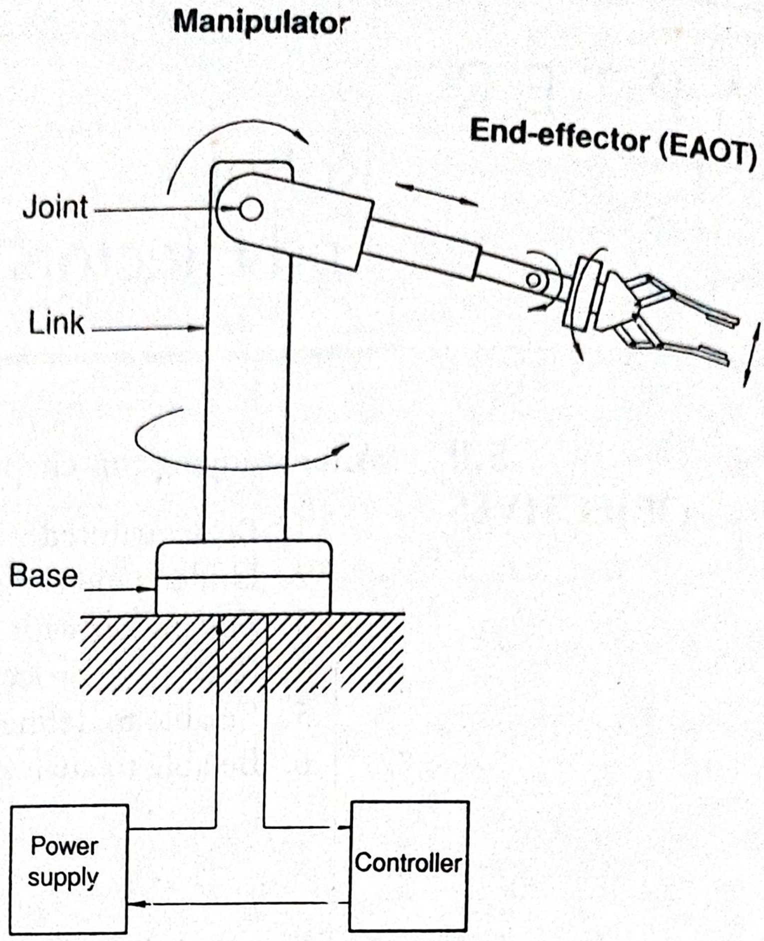

Figure 5.1.1 Components of a robot system

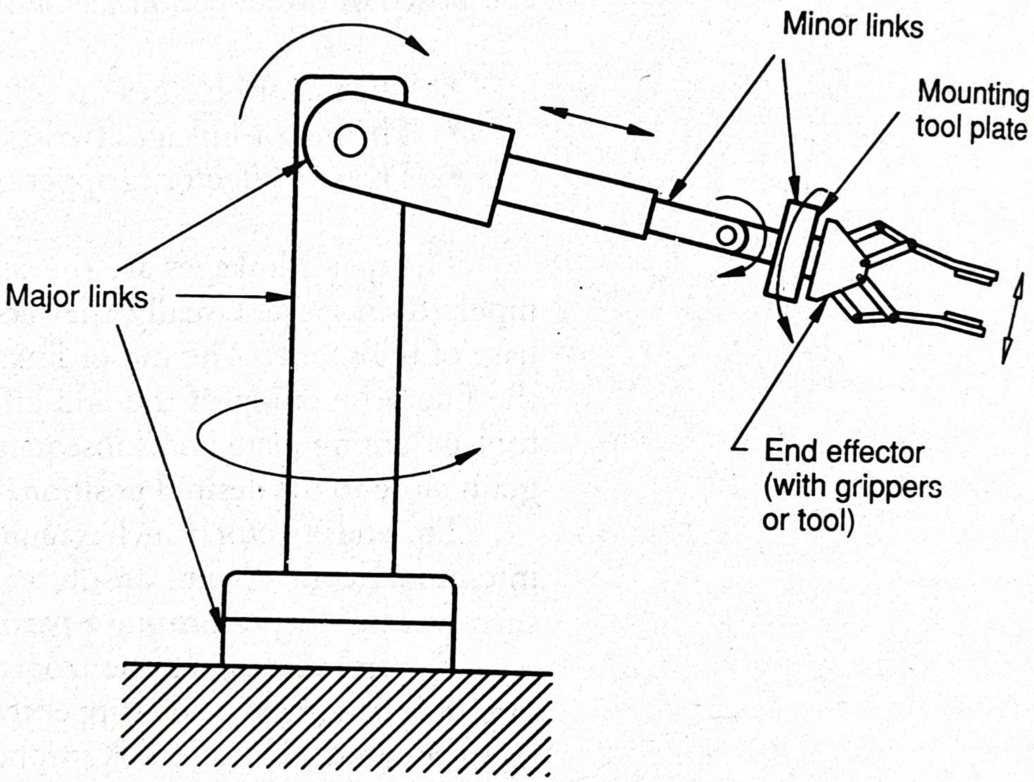

Figure 5.1.2 Components of a robot manipulator

There is a wide assortment of end effectors required to perform the variety of different work functions. The various types can be divided into two major categories: grippers and process tooling.

Grippers are end effectors used to grasp and hold objects. There may be two- or more-fingered devices designed to grasp an object or tool in a manner similar to the human hand and fingers.

Process tooling is an end effector designed to perform work on the part rather than to merely grasp it. By definition, the tool-type end effector is attached to the robot's wrist or tool-mounting plate. Process tooling may be any useful device, such as a spot-welding torch, a spray-painting gun, a vacuum cup, or a set of interchangeable tools.

Grippers may be designed as physical constraints or as friction devices. A physical constraint device might work like a spatula that slides under an object to enable one to lift it. A frictional device depends upon the frictional force between two materials to provide the gripping force.

Also, grippers can be classified as single grippers or double grippers. This classification applies best to mechanical grippers. The single gripper is distinguished by the fact that only one grasping device is mounted on the robot's wrist. A double gripper has two gripping devices attached to the wrist and is used to handle two separate objects. The two gripping devices can be activated independently. The double gripper is very useful in machine loading and unloading applications.

If two or more grasping mechanisms are fastened to the wrist, we call it a multiple gripper. Double grippers are a subset of multiple grippers. The occasions are somewhat rare when more than two grippers would be required in an application. There is also a cost-and-reliability penalty that accompanies an increasing number of gripper devices on one robot arm.

Another way of classifying grippers depends on whether the part is grasped on its exterior surface or its internal surface—for example, a ring-shaped part. The first type is called an external gripper if the part is grasped from the outside surface, and the second type is referred to as an internal gripper if the part is grasped from the inside surface.

Grippers are sometimes used to hold tools rather than work parts. The reason for using a gripper instead of attaching the process tooling directly to the robot's wrist is typically because the job requires several tools to be manipulated by the robot during the work cycle. An example of this kind of application would be a deburring operation in which several different tools must be used in order to reach all surfaces of the work part. In this case, the gripper serves as a quick-change device to provide the capability for a rapid changeover from one tool to the next.

A gripper, regardless of its type and capacity, must fulfill the following characteristics:

1. It must be capable of gripping, lifting, and releasing the part or family of parts required by the process.
2. Some grippers sense the presence of the part with their gripping action.

3. Tooling weight must be kept to a minimum.
4. Containment of the tooling part must be assured under conditions of maximum velocity and loss of holding power.
5. The gripper should be simple in design, accurate in operation, economical, and maintenance free.
6. It must be equipped with a collision sensor to accommodate overload conditions and safeguarding.

In addition to grippers and common process tooling, other types of fixturing and tooling are required in many industrial robot applications. These include holding fixtures, welding fixtures, alignment devices, and other forms of tooling to position the work part during the work cycle.

Therefore, the end effectors used on current robots can be classified further in the following three categories:

1. According to the method of gripping mechanism: standard grippers (mechanical), vacuum, magnetic, adhesive, and other miscellaneous devices.
2. According to process tooling and devices, including drills, welding guns and torches, paint sprayers, and grinders.
3. According to multiple-function capabilities, including special-purpose grippers and compliance devices currently in use.

5.2 MECHANICAL GRIPPERS

Mechanical grippers or standard grippers are end effectors that use **mechanical fingers** actuated by a mechanism to grasp an object. The fingers, sometimes called jaws, are the appendages of the grippers that actually make contact with the object. The fingers are either attached to the mechanism or are an integral part of the mechanism.

If the fingers are of the attachable type, they can be detached and replaced. The use of replaceable fingers allows for wear and interchangeability. Replaceable fingers also can be designed to accommodate different-part models. See Figure 5.2.1.

The function of the gripper mechanism is to translate some form of power input into the grasping action of the fingers against the part. The mechanism must be able to open and close the fingers and to exert sufficient force against the part to hold it securely.

The input power to the mechanism is supplied from the robot and can be pneumatic, hydraulic, electric, or mechanical (spring activated).

There are two ways of constraining the part in the gripper. The first is by physical constriction of the part within the fingers. In this approach, the gripper fingers enclose the part to some extent, thereby constraining the motion of the part. This is usually accomplished by designing the contacting surfaces of the fingers to be in the approximate shape of the part geometry. This method of constraining the part is illustrated in Figure 5.2.2. The second way of holding the part is by friction between the fingers and the work part. With this approach, the fingers must apply a force that is sufficient for friction to retain the part against

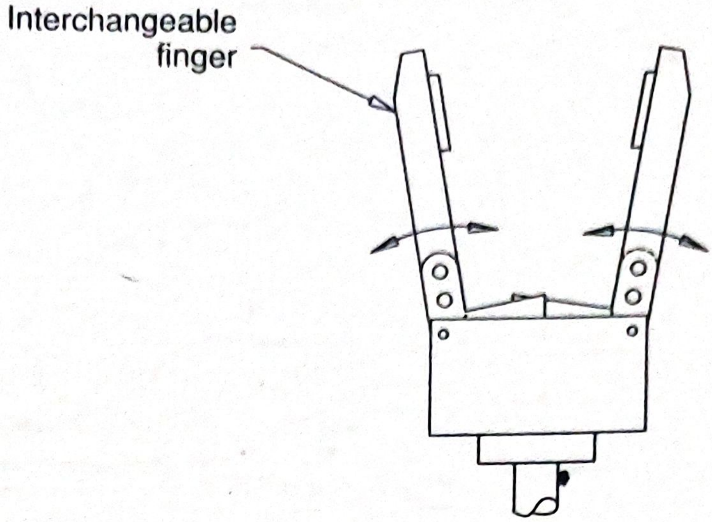

Figure 5.2.1 Interchangeable fingers used with the same gripper mechanism

gravity, acceleration, and any other force that might arise during the holding portion of the work cycle. The fingers, or the pads attached to the fingers that make contact with the part, are generally fabricated out of a material that is relatively soft. This tends to increase the coefficient of friction between the part and the contacting finger surface. It also serves to protect the part surface from scratching or other damage.

The friction method of holding the part results in a less complicated and, therefore, less expensive gripper design. However, there is a problem with the

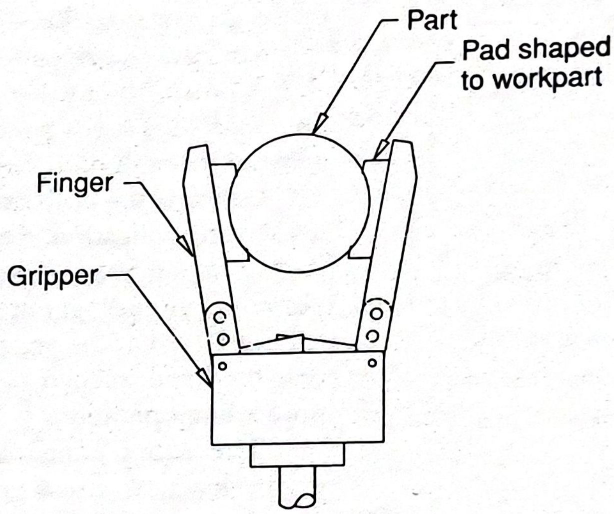

Figure 5.2.2 Constricted method of finger design

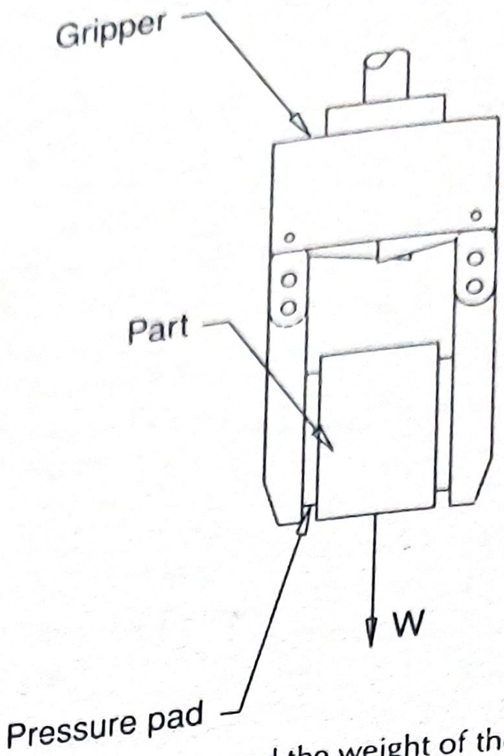

Figure 5.2.3 Force against a part must exceed the weight of the part.

friction method—if a force of sufficient magnitude is applied against the part in a direction parallel to the friction surfaces of the fingers, the part might slip out of the gripper. To resist this slippage, the gripper must be designed to exert a force that is greater than the weight of the part, as illustrated in Figure 5.2.3.

Mechanical grippers can have two different closing motions: angular or parallel. The action of the angular and parallel devices is illustrated in Figure 5.2.4. Some grippers are supplied with blank jaws that can be removed and machined into the configuration required for the application.

Grippers use both external and internal geometry features of the part to pick it up in an application. Another variation in mechanical grippers is the number of jaws or fingers used to grasp the part. Most applications use two-finger grippers. However, three-finger grippers and four-finger grippers are used when parts need to be centered by the gripping process, as shown in Figure 5.2.5. The gripper must be closed and opened by program commands as the robot moves through the production operation.

The robot controller supplies the electrical signals that result in the gripper's action. Most grippers are opened and closed with a pneumatic actuator. However, in limited applications, hydraulic or spring power is used. In some cases, grippers are spring-opened and power-closed less frequently; grip-

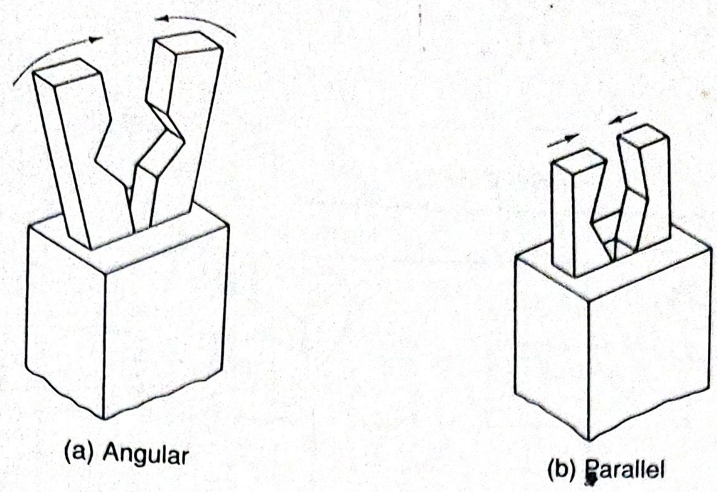

Figure 5.2.4 Standard angular and parallel grippers

pers are spring-closed and power-opened. Each of the types is based on a specific application.

Electrical-powered jaws are also used in limited light applications with a solenoid or DC servomotor providing the opening and closing action. Servo drives will be used more frequently when grippers are developed to vary the applied pressure to the object as it is grasped. Tactile or touch sensing must be developed beyond its present state. New developments coming to market include sensor fusion and smart sensors, which are capable of microcomputer-based calibration, computation, and decision making. A key component in robot design is the end effector. A mechanical gripper comprises between 5 and 10 percent of the robot cost. If a specially designed gripper is required, sometimes the cost for design and fabrication can exceed 20 percent of the total robot cost. See Figure 5.2.6 for the classification of mechanical grippers.

5.3 GRIPPER FORCE ANALYSIS

As indicated earlier, the purpose of the gripper mechanism is to convert input power into the required motion and force to grasp and hold an object. Let us illustrate how to determine the magnitude of the required input power in order to obtain a given gripping force. The following force equations can be used to determine the required magnitude of the gripper force as a function of the given factors.

$$\mu\eta F_g = w \quad \text{(Equation 5.3.1)}$$

$$\mu\eta F_p = wg \quad \text{(Equation 5.3.2)}$$

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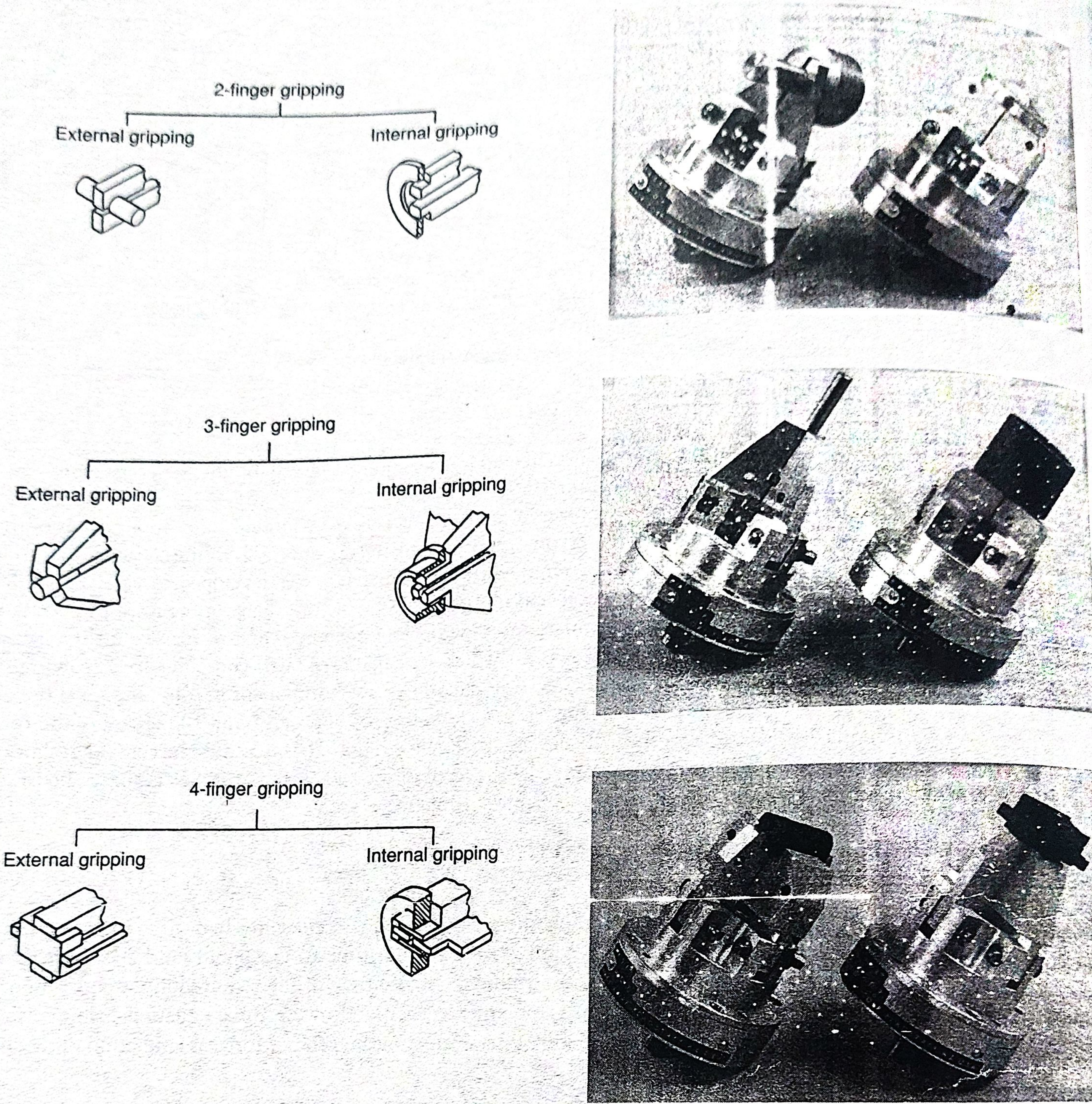


Figure 5.2.5 External and internal grippers with two, three, and four fingers. *(Courtesy of Mack Corporation)*

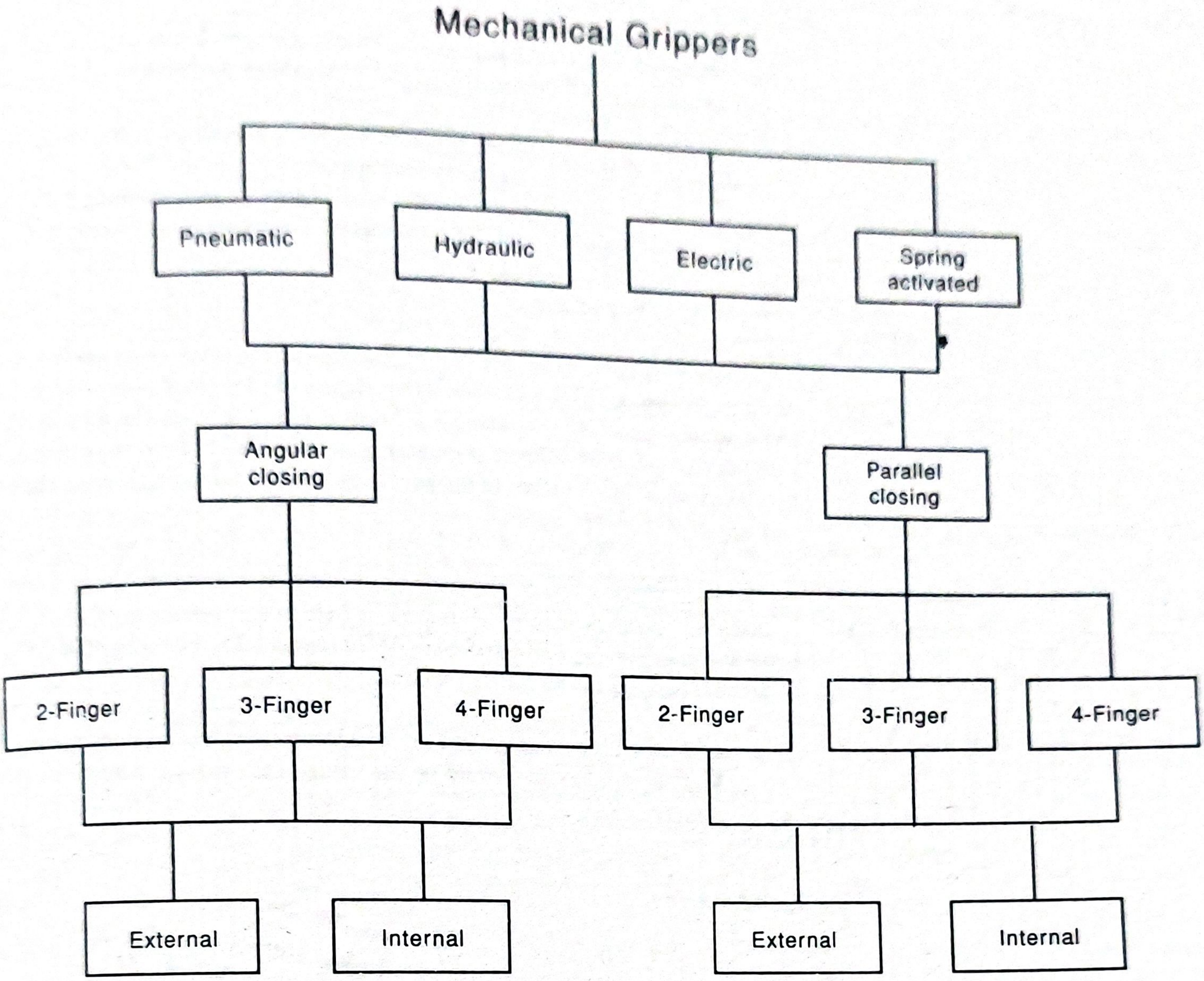


Figure 5.2.6 Classification scheme of mechanical grippers

where μ = coefficient of friction of the finger contacts surface against the part surface

η = number of contacting fingers

F = gripper force

w = weight of the part or object being gripped

g = factor of the combined effect of gravity and acceleration—given as follows:

$g = 3.0$, if the acceleration force is applied in the same direction as the gravity force

$g = 2.0$, if the acceleration is applied in a horizontal direction

$g = 1.0w$, if the acceleration is applied in the opposite direction of the gravity force

SF = safety factor

Equation 5.3.1 covers the case in which weight alone is the force tending to cause the part to slip out of the gripper when the force of gravity is directly parallel to the contacting surface. Equation 5.3.2 covers the case when the force tending to pull the part out of the finger is greater than the weight of the object because the acceleration or deceleration of the part could exert a force that is twice the weight of the part.

Example 5.1 A cardboard carton weighing 10 pounds is held in a gripper using friction against two opposing fingers. The coefficient of friction is 0.25. The weight of the carton is directed parallel to the finger surfaces.

a. Determine the required gripper force for the condition given.
b. If SF = 1.5, what would be the value of the gripper force?

Solution

Find $F = ?$

$$\mu = 0.25 \qquad \eta = 2 \qquad w = 10\text{lb} \qquad g = 3.0$$

a.

$$\mu\eta F = wg$$

$$F = \frac{wg}{\mu\eta} = \frac{(10)(3.0)}{0.25 \times 2} = 60\text{lb}$$

The gripper must cause a force of 60 pounds to be exerted by the fingers against the carton surface.

b. If $SF = 1.5$,

$$F = 1.5 \times 60 = 90 \text{ lb}$$

The required gripper force would be 90 pounds. This safety factor would help to compensate for the potential problem of the carton being grasped at a position other than its center of mass.

Example 5.2 Determine the actual value of g factor in Example 5.1. Assume that the carton will experience a maximum acceleration of 40 ft/sec/sec in a vertical direction when it is lifted by the gripper fingers.

Solution

Find $g = ?$

The value of g would be 1.0 plus the quotient of the actual acceleration divided by gravity acceleration of 32.2 ft./sec/sec.

$$g = 1.0 + \frac{40}{32.2} = 1.0 + 1.24 = 2.24$$

In the following two examples, we assume that a friction-type grasping action is being used to hold the part, and so we will use the gripper force calculated in Example 5.1 as our starting point. We will demonstrate the gripper force analysis. (A detailed study of mechanism analysis is beyond the scope of this text, and the reader may refer to the references.)

Example 5.3 An angular motion gripper is used for holding the cardboard carton, as shown in Figure 5.3.1. The gripper force, calculated in Example 5.1, is 60 pounds. The gripper is to be activated by a piston device to apply an actuating force *Fa*. Determine the piston device force *Fa* to close the gripper.

Solution

The analysis would require that the moments about the pivot arms be summed and made equal to zero.

$$\Sigma M = 0$$

$$FL - FaLa = 0$$

$$(60\text{lb})(12") - (\text{Fa})(3") = 0$$

$$Fa = \frac{720}{3} = 240 \text{ lb}$$

The piston device would have to provide an actuating force of 240 pounds to close the gripper with a force against the carton of 60 pounds.

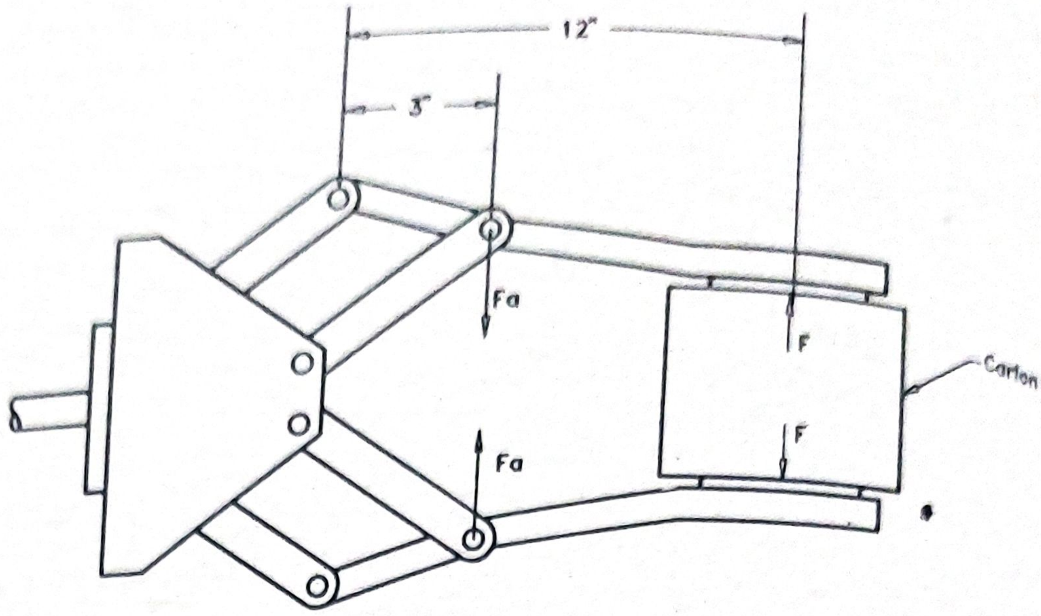


Figure 5.3.1 Pivot-type gripper used in Example 5.3

Example 5.4 Figure 5.3.2 shows the linkage mechanism and dimensions of a gripper used to handle a work part for a machining operation. The gripper force is determined to be 25 pounds. Determine the actuating force *Fa* applied to the plunger.

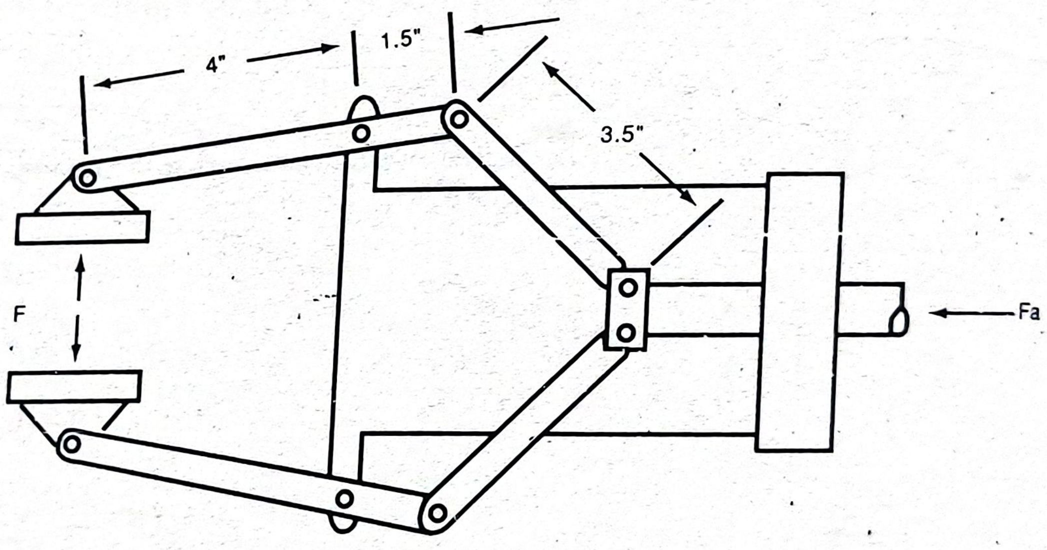


Figure 5.3.2 Gripper used in Example 5.4

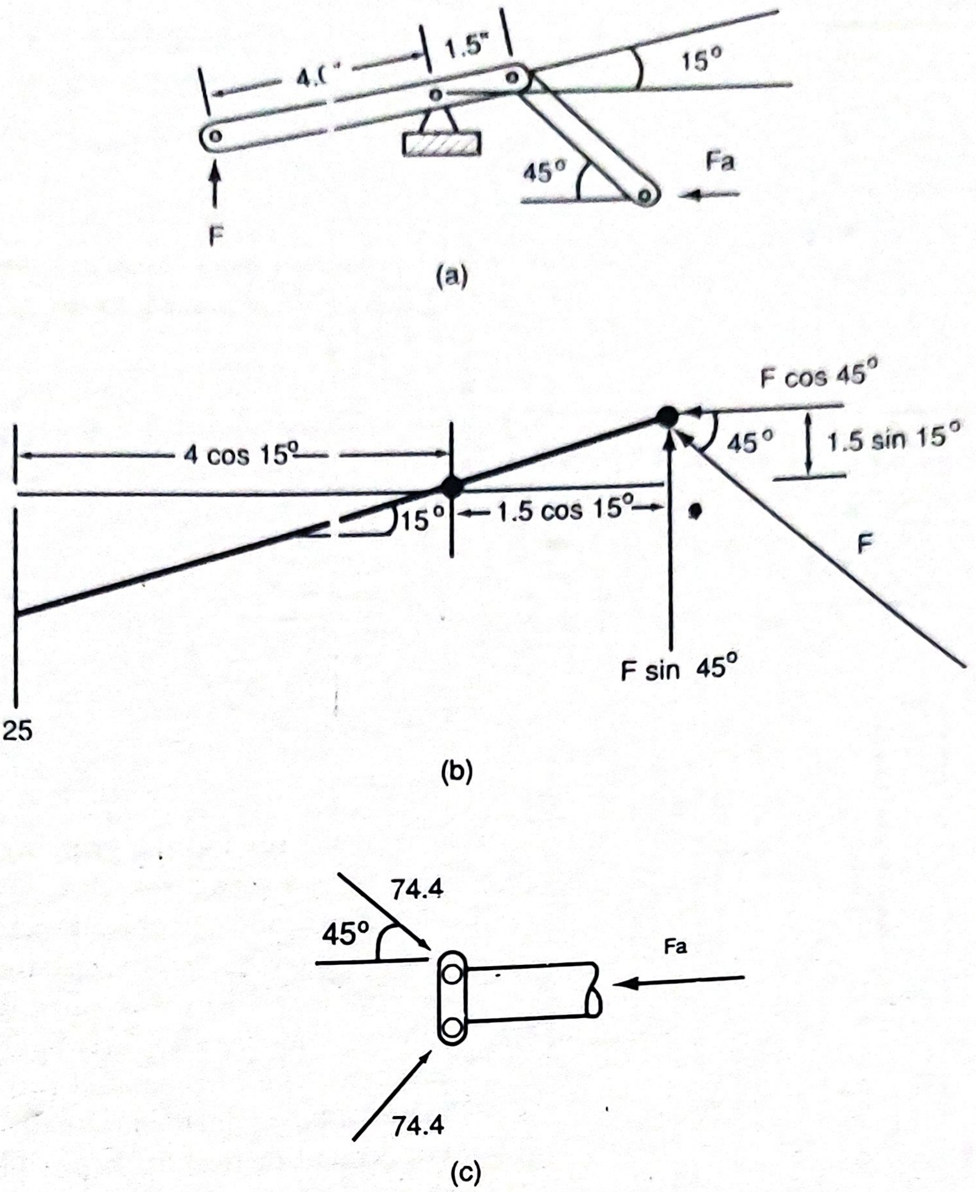


Figure 5.3.3 Linkage analysis of Example 5.4

Solution

Figure 5.3.3 (a) shows how the symmetry of the gripper can be used to advantage so that only one half of the mechanism needs to be considered. Figure 5.3.3 (b) shows how the moments might be summed about the pivot point for the finger line against which the 25-pound gripper force is applied. Therefore:

$$25(4\cos 15^\circ) = F\sin 45^\circ(1.5\cos 15^\circ) + F\cos 45^\circ(1.5\sin 15^\circ)$$

$$96.6 = (1.0246 + 0.2745)F = 1.2991F$$

$$F = 74.4\ \text{lb}$$

The actuating force applied to the plunger to deliver this force of 74.4 pounds to each finger is shown in Figure 5.3.3(c) and can be calculated as follows:

$$Fa = 2F \cos 45^\circ = 2 \times 74.4 \times \cos 45^\circ$$

$$Fa = 105.2 \text{ lb}$$

Some power input mechanism would be required to deliver this actuating force of 105.2 pounds to the gripper.

5.4 OTHER TYPES OF GRIPPERS

In addition to mechanical grippers, there are a variety of other devices that can be used to lift and hold objects. These devices are categorized according to the medium used for their gripping force, as follows:

1. Vacuum
2. Magnetic
3. Adhesive

Vacuum

Vacuum is used as the gripping force. The part or product is lifted by vacuum cups or by a vacuum surface.

The lifting power is a function of the degree of vacuum achieved and the size of the area on the part where the vacuum is applied.

Vacuum cups, also called suction cups, are made of neoprene or synthetic rubber. They are extremely lightweight and simple in construction. The number, size, and type of cups used will depend on the weight, size, shape, and type of material being handled. Usually they are between one and eight inches in diameter, round or oval in shape. The cups shown in Figure 5.4.1 are off-the-shelf items.

Multiple-cup vacuum grippers increase the contact surface area, as shown in Figure 5.4.2, and permit the size and weight of the workpiece to be increased.

The usual requirements of a workpiece to be handled by vacuum cups are to be smooth and in clean condition in order to form a satisfactory vacuum between the piece and the suction cup.

Vacuum grippers can be used on curved and contoured surfaces as well as on flat surfaces. They are ideal for handling fragile parts, such as glass, eggs, and sometimes flexible soft materials. In this last case, the suction cup would be made of a hard substance.

The flexibility of the vacuum cup provides the robot with a certain amount of compliance. However, to allow for surface unevenness, some vacuum cups are spring-loaded or mounted on a ball joint.

The lift capacity of the suction cup depends on the effective area of the cup and the negative air pressure between the cup and the object to be lifted. The relationship can be summarized in the following equation:

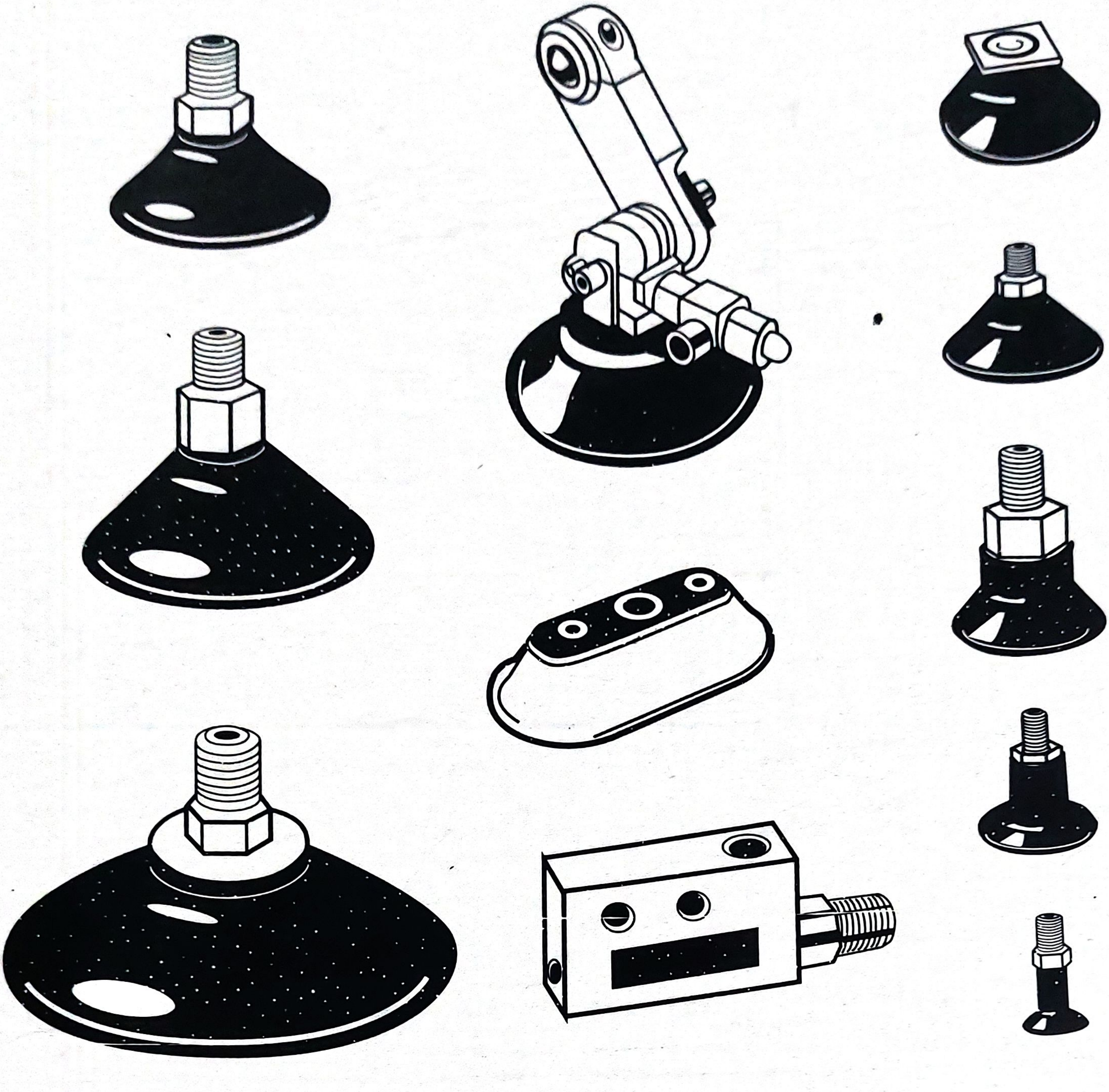


Figure 5.4.1 Commercial vacuum cups and venturi block

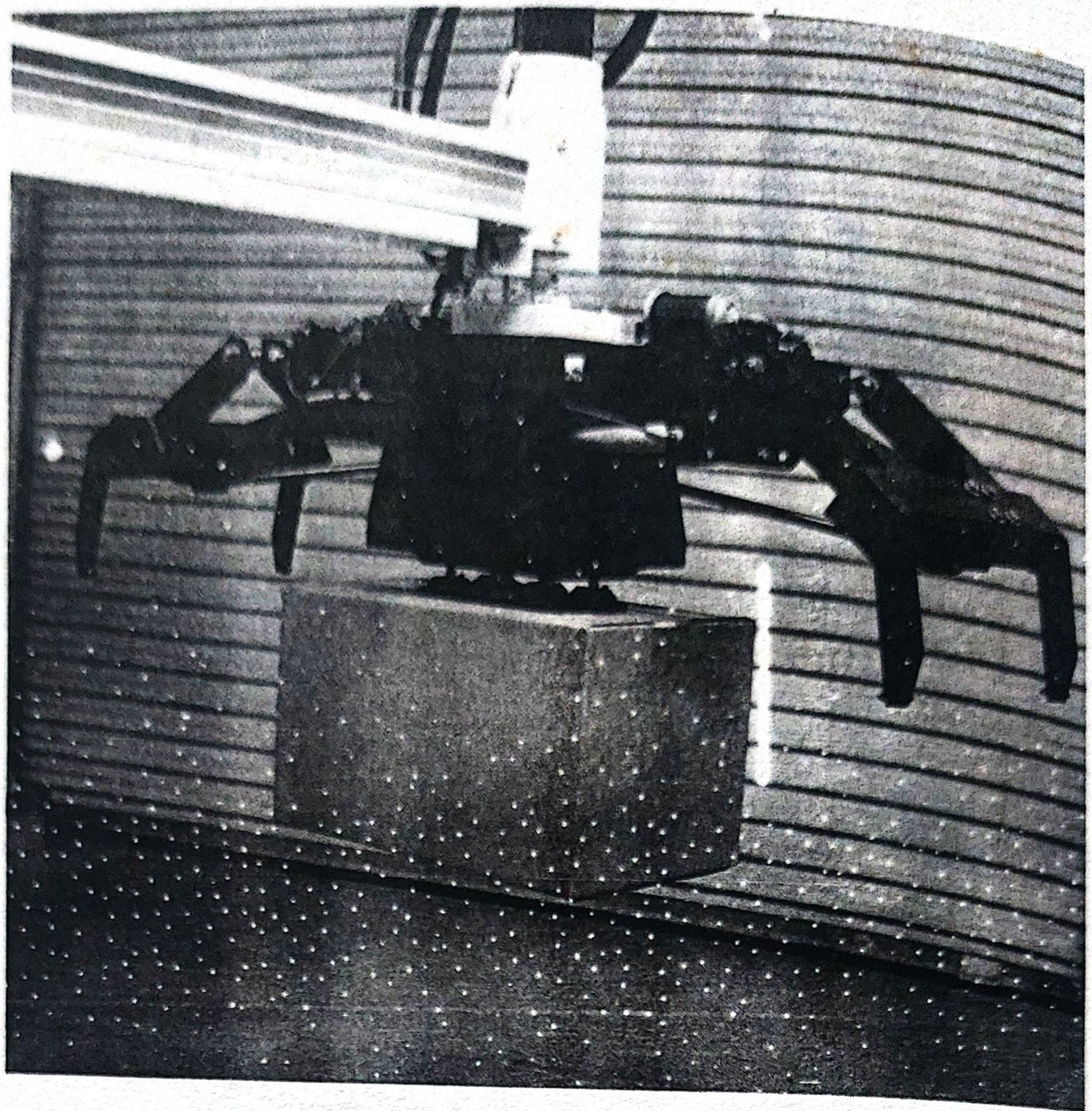


Figure 5.4.2 Multicup vacuum gripper *(Courtesy of Pacific Robotics Inc.)*

$$F = PA \qquad \text{(Equation 5.4.1)}$$

Where F = the force or lift capacity, lb
P = the negative pressure, lb/in.^{2}
A = the total effective area of the suction cup(s) used to create the vacuum, in.^{2}

The effective area of the cup is approximately equal to the area of the suction cup(s).

Example 5.5 A vacuum gripper is used to lift flat steel plates 0.25 x 24 x 36 inches. The gripper will utilize two suction cups, 5.0 inches in diameter each, and they will be located 18 inches apart for stability. A safety factor of 2 should be used to allow for acceleration of the plate. Determine the negative pressure required to lift the plates if the density of the steel is 0.28 lb/in.^{3}

Solution

The weight of the plate would be:

$$w = 0.28 \times 0.25 \times 24 \times 36 = 60.48 \text{ lb}$$

This would be equal to the force F that must be applied by the two suction cups. The area of each suction cup would be:

$$A = 3.14\left(\frac{5}{2}\right)^2 = 19.63 \; in.^2$$

The area of the two cups would be

$$2 \times 19.63 = 39.26 \; in.^2$$

From Equation 5.4.1:

$$P = \frac{w}{A} = 60.48/39.26 = 1.54 \text{ lb/in.}^2$$

Applying the safety factor of 2, we have:

$$P = 2 \times 1.54 \text{ lb/in.}^2 = 3.08 \text{ lb/in.}^2 \text{ negative pressure}$$

The advantages for using suction cup grippers are:

1. They require only one surface for grasping the part.
2. They apply a uniform pressure on the surface of the part.
3. They require a relatively lightweight gripper.
4. They are applicable to a variety of different materials.
5. They have a significantly low cost.

Vacuum surfaces are just an extension of the vacuum cup principle. In some material-handling applications the product to be lifted is not ridged enough for vacuum cups to be effective. To lift such material as cloth, paper, and plastic into place, a vacuum surface, as the one illustrated in Figure 5.4.3, is used. The vacuum gripper consists of a flat surface with tiny holes that forms one side of a vacuum chamber. Each hole in the vacuum surface provides a small lifting force so that the flexible cloth, paper, or plastic would be held into place against the vacuum surface from many points.

Vacuum grippers are usually venturi devices, applying Bernoulli's principle to create suction by using compressed air. The vacuum generator and venturi block (miniature vacuum pump) are two common devices used for this purpose. The vacuum generator is a piston-operated or vane-driven device powered by an electric motor, and it is capable of creating a relative high vacuum. The venturi on the other hand is a simple device, as shown in Figure 5.4.4, and can be operated

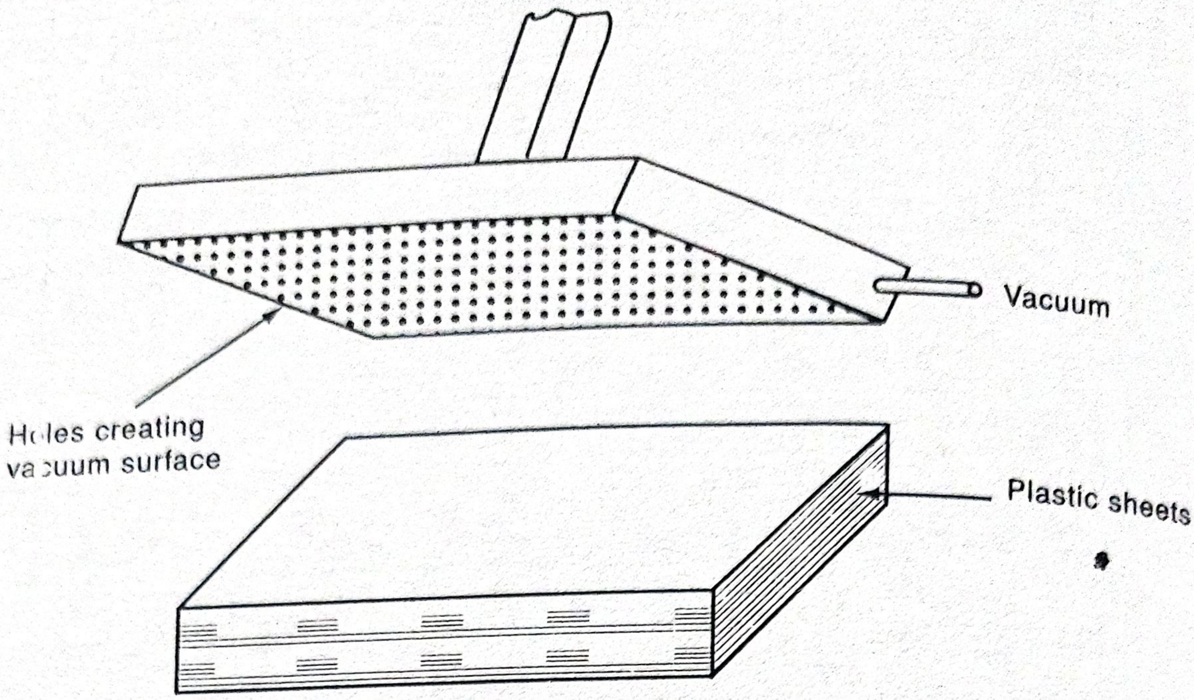


Figure 5.4.3 Vacuum surface

by means of shop air pressure. A single vacuum cup can produce 20+ inches of mercury vacuum from a 22 psi line. This enables the cup to support from 10 to 100 pounds of weight, depending on the sealing capabilities of the parts and the desired safety factor used.

Magnetic

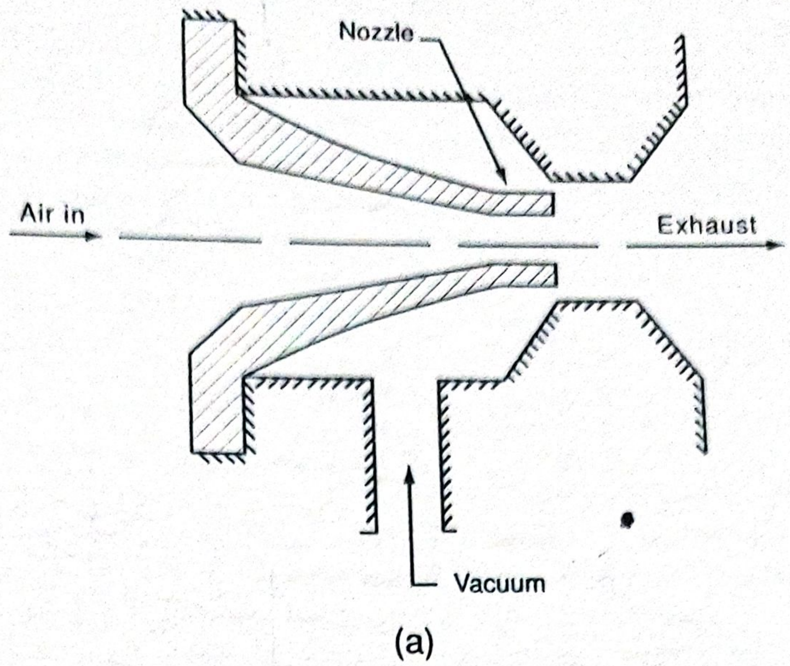
Magnetic devices can handle ferromagnetic materials. The material can be lifted in the form of a sheet or plate with an electromagnet mounted on the robot tool plate. Figure 5.4.5 shows a single magnetic gripper and a dual magnetic gripper.

Magnetic grippers are similar in operation to vacuum grippers. However, instead of using vacuum to pick up the object, they employ a magnetic field created by an electromagnet or permanent magnet. Objects that have a flat, smooth, clean surface are the easiest to handle. The advantages of using magnetic grippers are:

1. Pickup times are very fast.
2. Part-size variations can be tolerated.
3. They are able to handle metal parts with holes.
4. They require only one surface for gripping.

The disadvantages with magnetic grippers include:

1. The residual magnetism remaining in the workpiece may cause problems in subsequent handling.



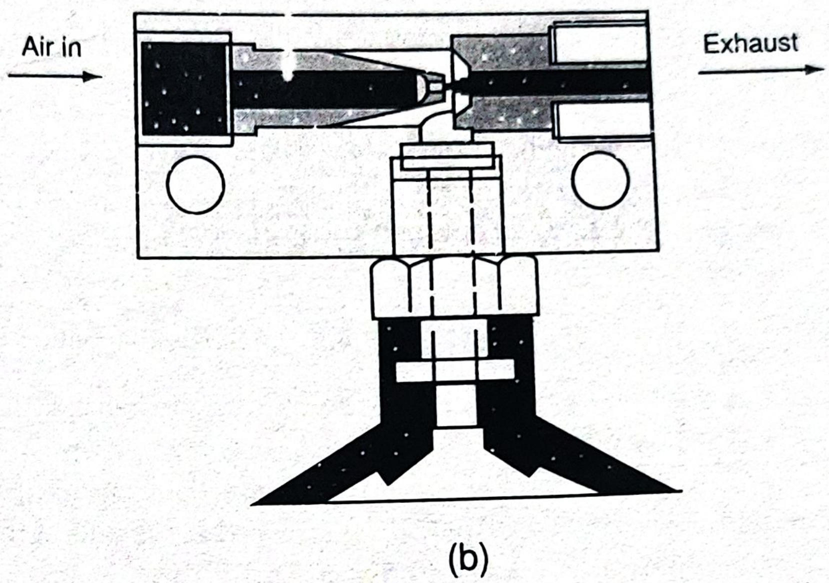
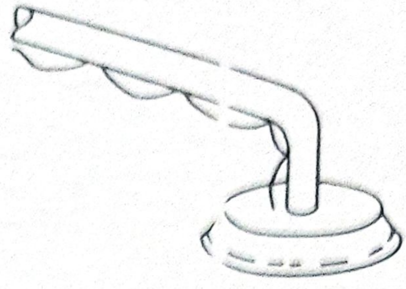


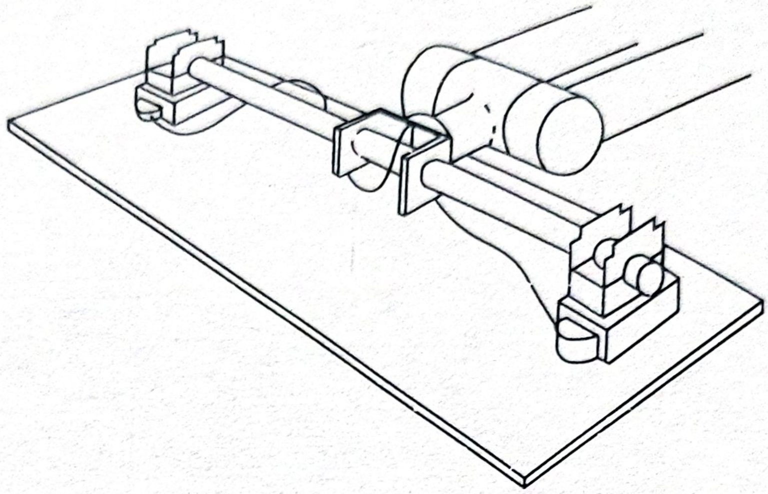
Figure 5.4.4 Vacuum cup with venturi device: (a) Bernoulli's principle that applies compressed air to form a vacuum; (b) assembly of suction cup and venturi device

2. The magnetic attraction tends to penetrate beyond the top layer in the stack, which can cause more than a single part to be lifted by the magnet.

Magnetic grippers can be divided into two categories, according to the type of magnets they use: electromagnets and permanent magnets. Electromagnetic grippers are easier to control but require DC power and an appropriate controller unit. Permanent magnets have the advantage of not requiring an external power



(a)



(b)

Figure 5.4.5 (a) Single magnetic gripper; (b) Dual magnetic gripper

source to operate the magnet. However, they require a stripping device for the part to be released at the end of the handling cycle. A stripping device is illustrated in Figure 5.4.6.

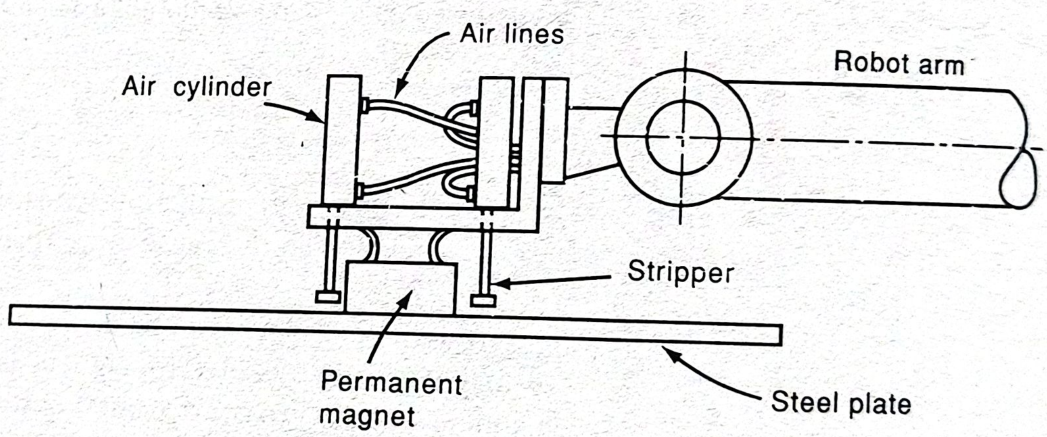


Figure 5.4.6 Stripper device with a permanent magnet gripper

Adhesive

Adhesive devices can be a very feasible means of handling fabrics and other lightweight materials. An adhesive substance is fed automatically to the robot wrist and performs the grasping action. The adhesive material is loaded in the form of a continuous ribbon into a feeding mechanism that is attached to the robot wrist and operates in a manner similar to a typewriter ribbon. The requirements of the items to be handled are that they must be gripped on one side only and that other forms of grasping, such as a vacuum or magnet, are not appropriate.

5.5 SPECIAL-PURPOSE GRIPPERS

Robot flexibility in various applications is responsible for the large variety of gripper devices. The development of off-the-shelf grippers to fill special applications is very limited. Often the user starts with an available basic design and then modifies the gripper to do the special job. In almost every case, special grippers must be fabricated to hold parts for specific jobs.

Research and development is being carried out with this objective of designing a universal gripper capable of grasping and handling a variety of objects with differing geometries. If such a universal device could be developed at a relatively low cost, it would save the time and expense of designing a special-purpose gripper for each new robot application.

Other miscellaneous devices can be used to grip parts or materials in robot applications.

Hook grippers can be used to handle containers of parts and to load and unload them from overhead conveyors. Obviously, the items must have some sort of handle to enable the hook to hold it.

Scoop and ladle grippers can be used to handle certain materials in liquid or powder form. A tool for ladling hot material, such as molded metal, is shown in Figure 5.5.1. One of this method's limitations is that the amount of material being scooped by the robot is sometimes difficult to control.

Collet grippers are used to pick and place cylindrical parts that are uniform in size. They obtain 360° of clamping contact with strong force for rapid part transfer. They are used for grinding and deburring operations. Collet grippers are available in round, square, or hex shapes. Figure 5.5.2 shows a round collet gripper.

Inflatable grippers have an inflatable diaphragm that expands to grasp the object. The inflatable diaphragm is fabricated out of rubber or other elastic material, which makes it appropriate for gripping fragile objects. The gripper applies a uniform grasping pressure against the surface of the object rather than a concentrated force typical of a mechanical gripper. Figure 5.5.3 shows an inflatable diaphragm grasping the inside diameter of a cup-shaped container.

Expandable grippers are similar to inflatable grippers but with a two- or three-finger design. Primarily, they are used to clamp an irregular-shaped workpiece. There are two types of expandable grippers: one that surrounds objects, gripping them from the outside, and one that grips hollow objects from the inside. In both cases, they make use of a hollow rubber envelope or other plastic material

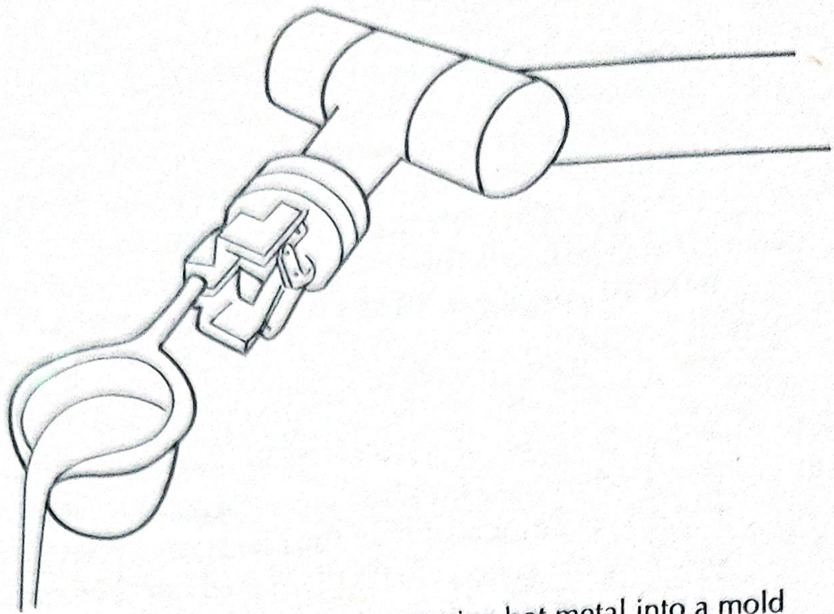


Figure 5.5.1 Ladle for pouring hot metal into a mold

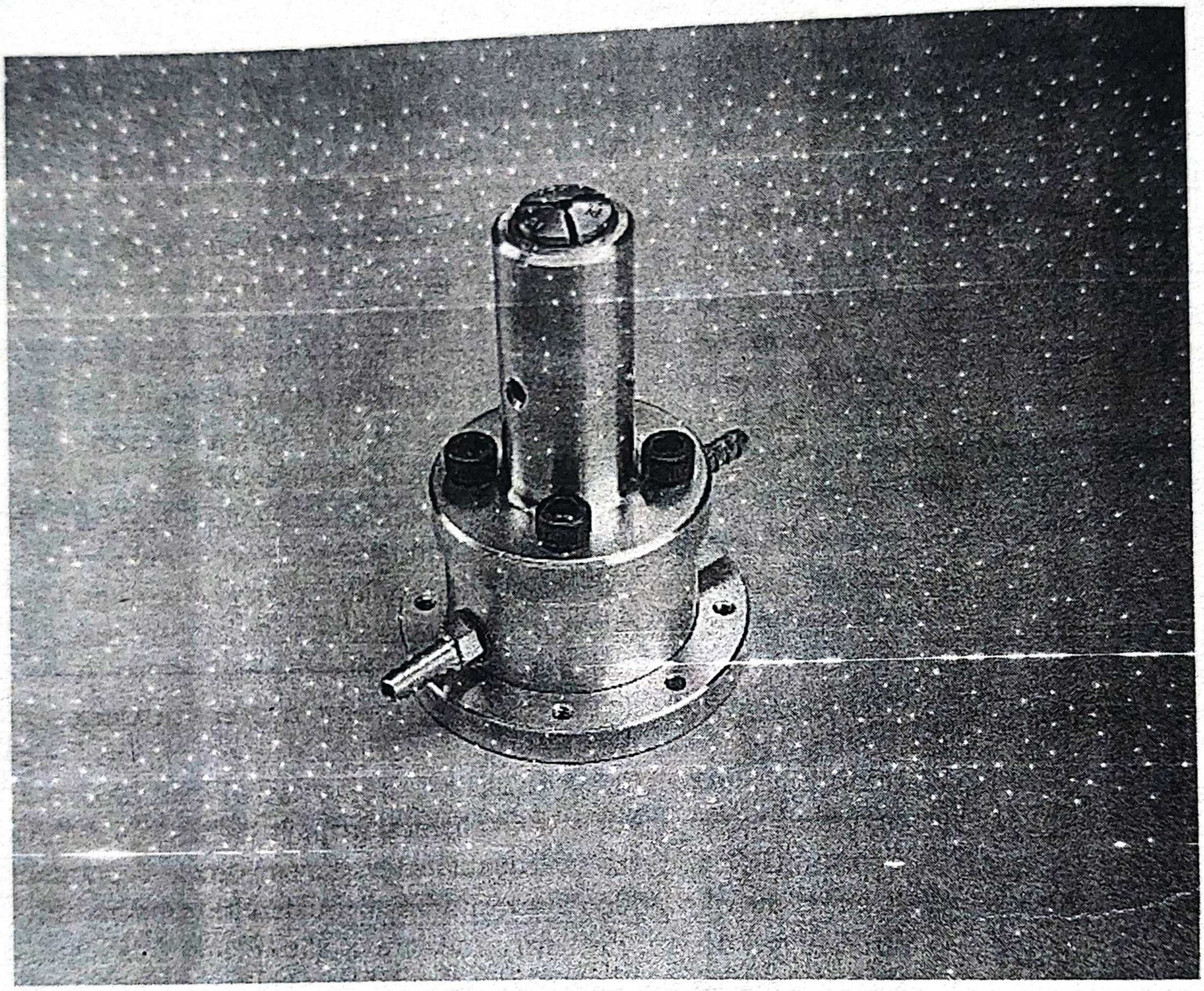


Figure 5.5.2 A round collet gripper *(Source: Robotic Accessories)*

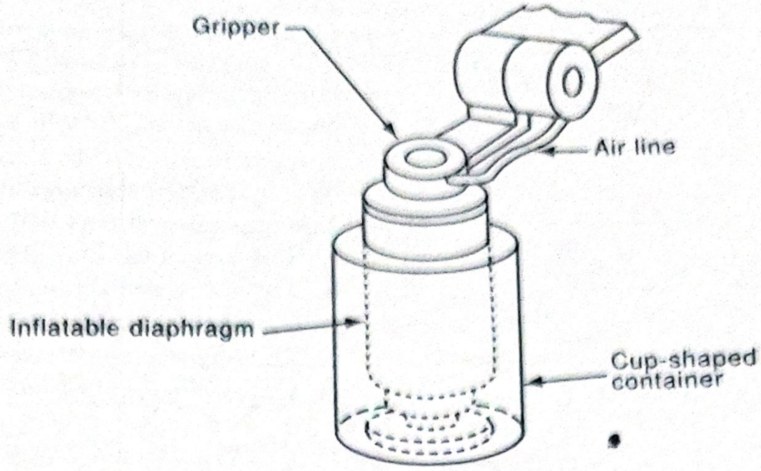


Figure 5.5.3 Inflatable gripper

that expands when pressurized. Expandable grippers are distributing even pressure on the part and are ideal for handling fragile parts or parts that vary a great deal in size.

In general, the grippers are classified in three categories:

1. Those that come in contact with only one face of the object to be lifted and use a method such as vacuum, magnetism, or adhesive action to capture the object.
2. Those that use two rigid fingers to grip an object. This type makes contact with the object at two specific points and may or may not deform the object.
3. Those that deform and attempt to increase the contact area between the gripper and object. This type includes multijointed fingers or a device operating on a principle similar to a balloon inflated inside or outside the object.

5.6 GRIPPER SELECTION AND DESIGN

The gripper selection capability is the most demanding process in any robot system to match the need for the production requirement. J. F. Engelberger, in *Robotics in Practice*, defines many of the factors that should be considered in assessing gripping requirements:

1. The part surface to be grasped must be reachable.
2. The size variation of the part must be accounted for because this might influence the accuracy of locating the part.
3. The gripper design must accommodate the change in size that occurs between part loading and unloading.

4. Consideration must be given to the potential problem of scratching and distorting the part during gripping.
5. If there is a choice between two different dimensions on the part, the larger dimension should be selected for grasping.
6. Gripper fingers can be designed to conform to the part shape by using resilient pads or self-aligning fingers.
7. The important factors that determine the required grasping force are:
   a. The weight of the object
   b. The speed and acceleration with which the robot arm moves, and the orientational relationship
   c. The physical constriction or friction that is used to hold the part
   d. The coefficient of friction between the object and the gripper fingers

5.7 PROCESS TOOLING

Process tooling is an end effector designed to perform work rather than to pick and place a work part. In a limited number of applications, the process tooling is a gripper that is designed to grasp and handle the tool. The reason for using a gripper in these applications is that there may be more than one tool to be used by the robot in the work cycle.

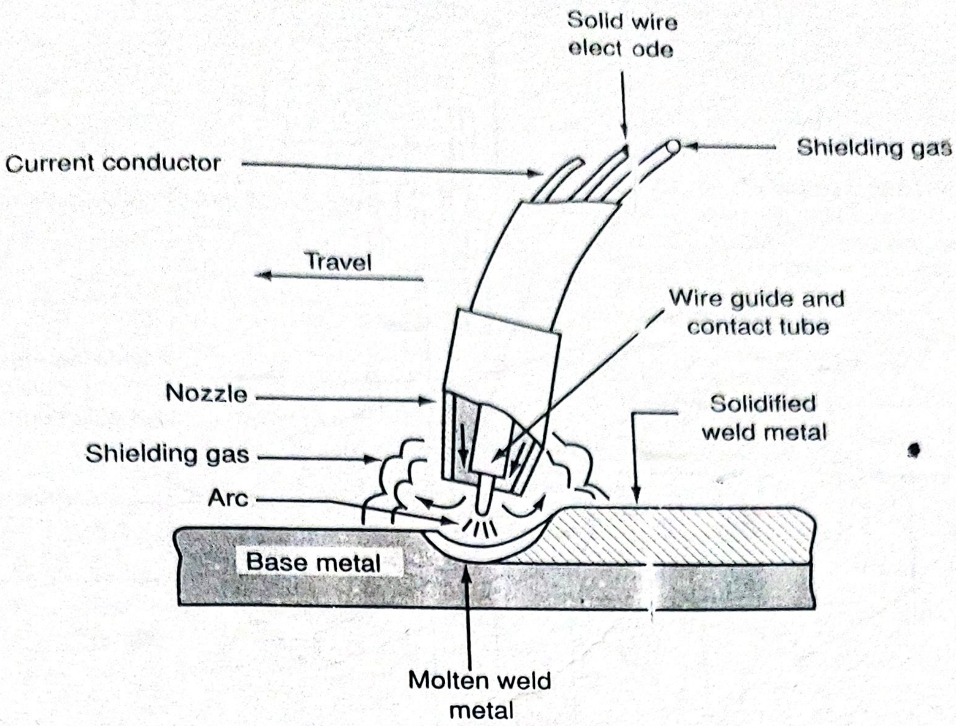
Process tooling refers to the general class of special end effectors that may be attached to the robot wrist.

A spot-welding gun can be attached to the robot wrist to place a series of welds on flat or curved surfaces. Generally, a three-degree-of-freedom wrist is required because of the dexterity required for maneuvering the gun. Gas-metal-arc-welding (GMAW) and Flux-core arc welding (FCAW) are the most commonly used methods for arc welding with robots. A welding gun can be attached to the robot wrist that carries the gas and bare wire for GMAW or cored electrode filled with flux for FCAW. The robot can position the welding gun for a single straight or curved run or use a weaving pattern for wider welds. Both methods are shown in Figures 5.7.1 and Figure 5.7.2. Spray-painting guns are also commonly used by industrial robots. In some cases, only two degrees of freedom may be required of the robot wrist for spray painting. The robot can spray parts with compound curved surfaces. Grinders, routers, wire brushing, or sanders are also easily attached to a robot wrist. Liquid cement applicators, heating torches, and waterjet cutting tools can also be incorporated in the robot wrist. A large class of assembly tools, such as drills, screwdrivers, and wrenches, can be used by the robot. In some cases, these tools are automatically interchangeable by the robot.

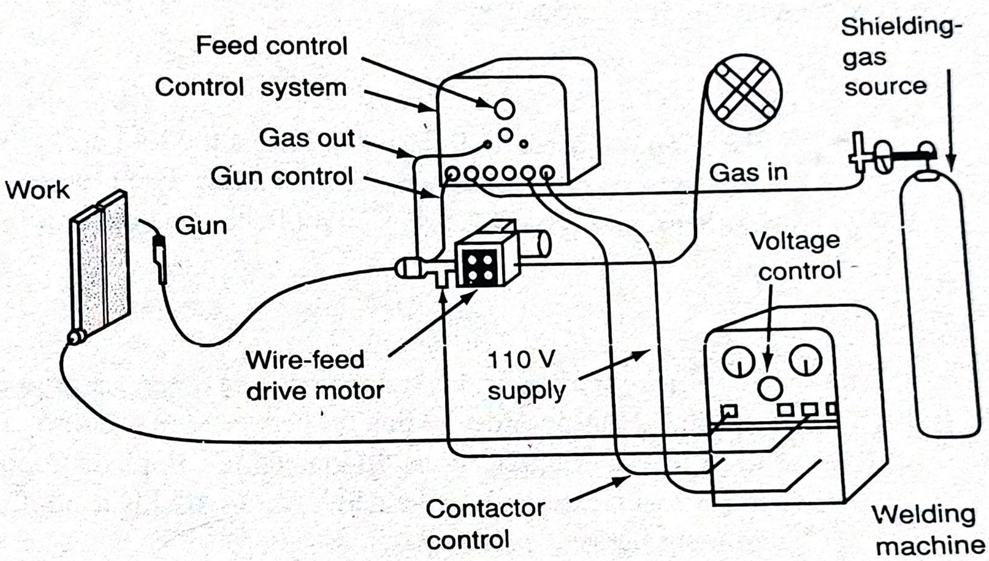
A variety of process tools are shown in Figure 5.7.3. These tools were developed by Unimation for the many applications of their industrial robots.

Multiple Tools

A single industrial robot can also handle several tools sequentially, with an automatic tool-changing operation programmed into the robot's memory. The tools can be different types or sizes, permitting multiple operations on the same work-



(a)



(b)

Figure 5.7.1 (a) Gas-metal-arc-welding process (GMAW); (b) Basic equipment used in gas-metal-arc-welding opera
(Source: American Welding Society)

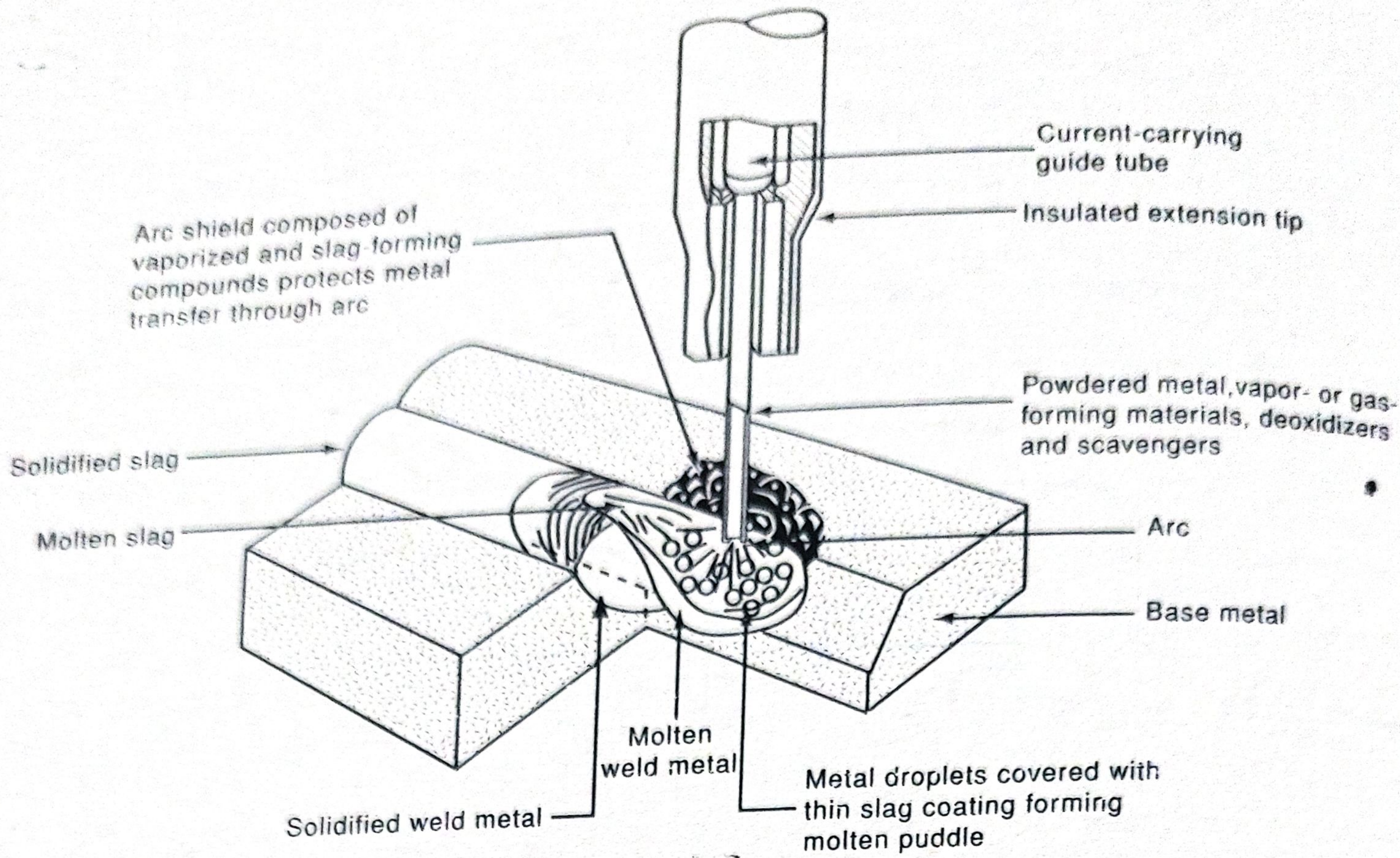


Figure 5.7.2 Schematic illustration of the Flux-core-arc-welding process (FCAW). The operation is similar to GMAW shown in Figure 5.7.1(b). *(Courtesy of the American Welding Society)*

place. To remove a tool, the robot lowers the tool into a cradle that retains the snap-in tool as the robot pulls its wrist away. The process is reversed to pick up another tool. Figure 5.7.4 shows a tool-changing operation.

5.8 COMPLIANCE

Compliance is a special end effector that is neither a gripper nor a process tool but rather a sensor or device that fits between the robot wrist and end effector for special assembly applications. In general, a compliant robot system is one that complies with externally generated forces to modify its motion for the purpose of alignment between mating parts.

If a robot uses a force sensor (piezoelectric, magnetic, or strain gauges) and modifies its control strategy based on that sensor's output, the term *active compliance* is used to describe the behavior. On the other hand, if the robot's gripper is constructed in such a way that the mechanical structure deforms to comply with those forces, the term *passive compliance* is used. Therefore, problems with mat-

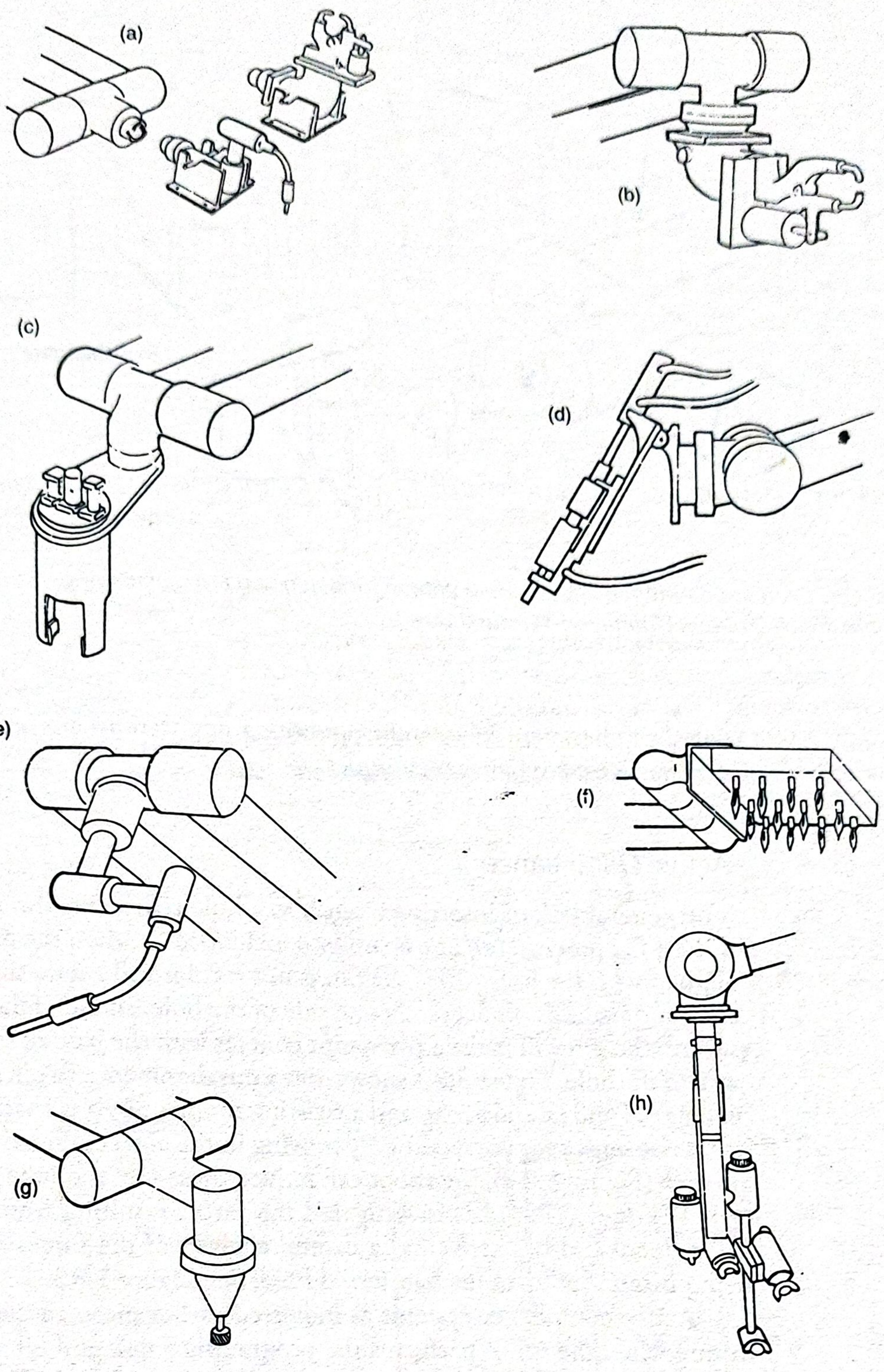


Figure 5.7.3 Various types of process tools: (a) Tool changing; (b) spotwelding gun; (c) pneumatic nut-runners, drills, and impact wrenches; (d) stud-welding head; (e) arc-welding torch; (f) heating torch; (g) routers, sanders, and grinders; (h) spray gun *(Source: Unimation-Westinghouse)*

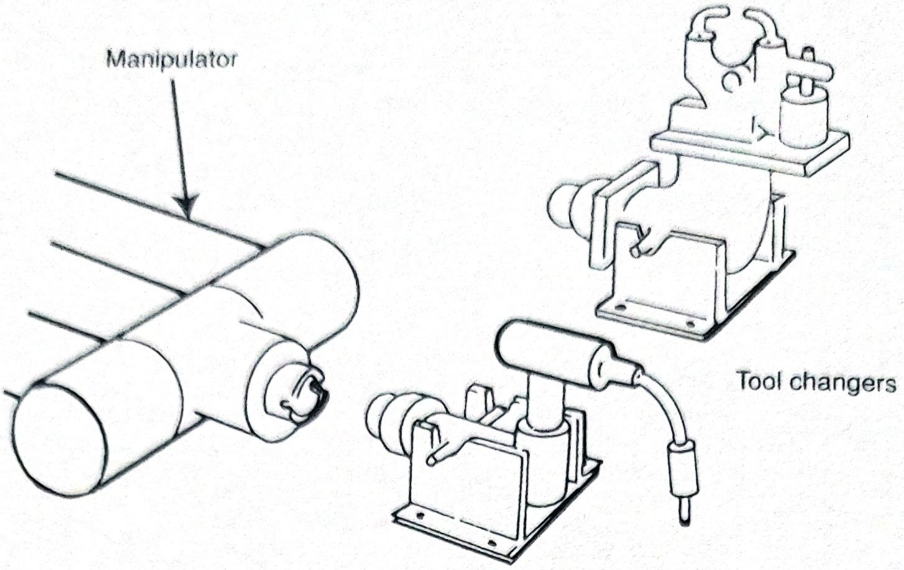


Figure 5.7.4 Tool changers decrease downtime and increase uptime for batchmode manufacturing, maintaining or repairing tools, and assembly applications *(Source: Unimation-Westinghouse)*

ing-part alignment in assembly and other applications are resolved using active and passive compliance techniques.

Active Compliance

The general task of inserting a pin into a hole represents three types of contact during the process: (a) The chamfer contact occurs when the pin is not perfectly aligned with the hole; (b) if the pin is not rigid it will rotate slightly and start to slide and make a contact along one side of the hole; and (c) if the misalignment is severe, the pin will make a two-point contact with the base of the pin and the far wall of the hole. Figure 5.8.1 shows how a misalignment of a pin into a hole results in an axial and lateral force, and a twisting moment by a contact force applied to the wrist sensor for correction. By moving in the correct direction with the compliance (Figure 5.8.2), the robot can reduce these forces on the pin.

Whitney (1983) has investigated the forces resulting from pin insertion in great detail and has arrived at a careful analysis of the forces acting on the pin being inserted into an unchamferred hole. See Figure 5.8.3.

Active compliance systems as indicated earlier measure the active force and torque when the robot performs the programmed task and often are called F/T-sensing systems. Force-sensing systems allow the robot to detect changes and variations in the workpiece or tooling during the operation and adapt the program to correct them. F/T sensing uses an adaptor placed between the gripper and the robot tool plate to measure the force and torque caused by contact between mating

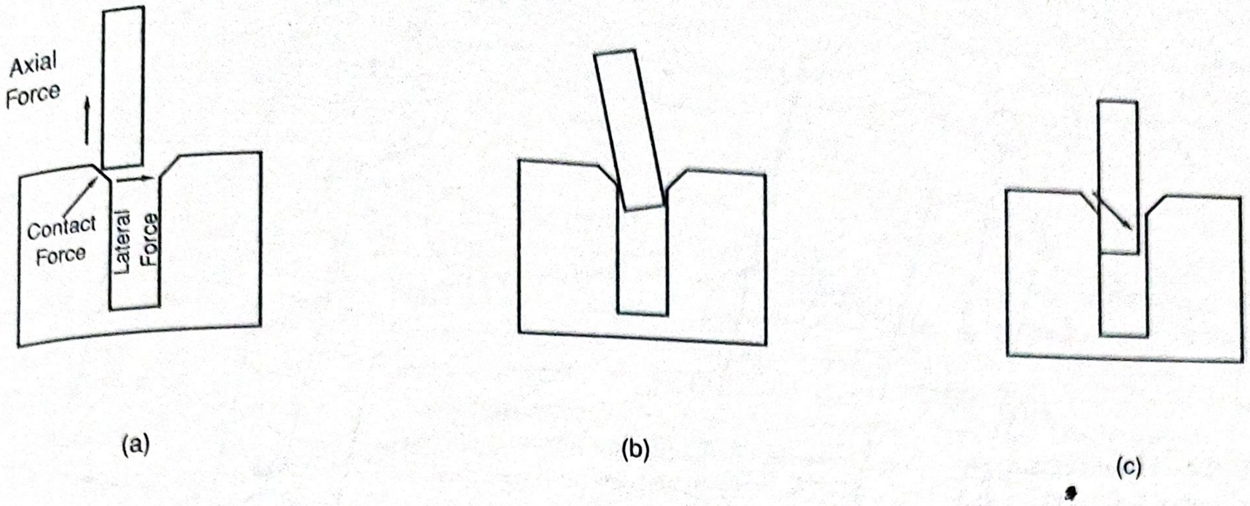


Figure 5.8.1 Compliance for inserting a pin into a chamfering hole: (a) Inserting with lateral error; (b) Inserting with rotational error; (c) Inserting with ax al error

parts. Figure 5.8.4 shows a typical device. This device consists of two parallel plates that are separated by two rigid rods firmly attached to one plate but with a ball joint on the other. In addition, three elastic members are also placed between the plates that keep them separated and parallel. The rods and plates are arranged so that one plate is fixed and the other one has limited rotation and deflection.

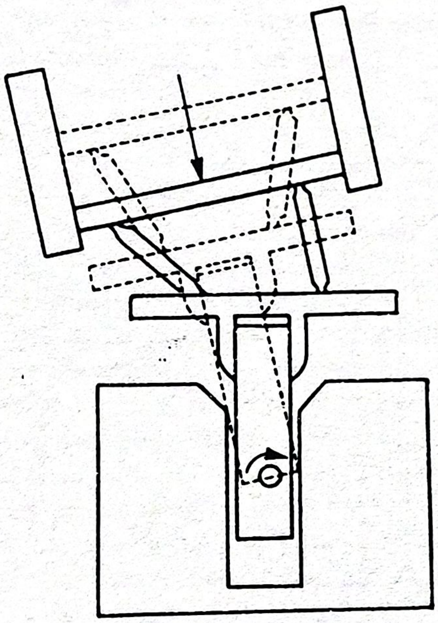


Figure 5.8.2 Compliance technique employed motion to reduce the force on the pin.

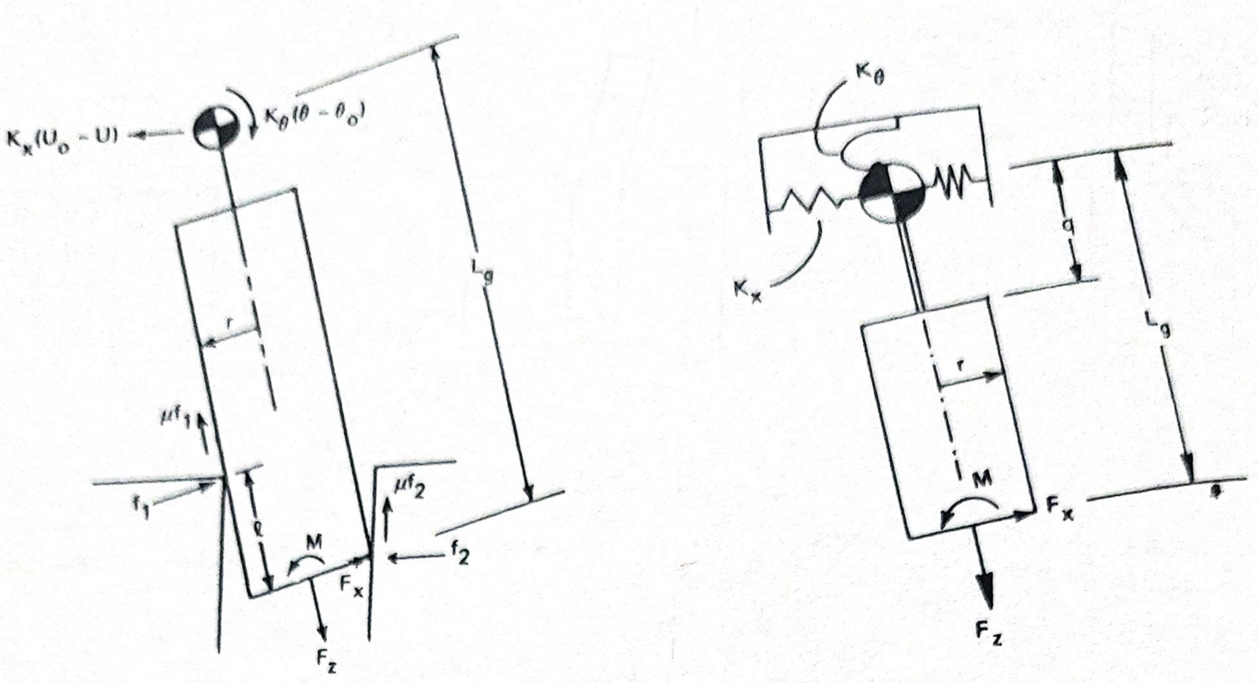


Figure 5.8.3 Active compliance: (a) forces acting on pin during two-point contact; (b) rigid peg supported compliantly by lateral springs K_x and angular spring K_θ at a distance *q* from peg's tip (*Source: ASME*)

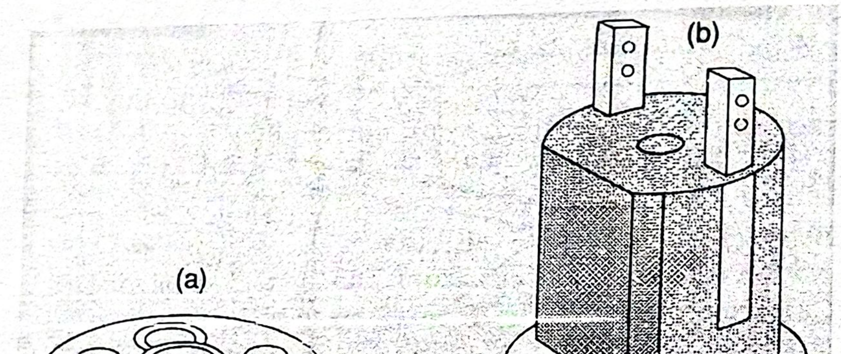


Figure 5.8.4 Force/Torque active compliance: (a) F/T transducer; (b) attached to the robot gripper

Other devices for assembly are also available. For example, engineers at the Kawasaki Laboratories in Japan can put together complex parts, such as motors and gearboxes, using high-precision feedback, cleverly designed grippers, and compliant fixtures.

Passive Compliance

Another approach to compliance is to allow the wrist to deform in such a way that the external forces are minimized. Passive compliance is using a spring-loaded wrist to provide the deformation. The concept of this principle applies to a Remote Center Compliance (RCC) device. This device was originally developed at the Charles Stark Draper Laboratories of Cambridge, Massachusetts, but now is available commercially in many forms by different manufacturers. The RCC device is a unique device that compensates for position errors due to machine inaccuracy, parts vibration, and fixturing tolerance. This minimizes the assembly forces and the possibility of parts jamming. Figure 5.8.5 shows how the device works.

The original RCC device consists of three plates: The center plate is connected to the top plate with four rods and to the bottom plate with four additional rods. In operation, four rods, one on each corner, are used for lateral compliance (only two rods are shown in Figure 5.8.5), and four angled rods, one on each corner, are used for rotational compliance (again, only two rods are shown). The flexible rods allow the plates to move relative to each other and provide a combination of lateral and rotational compliance; however, this device is rigid in the axial direction with no compliance provided.

Modern RCC devices, such as the model illustrated in Figure 5.8.6, consist of a set of six elastomertic shear pads sandwiched between two plates, and mechanical stops protect against overload movements in all directions.

The shear pads are stiff in the axial direction but highly compliant in the lateral and rotational directions. The upper plate is attached to the robot tool plate, and the lower plate is attached to the gripper. This device can also be furnished with a lockout feature. It is locked during movement and unlocked immediately before part insertions to allow the RCC to compensate for misalignment during assembly. This capability reduces assembly cycle time and increases the operation life of the shear pads.

In operation, the center of compliance is the point in space about which rotational and translation motion occurs. Positioning the center of compliance as the part-mating surface allows the part being inserted to translate laterally and rotate around the center of compliance, which reduces assembly forces and the possibility of parts jamming. This compensation for lateral and rotational misalignment reduces wear on the gripper as well as the need for high-accuracy machines and fixturing. The lockout device is illustrated in Figure 5.8.7.

Another form of passive compliance is found in some SCARA configuration robots. The Yamaha robot in Figure 5.8.8 uses SCARA technology to provide a variable tool movement for insertion compliance at programmed points. In oper-

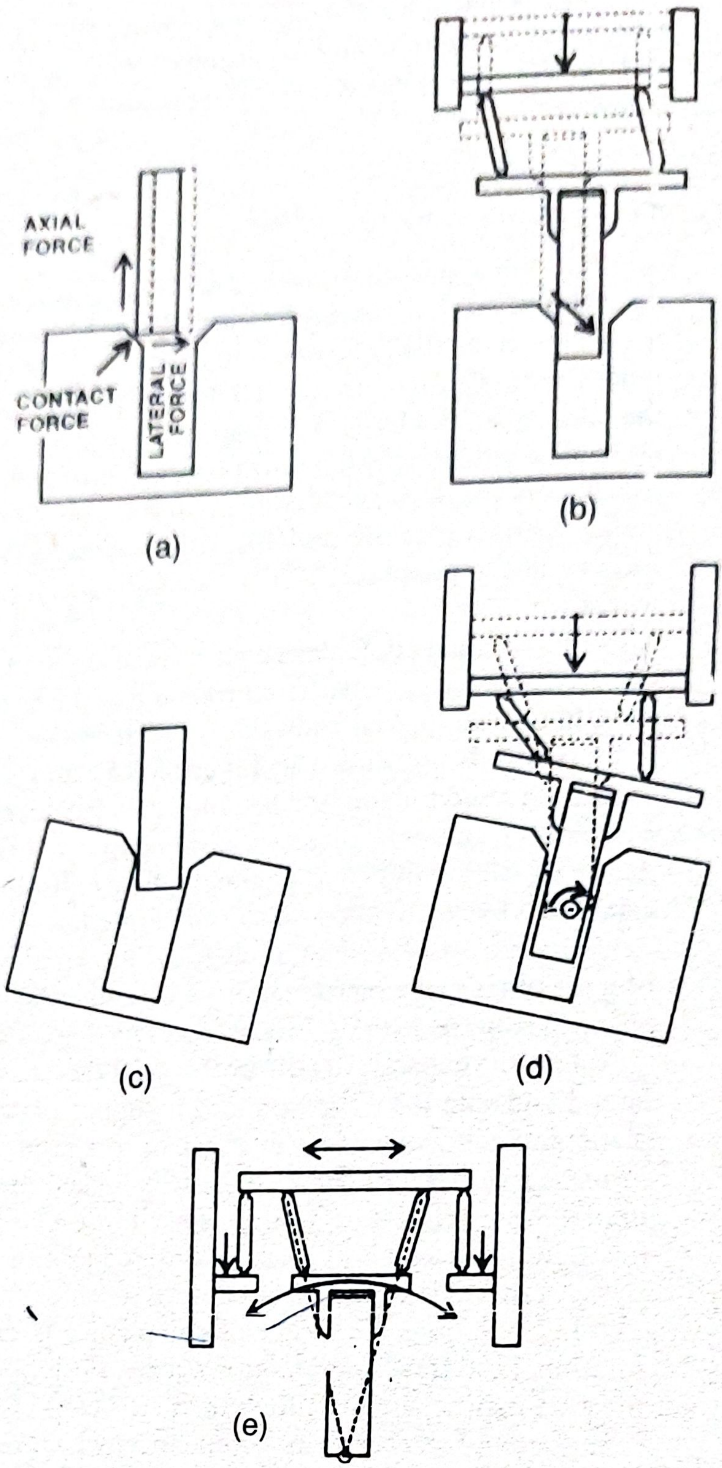
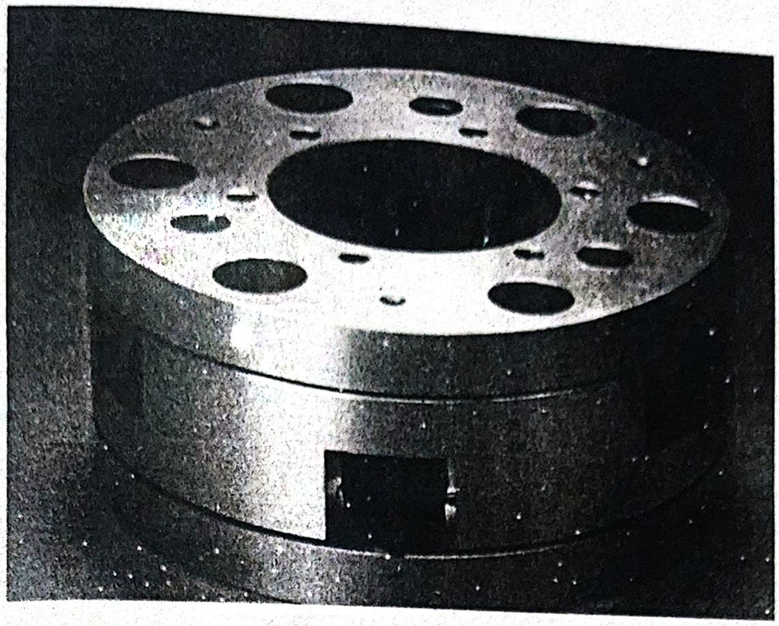


Figure 5.8.5 Operation of Remote Center Compliance (RCC) device: (a) lateral error; (b) axial error; (c) rotational error; (easily inserted by rotating about the compliance center; (e) combining the two modes of freedom to a useful compliant devi



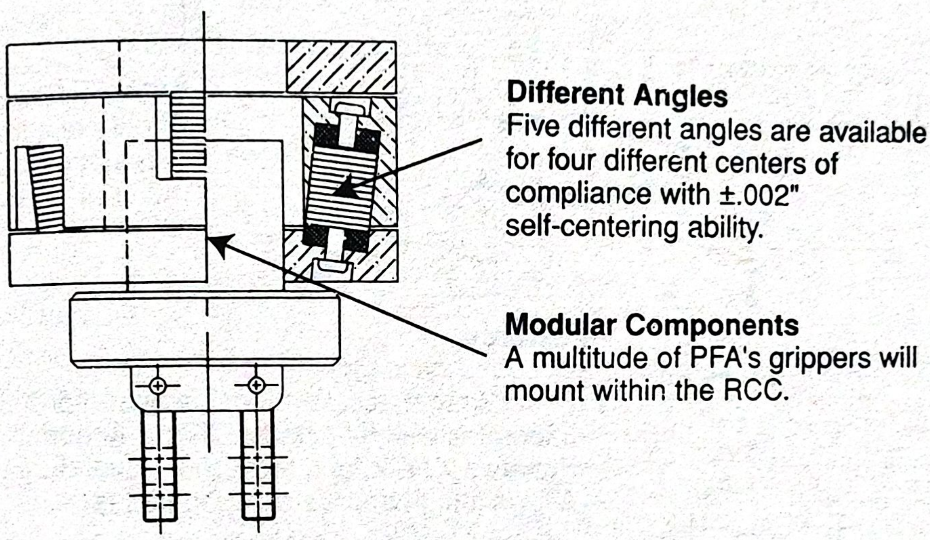
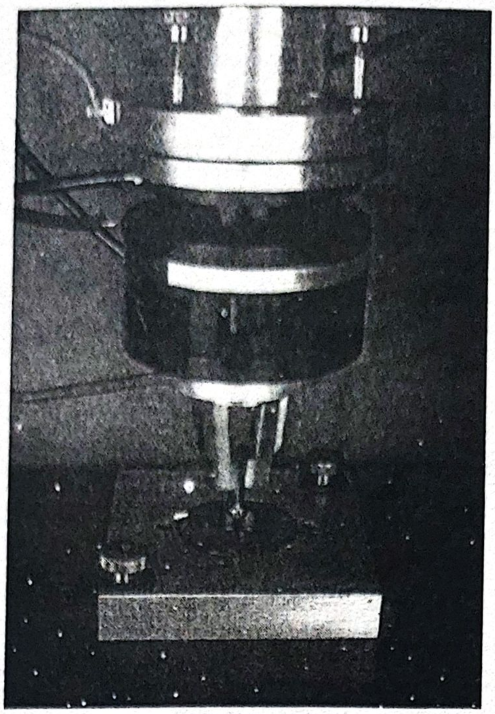


Figure 5.8.6 Automated assembly compliance device model ASP-85 *(Courtesy of PFA Inc.)*



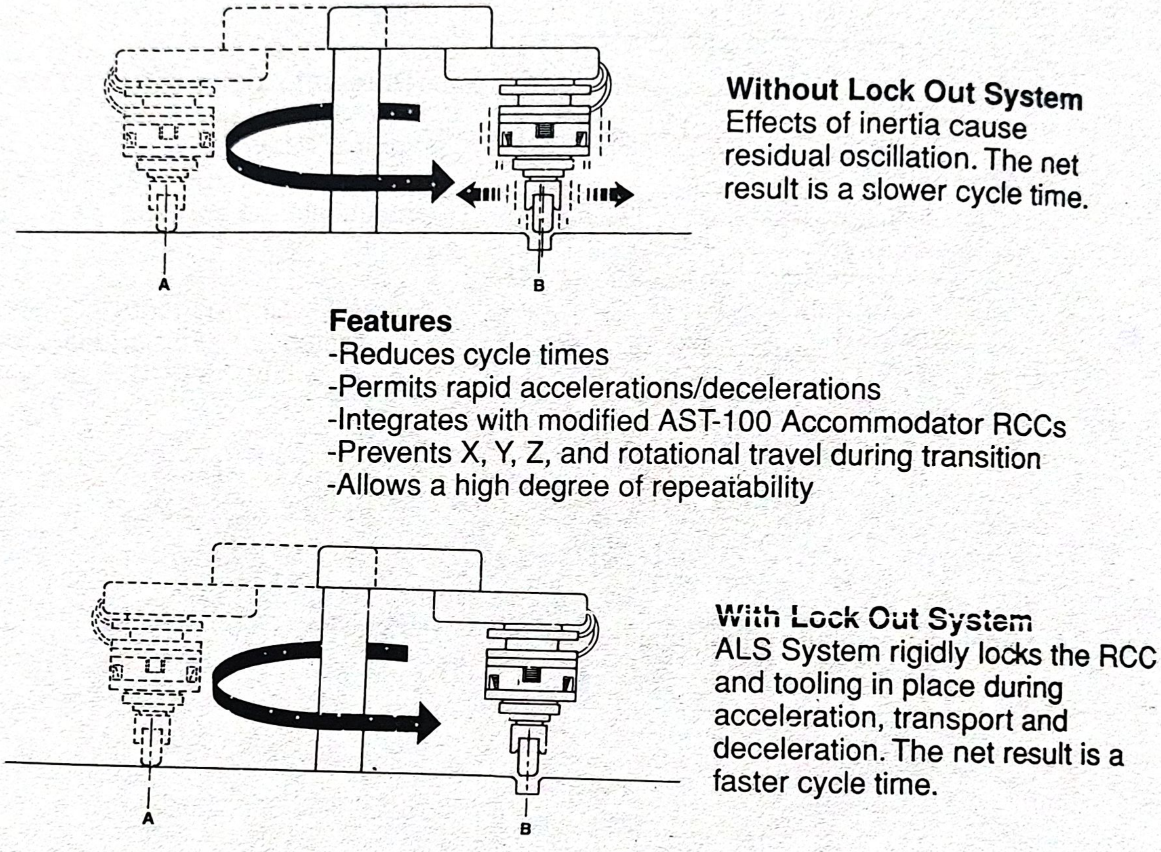
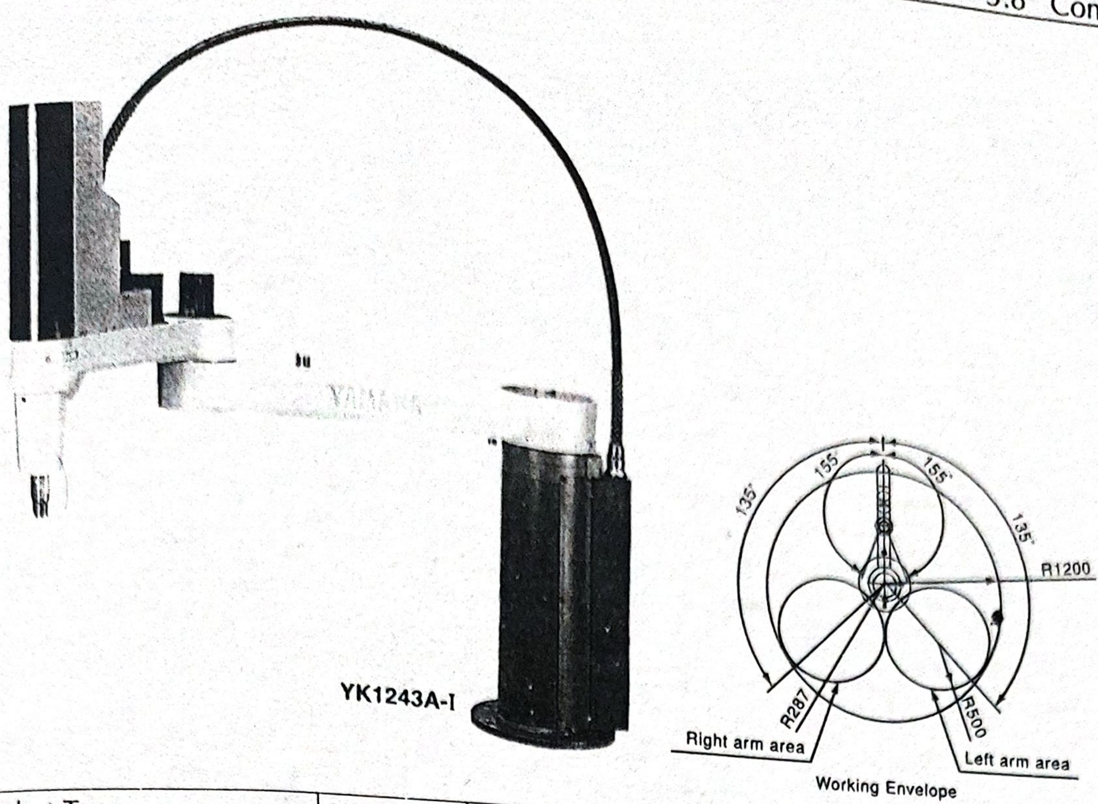


Figure 5.8.7 RCC Accommodator with PFA lockout system *(Courtesy of PFA Inc.)*



		Robot Type	YK541A-I	YK641-I	YK741-I	YK841-I	YK1041-I	YK1043A-I	YK1243-I
Number of Servo Motor Axes			4 Axes					4 Axes	
Axis Types	X Axis	Arm Length	250mm	350mm	350mm	450mm	550mm	500mm	700mm
		Max. Angle of Movement	±110°					±135°	
	Y Axis	Arm Length	250mm		350mm		450mm	500mm	
		Max. Angle of Movement	±145°		±140°			±145°	±155°
	Z Axis	Drive Method	Servo Motor					Servo Motor	
		Stroke	100, 200, 300mm		200, 400mm			200, 400mm	
	R Axis	Drive Method	Servo Motor					Servo Motor	
		Max. Angle of Movement	±180°					±180°	
Motor		X Axis	300W		400W			400W	
		Y Axis	100W		200W			400W	
		Z Axis	100W		200W			400W	
		R Axis	60W		100W			200W	
Max. Speed		X, Y Resultant	3.5m/sec	4.2m/sec	5.0m/sec	5.7m/sec	4.7m/sec	3.35m/sec	3.76m/sec
		Z Axis	500mm/sec					250mm/sec	
		R Axis	432°/sec					180°/sec	
Standard Cycle Time			0.9 sec		0.95sec		1.0sec		
Repeatability			±0.03mm				±0.05mm	±0.05mm	
Max. Payload			10kg		20kg			50kg	
Weight			34kg	35kg	78kg	79kg	84kg	88kg	90kg
Travel Limits			1. Soft Limit 2. Mechanical Limit (X, Y axis)						
Robot Cable			3.5m					3.5m	
R Axis Allowable Moment of Inertia*			$1.2 kg \bullet cm \bullet sec^2$		$3.2 kg \bullet cm \bullet sec^2$			$25 kg \bullet cm \bullet sec^2$	

*There are limits to the acceleration parameter settings.

Figure 5.8.8 Yamaha SCARA Industrial robot model YK1243A-1 shown. Other models with their parameters are listed in the table. *(Courtesy of Yamaha Robotics Inc.)*

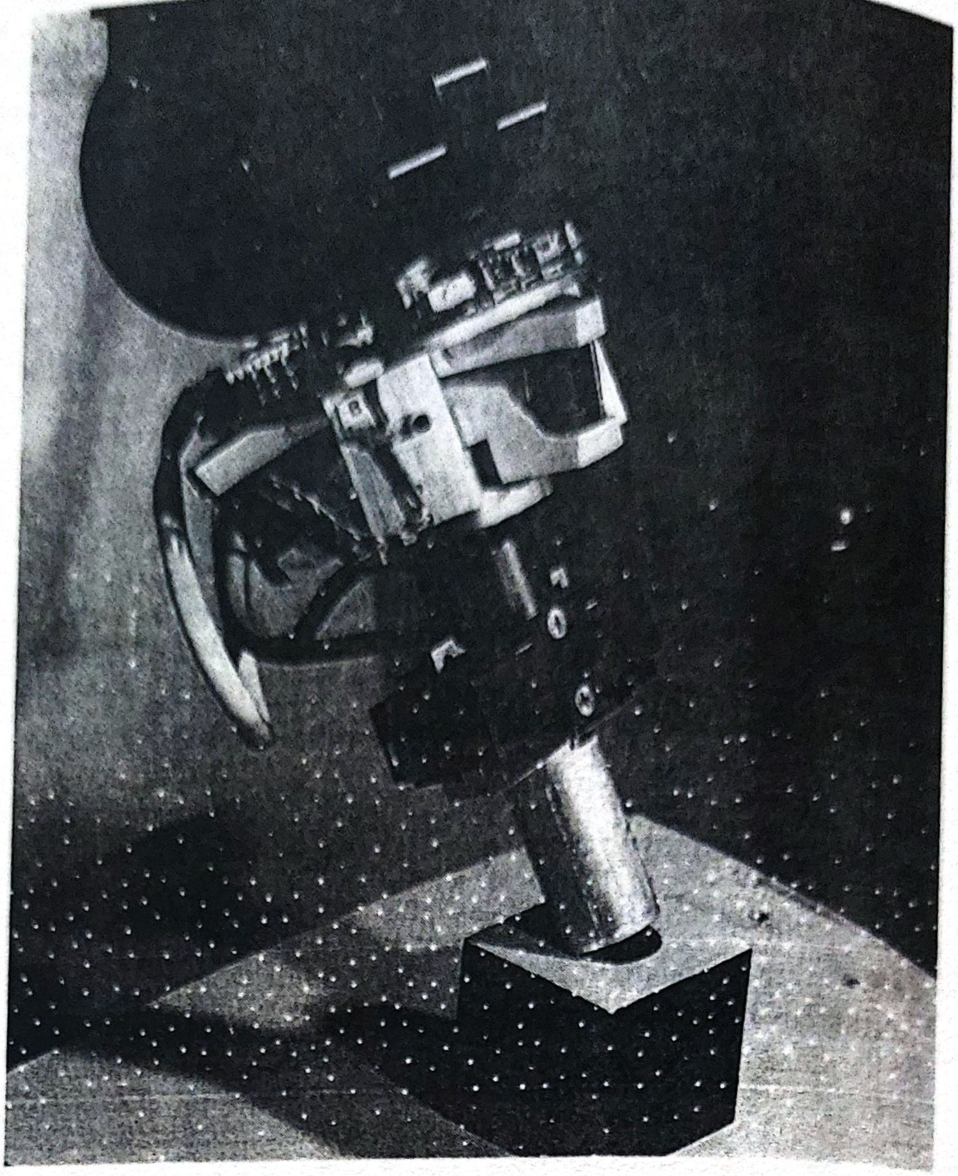


Figure 5.8.9 Chamferless insertion of a pin in a hole using an IRCC device *(Source: Charles Stark Draper Laboratories, Inc.)*

ation, when the tool reaches the programmed point, the controller frees the servo system so that the gripper can move freely over a selected distance in the x and y axes. If the gripper attempts to move beyond the selected range, the servo system stiffens and the gripper position is maintained.

In addition to the SCARA arms that initiated the selective compliance technique, other arms like the Seiko RT-300 have language commands that permit any of the axes to have compliance.

Also, by employing different types of displacement sensors on an RCC device, it is possible to obtain electrical signals proportional to various torques and forces that result in any misalignment between two parts. This information can then be utilized in a force or torque feedback scheme. Such sensors have been developed at the MIT Draper Laboratories, recently, and are called Instrumented Remote Center Compliance (IRCC). Figures 5.8.9 and 5.8.10 show such devices.

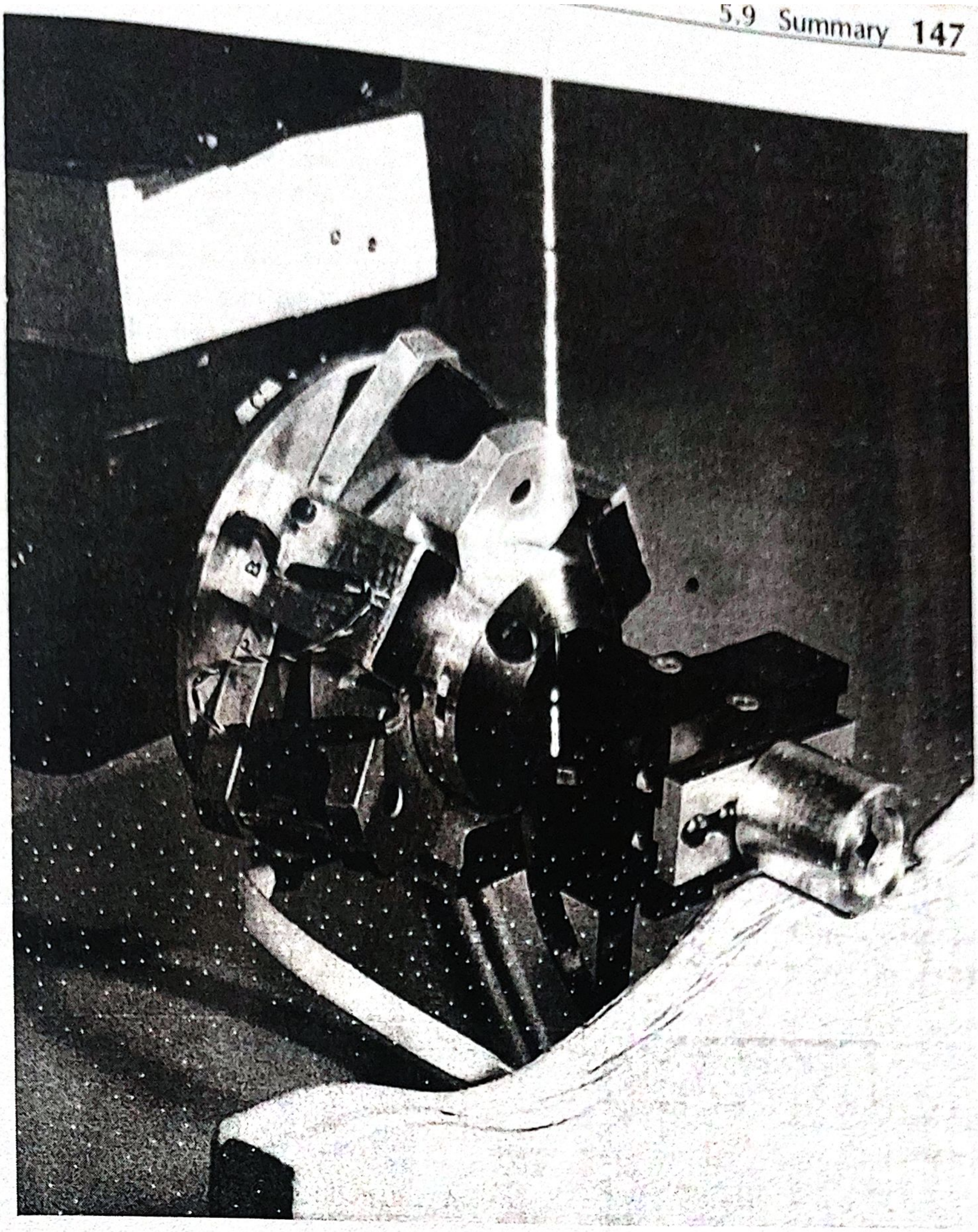


Figure 5.8.10 Edge-following rotary cutting tool using an IRCC *(Source: Charles Stark Draper Laboratories, Inc.)*

5.9 SUMMARY

The objective of this chapter was to introduce the different types of end effectors that are available today for use on robot arms. An end effector is a device mounted on the tool plate of the robot's wrist to perform a particular task. There are two major categories of end effectors: grippers and process tooling. Grippers are used to grasp, hold, and transfer objects. Process tooling is designed to perform work on an object rather than merely grasp it.

Grippers can be classified as:

a. Single grippers with two, three, or four fingers or jaws
b. Multiple grippers (two or more grippers mounted on the same robot's wrist)
c. Exterior and interior surface grippers
d. According to the method of gripping mechanism: vacuum, magnetic, adhesive, special-purpose grippers
e. According to input power of gripping mechanism: pneumatic, hydraulic, electric, mechanical (spring activated)
f. According to the closing motion of the jaws: angular closing, parallel closing

Process tooling can be classified as tool and fixture.

As a tool, it can be attached to the robot wrist to perform various operations, such as spot welding, arc welding, spray painting, drilling, routing, wire brushing, grinding, heating torches, water jet cutting, and as a cement applicator for assembly.

As a fixture, it is sometimes used to hold a set of interchangeable tools that are to be manipulated during the work cycle. An example of tool changing is shown in Figure 5.7.4.

Compliance is a device mounted between the robot wrist and end effector that allows for a certain amount of give-and-play in the motions of the end effector in various directions during assembly applications. Active compliance is the device using force sensors to detect the behavior of the parts to be assembled. Passive compliance is the device using mechanical structure of deformation to comply with the behavior of the parts.

5.10 REVIEW QUESTIONS

5.1 What is an end effector and what function does it serve?
5.2 What are the two major categories of end effectors?
5.3 In what ways do end effectors differ from the human hand?
5.4 What are the five characteristics that an end effector must satisfy?
5.5. What are the three classifications of an end effector?
5.6 Describe the classification and characteristics of mechanical grippers.
5.7 Describe the classification and characteristics of process tooling.
5.8 Describe vacuum, magnetic, and adhesive grippers.
5.9 Describe special-purpose grippers.
5.10 Describe the three categories of grippers.
5.11 What should you consider when selecting a gripper?
5.12 What is compliance?
5.13 Describe active and passive compliance.
5.14 What is an RCC and an IRCC device?
5.15 What other compliance techniques are available?

5.11 PROBLEMS

5.1 A part weighing 8 pounds is to be held by a gripper using friction against two opposing fingers. The coefficient of friction between the fingers and the part surface is 0.3. The *g* factor to be used in force calculations should be 3.0. Compute the required gripper force.

5.2 Solve Problem 5.1, this time using a safety factor of 1.5 in the calculations.

5.3 Solve Problem 5.1, using a maximum acceleration of 56 ft/sec/sec and a safety factor of 1.5. Find the required gripper force.

5.4 A part weighing 15 pounds is to be grasped by a mechanical gripper using friction between two opposing fingers. The coefficient of static friction is 0.35 and the coefficient of dynamic friction is 0.20. The direction of the acceleration force is parallel to the contacting surfaces of the gripper fingers. Which value of coefficient of friction is appropriate to use in the force calculations? Why? Compute the required gripper force by assuming a *g* factor of 2.0.

5.5. For the information given in the mechanical gripper design of Figure 5.11.1, determine the required actuating force if the gripper force is to be 30 pounds.

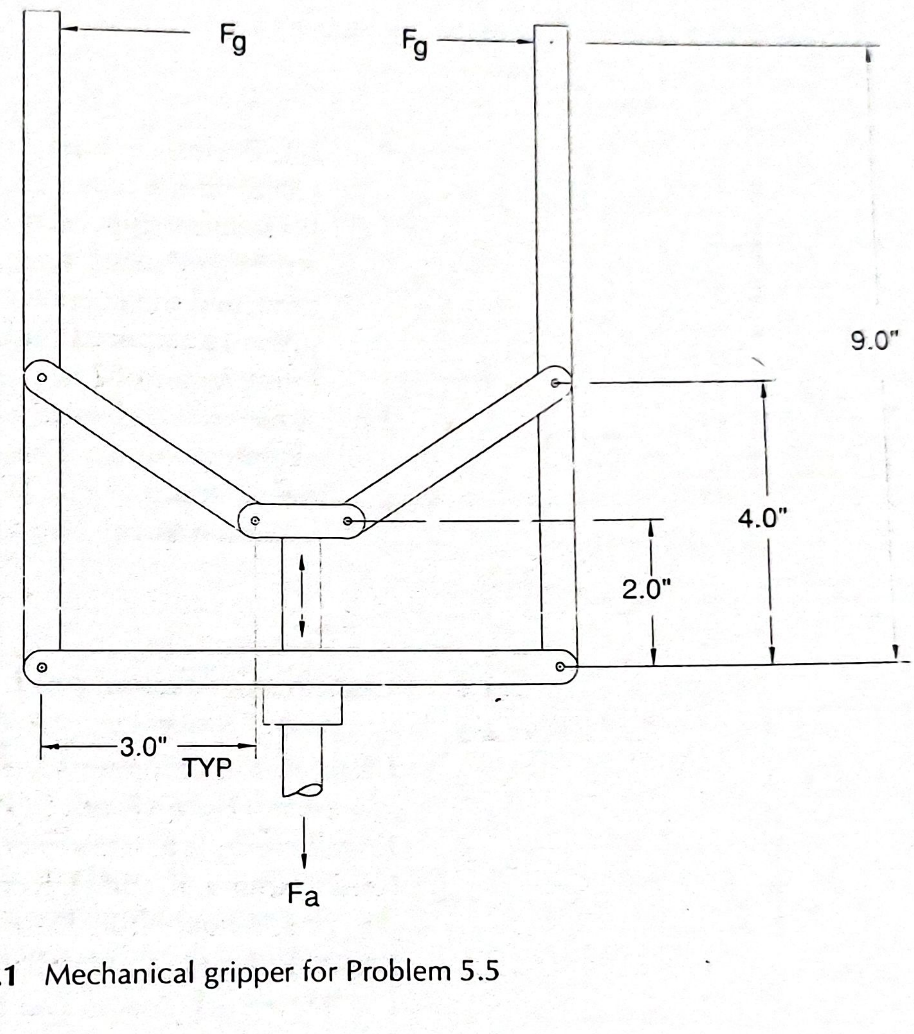


Figure 5.11.1 Mechanical gripper for Problem 5.5

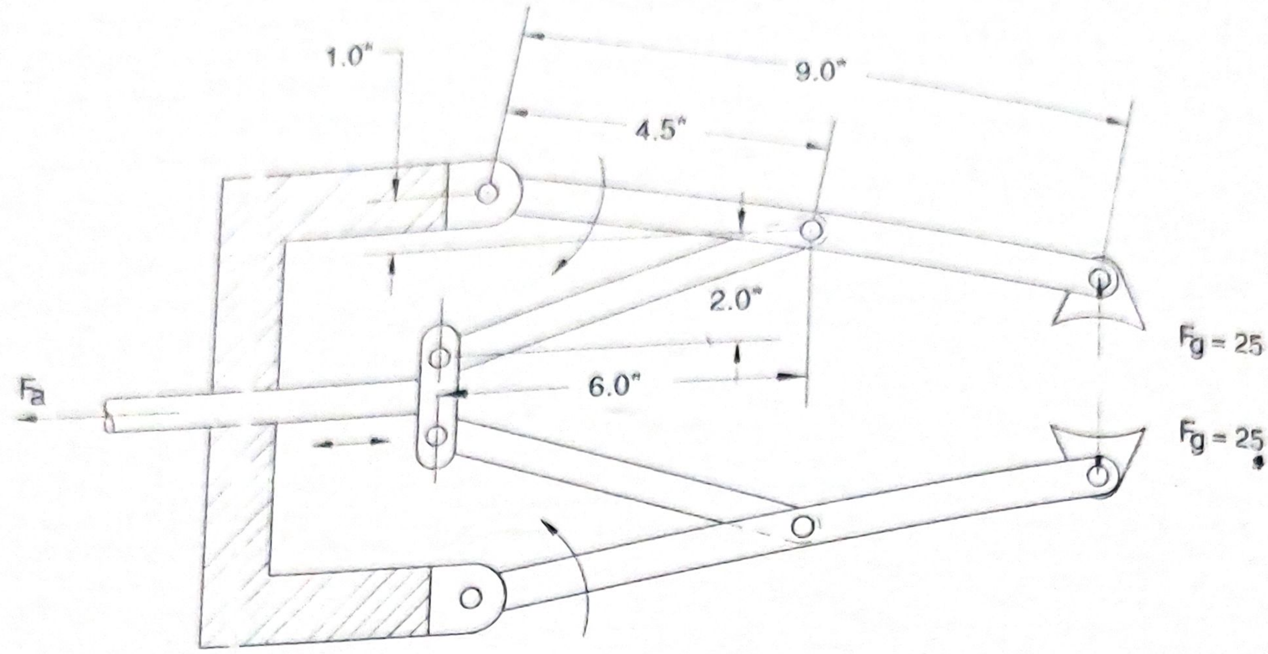


Figure 5.11.2 Mechanical gripper for Problem 5.6

5.6 For the information given in the mechanical gripper design in Figure 5.11.2, calculate the required actuating force *Fa*.

5.7 A vacuum gripper is to be designed to handle flat plate glass in an automobile windshield plant. Each plate weighs 35 pounds. A single suction cup will be used, and the diameter of the suction cup is 5.0 in. Determine the negative pressure required (below atmospheric pressure) to lift each plate. Use a safety factor of 2 in your calculations.

5.8 A piston is to be designed to exert an actuation force of 150 pounds on its extension stroke. The inside diameter of the piston is 2.0 in., and the ram diameter is 0.375 in. What shop air pressure will be required to provide this actuation force? Use a safety factor of 1.5.

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