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# 1

# *Fundamentals*

## 1.1 INTRODUCTION

Robotics, in different forms, has always been on people's minds, since the time we first built things. You may have seen machines that artisans made that tried to mimic a human's motions and behavior. Two examples of such machines are the statues in Venice that hit the clock on the hour and toys with repeating movements. Hollywood and movies have taken this desire one step further by portraying robots and humanoids as even superior to humans.

Although in principle humanoids are robots and are designed and governed by the same basics, in this book, we will primarily study industrial manipulator type robots. This book covers some basic introductory material that will get you familiar with the subject, presents analyses of the mechanics of robots, including kinematics and dynamics of robots, and discusses the elements that are used in robots and in robotics, such as actuators, sensors, and vision systems.

Robots are very powerful elements of today's industry. They are capable of performing many different tasks and operations precisely and do not require common safety and comfort elements humans need. However, it takes much effort and many resources to make a robot function properly. Most companies that made robots in the mid-1980s no longer exist, and only companies that made industrial robots remain in the market (such as Adept Robotics, Staubli Robotics, and Fanuc Robotics, North America, Inc.). Early predictions about the possible number of robots in industry never materialized, because high expectations could not be satisfied with the present robots. As a result, although there are many thousands of robots in industry, they have not overwhelmingly replaced workers. They are used where they are useful. As with humans, robots can do certain things, but not other things. As long as they are designed properly for the intended purpose, they are very useful and will continue to be used.

The subject of robotics covers many different areas. Robots alone are hardly ever useful. They are used together with other devices, peripherals, and other manufacturing machines. They are generally integrated into a system, which as a whole is designed to perform a task or do an operation. In this book, we will refer to some of these other devices and systems that are used with robots.

## 1.2 WHAT IS A ROBOT?

If you compare a conventional robotic manipulator with a crane attached to, say, a utility or towing vehicle, you will notice that the robot manipulator is very similar to the crane. Both posses a number of links attached serially to each other with joints, where each joint can be moved by some type of actuator. In both systems, the "hand" of the manipulator can be moved in space and be placed in any desired location within the workspace of the system, each one can carry a certain amount of load, and each one is controlled by a central controller which controls the actuators. However, one is called a robot and the other a manipulator (or, in this case, a crane). The fundamental difference between the two is that the crane is controlled by a human who operates and controls the actuators, whereas the robot manipulator is controlled by a computer that runs a program. This difference between the two determines whether a device is a simple manipulator or a robot. In general, robots are designed, and meant, to be controlled by a computer or similar device. The motions of the robot are controlled through a controller that is under the supervision of the computer, which, itself, is running some type of a program. Thus, if the program is changed, the actions of the robot will be changed accordingly. The intention is to have a device that can perform many different tasks and thus is very flexible in what it can do, without having to redesign the device. Thus, the robot is designed to be able to perform any task that can be programmed (within limit, of course) simply by changing the program. The simple manipulator (or the crane) cannot do this without an operator running it all the time.

WRONG!

Different countries have different standards for what they consider to be a robot. By American standards, a device must be easily reprogrammable to be considered a robot. Thus, manual-handling devices (i.e., a device that has multiple degrees of freedom and is actuated by an operator) or fixed-sequence robots (i.e., any device controlled by hard stops to control actuator motions on a fixed sequence and difficult to change) are not considered to be robots.

## 1.3 CLASSIFICATION OF ROBOTS

The following is the classification of robots according to the Japanese Industrial Robot Association (JIRA):

- Class 1: *Manual-Handling Device:* A device with multiple degrees of freedom that is actuated by an operator. REMOTE CONTROL

(*a*) (*b*)

**Figure 1.1** A robot and a crane are very similar in the way they operate and in the way they are designed. However, the crane is controlled by an operator, whereas the robot is controlled by a computer. Thus, by simply changing the computer program, the robot will function differently. (a) A Kuhnezug truck-mounted crane. Reprinted with permission from Kuhnezug Fordertechnik GmbH. (b) Fanuc S-500 robots performing seam-sealing on a truck. Reprinted with permission from Fanuc Robotics, North America, Inc.

- Class 2: *Fixed-Sequence Robot:* A device that performs the successive stages of a task according to a predetermined, unchanging method and is hard to modify.
- Class 3: *Variable-Sequence Robot:* Same as class 2, but easy to modify.
- Class 4: *Playback Robot:* A human operator performs the task manually by leading the robot, which records the motions for later playback. The robot repeats the same motions according to the recorded information.

USE TEACH PENDANT

- Class 5: *Numerical Control Robot:* The operator supplies the robot with a movement program rather than teaching it the task manually.
- Class 6: *Intelligent Robot:* A robot with the means to understand its environment and the ability to successfully complete a task despite changes in the surrounding conditions under which it is to be performed. ADAPTIVE

The Robotics Institute of America (RIA) only considers classes 3–6 as robots. The Association Française de Robotique (AFR) has the following classification:

- Type A: Handling devices with manual control to telerobotics.
- Type B: Automatic handling devices with predetermined cycles.
- Type C: Programmable, servo controlled robots with continuous or point-to-point trajectories.
- Type D: Same as type C, but with capability to acquire information from its environment.

## 1.4 WHAT IS ROBOTICS?

Robotics is the art, knowledge base, and the know-how of designing, applying, and using robots in human endeavors. Robotic systems consist of not just robots, but also other devices and systems that are used together with the robots to perform the necessary tasks. Robots may be used in manufacturing environments, in underwater and space exploration, for aiding the disabled, or even for fun. In any capacity, robots can be useful, but need to be programmed and controlled. Robotics is an interdisciplinary subject that benefits from mechanical engineering, electrical and electronic engineering, computer science, biology, and many other disciplines.

## 1.5 HISTORY OF ROBOTICS

Disregarding the early machines that were made to mimic humans and their actions and concentrating on the recent history, one can see a close relationship between the state of industry, the revolution in numeric and computer control of machinery, space exploration, and the vivid imagination of creative people. Starting with Karel Čapek and his book, *Rossam's Universal Robots* [1], and continuing with movies like *Flash Gordon, Metropolis, Lost in Space, The Day The Earth Stood Still,* and *The Forbidden Planet* [2], we see that the stage was being set for a machine to be built to do human's job (and of course, R2D2, C3PO, and Robocop continued the trend). Čapek dreamt of a situation where a bioprocess could create human-like machines, devoid of emotions and souls, who were strong, obeyed their masters, and could be produced quickly and cheaply. Soon, the market grew tremendously when all major countries wanted to equip their armies with hundreds of thousands of slave robotic soldiers, who would fight with dedication, but whose loss no one would care about. Eventually, the robots decided that they were actually superior to the humans and tried to take over the whole world. In this story, the word "rabota," or worker, was coined, and is used even today. After World War II, automatic machines were designed to increase productivity, and machine-tool manufacturers made numerically controlled (NC) machines to enable manufacturers to produce better products. At the same time, for work on nuclear materials, multiple degree-of-freedom manipulators were being developed. A marriage between the NC capability of machine tools and the manipulators created a simple robot. The first robots were controlled by strips of paper with holes, which electric eyes could detect and which controlled the robot's movements. As industry improved, the strip of paper gave way to magnetic tapes, memory devices, and personal computers. The following is a summary of events that have marked changes in the direction of this industry:

| | |
|---|---|
| 1922 | Czech author Karel Čapek wrote a story called *Rossum's Universal Robots* and introduced the word "Rabota" (meaning worker). |
| 1956 | George Devol developed the magnetic controller, a playback device. Eckert and Mauchley built the ENIAC computer at the University of Pennsylvania. |

| | |
|---|---|
| 1952 | The first NC machine was built at MIT. |
| 1954 | George Devol developed the first programmable robot. |
| 1955 | Denavit and Hartenberg developed homogeneous transformation matrices. |
| 1961 | U.S. patent 2,988,237 was issued to George Devol for "Programmed Article Transfer," a basis for Unimate™ robots. |
| 1962 | Unimation was formed, first industrial robots appeared, and GM installed its first robot from Unimation. |
| 1967 | Unimate™ introduced the MarkII™ robot. The first robot was imported to Japan for paint-spraying applications. |
| 1968 | An intelligent robot called Shakey was built at Stanford Research Institute (SRI). |
| 1972 | IBM worked on a rectangular coordinate robot for internal use. It eventually developed the IBM 7565 for sale. |
| 1973 | Cincinnati Milacron™ introduced the T3 model robot, which became very popular in industry. |
| 1978 | The first PUMA robot was shipped to GM by Unimation. |
| 1982 | GM and Fanuc of Japan signed an agreement to build GMFanuc robots. Westinghouse bought Unimation, which was later sold to Staubli of Switzerland. |
| 1983 | Robotics became a very popular subject, both in industry, as well as academia. Many programs in the nation started teaching courses in robotics. |
| 1990 | Cincinnati Milacron was acquired by ABB of Switzerland. Most small robot manufacturers went out of the market. Only a few large companies, which primarily produce industrial robots, remained. |

## 1.6 ADVANTAGES AND DISADVANTAGES OF ROBOTS

- 1 Robotics and automation can, in many situations, increase productivity, safety, efficiency, quality, and consistency of products.
- 2 Robots can work in hazardous environments without the need for life support, comfort, or concern about safety.
- 3 Robots need no environmental comfort, such as lighting, air conditioning, ventilation, and noise protection.
- 4 Robots work continuously without experiencing fatigue or boredom, do not get mad, do not have hangovers, and need no medical insurance or vacation.
- 5 Robots have repeatable precision at all times, unless something happens to them or unless they wear out.
- 6 Robots can be much more accurate than humans. Typical linear accuracies are a few thousands of an inch. New wafer-handling robots have microinch accuracies.

- 7 Robots and their accessories and sensors can have capabilities beyond that of humans. STRENGTH, SENSES, ETC.
- 8 Robots can process multiple stimuli or tasks simultaneously. Humans can only process one active stimulus.
- 1 Robots replace human workers creating economic problems, such as lost salaries, and social problems, such as dissatisfaction and resentment among workers.
- 2 Robots lack capability to respond in emergencies, unless the situation is predicted and the response is included in the system. Safety measures are needed to ensure that they do not injure operators and machines working with them [3]. This includes:
    - Inappropriate or wrong responses
    - A lack of decision-making power
    - A loss of power
    - Damage to the robot and other devices
    - Human injuries OFTEN?
- 3 Robots, although superior in certain senses, have limited capabilities in
    - Degrees of freedom
    - Dexterity
    - Sensors
    - Vision systems
    - Real-time response
- 4 Robots are costly, due to
    - Initial cost of equipment
    - Installation costs
    - Need for peripherals
    - Need for training
    - Need for programming

## 1.7 ROBOT COMPONENTS

A robot, as a system, consists of the following elements, which are integrated together to form a whole:

**Manipulator, or rover** This is the main body of the robot and consists of the links, the joints, and other structural elements of the robot. Without other elements, the manipulator alone is not a robot (Figure 1.2).

**End effector** This is the part that is connected to the last joint (hand) of a manipulator, which generally handles objects, makes connection to other machines, or performs the required tasks (Figure 1.2). Robot manufacturers generally do not design or sell end effectors. In most cases, all they supply is a simple gripper. Generally, the hand of a robot has provisions for connecting specialty end effectors that are specifically designed for a purpose. This is the job of a company's engineers or

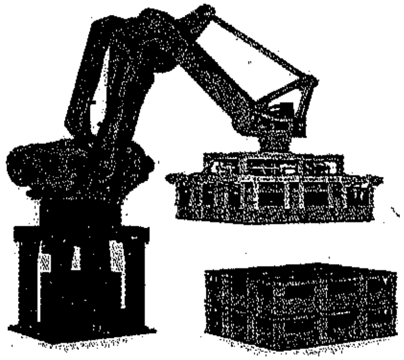


**Figure 1.2** A Fanuc M-410iWW palletizing robotic manipulator with its end effector. (Reprinted by permission from Fanuc Robotics, North America, Inc.)

outside consultants to design and install the end effector on the robot and to make it work for the given situation. A welding torch, a paint spray gun, a glue-laying device, and a parts handler are but a few of the possibilities. In most cases, the action of the end effector is either controlled by the robot's controller, or the controller communicates with the end effector's controlling device (such as a PLC).

**Actuators** Actuators are the "muscles" of the manipulators. Common types of actuators are servomotors, stepper motors, pneumatic cylinders, and hydraulic cylinders. There are also other actuators that are more novel and are used in specific situations. This will be discussed in Chapter 6. Actuators are controlled by the controller.

**Sensors** Sensors are used to collect information about the internal state of the robot or to communicate with the outside environment. As in humans, the robot controller needs to know where each link of the robot is in order to know the robot's configuration. Even in absolute darkness, you still know where your arms and legs are! This is because feedback sensors in your central nervous system embedded in your muscle tendons send information to your brain. The brain uses this information to determine the length of your muscles, and thus, the state of your arms, legs, etc. The same is true for robots; sensors integrated into the robot send information about each joint or link to the controller, which determines the configuration of the robot. Robots are often equipped with external sensory devices such as a vision system, touch and tactile sensors, speech synthesizers, etc., which enable the robot to communicate with the outside world.

OPTICAL ENCODERS OR VARIABLE RESISTORS

"HAPTIC"

**Controller** The controller is rather similar to your cerebellum, and although it does not have the power of your brain, it still controls your motions. The controller receives its data from the computer, controls the motions of the actuators, and coordinates the motions with the sensory feedback information. Suppose that in order for the robot to pick up a part from a bin, it is necessary that its first joint be at 35°. If the joint is not already at this magnitude, the controller will send a signal to the actuator (a current to an electric motor, air to a pneumatic cylinder, or a signal

CONTROL SCHEMES; ① POSITION CONTROL
② VELOCITY CONTROL
③ ACCELERATION CONTROL
CAN ADD FORCE FEEDBACK TO ANY OF THESE

to a hydraulic servo valve), causing it to move. It will then measure the change in the joint angle through the feedback sensor attached to the joint (a potentiometer, an encoder, etc.). When the joint reaches the desired value, the signal is stopped. In more sophisticated robots, the velocity and the force exerted by the robot are also controlled by the controller.

ASICS MOTOR CONTROL CHIPS

**Processor** The processor is the brain of the robot. It calculates the motions of the robot's joints, determines how much and how fast each joint must move to achieve the desired location and speeds, and oversees the coordinated actions of the controller and the sensors. The processor is generally a computer, which works like all other computers, but is dedicated to a single purpose. It requires an operating system, programs, peripheral equipment such as monitors, and has many of the same limitations and capabilities of a PC processor.

CUSTOM REAL-TIME O.S. SOME TIMES

**Software** There are perhaps three groups of software that are used in a robot. One is the operating system, which operates the computer. The second is the robotic software, which calculates the necessary motions of each joint based on the kinematic equations of the robot. This information is sent to the controller. This software may be at many different levels, from machine language to sophisticated languages used by modern robots. The third group is the collection of routines and application programs that are developed in order to use the peripheral devices of the robots, such as vision routines, or to perform specific tasks.

It is important to note that in many systems, the controller and the processor are placed in the same unit. Although these two units are in the same box, and even if they are integrated into the same circuit, they have two separate functions.

## 1.8 ROBOT DEGREES OF FREEDOM

D.O.F.

As you may remember from your engineering mechanics courses, in order to locate a point in space, one needs to specify three coordinates, such as the *x*-, *y*-, and *z*-coordinates along the three Cartesian axes. Three coordinates are necessary and sufficient to define the location of the point. Although the three coordinates may be expressed in terms of different coordinate systems, they are always necessary. However, it is not possible to have two or four coordinates, since two is inadequate to locate a point in space, and four is impossible in three dimensions. Similarly, if you consider a three-dimensional device with three degrees of freedom, within the workspace of the device, you should be able to place any point at any desired location. For example, a gantry $(x,y,z)$ crane can place a ball at any location within its workspace as specified by the operator.

Similarly, to locate a rigid body (a three-dimensional object rather than a point) in space, one needs to specify the location of a selected point on it, and thus it requires three pieces of information to be located as desired. However, although the location of the object is specified, there are infinitely many possible ways to orientate the object about the selected point. To fully specify the object in space, in addition to the location of a selected point on it, one needs to specify the orientation of the object. This means that there is need for a total of six pieces of information to

REQUIRES FULL DYNAMIC MODEL ∴ RARELY DONE

fully specify the location and orientation of a rigid body. By the same token, there needs to be six degrees of freedom available to fully place the object in space and also orientate it as desired. If there are fewer than six degrees of freedom, the robot's capabilities are limited.

To demonstrate this, consider a robot with three degrees of freedom, where it can only move along the *x*-, *y*-, and *z*-axes. In this case, no orientation can be specified; all the robot can do is to pick up the part and to move it in space, parallel to the reference axes. The orientation always remains the same. Now consider another robot with five degrees of freedom, capable of rotating about the three axes, but only moving along the *x*- and *y*-axes. Although you may specify any orientation desired, the positioning of the part is only possible along the *x*- and *y*-axes, but not *z*-axis.

"REDUNDANT MANIPULATOR" IF > 6 DOF

A system with seven degrees of freedom does not have a unique solution. This means that if a robot has seven degrees of freedom, there are an infinite number of ways it can position a part and orientate it at the desired location. For the controller to know what to do, there must be some additional decision making routine that allows it to pick only one of the infinite ways. As an example, one may use an optimization routine to pick the fastest or the shortest path to the desired destination. Then the computer has to check all solutions to find the shortest or fastest response and perform it. Due to this additional requirement, which can take much computing power and time, no seven-degree-of-freedom robot is used in industry. A similar issue arises when a manipulator robot is mounted on a moving base such as a mobile platform or a conveyor belt (Figure 1.3). The robot then has an additional degree of freedom, which, based on the preceding discussion, is impossible to control. The robot can be at a desired location and orientation from infinitely many distinct positions on the conveyor belt or the mobile platform. However, in this case, although there are too many degrees of freedom, generally, the additional degrees of freedom are not solved for. In other words, when a robot is mounted on a conveyor belt or is otherwise mobile, the location of the base of the robot relative to the belt or other reference frame is known. Since this location does not need to be defined by the controller, the remaining number of degrees of freedom are still 6, and thus, unique. So long as the location of the base of the robot on the belt or the location of the mobile platform is known (or picked), there is no need to find it by solving a set of equations of robot motions, and, thus, the system can be solved.

WRONG!

CAN USE EXTRA DOF TO OPTIMIZE:
1) SPEED OR 2) SHORTEST PATH
3) OBSTACLE AVOIDANCE
4) DEXTERITY (MANAPULABILITY)
5) JOINT TORQUES
6) AVOIDE "SINGULARITIES" (i.e. WHEN JOINT ANGLE 0° OR 180°, CAN GET ∞ VELOCITIES BECAUSE OF MATHEMATICS)

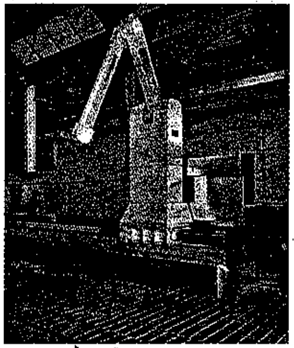


**Figure 1.3** A Fanuc P-15 robot. Reprinted with permission from Fanuc Robotics, North America, Inc.

Can you determine how many degrees of freedom the human arm has? This should exclude the hand (palm and the fingers), but should include the wrist. Before you go on, please try to see if you can determine it.

You will notice that the human arm has three joint clusters in it, the shoulder, the elbow and the wrist. The shoulder has three degrees of freedom, since the upper arm (humerus) can rotate in the sagittal plane (parallel to the mid-plane of the body), the coronal plane (a plane from shoulder to shoulder), and about the humerus. (Verify this by rotating your arm about the three different axes.) The elbow has only one degree of freedom; it can only flex and extend about the elbow joint. The wrist also has three degrees of freedom. It can abduct and adduct, flex and extend, and since the radius bone can role over the ulna bone, it can rotate longitudinally (pronate and supinate). Thus, the human arm has a total of seven degrees of freedom, even if the ranges of some movements are small. Since a seven-degree-of-freedom system does not have a unique solution, how do you think we can use our arms?

You must realize that in a robot system, the end effector is never considered as one of the degrees of freedom. All robots have this additional capability, which may appear to be similar to a degree of freedom. However, none of the movements in the end effector are counted towards the robot's degrees of freedom.

There are cases where a joint may have the ability to move, but its movement is not fully controlled. For example, consider a linear joint actuated by a pneumatic cylinder, where the arm is fully extended or fully retracted, but no controlled position can be achieved between the two extremes. In this case, the convention is to assign only a 1/2-degree of freedom to the joint. This means that the joint can only be at specified locations within its limits of movement. Another possibility for a 1/2 degree of freedom is to assign only particular values to the joint. For example, suppose that a joint is made to be only at 0, 30, 60, and 90 degrees. Then, as before, the joint is limited to only a few possibilities, and thus, has a limited degree of freedom.

There are many robots in industry that possess fewer than six degrees of freedom. In fact, robots with 3.5, 4, and 5 degrees of freedom are very common. So long as there is no need for the additional degrees of freedom, these robots perform very well. As an example, suppose that you desire to insert electronic components into a circuit board. The circuit board is always laid flat on a known work surface; thus, its height ($z$-value) relative to the base of the robot is known. Therefore, there is only need for two degrees of freedom along the $x$- and $y$-axes to specify any location on the board for insertion. Additionally, suppose that the components would be inserted in any direction on the board, but that the board is always flat. In that case, there will be need for one degree of freedom to rotate about the vertical axis ($z$) in order to orientate the component above the surface. Since there is also need for a 1/2-degree of freedom to fully extend the end effector to insert the part, or to fully retract it to lift the robot before moving, all that is needed is 3.5 degrees of freedom; two to move over the board, one to rotate the component, and 1/2 to insert or retract. Insertion robots are very common and are used extensively in electronic industry. Their advantage is that they are simple to program, are less expensive, and are smaller and faster. Their disadvantage is that although they may be programmed to insert components on any size board in any direction, they cannot perform other jobs. They are limited to what 3.5 degrees of freedom can achieve, but they can perform a variety of functions within this design limit.

S

## 1.9 ROBOT JOINTS

Robots may have different types of joints, such as linear, rotary, sliding, or spherical. Although spherical joints are common in many systems, since they posses multiple degrees of freedom, and thus, are difficult to control, spherical joints are not common in robotics, except in research. Most robots have either a linear (prismatic) joint or a rotary (revolute) joint.

P

Prismatic joints are linear; there is no rotation involved. They are either hydraulic or pneumatic cylinders, or they are linear electric actuators. These joints are used in gantry, cylindrical, or similar joint configurations.

R

Revolute joints are rotary, and although hydraulic and pneumatic rotary joints are common, most rotary joints are electrically driven, either by stepper motors or, more commonly, by servomotors.

## 1.10 ROBOT COORDINATES

MOST COMMON

Robot configurations generally follow the coordinate frames with which they are defined, as shown in Figure 1.4. Prismatic joints are denoted by P, revolute joints are denoted by R, and spherical joints are denoted by S. Robot configurations are specified by a succession of P's, R's, or S's. For example, a robot with three prismatic and three revolute joints is specified by 3P3R. The following configurations are common for positioning the hand of the robot:

**Cartesian/rectangular/gantry (3P)** These robots are made of three linear joints that position the end effector, which are usually followed by additional revolute joints that orientate the end effector.

**Cylindrical (R2P)** Cylindrical coordinate robots have two prismatic joints and one revolute joint for positioning the part, plus revolute joints for orientating the part.

**Spherical (2RP)** Spherical coordinate robots follow a spherical coordinate system, which has one prismatic and two revolute joints for positioning the part, plus additional revolute joints for orientation.

**Articulated/anthropomorphic (3R)** An articulated robot's joints are all revolute, similar to a human's arm. They are perhaps the most common configuration for industrial robots.

**Selective Compliance Assembly Robot Arm (SCARA)** SCARA robots have two revolute joints that are parallel and allow the robot to move in a horizontal plane, plus an additional prismatic joint that moves vertically (Figure 1.5). SCARA robots are very common in assembly operations. Their specific characteristic is that they are more compliant in the $x$–$y$-plane, but are very stiff along the

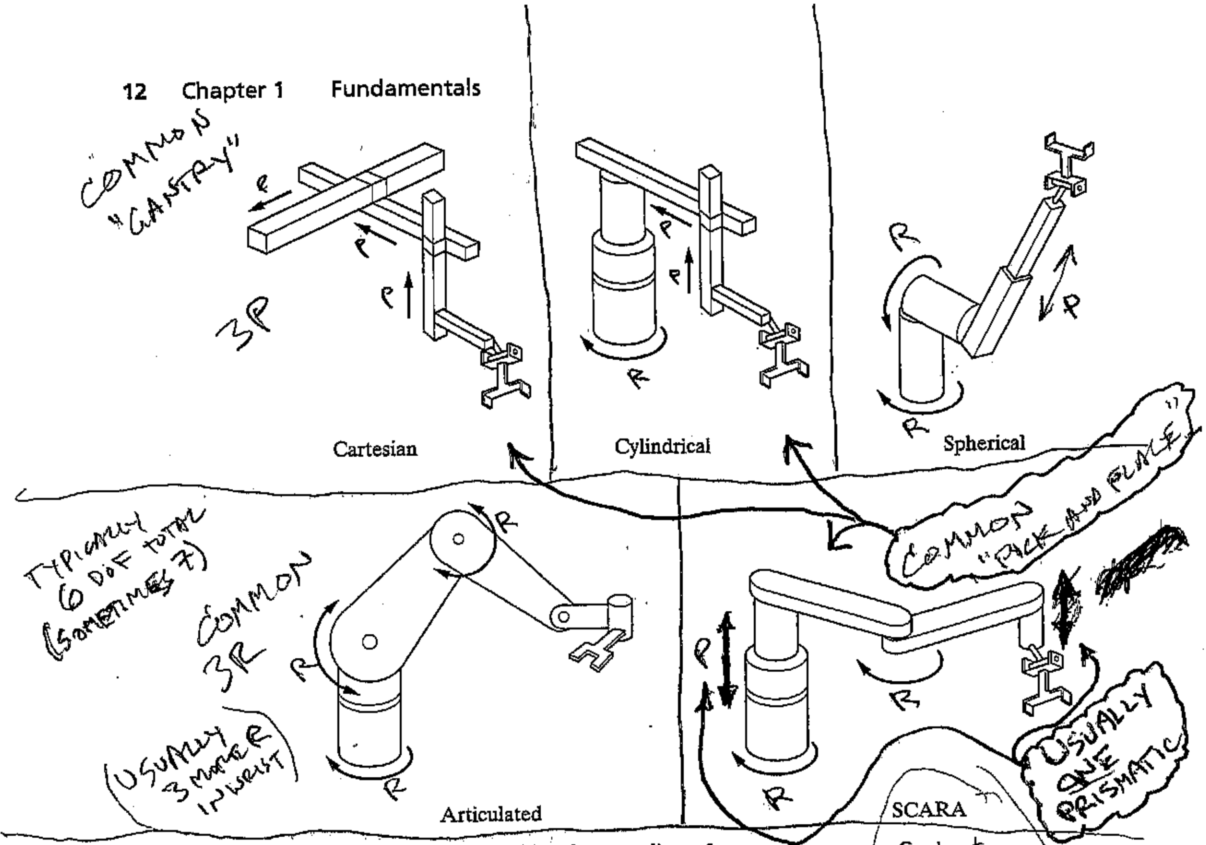


**Figure 1.4** Some possible robot coordinate frames.

Selective Compliance Assembly Robot Arm

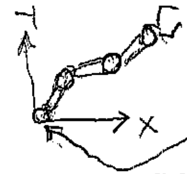
SORT OF

**Figure 1.5** An Adept SCARA robot. Reprinted with permission from Adept Technology, Inc.

$z$-axis, and thus have selective compliance. This is an important issue in assembly and will be discussed later.

## 1.11 ROBOT REFERENCE FRAMES

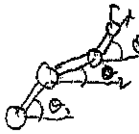
Robots may be moved relative to different coordinate frames. In each type of coordinate frame, the motions will be different. Usually, robot motions are accomplished in the following three coordinate frames (Figure 1.6):



ALL COORDINATES WITH RESPECT TO ORIGIN

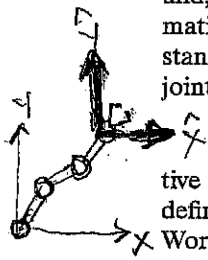
CARTESION SPACE

**World Reference Frame,** which is a universal coordinate frame, as defined by $x$, $y$, $z$-axes. In this case, the joints of the robot move simultaneously so as to create motions along the three major axes. In this frame, for example, no matter where the arm is, a positive $x$-axis movement is always in the positive direction of the $x$-axis; this coordinate is used to define the motions of the robot relative to other objects, to define other parts and machines that the robot communicates with, and to define motion paths.



"JOINT-ANGLE" SPACE

**Joint Reference Frame,** which is used to specify movements of each individual joint of the robot. Suppose that you want to move the hand of a robot to a particular position. You may decide to move one joint at a time in order to direct the hand to the desired location. In this case, each joint may be accessed individually, and, thus, only one joint moves at a time. Depending on the type of joint used (prismatic, revolute, or spherical), the motion of the robot hand will be different. For instance, if a revolute joint is moved, the hand will move around a circle defined by the joint axis.



**Tool Reference Frame,** which specifies movements of the robot's hand relative to a frame attached to the hand. The $x'$-, $y'$-, and $z'$-axes attached to the hand define the motions of the hand relative to this local frame. Unlike the universal World frame, the local Tool frame moves with the robot. Suppose that the hand is pointed as shown in Figure 1.6. Moving the hand relative to the positive $x$-axis of the local Tool frame will move the hand along the $x'$-axis of the Tool frame. If the arm were pointed elsewhere, the same motion along the local $x'$-axis of the Tool frame would be completely different from the first motion. The same $+x'$-axis movement would be upward if the $x'$-axis were pointed upwards, and it would be downward if the $x'$-axis were pointed downward. As a result, the Tool reference frame is a moving frame that changes continuously as the robot moves, so the ensuing motions relative to it are also different, depending on where the arm is and what direction the Tool frame has. All joints of the robot must move simultaneously to create coordinated motions about the Tool frame. The Tool reference frame is an extremely useful frame in robotic programming, where the robot is to approach and depart from other objects or to assemble parts.

STILL NEED TO KEEP A REFERENCE TO ORIGIN WITH LOCATION VECTOR $\vec{P}$

## 1.12 PROGRAMMING MODES

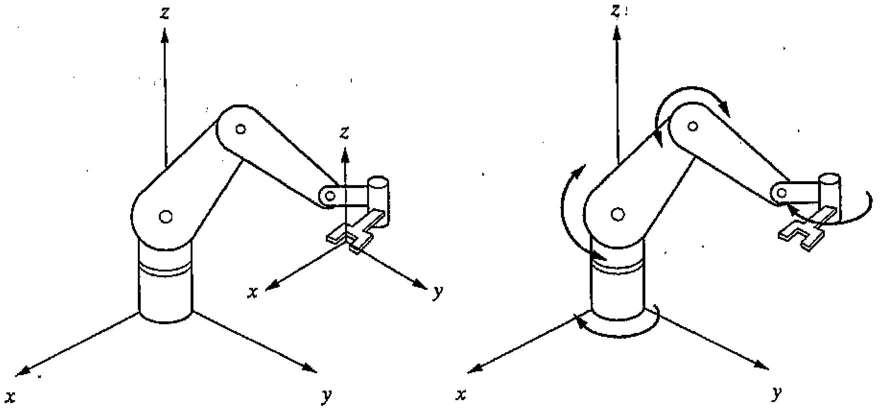
TECHNICIAN PROGRAMS LADDER LOGIC (EASY)

Robots may be programmed in a number of different modes, depending on the robot and its sophistication. The following programming modes are very common:

① **Physical Setup** In this mode, an operator sets up switches and hard stops that control the motion of the robot. This mode is usually used along with other devices, such as Programmable Logic Controllers (PLC). TYPICALLY "POSITION CONTROL"

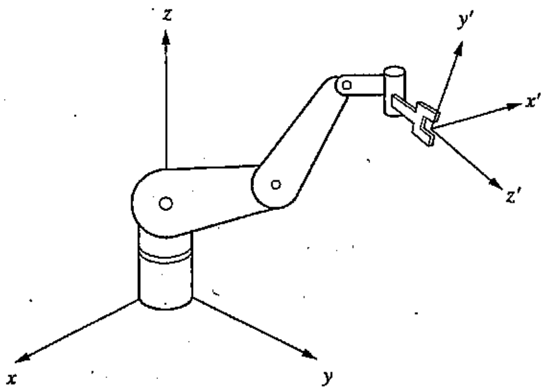
② **Lead Through or Teach Mode** In this ~~mode~~, the robot's joints are moved with a teach pendant. When the desired location and orientation is achieved, the

TECHNICIAN "POSITION CONTROL"



World reference frame

Joint reference frame



Tool reference frame

**Figure 1.6** A robot's World, Joint, and Tool reference frames. Most robots may be programmed to move relative to either of these reference frames.

OR TRANSFERRED FROM A MOTION-CAPTURE MODEL OF HUMAN WORKING

location is entered (taught) into the controller. During playback, the controller will move the joints to the same locations and orientations. This mode is usually point to point, where the motion between points is not specified or controlled. Only the points that are taught are guaranteed to reach.

PRECISE PATH (NOT JUST POINTS) CAPTURED (MAY ALSO USE TEACH PENDANT)

③ **Continuous Walk-Through Mode** In this mode, all robot joints are moved simultaneously, while the motion is continuously sampled and recorded by the controller. During playback, the exact motion that was recorded is executed. The motions are taught by an operator, either through a model, by physically moving the end effector, or by directing the robot arm and moving it through its work-

TYPICALLY "VELOCITY CONTROL"

space. Painting robots, for example, are programmed by skilled painters through this mode.

4

**Software Mode** In this mode of programming the robot, a program is written off-line or on-line and is executed by the controller to control the motions. The programming mode is the most sophisticated and versatile mode and can include sensory information, conditional statements (such as if...then statements), and branching. However, it requires the knowledge of the operating system of the robot before any program is written.

Most industrial robots can be programmed in more than one mode.

## 1.13 ROBOT CHARACTERISTICS

The following definitions are used to characterize robot specifications:

**Payload** Payload is the weight a robot can carry and still remain within its other specifications. For example, a robot's maximum load capacity may be much larger than its specified payload, but at the maximum level, it may become less accurate, may not follow its intended path accurately, or may have excessive deflections. The payload of robots compared with their own weight is usually very small. For example, Fanuc Robotics LR Mate™ robot has a mechanical weight of 86 lbs and a payload of 6.6 lbs, and the M-16i™ robot has a mechanical weight of 594 lbs and a payload of 35 lbs.

[redacted]

**Reach** Reach is the maximum distance a robot can reach within its work envelope. As we will see later, many points within the work envelope of the robot may be reached with any desired orientation (called dexterous). However, for other points, close to the limit of robot's reach capability, orientation cannot be specified as desired (called nondexterous point). Reach is a function of the robot's ~~joint~~ LINK lengths and its configuration. ☆

[redacted]

[illegible] PRECISION IS WELL

**~~Precision~~ (validity)** ~~Precision is defined as~~ how ~~accurately~~ a specified point can be reached. This is a function of the resolution of the actuators, as well as its feedback devices. Most industrial robots can have ~~precision~~ of 0.001 inch or better.

[redacted]

[illegible] ACCURATELY

**Repeatability (variability)** Repeatability is how ~~accurately~~ the same position can be reached if the motion is repeated many times. Suppose that a robot is driven to the same point 100 times. Since many factors may affect the accuracy of the position, the robot may not reach the same point every time, but will be within a certain radius from the desired point. The radius of a circle that is formed by this repeated motion is called repeatability. Repeatability is much more important that precision. If a robot is not precise, it will generally show a consistent error, which can be predicted and thus corrected through programming. As an example, suppose that a robot is consistently off 0.05 inch to the right. In that case, all desired points can be specified at 0.05 inch to the left, and thus the error can be eliminated. However, if the error is random, it cannot be predicted and thus cannot be eliminated.

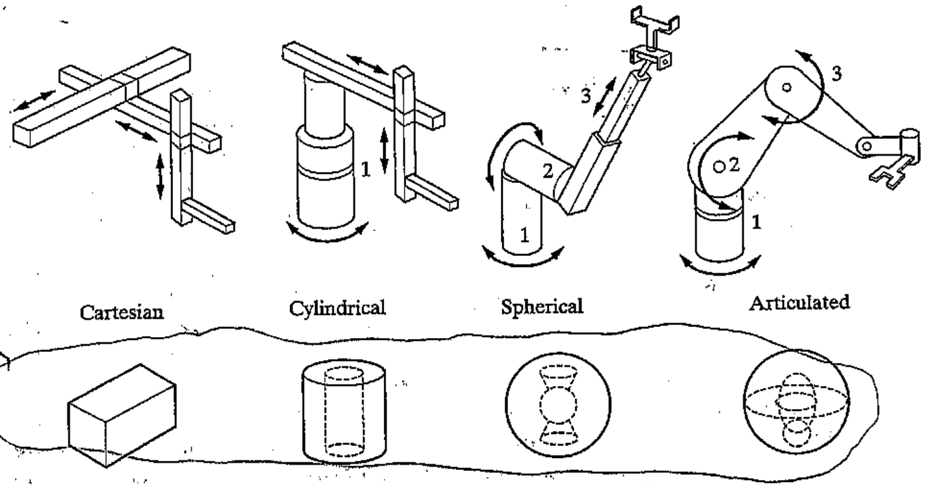
Repeatability defines the extent of this random error. Repeatability is usually specified for a certain number of runs. More tests yield larger (bad for manufacturers) and more realistic (good for the users) results. Manufacturers must specify repeatability in conjunction with the number of tests, the applied payload during the tests, and the orientation of the arm. For example, the repeatability of an arm in a vertical direction will be different from when the arm is tested in a horizontal configuration. Most industrial robots have repeatability in the 0.001 inch range.

## 1.14 ROBOT WORKSPACE "ENVELOPE"

Depending on their configuration and the size of their links and wrist joints, robots can reach a collection of points called a workspace. The shape of the workspace for each robot is uniquely related to its characteristics. The workspace may be found mathematically by writing equations that define the robot's links and joints and including their limitations, such as ranges of motions for each joint [4]. Alternatively, the workspace may be found empirically, by moving each joint through its range of motions and combining all the space it can reach and subtracting what it cannot reach. Figure 1.7 shows the approximate workspace for some common configurations. When a robot is being considered for a particular application, its workspace must be studied to ensure that the robot will be able to reach the desired points. For accurate workspace determination, please refer to manufacturers' data sheets.

## 1.15 ROBOT LANGUAGES

There are perhaps as many robotic languages as there are robots. Each manufacturer designs its own robotic language, and thus, in order to use any particular



~ SORT OF
SEE MANUFACTURER DATA SHEETS

**Figure 1.7** Typical workspaces for common robot configurations.

robot, its brand of programming language must be learned. Many robot languages are based on some other common language, such as Cobol, Basic, C, and Fortran. Other languages are unique ~~and not directly~~ related to any other common language.

Robotic languages are at different levels of sophistication, depending on their design and application. This ranges from machine level to a proposed human intelligence level [5,6,7]. High-level languages are either interpreter based or compiler based.

Interpreter-based languages execute one line of the program at a time, and each line has a line number. The interpreter interprets the line every time it is encountered (by converting the line to a machine language that the processor can understand and execute) and executes each line sequentially. The execution continues until the last line is encountered or until an error is detected. The advantage of an interpreter-based language is in its ability to continue execution until an error is detected, which allows the user to run and debug the program portion by portion. Thus, debugging programs is much faster and easier. However, because each line is interpreted every time, execution is slower and not very efficient. Many robot languages, such as Unimation™ VAL® and IBM's AML® (A Manufacturing Language), are interpreter based [8,9].

Compiler-based languages use a compiler to translate the whole program into machine language (which creates an object code) before it is executed. Since the processor executes the object code during execution, these programs are much faster and more efficient. However, since the whole program must first be compiled, it is impossible to run any part of the program if any error is present. As a result, debugging compiler-based programs is much more difficult. Certain languages, such as AL©, are more flexible. They allow the user to debug the program in interpreter mode, while the actual execution is in compiler mode.

The following is a general description of different levels of robotic languages [5]:

+ COMPLETE CONTROL
+ COMPLETE UNDERSTANDING
− TEDIUS

ALL POWERFUL "
POSITION, VELOCITY
OR ACCELERATION
CONTROL

**Microcomputer Machine Language Level** In this level, the programs are written in machine language. This level of programming is the most basic and is very efficient, but difficult to understand and to follow. All languages will eventually be interpreted or compiled to this level. However, in the case of higher level programs, the user writes the programs in a higher level language, which is easier to follow and understand. SEE MOTOROLA MOTION CONTROL CHIPS

"
POSITION
CONTROL

**Point-to-Point Level** In this level (such as in Funky© and Cincinnati Milacron's T3©), the coordinates of the points are entered sequentially, and the robot follows the points as specified. This is a very primitive and simple type of program; is easy to use, but not very powerful. It also lacks branching, sensory information, and conditional statements.

ONLY
VELOCITY "
CONTROL

**Primitive Motion Level** In these languages, it is possible to develop more sophisticated programs, including sensory information, branching, and conditional
PRECISE PATHS

statements (such as VAL by Unimation™). Most languages of this level are interpreter based.

POSITION, VELOCITY, OR ACCELERATION CONTROL

**Structured Programming Level** Most languages of this level are compiler based, are powerful, and allow more sophisticated programming. However, they are also more difficult to learn.

FUTURE EXOWN ROBOTS,

**Task-Oriented Level** Currently, there are no actual languages of this level in existence. Autopass, proposed by IBM in the 1980s, never materialized. Autopass was supposed to be task oriented. This means that instead of programming a robot to perform a task by programming each and every step necessary to complete the task, the user was simply to mention the task, while the controller would create the necessary sequence. Imagine that a robot is to sort three boxes by size. In all existing languages, the programmer will have to tell the robot exactly what to do, which means that every step must be programmed. The robot must be told how to go to the largest box, how to pick up the box, where to place it, go to the next box, etc. In Autopass, the user would only indicate "sort," while the robot controller would create this sequence automatically.

EXAMPLE PRIMITIVE MOTION LANGUAGE

**Example 1.1**

The following is an example of a program written in VAL-II. This robotic language, released in 1979, is used with Unimation® and Puma® robots; it is interpreter based and allows for branching, sensory input, and output communication, straight-line movements, and many other features. For example, the user may define a distance "height" along the *a*-axis of the end effector that can be used with a command called APPRO (for approach) and DEPART in order to approach an object or depart from an object without collision. A command called MOVE will allow the robot to move from its present location to the next specified location. However, MOVES will do the same in a straight line. The difference is discussed in detail in Chapter 5. In the following listing, a number of different commands are described in order to show some of VAL-II's capabilities:

of END-EFFECTOR

ROBOTS MAY no FASTER

| | | |
|---|---|---|
| 1 | .PROGRAM TEST | Declaration of the program name. |
| 2 | SPEED 30 ALWAYS | Sets the speed of the robot. |
| 3 | height=50 | Specifies a distance for the liftoff and setdown points along the a-axis of the end effector. |
| 4 | MOVES p1 | Moves the robot in straight line to point p1. |
| 5 | MOVE p2 | Moves the robot to a second point p2 in joint interpolated motion. |
| 6 | REACTI 1001 | Stops the robot immediately if an input signal to port 1 goes high (is closed). |
| 7 | BREAK | Stops execution until the previous motion is finished. |
| 8 | DELAY 2 | Delays execution for 2 seconds. |
| 9 | IF SIG(1001) GOTO 100 | Checks input port 1. If it is high (closed), execution continues at line 100. Otherwise, execution continues with the next line. |
| 10 | OPEN | Opens the gripper. |

```
11   MOVE p5               Moves to point p5.
12   SIGNAL 2              Turns on output port 2.
13   APPRO p6, height      Moves the robot towards p6, but away from it a distance
                           specified as "height," along the a-axis of the gripper
                           (Tool frame). This is called a liftoff point.
14   MOVE p6               Moves to the object at point p6.
15   CLOSEI                Closes the gripper and waits until it closes.
16   DEPART height         Moves up along the z-axis of the gripper (Tool frame) a
                           distance specified by "height."
17   MOVE p1               Moves the robot to point p1.
18   TYPE "all done."      Writes the message to the monitor.
19 .END
```

EXAMPLE PRIMITIVE MOTION LANGUAGE

### Example 1.2

The following is an example of a program written in IBM's AML (A Manufacturing Language). The program is written for a 3P3R robot, with three prismatic linear positioning joints, three revolute orientation joints, and a gripper. Joints may be referred to by joint numbers <1, 2, 3, 4, 5, 6, 7>, where 1, 2, 3 indicate the prismatic joints; 4, 5, 6, indicates the revolute joints; and 7 indicates the gripper. The joints may also be referred to by index letters JX, JY, JZ, for motions along the *x*-, *y*-, *z*-axes, respectively, JR, JP, JY, for rotations about the Roll, Pitch, and Yaw axes (used for orientation), and JG, for the gripper.

There are two types of movements allowed in AML. MOVE commands are absolute. This means that the robot will move along the specified joint to the specified value. DMOVE commands are differential. This means that the joint will move the specified amount from wherever it is. Thus, MOVE (1, 10) means that the robot will move along the *x*-axis to 10 inches from the origin of the reference frame, whereas DMOVE (1, 10) means that the robot will move 10 inches along the *x*-axis from its current position. There is a large number of commands in AML, allowing the user to write sophisticated programs.

The following program will direct the robot to pick and place an object from one place to another. This is written to show you how a robotic program may be structured:

TOOL FRAME ORIGIN

```
10   SUBR( PICK-PLACE);                      Subroutine's name.
20   PT1: NEW <4., -24, 2, 0, 0, -13>;        Declaration of a location.
30   PT2: NEW <-2, 13, 2, 135, -90, -33>;
40   PT3: NEW <-2, 13, 2, 150, -90, -33, 1>;
50   SPEED (0.2);                            Specifies velocity of the robot (20% of full speed).
60   MOVE (ARM,0.0);                         Moves the robot (ARM) to its reset position at the
                                             origin of the reference frame.
70   MOVE (<1,2,3,4,5,6>,PT1);               Moves the arm to a point 1 above the object.
80   MOVE (7,3);                             Opens the gripper to 3 inches.
90   DMOVE (3, -1);                          Moves the arm down 1 inch along z-axis.
100  DMOVE (7,-1.5);                         Closes the gripper by 1.5 inches.
110  DMOVE (3, 1);                           Moves up 1 inch along z-axis to lift the object.
120  MOVE (<JX, JY, JZ, JR, JP, JY>, PT2);   Moves the arm to point 2.
130  DMOVE (JZ, -3);                         Moves the arm down 3 inches along z-axis to
                                             place the object.
```

ONE MOTOR MOVING

```
140  MOVE (JG,3);                Opens the gripper to 3 inches.
150  DMOVE (JZ, 11);             Moves the arm up 11 inches along the z-axis.
160  MOVE (ARM, PT3);            Moves the arm to point 3.
170  END;
```

## 1.16 ROBOT APPLICATIONS

Robots are best suited to work in environments where humans cannot perform the tasks. Robots have already been used in many industries and for many purposes. They can often perform better than humans and at lower costs. For example, a welding robot can probably weld better than a human welder, because the robot can move more uniformly and more consistently. In addition, robots do not need protective goggles, protective clothing, ventilation, and many other necessities that their human counterparts do. As a result, robots can be more productive and better suited for the job, as long as the welding job is set up for the robot for automatic operations and nothing changes and as long as the welding job is not too complicated. Similarly, a robot exploring the ocean bottom would require far less attention than a human diver. Also, the robot can stay underwater for long periods and can go to very large depths and still survive the pressure; it also does not require oxygen.

The following is a list of some applications where robots are useful. The list is not complete by any stretch of imagination. There are many other uses as well, and other applications find their way into the industry and the society all the time:

POWER!

① **Machine loading,** where robots supply parts to or remove parts from other machines (Figure 1.8). In this type of work, the robot may not even perform any operation on the part, but is only a means of handling parts within a set of operations.

REPEATABILITY!

② **Pick and place operations,** where the robot picks up parts and places them elsewhere (Figure 1.9). This may include palletizing, placing cartridges, simple assembly where two parts are put together (such as placing tablets into a bottle), placing parts in an oven and removing the treated part from the oven, or other similar routines.

SOME 7 DOF TO GET INTO UNI-BODIES

③ **Welding,** where the robot, along with proper setups and a welding end effector, is used to weld parts together. This is one of the most common applications of robots in the auto industry. Due to the robots' consistent movements, the welds are

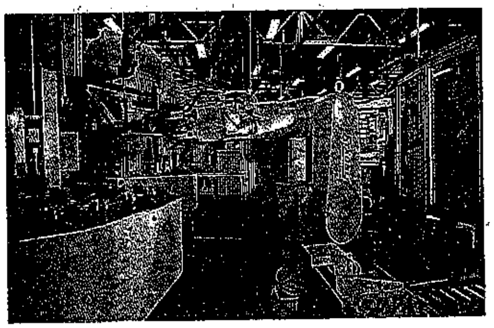


**Figure 1.8** A Staubli robot loading and unloading components into and from a machining center. Reprinted with permission from Staubli Robotics.

**Figure 1.9** Staubli robots placing dishwasher tubs into welding stations. Reprinted with permission from Staubli Robotics.

**Figure 1.10** An AM120 Fanuc robot. Reprinted with permission from Fanuc Robotics, North America, Inc.

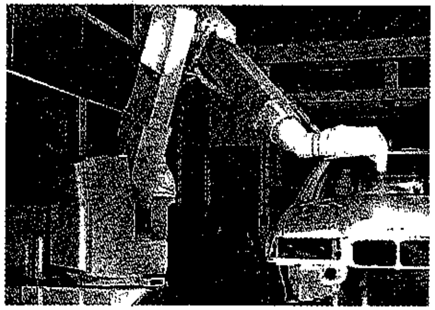


**Figure 1.11** A P200 Fanuc robot painting automobile bodies. Reprinted with permission from Fanuc Robotics, North America, Inc.

very uniform and accurate. Welding robots are usually large and powerful (Figure 1.10).

SAFETY
CONSISTANCY

**Painting** is another very common application of robots, especially in the automobile industry. Since maintaining a ventilated, but clean, room suitable for humans is difficult and compared with those performed by humans, robotic operations are more consistent, painting robots are very well suited for their job (Figure 1.11).

**Inspection** of parts, circuits boards, and other similar products is also a very common application for robots. In general, some other device is integrated into the system for inspection. This may be a vision system, an X-ray device, an ultrasonic detector, or other similar devices (Figure 1.12). In one application, a robot equipped

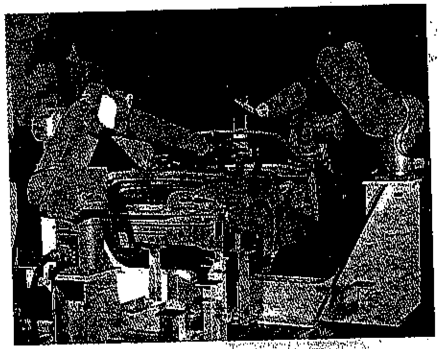


**Figure 1.12** Staubli RX FRAMS (Flexible Robotic Absolute Measuring System) robots in a BMW manufacturing facility. Reprinted with permission from Staubli Robotics.

with an ultrasound crack detector was given the computer-aided design (CAD) data about the shape of an airplane fuselage and wings, and was used to follow the airplane's body contours and check each joint, weld, or rivet. In a similar application, a robot was used to search for and find the location of each rivet, detect and mark the rivets with fatigue cracks, drill them out, and move on. The technicians would insert and install new rivets. Robots have also been extensively used for circuit board and chip inspection. In most such applications, including part identification, the characteristics (such as the circuit diagram of a circuit board, the nameplate of a part, etc.) of the part are stored in the system in a data library. The system uses this information to match the part with the stored data. The part is either accepted or rejected, based on the result of the inspection.

**Sampling** with robots is used in many industries, including in agriculture. Sampling can be similar to pick and place and inspection, except that it is performe
only on a certain number of products.

⑤ **Assembly operations** are among the most difficult for the robot to do. Usuall
assembling components into a product involves many operations. For example, th
parts must be located and identified, carried in a particular order with many obsta
cles around the setup, fitted together, and then assembled. Many of the fitting an
assembling tasks are complicated as well, and may require pushing, turning, ben
ing, wiggling, pressing, and snapping the tabs to connect the parts. Slight variatio
in parts and their dimensions due to larger tolerances also complicate the proces
since the robot has to know the difference between variations in parts and wro
parts.

⑥ MISC OTHER **Manufacturing** by robots may include many different operations, such as m
terial removal (Figure 1.13), drilling, deburring, laying glue, cutting, etc. It also i
cludes insertion of parts, such as electronic components into circuit boar
installation of boards into electronic devices such as VCR's, and other similar op
ations. Insertion robots are also very common and are extensively used in electr
ic industry.

**Surveillance** by robots has been tried, but was not too successful. However,
use of vision systems for surveillance has been very extensive, both in security
dustry and in traffic control. For example, in one part of the highway system

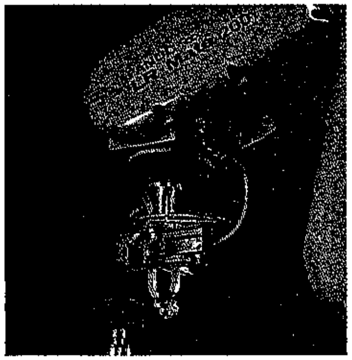


**Figure 1.13** A Fanuc LR Mate 200i robot is used in a material removal operation on a piece of jewelry. Reprinted with permission from Fanuc Robotics, North America, Inc.

Southern California, one lane of traffic has been leased out to private industry, which maintains the road and provides services, but also charges users. Surveillance cameras are used to detect the license plates of the cars that use the road, which are subsequently charged a toll for road use.

TELE-OPERATED

(7) **Medical applications** are also becoming increasingly common. For example, the Robodoc was designed to assist a surgeon in total-joint-replacement operations. Since many of the functions that are performed during this procedure, such as cutting of the head of the bone, drilling a hole in the bone's body, reaming the hole for precise dimension, and installation of the manufactured implant joint, can be performed by a robot with better precision AND ACCURACY than by a human, the mechanical parts of the operation are assigned to the robot. In addition, the orientation and the shape of the bone can be determined by CAT-scan and downloaded to the robot controller, where it is used to direct the motions of the robot for best fit with the implant. Similarly, many other robots have been used to assist surgeons during microsurgery, including operation on heart valves in Paris and Liepzig [10 ]. Another robot called da Vinci Surgical Robot, which is approved by U.S. Food and Drug Administration (FDA), was used to perform abdominal surgery [11].

SEE Dr. W, AI, Dupont research

(8) **Assisting disabled individuals** has also been tried with interesting results. There is much that can be done to help the disabled in their daily lives. In one study, a small table-top robot was programmed to communicate with a disabled person and to perform simple tasks such as placing a food plate into the microwave oven, removing the plate from the oven, and placing the plate in front of the disabled person to eat [12]. Many other tasks were also programmed for the robot to perform.

SAFETY!

(9) **Hazardous environments** are well suited for robotics use. Because of their inherent danger in these environments, humans must be well protected against the dangers. However, robots can access, traverse, maintain, and explore these areas without the same level of concern. Servicing a radioactive environment, for instance, can be done much easier with a robot than with a human. In 1993, an eight-legged robot called Dante was to reach the lava lake of constantly erupting volcano of Mount Erebus in Antarctica and study its gases [13].

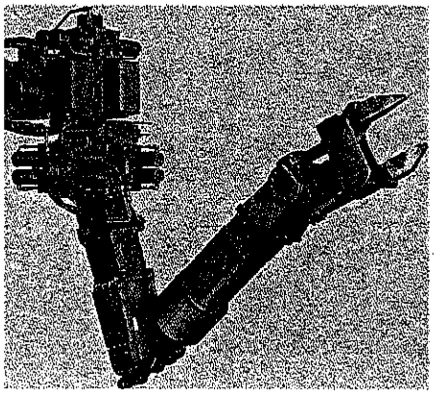


**Figure 1.14** The Arm, a six-degree-of-freedom bilateral force-feedback manipulator, used primarily on manned submersibles and remotely operated vehicles. Reprinted with permission from Western Space and Marine, Inc.

TELE-OPERATED PLUS SEMI-AUTONOMOUS

(10) **Underwater, space, and remote ~~locations~~** EXPLORATION can also be serviced or explored by robots. Although no human has yet been sent to Mars, there have been a number of rovers that have already landed and explored it [14]. The same is true for other space and underwater applications [15,16,17]. Until recently, for example, very few sunken ships were explored in deep oceans, because no one could access those depths. Many crashed airplanes, as well as sunken ships and submarines, are nowadays recovered quickly by underwater robots.

In an attempt to clean the smudge from inside of a steam generator blowdown pipe, a teleoperated robot called Cecil was designed to crawl down the pipe and wash away the smudge with a stream of water at 5,000 psi [18]. Figure 1.14 shows The Arm, a six-degree-of-freedom bilateral force-feedback manipulator, used primarily on manned submersibles and remotely operated vehicles. The Arm is controlled via a remote master that also "feels" everything that the slave arm "feels." The system can also perform preprogrammed motions through a teach-and-repeat system.

In another application, a telerobot was used for microsurgery [19]. In this case, the location of the telerobot is of secondary concern. The primary intention is to have the telerobot repeat the surgeon's hand movements at smaller scale for reduced tremor during microsurgery.

## 1.17 OTHER ROBOTS AND APPLICATIONS

With the same interest that helped scientists and engineers design human-like robots, other robots have been designed to imitate insects and other animals. Examples include six- and eight-legged robots [20,21], wormlike robots [22], snakelike robots [23,24], robots that swim like a fish [25], a robot that behaves like a dog, a Lobster-like robot [26], and unidentified life forms [27]. Some of these robots, such as Odetics, Inc. Odex robot [28], are very large and powerful; others are very small and lightweight. Most of these robots are developed for research purposes.

11

12

However, others are designed to be used in military operations [28], in medical operations, or for entertainment. In one case, a small robotic mine-sweeper was developed to search for mines and to explode them. The rationale is that it is far better to destroy a low-cost robot in exploding a mine than it is to lose a life or have casualties [29].

Animatronics refers to the design and development of systems that are used in animated robotic figures and machines that look and behave like humans and other animals. Examples include animatronic lips [30], eyes [31] , and hands. As more sophisticated animatronic components become available, the action figures they replace become increasingly real.

13

Another area that is somewhat related to robotics and its applications is Micro-Electro-Mechanical-Systems (MEMS). These are microlevel devices that are designed to perform functions within a system, which may include medical, mechanical, electrical, and physical tasks. For example, a microlevel robotic device may be sent through major veins to the heart for exploratory or surgical functions, a MEMS sensor may be used to measure the levels of various elements in blood, or a MEMS actuator may be used to deploy automobile airbags in a collision [32,33].

## 1.18 SOCIAL ISSUES

One has to always consider the social consequences that may result from using robots. Although there are many applications for which robots are used because there are no workers who can do the same job, there are many other applications for which a robot replaces a human worker. The worker who is replaced by a robot will lose his or her income. If the trend continues without consideration, it is conceivable that there may be a situation where most products are made by robots, without the need for any human workers. The result will be increasingly fewer workers with jobs, who lack the money to buy the products the robots make. More importantly, the issue to consider is the social and economic problems that arise as increasingly more workers become unemployed. One of the important points of negotiations between the automobile manufacturers and the United Auto Workers (UAW) is how many human jobs, and at what rate, may be replaced by robots.

Although no solution is presented in this writing, many references are available for further study of the problem [34,35]. However, as an engineer who strives to make better products at lower costs, and who may consider the use of robots to replace a human worker, one must always remember the consequences of this choice. Our academic and professional interest in robotics must always be intertwined with the social and economic considerations of robotics.

## 1.19 SUMMARY

Many people interested in robotics have some knowledge about robots, and, in many cases, they have had some interaction with robots. However, it is necessary that certain ideas be understood by everyone. In this chapter, we discussed some