11

Design of Robotic End Effectors

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11.1 Introduction

Aside from the robot itself, the most critical device in a robotic automation system is the end effector. Basic grasping end effector forms are referred to as grippers. Designs for end effectors are as numerous as the applications employing robots. End effectors can be part of the robot's integral design or added-on to the base robot. The design depends on the particular robot being implemented, objects to be grasped, tasks to be performed, and the robot work environment.

This chapter outlines many of the design and selection decisions of robotic end effectors. First, process and environment considerations are discussed. Robot considerations including power, joint compliance, payload capacity, and attachment are presented. Sections reviewing basic end effector styles and design guidelines follow this. Sensors and control issues are also presented. The chapter concludes with an end effector design.

11.2 Process and Environment

Robots vary in size and payload capacities for many diverse operations. Some robots are designed for specific, singular tasks such as materials handling, painting, welding, cutting, grinding, or deburing. These robots use specific tools as end effectors. Primary considerations for end effector designs, in these instances, are the tool, orientation, and control of the tool for effective processing, as well as the robot payload capacity (to be discussed later). Other robots are designed for general purposes and material handling. These robots require additional engineering detail in end effector design. In all cases the tasks and the robot environment must be considered when selecting or designing the appropriate robot and end effector. The end effector is seen as part of the overall system design subject to the same constraints as the entire system.

11.2.1 System Design

The end effector is but part of a system. As with all system designs, it is important to have a process flow diagram describing the tasks and how they are to be accomplished, before designing the end effector. This will clarify the process in terms of the objects to be handled and what functions are necessary for the end effector, as well as the entire system. A typical process flow chart defines the items to be handled, where it is grasped, what is done to the item, where it is placed, and special orientations. A sample chart is shown in Figure 11.1. This defines the roles of the robot, system controller, peripheral devices, end effector, and specialized tools. From the activities necessary to complete the process, the end effector design requirements and specifications are formed.

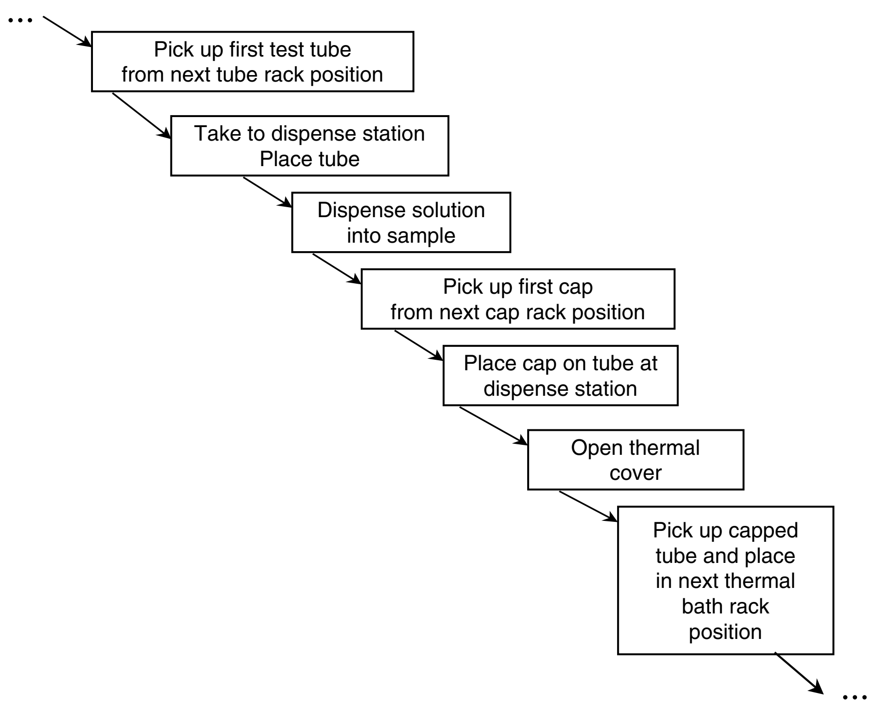

FIGURE 11.1 Sample process flow chart.

Many other aspects affect the design of the end effectors. Even with robot, process, and system requirements and specifications available, not enough necessary information may be provided about a process. Many questions will need to be examined to complete the system and end effector design.

For example, answers to these questions and others will be necessary for designing end effectors.

1. What are the shape and weight of the grasped objects?
2. What is the uniformity or tolerance of handled objects?
3. Are the objects' surfaces smooth? What is the coefficient of friction?
4. What is the spacing of objects?
5. How will they be oriented and presented?
6. What placement and spacing dimensions can be modified?
7. What are placement tolerances?
8. What are grasping forces or pressure limits?
9. Are complementary tools needed?
10. Is compliance necessary for assembling parts?
11. Are there special environmental considerations?

11.2.2 Special Environments

Many industrial situations have special system environmental requirements that impact the robot and end effector design. A large area of operation for robots is semi-conductor manufacturing. Here robots must operate in various clean room conditions. End effectors must be selected for compatibility to the class of clean room in which the robot will operate. It is important that the end effector not generate many particles in this situation. End effectors must be designed with all surfaces to be either stainless steel or polymer or to be coated with a clean room acceptable material (such as an anodized aluminum surface or a baked-on powder coat). Polymer (oil-less) washers and bearings should be used in the end effector mechanisms to ensure that the surfaces do not contact, wear, or generate particles. In some circumstances, mechanisms must be enclosed with seals or bellows. To meet the requirements for Class 1 clean room operation, air bearings may be required. Many manufacturers sell end effectors designed for clean room operation.

A different problem arises in hazardous environments such as in the presence of highly reactive chemicals (e.g., chlorides, fluorides). Here the robot and end effector must be protected. Robot systems must be designed for chemical resistance. If using a custom end effector, component materials should be selected to be as inert as possible based on the chemicals present. Nickel or aluminum alloys, for example, work fairly well with oxidizers such as chlorine, fluorine, or high concentrations of oxygen. In many cases a covering (including a glove for the end effector) with a pressurized gas purge system must be provided to prevent gaseous vapors or aerosols from reacting with the end-effector or robot.

Another robotic environment requiring special treatments is food processing. In food handling tasks, the end effector and robot must be able to be cleaned and sterilized to kill germs and bacteria. High temperature water and disinfectant sprays are commonly used to clean equipment. Non-corrosive materials and sealed electrical connections for wash downs are required.

11.3 Robot Attachment and Payload Capacity

End effectors for general purpose robots are mounted at the end of the robot arm or wrist for articulating arm robots, or at the end of the last affixed stage or motion device for SCARA and Cartesian coordinate robots. Some robots have built-in grippers. Aside from these self-contained mechanisms, end effectors are selected from standard components, a custom design, or most likely a combination of both. End effectors can have multiple tools or grippers, but they must conform to the mounting attachment and payload limits of the individual robot.

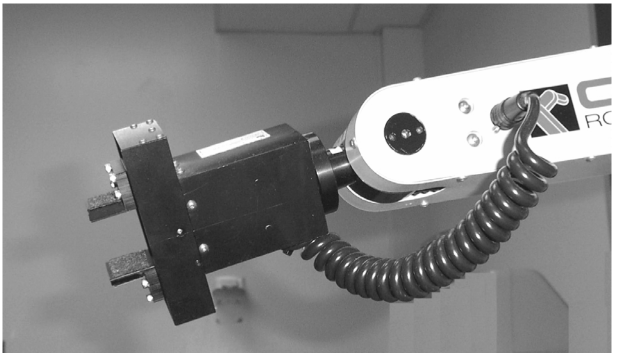

FIGURE 11.2 Robot end effector integrated into arm controller.

11.3.1 Integrated End Effector Attachment

Several types of robots have their end effectors highly integrated into the robot. In specialized applications such as welding, painting, gluing, and plasma cutting, the end effector is essentially a pre-engineered subsystem of the robot. For example, Fanuc offers arc welders as end effectors for their robots, as a complete system. Several smaller robots, such as those used in light manufacturing or bench-top applications, have the basic motion of the end effector built into the robot itself. These integral end effectors are basic gripper designs. The gripper integration feature is seen in robots such as the Microbot Alpha II (Questech, Inc.) and the A465 (Thermo-CRS, Ltd.) (Figure 11.2). The Microbot uses two parallel beam mechanisms for each side of the gripper, as seen in Figure 11.3. The control is provided by springs for opening the grippers and by a motor spooling a lightweight cable to close the grippers. The A654 robot has a servo controlled parallel jaw gripper. Control of the gripper opening is included in the robot controller. Even using the existing mechanisms, custom application jaws for the gripper can be designed and mounted to the gripper base. Note: these robots allow the removal of the standard gripper and provide a mounting base for other end effectors.

11.3.2 Attachment Precision

The attachment of the end effector to the robot must be secure and maintain the desired precision of the robot system. Location and tolerance are extremely critical for maintenance and end effector replacement. Precision dowel pins are used to locate and provide orientation for the end-effector while bolts secure it to the robot. Figure 11.2 and Figure 11.4 show mounting configurations at the end of industrial robot arms. Attachment means vary. Figure 11.2 shows an integral control attachment, while Figure 11.4 depicts an internal passageway provided for power connections.

It is still possible for a replacement end effector to lose positional accuracy, even with previously described design precautions. Thus, calibration of a newly placed end effector is necessary. This can be accomplished

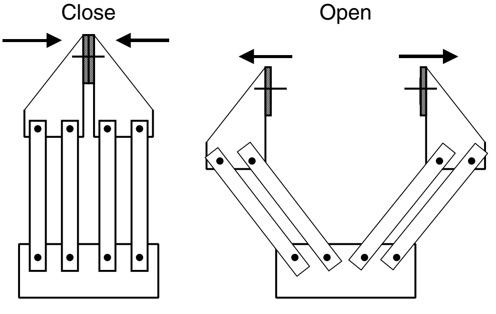

FIGURE 11.3 Four bar linkages gripper arms.

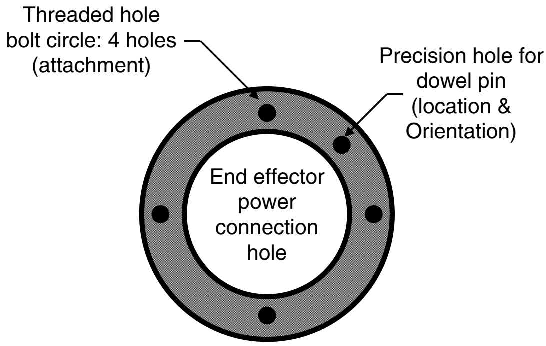

FIGURE 11.4 Typical robot arm end.

in several ways. The most common techniques are to place the robot in teach mode to redefine key geometry locations to hard stop locations, or to have specialized devices with proximity sensors to programmatically locate a position or grasped object. Since all components of a robot and the grasped objects may have varying tolerances, it is better to locate from a grasped artifact of calibrated dimensions, rather than a sample of the actual grasped object, unless the object meets the desired tolerance specifications.

11.3.3 Special End Effector Locations

In grasping large objects such as metal sheets, special attention must be given to the location of grippers (here multiple grippers are used in the end effector). Stability and preventing damage to the sheet are the primary concerns. The reader is referred to Ceglarek et al. [1] for additional information.

11.3.4 Wrist Compliance: Remote Compliance Centers

Robots, workpieces, and fixturing have limited and defined tolerances. Some variation in workpieces or orientation from fixturing may exist. In robotic or automation applications of part insertion into another component or assembly, the use of a remote center compliance device (RCC) (typically wrist mounted) is often required. The RCC allows an assembly robot or machine to compensate for positioning errors (misalignments) during insertion. These position errors are due to machine or workpiece fixturing inaccuracy, vibration, end effector path error, or tolerances. The RCC accomplishes this by lowering contact forces (perpendicular to the axis of insertion) via lower horizontal and rotational stiffnesses while retaining relatively higher axial insertion stiffness. This compliance can reduce or avoid the potential for part, robot, or end effector damage.

A typical remote compliance center design is seen in Figure 11.5. When the remote compliance center is near the contact point, the part will align with the hole automatically; correcting lateral and rotational misalignment. RCC are typically passive mechanical devices with high axial stiffness but low lateral stiffness. Many commercial designs use elastomer shear pads or springs or pneumatic pistons to create the compliance. Other custom designs use a simple beam with greater horizontal than axial compliance (Ciblak [2]). In all cases the RCC has limits on rotational or horizontal misalignments (typically less than $+/-0.25$ in. and $+/-10^\circ$ [3]). Considerations for using an RCC are the added weight of the device and increased moment caused by the additional length of end effector. However, if accounted for properly in design, the RCC is a great aid for speedy part insertion.

11.3.5 Payloads

For all end effector designs the payload capacity of the robot must be carefully considered in the design. Manufacturers specify the payload for each robot. It is important to consider acceleration forces and moments as part of the load, if not already accounted for by the manufacturer.

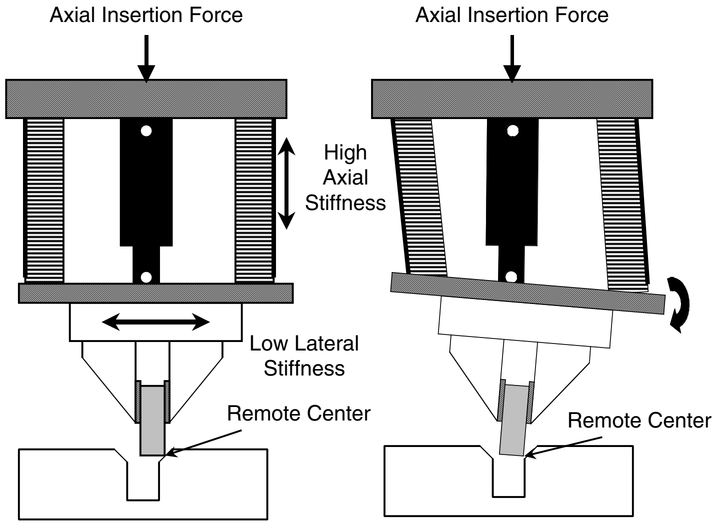

FIGURE 11.5 Remote compliance center device.

Where the end effector is provided or integrated into the robot by the manufacturer, the payload is specified as a weight or mass at a given distance on the gripper jaw of the end effector. These robots have lighter allowable payloads (e.g., 2 kg for the CRS A465 [4]) with the manufacturer provided end effector. If the standard end effector or rigid gripper attachment is replaced with a longer jaw, the allowable payload will be less. This is because a higher torque will be generated at the robot joints.

Most general-purpose, articulating robots have specified the payload capacity in force and moment load limits at the end of arm wrist attachment as well as other joint locations. The load and moment limits must be adhered to when designing the end effector and gripper attachments. In these cases the acceleration of the payload must also be included in addition to gravitational loading. For SCARA or Cartesian coordinate style robots, payload capacity and maximum final joint inertia are sufficient, given the robot kinematics.

11.3.6 Payload Force Analysis

Force calculations for end effector payloads must be determined at all critical locations including the gripper jaws and end of arm payload wrist reactions. Jaw designs and part-grasped orientation must be known or have a bounding estimate. Figure 11.6 and Figure 11.7 depict typical force and moment locations for end of arm geometry. The three-dimensional reaction force and moment at the end of arm location is given in Cartesian coordinates by Equation (11.1) and Equation (11.2). Note that in developing dynamical relationships for control design other coordinate systems, such as a polar or the generalized coordinate methods developed by Kane [5] may be more advantageous.

$$\vec{F}_R = F_X\hat{\imath} + F_Y\hat{\jmath} + F_Z\hat{k} \tag{11.1}$$

$$\vec{M}_R = M_X\hat{\imath} + M_Y\hat{\jmath} + M_Z\hat{k} \tag{11.2}$$

The apparent force of an accelerated, grasped object is determined by application of Newton's Second Law, Equation (11.3). Note: In the configuration examined here, gravity is assumed to be present only in the negative Y-direction. The subscript o denotes parameters associated with the object to be grasped, while the g subscript indicates those parameters associated with the gripper/end effector.

$$\vec{F}_R = (m_g + m_o)(A_X\hat{\imath} + |A_Y + g_Y|\hat{\jmath} + A_Z\hat{k}) \tag{11.3}$$

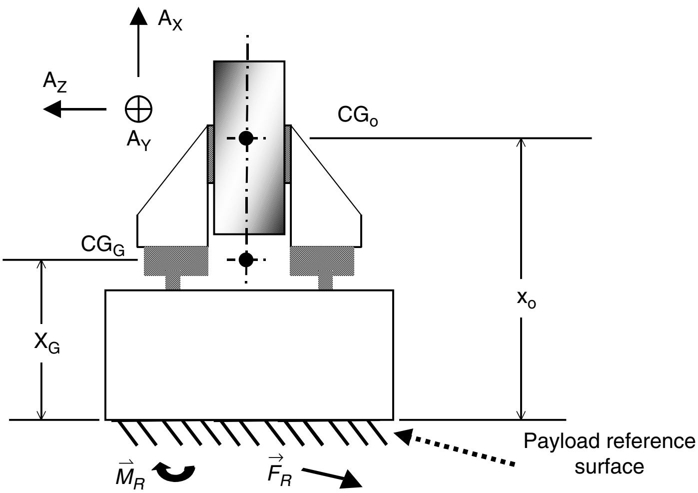

FIGURE 11.6 Payload force and moment: X-Z plane.

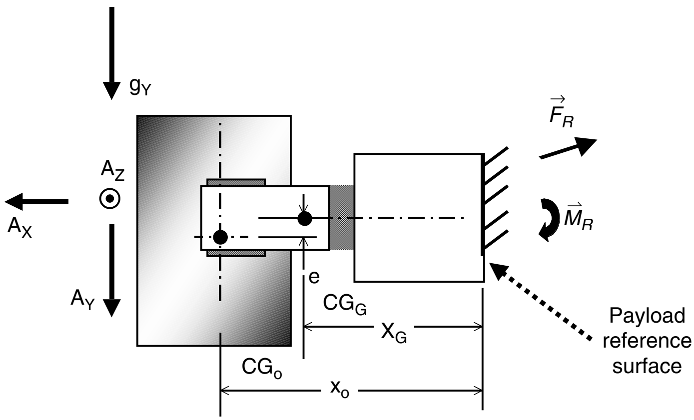

FIGURE 11.7 Payload force and moment: X-Y plane.

Equation (11.4) is the apparent moment at the end effector attachment for a object grasped as shown in Figure 11.6 and Figure 11.7, where the objects center of mass is located at the same X and Z coordinates as the gripper's center of mass. In this instance the centers of mass in the Y-direction are not coincident.

$$\vec{M}_R = \sum \vec{r} \times \vec{F} \tag{11.4}$$

$$\vec{M}_R = (x_g\hat{i}) \times m_g(A_X\hat{i} + |A_Y + g_Y|\hat{j} + A_Z\hat{k}) + (x_o\hat{i} + e\hat{j}) \times m_o(A_X\hat{i} + |A_Y + g_Y|\hat{j} + A_Z\hat{k}) \tag{11.5}$$

As can be seen from the equations the acceleration components may be more significant than the gravitational force alone.

11.4 Power Sources

Power sources for end effectors are generally electrical, pneumatic, vacuum, or hydraulic. Many robots have internal routings for a variety power and control options for end effectors. Common power sources and actuators are discussed with their application advantages.

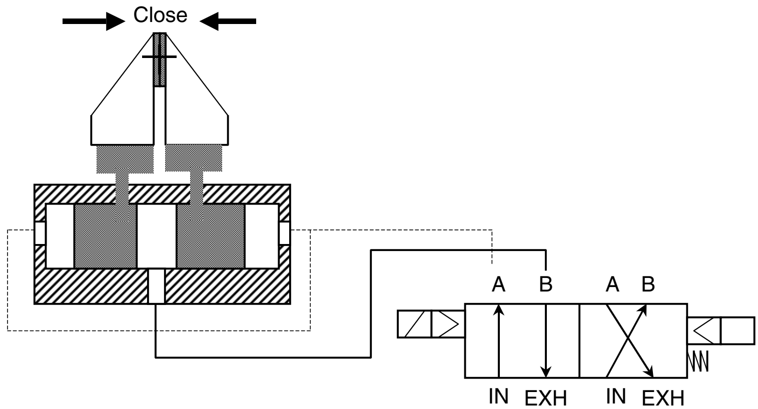

FIGURE 11.8 Pneumatic valve connections for safety.

11.4.1 Compressed Air

The most common end effector power source is compressed air. Compressed air is reliable, Readily available in most industrial settings, and can be adjusted to preset gripper clamping force. Pneumatic grippers and associated valve and piping components can be lightweight, low cost, and safe when designed properly. A variety of pneumatic grippers can be purchased from industrial manufacturers.

When using a pneumatically operated end effector, caution should be taken in the selection of the pneumatic valve connections so that that the gripper will retain a held object if electric power is interrupted. Pneumatic solenoid valves activate air operated grippers and have both normally open or normally closed valve ports. The normally open valve port of the valve should be used to supply air to close the gripper. Figure 11.8 shows a typical connection using a four-way valve. This will help prevent a held object from being released unintentionally, in the case of interrupted electric power. Compressed air supply is less susceptible to interruptions than electric power. Note that three-way solenoid valves may be used if the pneumatic cylinder has a spring return for opening. For added safety, use four-way solenoid valves with dual operators; thus, both the exhaust and supply will be isolated in the event of a power failure. If using pneumatic speed adjustments, they should be placed on the exhaust side of the air cylinder to allow full flow into the cylinder.

For clean room operation, the compressed air exhausts from the gripper air cylinder should be ported away from the clean room. However, if a clean, dry air source is used in an application, the exhausts can be released into the clean room if necessary. Care must be taken to use non-lubricated seals in the pneumatic cylinder, as there is no oil mist in a clean dry air supply.

11.4.2 Vacuum

Vacuum suction devices are used in many instances for lifting objects that have a smooth relatively flat surface. The vacuum either is obtained from a vacuum pump or, in most cases, is generated from compressed air blowing across a venturi. Using compressed air is the common and least expensive approach. Many commercial sources of these devices are available.

11.4.3 Hydraulic Fluid Power

In heavy lifting operations, hydraulic fluid is used to obtain higher pressures and resulting higher gripping forces than could be attained with compressed air. Many gripper devices are available as either pneumatic or hydraulic power equipped.

11.4.4 Electrical Power

Electrical devices can be heavy (electromagnets, DC motors, solenoids), limiting their use in end effectors of lighter payload robot arms. Many new end effectors are commercially available with electric motor actuation. Typically DC servomotors are used with electric power application. To reduce payload weight, lightweight and high strength cables can be used to connect the gripper mechanism to the drive motor remote from the wrist. For limited gripping force applications, stepper motor actuation is available.

For lifting of ferrous materials, electomagnets are potential end effector alternatives. This is a relatively simple design but has a high weight. Positional accuracy is also limited.

11.4.5 Other Actuators

While most industrial applications can adequately power end effectors with standard actuators, special applications and university research are exploring other novel power devices. Among the latest actuators are piezoelectrics, magnetostrictive materials, and shape memory alloys.

For high precision with nanoscale displacements, piezoelectric drives are of primary use. These high stiffness actuators change shape with a charge applied. Magnetostrictive actuators provide a similar scale and precision movement. Magnetostrictive materials, such as Terfenol-D, displace when a magnetic field is applied. Both types of actuators are commercially available.

A promising device under current study is shape memory metal alloys (Yang and Gu [6]). Controlled electrical heating is used to change shape between crystalline phases of alloys such as nickel-titanium. These actuator designs have a weight-to-strength ratio advantage over other alternative actuator strategies but are not commercially available.

11.5 Gripper Kinematics

Grippers are a basic element of end effectors. The geometric motion and kinematics of the end effector gripper are of great importance in the design of the gripper attachments, motion, object spacing, and auxiliary tooling. The design of end effectors or simple grippers is infinite. However, there are several simple functional kinematic designs widely used as gripper mechanisms. The majority of these designs have planar motion.

11.5.1 Parallel Axis/Linear Motion Jaws

The most common gripper design is a parallel axis design where two opposing parallel jaws (or fingers) move either toward or away from each other (Figure 11.9). Linear motion slides or slots are used to keep both gripper attachments parallel and collinear. This form of gripper is readily designed using a pneumatic cylinder as power for each jaw. For successful object centered grasping, it is important that the mechanism constrains the jaw movements to be synchronized. Otherwise the object may be pushed out of the grasp by

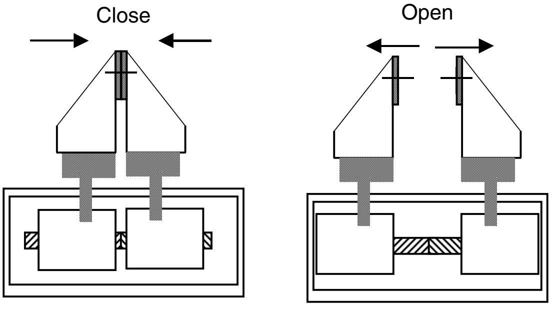

FIGURE 11.9 Parallel axes/linear jaws.

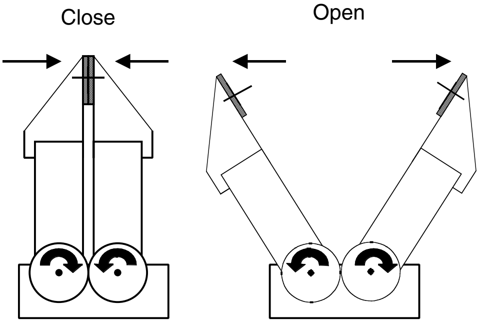

FIGURE 11.10 Rotating axes/pivoting jaws.

one jaw. An advantage of this style of gripper is that the center of the jaws does not move perpendicular to the axis of motion. Thus, once the gripper is centered on the object, it remains centered while the jaws close.

11.5.2 Pivoting/Rotary Action Jaws

Another basic gripper design is the pivoting or rotating jaws mechanism of Figure 11.10. Again this design is well suited to pneumatic cylinder power (Figure 11.11). Symmetric links to a center air cylinder or a rack with two pinions or two links may be used. While this design is simple and only requires one power source for activation, it has several disadvantages including jaws that are not parallel and a changing center of grasp while closing.

11.5.3 Four-Bar Linkage Jaws

A common integrated gripper design is a four-bar linkage, as previously depicted in Figure 11.3. Each jaw is a four-bar linkage that maintains the opposing jaws parallel while closing. A disadvantage of this design is the changing center of grasp while closing the jaws. Moving the robot end effector while closing will compensate for this problem. This requires more complicated and coordinated motions. A cable-linked mechanism allows one source of power to supply motion to both jaws. An implementation of this design is the Microbot Alpha II.

11.5.4 Multiple Jaw/Chuck Style

When objects are rod-like and can be grasped on an end, a chuck-style gripper with multiple jaws (typically three or four) can be used. Gripper jaws operated similarly to a machine tool multi-jaw chuck as seen in

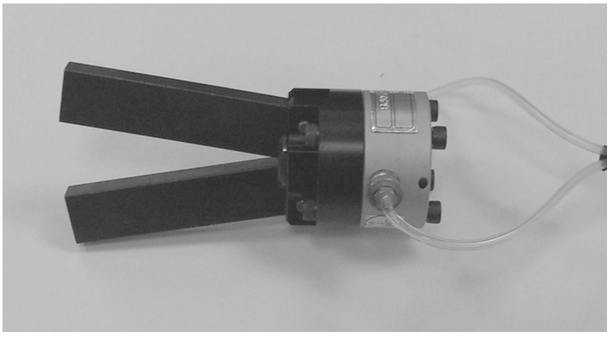

FIGURE 11.11 Rotating axes pneumatic gripper.

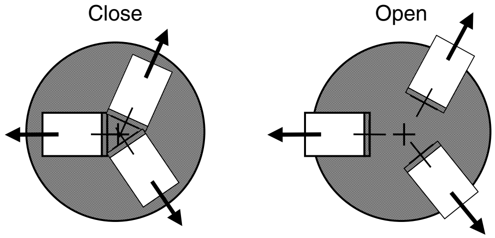

FIGURE 11.12 Multi-jaw chuck axes.

Figure 11.12. These devices are more complicated and heavier, but they can provide a significantly stronger grip on a rod-like object. Drawbacks to these multi-jaw designs are heavier weight and limited application.

11.5.5 Articulating Fingers

The current state-of-the-art design in robotic end effectors is the articulating fingered hand. The goal of these designs is to mimic human grasping and dexterous manipulation. These types of end effectors allow three-dimensional grasping. A minimum of three fingers is required to grasp in this manner. A distinct advantage of this design is the potential to grasp irregular and unknown objects [7]. These anthropomorphic end effectors require force sensing and significant computer control to operate effectively. Currently, the application of articulating fingers as end effector is limited. There are no commercially available end effectors of this type.

However, these designs remain an active university research area. Recent research on articulating finger grasping includes finger-tip force control mechanical drives mimicking tendons with Utah/MIT Dexterous Hand Project. Universities are exploring many new avenues of these end effectors [8–14].

11.5.6 Multi-Component End Effectors

In some industrial situations, it is desirable to have more than one type of grasping device on an end effector. A typical situation is in sheet metal fabrication. Thin sheets of sheet metal must be lifted from stacks or conveyors. Vacuum suction cups are used to lift and relocate the flat sheets, while mechanical grippers then provide the grasping for bending operations (Figure 11.19).

11.6 Grasping Modes, Forces, and Stability

11.6.1 Grasping Stability

Robotic grasping has been the topic of numerous research efforts. This is best summarized by Bicchi and Kumar [15]. Stable object grasping is the primary goal of gripper design. The most secure grasp is to enclose the gripper jaws or finger around the center of gravity of the object.

Six basic grasping patterns for human hands have been identified by Taylor and Schwarz [16] in the study of artificial limbs. Six grasping forms of (1) spherical, (2) cylindrical, (3) hook, (4) lateral, (5) palmar, and (6) tip are identified in Figure 11.13. For conventional two-dimensional grippers described in the previous sections, only the cylindrical, hook, and lateral grips apply. To securely grasp an object the cylindrical and lateral grips are effective for plane motion grippers. The two-jaw mechanisms of most end effectors/grippers most closely approximate the cylindrical grasp.

Kaneko [9] also discusses stability of grasps for articulating multi-fingered robots. Envelop or spherical grasping is the most robust, as it has a greater number of contact points for an object that is enclosed by articulating fingers.

For plane-motion grippers using a cylindrical style of grasp, stability can be similarly defined. Stability increases as the object has more points of contact on the gripper jaws and when the object's center of

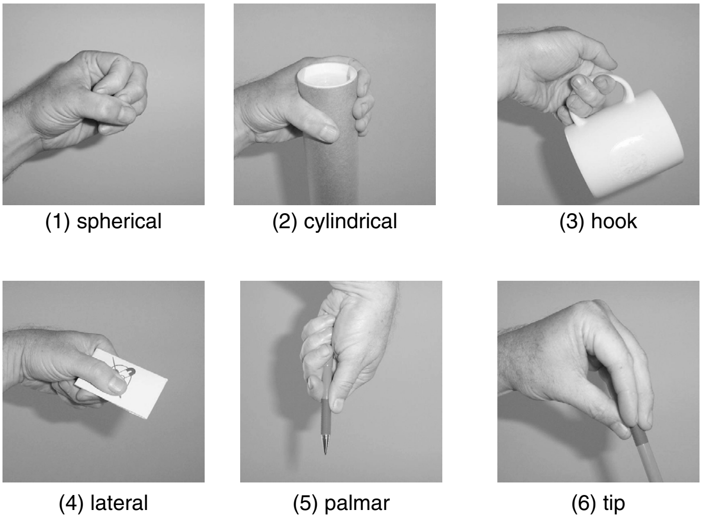

FIGURE 11.13 Grasp types for human hands.

gravity is most closely centered within the grasp. When using a cylindrical grip, it is desirable to grasp an object in a safe, non-slip manner if possible. For example, when grasping a cylindrical object with a flange, the jaws of the gripper should be just below the flange. This allows the flange to contact the top of the gripper jaws, to remove any possibility of slipping. If a vertical contact feature is not available, then a frictional grip must be used.

11.6.2 Friction and Grasping Forces

While a slip-proof grasp previously described is preferred for end effectors, in the majority of cases a frictional grip is all that can be attained. When designed properly, the frictional grip is very successful. Friction forces can be visualized on a gripper jaw in Figure 11.14. It is desirable to have the center of gravity for grasped objects and end effector coincident in the Z-direction, to not have moments at the jaw surfaces. To successfully grasp an object the applied gripping frictional force on each jaw of a two-jaw gripper must be equal to or greater than the half the vertical weight and acceleration payload, as defined by Equation (11.6). From this the applied gripping normal force is found by dividing the required friction force by the static coefficient of friction. Typically a factor of safety is applied [17].

$$F_{friction} = \mu F_{grip} \geq \frac{(1 + A_{vert}/g)w}{2} \tag{11.6}$$

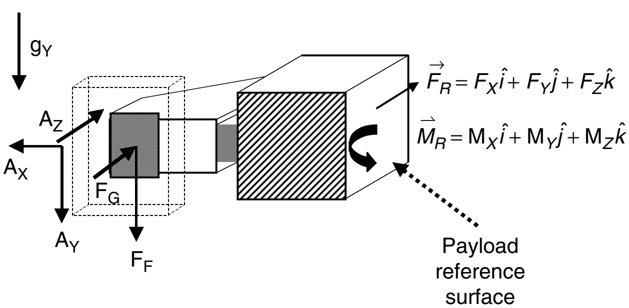

FIGURE 11.14 Gripper forces and moments.

Friction coefficients are a function of materials and surface geometries. Estimates can be found using standard references. Typically most surfaces will have a static coefficient of friction greater than 0.2. For metal to metal contacts, the static coefficient of friction is much higher (e.g., aluminum to mild steel has 0.6 and mild steel to hard steel has 0.78) [18].

In addition to an object's weight, surface texture, rigidity, and potential damage must also be considered in the selection or design of an end effector or the gripper. Pads are used on the jaws of the end effector to prevent surface damage to the object. Pads can also be used to increase the coefficient of friction between the object and the gripper jaws.

11.7 Design Guidelines for Grippers and Jaws

11.7.1 Gripper and Jaw Design Geometry

Gripper jaw design is best done graphically using computer aided design and drafting tools. The footprint of the gripper must be examined to determine how to approach an object and grasp it. Typically footprint is thought of in terms of only the vertical projection of the gripper. However, grasping is a three-dimensional issue, especially in a dense object environment. Gripper motion, either opening or closing, should be free of interferences from an adjacent object or a geometric feature of the grasped object. Smaller jaw footprints are more desirable for denser spacing of objects.

For example, a gripper designed to grasp a flanged object may require additional opening of the gripper as the end effector passes over the flange of the object. This may push neighboring parts out of the way of the object. Spacing of objects may need to be adjusted if possible.

Much has been said already on design considerations for end effectors. Causey and Quinn [19] have provided an excellent reference for design guidelines for grippers in modular manufacturing. Others [20] have also contributed to important design parameters for end effectors. Application of these general design considerations should result in a more robust and successful gripper design. A summary of general design guidelines for end effectors grippers follows.

11.7.2 Gripper Design Procedure

1. Determine objects, spacing, orientation, and weights for grasping. While objects are predetermined, based on the task to be accomplished, spacing and orientation may be adjustable. Note: All the grasping surfaces, support ledges, and other graspable features of each object must be identified.
2. Determine roughly how each object will be grasped (i.e., from top, from side, gripper opening), based on part geometry and presentation. If part presentation (orientation and spacing) is variable, choose the most stable grasp orientation, with the widest spacing around the object.
3. Calculate end effector payload reactions; estimate accelerations on controller information if none are specified. Establish necessary and safe grasping forces not to damage the object. Account for friction in frictional grasps.
4. Make preliminary selection of the gripper device based on weight and system design parameters.
5. Determine gripper maximum variable or fixed stroke. This may be a preliminary number if a variety of strokes is available. A trade-off between stroke and the physical dimensions and weight exists, so the minimum acceptable stroke is generally the best.
6. Design grippers to allow grasping of all objects. Objects must be grasped securely. Multiple grippers may be required to an individual end effector.
7. The grasp center of each gripper mechanism should be at the object center of gravity whenever possible. Also, keep the jaw lengths as short as possible and the grasp center close to robot wrist to minimize moment loading and to maximize stiffness.
8. Jaws must work reliably with the specific parts to being grasped and moved. The jaws should be self-centering to align parts, if desired. Ideally the jaws should conform to the surface of the held part. At a minimum, three-point or four-point contact is required. V-groove styles are often used

to accomplish this feature. It is also good practice to have chamfered edges on grippers to more closely match the part geometry and allow for greater clearance when grasping.

9. Determine the footprint of objects and presentation spacing with the gripper jaw design. Horizontal and vertical footprints must be checked with grippers open and closed so that there is no interference with other parts or features of the part being grasped. Minimize footprint of the gripper jaws.
10. Revise payload reaction calculations. To minimize gripper weight to reduce the payload, lightening holes are often added.
11. Gripper stiffness and strength must also be evaluated prior to completing the design. Note: Low end effector stiffness can cause positioning errors.
12. Iteration on the jaw design and part presentation may be necessary to converge on a good design.

11.7.3 Gripper Design: Case Study

The selection and design of an end effector for a small flexible automation system is worked through as an example. The objects to be grasped are cylindrical and have diameters of 6, 50, and 90 mm, with masses of 0.20 kg, 0.100 kg, and 0.350 kg, respectively. Surfaces of the objects are glass and the end effector was specified as aluminum. The objects must be presented on end, and the 90 mm object has a 100 mm top circular flange. The robot selected for the application has a payload capacity at the arm end of 3 kg, a maximum allowable attached inertia of $0.03 \text{ kg} \cdot \text{m}^2$, and a maximum moment of $2.94 \text{ N} \cdot \text{m}$ [21].

For ease in grasp centering, a parallel gripper mechanism is selected for the design. While gripper jaw designs are infinite, two basic jaw designs evolved using footprints of the grasped objects: a single gripper jaw using a 70 mm minimum stroke or dual-jaw design with a 25 mm minimum stroke. Figure 11.15 and Figure 11.16 show the vertical footprints of jaw designs with the objects. Note the chamfering of the jaws to conform to the cylinders. Also notice the use of V-grooves for grasping the small cylinder. The dual jaw design requires a wrist rotation of 180° when alternating between object grasping and limits entry and exit ease of grasped objects. The longer stroke single jaw design has a higher payload moment. In this case the longer stroke is preferred for simplicity if the allowable payload is not exceeded. A three-dimensional rendering (Figure 11.17) shows an offset is needed near the gripper attachment point to prevent gripper interference while grasping under the object's flange. For strength and weight considerations, aluminum (e.g., 6061T6, 6063T6, or 5052H32) would be a good candidate material.

A standard industrial pneumatic gripper with parallel motion is commercially available with a total stroke of 90 mm. The cylinder bore is 14 mm. The total gripper mass (m_g) is 0.67 kg, without jaws. The gripper body center of gravity (X_g) is 17 mm from the attachment side. Each of 3 mm thick aluminum jaws weighs 40 g. The mass of the jaws will be lumped with the object as a conservative approximation. The

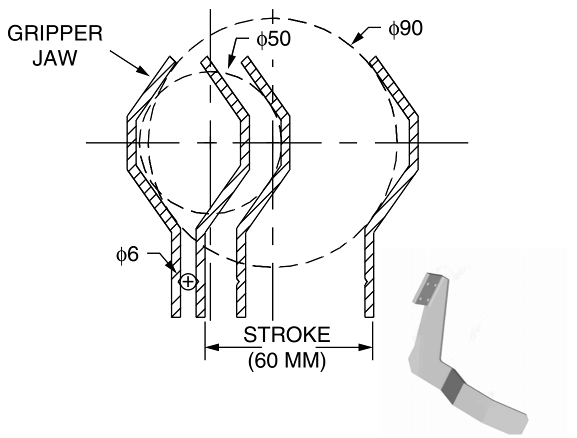

FIGURE 11.15 Single jaw gripper design.

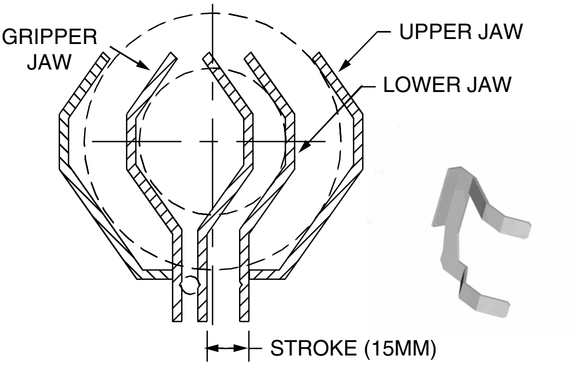

FIGURE 11.16 Multi-jaw gripper design.

total weight of the heaviest object plus jaws (m_o) is 0.43 kg, at location (X_o) of 96 mm from the end of arm attachment (refer to Figure 11.6 and Figure 11.7). The reaction forces and moments can be determined for robot limits load and deflection analysis using Equation (11.3) and Equation (11.5), after establishing acceleration limits.

Using 1g accelerations in all directions plus y-axis gravitational acceleration, reactions are evaluated. The maximum resulting magnitudes of force and moment are 26.4 N (2.69 kg equivalent static mass) and 1.34 N · m. Both are within the specified arm limitations of 3 kg and 2.94 N · m. A finite element analysis indicates the maximum loading; maximum stresses are less than 4% of material elastic yield. Deflections are under 0.010 mm for this loading, indicating a sufficient stiffness.

Frictional considerations may require jaw pads as the objects grasped are glass, and the gripper jaws will be anodized aluminum. Coefficient of friction is estimated at 0.20 between glass and various metals, while it is approximately 0.9 between rubber and glass. A vector magnitude of a 2 g vertical acceleration (including gravity) and 1 g horizontal acceleration on the 0.35 kg payload will cause a frictional force of slightly less than 3 N per gripper jaw, using Equation (11.6). With a 0.2 coefficient of friction and a factor of safety of 2, a minimum gripper pressure of 2 bar is required. Since this pressure is less than the readily available supply of air pressure of 6 bar, friction pads on the gripper are not required. The end effector with gripper jaw mechanical design is complete.

11.7.4 Gripper Jaw Design Algorithms

As indicated by the previous, most gripper jaw designs are ad hoc and follow rules of thumb. There is current research focusing on optimizing jaw features. A common problem is the orienting and fixturing of grasped parts. Typically parts are oriented for the end effector to grasp. Some part alignment can be accomplished for simple shapes such as cylinders and cubes.

FIGURE 11.17 Jaw with grasped object.

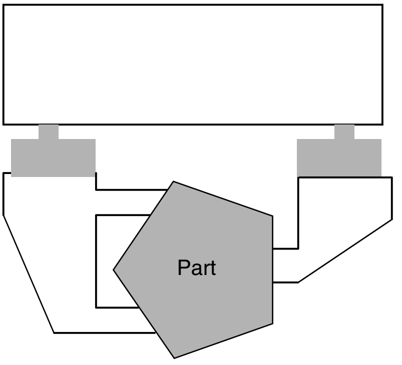

FIGURE 11.18 Part orienting gripper design.

Special algorithms have been developed for use with parallel axis grippers (the most common) to design trapezoid jaw shapes that will orient multi-sided parts for assembly (Zhang and Goldberg [22]). It has been shown that the jaw shapes need not be solid or continuous. In fact smaller contact areas are of value to allow parts to topple, slide, and rotate into alignment while being grasped. Figure 11.18 shows a simple example of this technique to orient parts. A limitation of this design procedure is that the gripper is optimized for one particular part geometry.

11.7.5 Interchangeable End Effectors

In many situations it is not feasible for a single end-effector or gripper to grasp all the objects necessary. An option is the use of interchangeable end effectors. While this will simplify the task performance, additional design constraints are placed on the system.

Key design considerations in developing interchangeable end effectors are attachment means, registration of connection points from the robot to the end effector, ease of change, and security of the tool connection. The system base is a coupling plate attached to the end of the arm and mating tool plates integrated into tools/end effectors. The most important feature of a design is the secure and fail-safe mounting of the end effector [23].

The additional end effectors require locating fixtures that occupy some of the robot work envelope. Aside from increased cost, the interchangeable end effectors also reduce repeatability, graspable payload, and range of movements. The flexibility of the additional end effectors can require significant hardware, engineering and programming costs. However, this option is significantly less expensive than purchasing an additional robot. The decision to use interchangeable end effectors must be carefully weighed.

If the decision to use interchangeable end effectors is made, it is important to note that systems are commercially available for robots.

11.7.6 Special Purpose End Effectors/Complementary Tools

Complementary tools can augment the usability of end effectors. These tools can assist in the dispensing or transfer of liquids or in the pick up of objects not easily grasped by fixed grippers. Tools can ease the constraints on end effectors. The shape of the tool handle will have a grasping center similar to the other grasped objects. The tools add function to the effector. Each tool will require a storing and locating rack. Festoon cable systems and constant force reel springs on overhead gantries are sometimes necessary to reduce weight and forces of the tool and attachments to not exceed the robot payload limits.

Tools will depend on the task to be performed. Some of the more common special purpose tools are liquid transfer tools including pipettes and dispensers, vacuum pick-ups, and electromagnets. Examples of vacuum and pipette tools are shown with their location rack in Figure 11.19. These tool elements can be off-the-shelf items with custom grips, such as the vacuum pick-up tool.

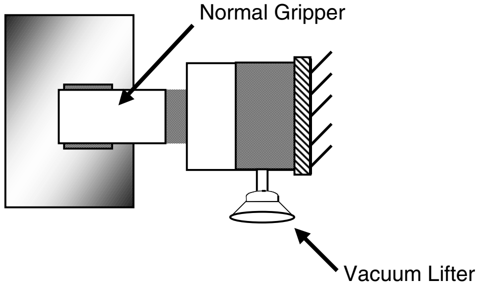

FIGURE 11.19 Multi-tool end effector.

11.8 Sensors and Control Considerations

A variety of sensors is available for inclusion in end effectors. The most common sensors employed in end effectors measure proximity, collision, and force.

11.8.1 Proximity Sensors

Through beam and reflective optical proximity sensors are widely used to verify the grasping of an object. Typically the sensors are used as presence indicators. The weight of the sensor on the end effector should be minimized because of payload considerations. Most optical proximity sensors are available with an optical fiber end connection so that sensor electronics will not necessarily be located on the end effector. Place as much sensor hardware as possible remote to the end effector. Grippers may be designed with built-in limit switches for grasping fixed dimensional objects. A common implementation of this is the use of Hall effect or reed switches with air cylinder pistons.

Inductive and capacitive proximity sensors may be used with compatible object materials such as carbon steels. Materials such as stainless steel, aluminum, brass, and copper may also be sensed but at a reduced detection distance.

If a non-contact distance measurement is required rather than a presence verification, laser diode-based analog sensors or a machine vision sensor can be used. For extremely close-range and precise measurements (such as part dimensional measurements) eddy current sensors may be used on metallic components.

11.8.2 Collision Sensors

Although compliance centers (discussed earlier) help align parts, ease assembly, and reduce potential damage, damage may still occur because of design limits (angle and position tolerances, as specified by manufacturers or design). Thus, a collision detection sensor can be a good end effector component to mitigate damage to the robot, inserted part, or workpiece where the part is being attached. Collision detection sensors detect the first onset of a collision in all directions. After detecting the start of a collision, the robot can be stopped or backed away before damage has occurred. (Note that while proximity sensors can also be used as collision avoidance devices, most are unidirectional with a limited field of view.) Collision detection devices are usually attached at the end of arm before the end effector.

There are several types of collision detection sensors available for wrist mounting. These include force sensors as an active control device. Force sensors are primarily strain gauge devices and require additional programming for monitoring and control.

Specific collision detection sensors are readily available in the market place. These are passive devices. Some utilize compressed air for variability of fault loading in three-dimensional space. Other collision sensor designs are based on mechanical springs at preset loads. Both types indicate a collision by the opening of a normally closed switch. This design can be hardwired into the E-stop circuit for safety or be wired to a digital input for programmatic monitoring.

11.8.3 Tactile Feedback/Force Sensing

Force sensing during grasping is important for successful grasping of varying parts, compliant part, and for reduction of part deformation. In the past strain gauge sensors were the primary device used. These, however, are of limited use in the multiple-point force sensing. Piezoelectric force sensors are also available but are better for measuring dynamic loads because of charge leakage.

Piezoresistor force sensors can be used for tactile force sensing using the principle that the resistance of silicon-implanted piezoresistors will increase when the resistors flex under any applied force. The sensor concentrates the applied force through a stainless steel plunger directly onto the silicon sensing element. The amount of resistance changes in proportion to the amount of force being applied. This change in circuit resistance results in a corresponding mV output level.

A relatively new development is the commercial availability of force sensing resistors (FSR). The FSR is a polymer thick film (0.20 to 1.25 mm PTF) device which produces a decrease in resistance with any increase in force applied to its surface. Although FSRs have properties similar to load cells, they are not well suited for precision measurement equipment (variation of force from grasping can be on the order of 10%). Its force sensitivity is optimized for use in human touch control switches of electronic devices with pressure sensitivity in the range of 0.5 to 150 psi (0.03 to 10 kg/cm^2) [24].

In general, the FSR's resistance vs. force curve approximately follows a power-law relationship (resistance decreasing with force). At the low force end of the force-resistance characteristic, a step response is evident. At this threshold force, the resistance drops substantially. At the high force end of the sensor range, the resistance deviates from the power-law behavior and ultimately levels to an output voltage saturation point. Between these extremes is a limited but usable region of a fairly linear response. The relatively low cost, small thickness, and reasonable accuracy make these sensors attractive for multi-sensor tactile control.

11.8.4 Acceleration Control for Payload Limits

Another important control aspect is the force caused during acceleration. Thus, the accelerations of the joints must be known and prescribed (or carefully estimated). In most instances the acceleration limits on each joint are known. Typically accelerations are defined by S-curves for velocity, with maximum accelerations limits.

11.8.5 Tactile Force Control

Traditional position and velocity control for trajectories are obviously important for painting, welding, and deburing robots. However, to create quality products, it is also necessary to have force control for material removal operations such as grinding and deburing. In these situation the compliance of the robot, end effector, and tool make up total compliance (flexibility). When a tool is moved against an object, the inverse of this compliance (stiffness) creates a force. To assure that dimensional accuracy is maintained, an additional position measurement of the tool tip must be made or position must be taken into account by the use of a compliance model. The stiffness of each joint is easily determined. However, each unique position of the joints creates a unique stiffness.

Generally fixed-gain controllers (such as PID-type controllers) are preferred for force applications because of their simplicity in implementation. These controllers are easily tuned using standard approaches.

Tuning the force control loop is best done using position control and the effective stiffness from the end effector-workpiece interaction. Many industrial controllers provide utilities for automatic tuning of position loops. Many are based on the Ziegler-Nichols PID tuning [25] or other heuristic techniques. Although this technique is based on continuous systems for very fast sampling rates (greater than 20 times the desire bandwidth), the results also apply well to discrete systems.

11.9 Conclusion

From the preceding text it is clear that the design, selection, control, and successful implementation of a robotic system relies heavily on the end effector subsystem. End effector designs and technology continue to evolve with new actuators, sensors, and devices.

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