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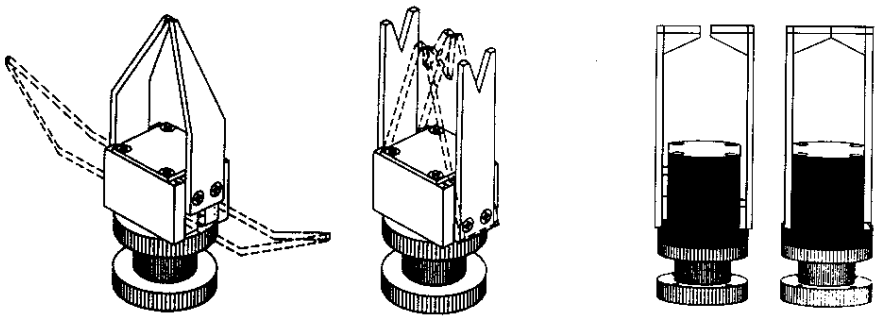
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33.6 End Effectors and End-of-Arm Tooling

End effectors and end-of-arm tooling are the devices through which the robot manipulator interacts with the world around it, grasping and manipulating parts, inspecting surfaces, and so on [Wright and Cutkosky 1985]. End effectors should not be considered as accessories, but as a major component in any workcell; proper selection and/or design of end effectors can make the difference between success and failure in many process applications, particularly when one includes reliability, efficiency, and economic factors. End effectors consist of the *fingers*, the *gripper*, and the *wrist*. They can be either standard commercially available mechanisms or specially designed tools, or can be complex systems in themselves (e.g., welding tools or dextrous hands). Sensors can be incorporated in the fingers, the gripper mechanism, or the wrist mechanism. All end effectors, end-of-arm tooling, and supply hoses and cables (electrical, pneumatic, etc.) must be taken into account when considering the manipulator payload weight limits of the manufacturer.

Part Fixtures and Robot Tooling

In most applications the end effector design problem should not be decoupled from the part fixturing design problem. One should consider the wrist, gripper, fingers, and part fixturing as a *single system*. Integrated design can often yield innovative solutions to otherwise intractable problems; nonintegrated design can often lead to unforseen problems and unexpected failure modes. Coordinated design of fixtures and end effectors can often avoid the use of high-level expensive sensors (e.g., vision) and/or complex feedback control systems that required overall coordinated control of the robot arm motion, the gripper action, and the part pose. An ideal example of a device that allows simplified control strategies is the **remote-center-of-compliance (RCC)** wrist in Fig. 33.17(b), if correctly used.



(a) (b)

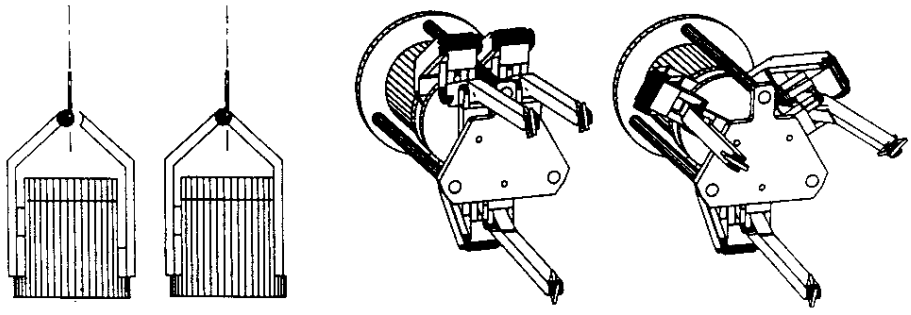
FIGURE 33.15 Angular and parallel motion robot grippers: (a) angular motion gripper and (b) parallel motion gripper, open and closed. (*Source:* Courtesy of Robo-Tech Systems, Gastonia, NC. With permission.)

Grippers and Fingers

Commercial catalogs usually allow one to purchase end effector components separately, including fingers, grippers, and wrists. Grippers can be actuated either pneumatically or using servomotors. Pneumatic actuation is usually either open or closed, corresponding to a binary command to turn the air pressure either off or on. Grippers often lock into place when the fingers are closed to offer failsafe action if air pressure fails. Servomotors often require analog commands and are used when finer gripper control is required. Available gripping forces span a wide range up to several hundred pounds force.

Gripper Mechanisms. *Angular motion grippers*, see Fig. 33.15(a), are inexpensive devices allowing grasping of parts either externally or internally (e.g., fingers insert into a tube and gripper presses them outward). The fingers can often open or close by 90°. These devices are useful for simple pick-and-place operations. In electronic assembly or tasks where precise part location is needed, it is often necessary to use *parallel grippers*, see Fig. 33.15(b), where the finger actuation affords exactly parallel closing motion. Parallel grippers generally have a far smaller range of fingertip motion that angular grippers (e.g., less than 1 in). In some cases, such as electronic assembly of parts positioned by wires, one requires *center seeking grippers*, see Fig. 33.16(a), where the fingers are closed until one finger contacts the part, then that finger stops and the other finger closes until the part is grasped.

There are available many grippers with advanced special-purpose mechanisms, including Robo-Tech's Versagrip III shown in Fig. 33.16(b), a 3-fingered gripper whose fingers can be rotated about a longitudinal



(a) (b)

FIGURE 33.16 Robot grippers: (a) center seeking gripper showing part contact by first finger and final closure by second finger and (b) Versagrip III adjustable three-finger gripper. (*Source:* Courtesy of Robo-Tech Systems, Gastonia, NC. With permission.)

axis to offer a wide variety of 3-fingered grasps depending on the application and part geometry. Finger rotation is affected using a fine motion servomotor that can be adjusted as the robot arm moves.

The gripper and/or finger tips can have a wide variety of sensors including binary part presence detectors, binary closure detectors, analog finger position sensors, contact force sensors, temperature sensors, and so on (section 33.7).

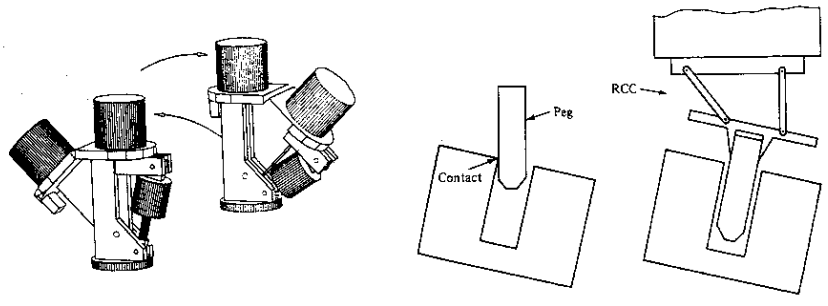
The Grasping Problem and Fingers. The study of the *multifinger grasping problem* is a highly technical area using mathematical and mechanical engineering analysis techniques such as rolling/slipping concepts, friction studies, force balance and center of gravity studies, etc. [Pertin-Trocaz 1989] These ideas may be used to determine the required gripper mechanisms, number of fingers, and finger shapes for a specific application. Fingers are usually specially designed for particular applications, and may be custom ordered from end-effector supply houses. Improper design and selection of fingers can doom to failure an application of an expensive robotic system. By contrast, innovative finger and contact tip designs can solve difficult manipulation and grasping problems and greatly increase automation reliability, efficiency, and economic return.

Fingers should not be thought of as being restricted to anthropomorphic forms. They can have vacuum contact tips for grasping smooth fragile surfaces (e.g., auto windshields), electromagnetic tips for handling small ferrous parts, compliant bladders or wraparound air bladders for odd-shaped or slippery parts, Bernoulli effect suction for thin fragile silicon wafers, or membranes covering a powder to distribute contact forces for irregular soft fragile parts [Wright and Cutkosky 1985].

Multipurpose grippers are advantageous in that a single end effector can perform multiple tasks. Some multipurpose devices are commercially available; they are generally expensive. The ideal multipurpose end effector is the *anthropomorphic dextrous hand.* Several dextrous robot hands are now available and afford potential applications in processes requiring active manipulation of parts or handling of many sorts of tooling. Currently, they are generally restricted to research laboratories since the problems associated with their expense, control, and coordination are not yet completely and reliably solved.

Robot Wrist Mechanisms

Wrist mechanisms couple the gripper to the robot arm, and can perform many functions. Commercial *adapter plates* allow wrists to be mounted to any commercially available robot arm. As an alternative to expensive multipurpose grippers, *quick change wrists* allow end effectors to be changed quickly during an application, and include quick disconnect couplings for mechanical, electrical, pneumatic and other connections. Using a quick change wrist, required tools can be selected from a magazine of available tools/end effectors located at the workcell. If fewer tools are needed, an alternative is provided by inexpensive *pivot gripper wrists*, such as the 2-gripper-pivot device shown in Fig. 33.17(a), which allows one of two grippers



(a) (b)

FIGURE 33.17 Robot wrists. (a) Pivot gripper wrist. (*Source:* Courtesy of Robo-Tech Systems, Gastonia, NC. With permission.) (b) Remote-center-of-compliance (RCC) wrist. (*Source:* Courtesy of Lord Corporation, Erie, PA. With permission.)

to be rotated into play. With this device, one gripper can unload a machine while the second gripper subsequently loads a new blank into the machine. Other *rotary gripper wrists* allow one of several (up to six or more) grippers to be rotated into play. With these wrists, the grippers are mounted in parallel and rotate much like the chamber of an old-fashioned western Colt 45 revolver; they are suitable if the grippers will not physically interfere with each other in such a parallel configuration.

Safety wrists automatically deflect, sending a fault signal to the machine or job coordinator, if the end-of-arm tooling collides with a rigid obstacle. They may be reset automatically when the obstacle is removed.

Part positioning errors frequently occur due to robot end effector positioning errors, part variations, machine location errors, or manipulator repeatibility errors. It is unreasonable and expensive to require the robot joint controller to compensate exactly for such errors. *Compliant wrists* offset positioning errors to a large extent by allowing small passive part motions in response to forces or torques exerted on the part. An example is pin insertion, where small positioning errors can result in pin breakage or other failures, and compensation by gross robot arm motions requires sophisticed (e.g., expensive) force-torque sensors and advanced (e.g., expensive) closed-loop feedback force control techniques. The compliant wrist allows the pin to effectively adjust its own position in response to sidewall forces so that it slides into the hole. A particularly effective device is the remote-center-of-compliance (RCC) wrist, Fig. 33.17(b), where the rotation point of the wrist can be adjusted to correspond, e.g., to the part contact point [Groover et al. 1986]. Compliant wrists allow successful assembly where vision or other expensive sensors would otherwise be needed.

The wrist can contain a wide variety of sensors, with possibly the most important class being the *wrist force-torque sensors* (section 33.7), which are quite expensive. A general rule-of-thumb is that, for economic and control complexity reasons, robotic force/torque sensing and control should be performed at the lowest possible level; e.g., fingertip sensors can often provide sufficient force information for most applications, with an RCC wrist compensating for position inaccuracies between the fingers and the parts.

Robot/Tooling Process Integration and Coordination

Many processes require the design of sophisticated end-of-arm tooling. Examples include spray painting guns, welding tools, multipurpose end effectors, and so on. Indeed, in some processes the complexity of the tooling can rival or exceed the complexity of the robot arm that positions it. Successful coordination and sequencing of the robot manipulator, the end effector, and the end-of-arm tooling calls for a variety of considerations at several levels of abstraction in Fig. 33.7.

There are two philosophically distinct points of view that may be used in considering the robot manipulator plus its end-of-arm tooling. In the first, the robot plus tooling is viewed as a *single virtual agent* to be assigned by an upper-level organizer/manager and commanded by a midlevel job coordinator. In this situation, all machine-level robot/tool coordination may be performed by the internal virtual robot machine coordinator shown in Fig. 33.7. This point of view is natural when the robot must perform sophisticated trajectory motion during the task and the tool is unintelligent, such as in pick-and-place operations, surface finishing, and grinding. In such situations, the end effector is often controlled by simple binary on/off or open/close commands through digital input/output signals from the machine coordinator. Many commercially available robot controllers allow such communications and support coordination through their programming languages (section 33.12).

In the second viewpoint, one considers the manipulator as a dumb platform that positions the tooling or maintains its relative motion to the workpiece while the tooling performs a job. This point of view may be taken in the case of processes requiring sophisticated tooling such as welding. In this situation, the robot manipulator and the tooling may be considered as *two separate agents* which are coordinated by the higher level job coordinator shown in Fig. 33.7.

A variety of processes fall between these two extremes, such as assembly tasks which require some coordinated intelligence by both the manipulator and the tool (insert pin in hole). In such applications both machine-level and task-level coordination may be required. The decomposition of coordination

commands into a portion suitable for machine-level coordination and a portion for task-level coordination is not easy. A rule-of-thumb is that any coordination that is invariant from process to process should be apportioned to the lower level (e.g., do not open gripper while robot is in motion). This is closely connected to the appropriate definition of robot/tooling behaviors in the fashion of Brooks et al. [1986].