1.2 ROBOTICS

The term **robot** was first introduced into our vocabulary by the Czech playwright Karel Capek in his 1920 play *Rossum's Universal Robots*, the word *robota* being the Czech word for work. Since then the term has been applied to a great variety of mechanical devices, such as teleoperators, underwater vehicles, autonomous land rovers, etc. Virtually anything that operates with some degree of autonomy, usually under computer control, has at some point been called a robot. In this text the term robot will mean a computer controlled industrial manipulator

and interesting research problems.

An official definition of such a robot comes from the **Robot Institute of America** (RIA): *A robot is a reprogrammable multifunctional manipulator designed to move material, parts, tools, or specialized devices through variable programmed motions for the performance of a variety of tasks.*

The key element in the above definition is the reprogrammability of robots. It is the computer brain that gives the robot its utility and adaptability. The so-called robotics revolution is, in fact, part of the larger computer revolution.

Even this restricted version of a robot has several features that make it attractive in an industrial environment. Among the advantages often cited in favor of the introduction of robots are decreased labor costs, increased precision and productivity, increased flexibility compared with specialized machines, and more humane working conditions as dull, repetitive, or hazardous jobs are performed by robots.

The robot, as we have defined it, was born out of the marriage of two earlier technologies: that of **teleoperators** and **numerically controlled milling machines**. Teleoperators, or master–slave devices, were developed during the second world war to handle radioactive materials. Computer numerical control (CNC) was developed because of the high precision required in the machining of certain items, such as components of high performance aircraft. The first robots essentially combined the mechanical linkages of the teleoperator with the autonomy and programmability of CNC machines. Several milestones on the road to present day robot technology are listed below[17],[21]:

1947—the first servoed electric powered teleoperator is developed

1948—a teleoperator is developed incorporating force feedback

1949—research on numerically controlled milling machines is initiated

1954—George Devol designs the first **programmable robot**

1956—Joseph Engelberger, a Columbia University physics student, buys the rights to Devol's robot and founds the Unimation Company

1961—the first **Unimate** robot is installed in a Trenton, New Jersey plant of General Motors (to tend a die casting machine)

1961—the first robot incorporating force feedback information is developed

1963—the first robot vision system is developed

1971—the **Stanford Arm** is developed at Stanford University

1973—the first robot programming language (WAVE) is developed at Stanford

1974—Cincinnati Milacron introduces the T^3 robot with computer control

1975—Unimation Inc. registers its first financial profit

1976—the Remote Center Compliance (RCC) device for part insertion in assembly is developed at Draper Labs in Boston

1978—Unimation introduces the PUMA robot, based on designs from a General Motors study

1979—the SCARA robot design is introduced in Japan

1981—the first **direct-drive** robot is developed at Carnegie-Mellon University

The first successful applications of robot manipulators generally involved some sort of material transfer, such as injection molding or stamping where the robot merely attended a press to unload and either transfer or stack the finished part. These first robots were capable of being programmed to execute a sequence of movements, such as moving to a location A, closing a gripper, moving to a location B, etc., but had no external sensory capability. More complex applications, such as welding, grinding, deburring, and assembly require not only more complex motion but also some form of external sensing such as vision, tactile, or force sensing, due to the increased interaction of the robot with its environment. For a comprehensive discussion of robotic applications the reader is referred to the references at the end of this chapter, especially [6] and [8].

It should be pointed out that the important applications of robots are by no means limited to those industrial jobs where the robot is directly replacing a human worker. There are many other applications of robotics in areas where the use of humans is impractical or undesirable. Among these are undersea and planetary exploration, satellite retrieval and repair, the defusing of explosive devices, and work in radioactive environments. Finally, prostheses, such as artificial limbs, are themselves robotic devices requiring methods of analysis and design similar to those of industrial manipulators.

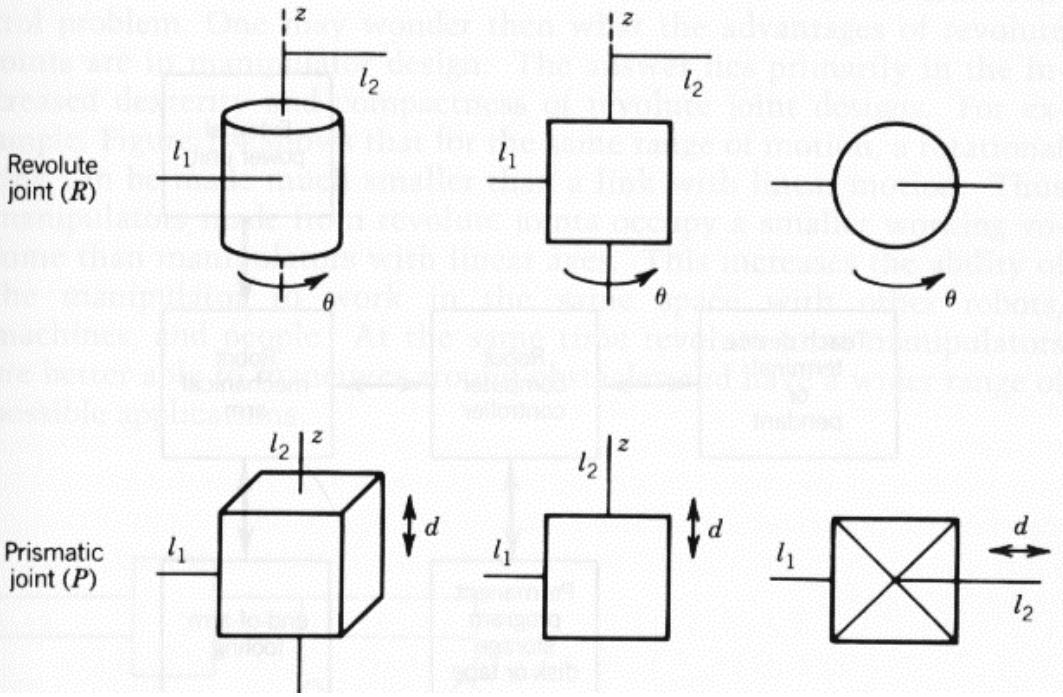
1.3 COMPONENTS AND STRUCTURE OF ROBOTS

Robot Manipulators are composed of **links** connected by **joints** into an **open kinematic chain**. Joints are typically rotary (revolute) or linear (prismatic). A **revolute** joint is like a hinge and allows relative rotation between two links. A **prismatic** joint allows a linear relative motion

between two links. We use the convention (R) for representing revolute joints and (P) for prismatic joints as shown in Figure 1-2. Each joint represents the interconnection between two links, say, ℓ_i and ℓ_{i+1}. We denote the axis of rotation of a revolute joint, or the axis along which a prismatic joint slides, by z_i if the joint is the interconnection of links i and $i+1$. The **joint variables**, denoted by θ_i for a revolute joint and d_i for a prismatic joint, represent the relative displacement between adjacent links. We will make this precise in Chapter Three.

The joints of a manipulator may be electrically, hydraulically, or pneumatically actuated. The number of joints determines the **degrees-of-freedom** (DOF) of the manipulator. Typically, a manipulator should possess at least six independent DOF: three for **positioning** and three for **orientation**. With fewer than six DOF the arm cannot reach every point in its work environment with arbitrary orientation. Certain applications such as reaching around or behind obstacles require more than six DOF. The difficulty of controlling a manipulator increases rapidly with the number of links. A manipulator having more than six links is referred to as a **kinematically redundant** manipulator.

The **workspace** of a manipulator is the total volume swept out by the end-effector as the manipulator executes all possible motions. The workspace is constrained by the geometry of the manipulator as well as mechanical constraints on the joints. For example, a revolute joint may be limited to less than a full 360^o of motion. The workspace is



often broken down into a **reachable workspace** and a **dextrous workspace**. The reachable workspace is the entire set of points reachable by the manipulator, whereas the dextrous workspace consists of those points that the manipulator can reach with an arbitrary orientation of the end-effector. Obviously the dextrous workspace is a subset of the reachable workspace.

A robot manipulator should be viewed as more than just a series of mechanical linkages. The mechanical arm is just one component to an overall **Robotic System**, shown in Figure 1-3, which consists of the **arm**, **external power source**, **end-of-arm tooling**, **external and internal sensors**, **servo**, **computer interface**, and **control computer**. Even the programmed software should be considered as an integral part of the overall system, since the manner in which the robot is programmed and controlled can have a major impact on its performance and subsequent range of applications.

1.3.1 Accuracy and Repeatability

The **accuracy** of a manipulator is a measure of how close the manipulator can come to a given point within its workspace. **Repeatability** is a measure of how close a manipulator can return to a previously taught point. Most present day manipulators are highly repeatable but not very accurate. The primary method of sensing positioning errors in most cases is with position encoders located at the joints, either on the shaft of the motor that actuates the joint or on the joint itself. There is

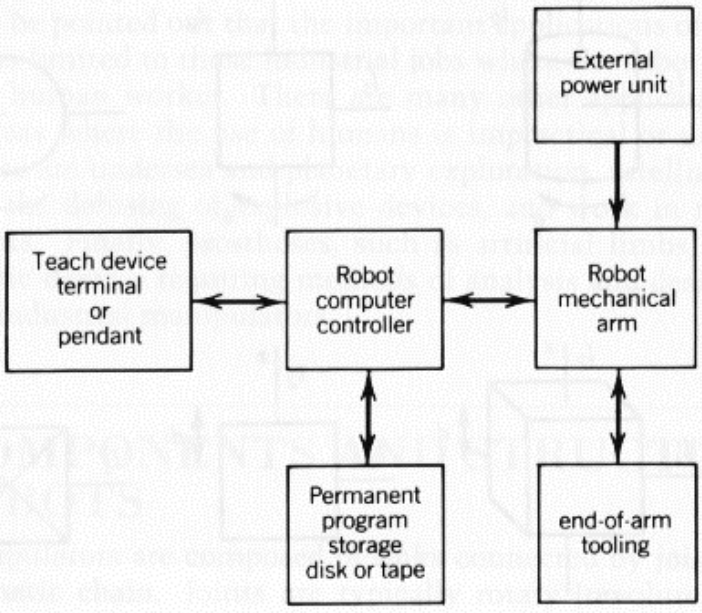


Figure 1-3
Components of a robotic system

typically no direct measurement of the end-effector position and orientation. One must rely on the assumed geometry of the manipulator and its rigidity to infer (i.e., to calculate) the end-effector position from the measured joint angles. Accuracy is affected therefore by computational errors, machining accuracy in the construction of the manipulator, flexibility effects such as the bending of the links under gravitational and other loads, gear backlash, and a host of other static and dynamic effects. It is primarily for this reason that robots are designed with extremely high rigidity. Without high rigidity, accuracy can only be improved by some sort of direct sensing of the end-effector position, such as with vision.

Once a point is taught to the manipulator, however, say with a teach pendant, the above effects are taken into account and the proper encoder values necessary to return to the given point are stored by the controlling computer. Repeatability therefore is affected primarily by the controller resolution. **Controller resolution** means the smallest increment of motion that the controller can sense. The resolution is computed as the total distance traveled by the tip divided by 2^n, where n is the number of bits of encoder accuracy. In this context linear axes, that is, prismatic joints, typically have higher resolution than revolute joints, since the straight line distance traversed by the tip of a linear axis between two points is less than the corresponding arclength traced by the tip of a rotational link.

In addition, as we will see in later chapters, rotational axes usually result in a large amount of kinematic and dynamic coupling among the links with a resultant accumulation of errors and a more difficult control problem. One may wonder then what the advantages of revolute joints are in manipulator design. The answer lies primarily in the increased dexterity and compactness of revolute joint designs. For example, Figure 1-4 shows that for the same range of motion, a rotational link can be made much smaller than a link with linear motion. Thus manipulators made from revolute joints occupy a smaller working volume than manipulators with linear axes. This increases the ability of the manipulator to work in the same space with other robots, machines, and people. At the same time revolute joint manipulators are better able to maneuver around obstacles and have a wider range of possible applications.

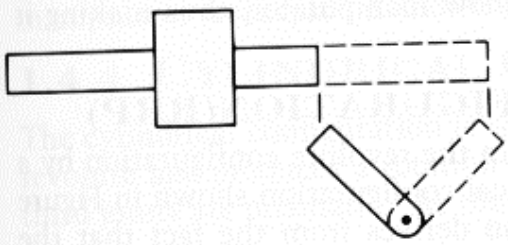


FIGURE 1-4
Linear vs. rotational link motion