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Fundamentals

1.1 Introduction

Robotics, the fascinating world of creating devices that mimic living creatures and are capable of performing tasks and behaving as if they are almost alive and able to understand the world around them, has been on humans' minds since the time we could build things. You may have seen machines made by artisans, which try to mimic humans' motions and behavior. Examples include the statues in Venice's San Marcos clock tower that hit the clock on the hour, figurines that tell a story in the fifteenth century astronomical clock on the side of the Old Town Hall tower in Prague, and the systems that Leonardo da Vinci sketched in his notebooks. Toys, from very simple types to very sophisticated machines with repeating movements, are other examples. In Hollywood, movies have even portrayed robots and humanoids as superior to humans.

Although humanoids, autonomous cars, and mobile robots are fundamentally robots and are designed and governed by the same basics, in this book we primarily study industrial manipulator-type robots. This book covers some basic introductory material that familiarizes you with the subject; presents an analysis of the mechanics of robots including kinematics, dynamics, and trajectory planning; and discusses the elements that are used in robots and in robotics, such as actuators, sensors, vision systems, and so on. Robot rovers are no different, although they usually have fewer degrees of freedom (DOF) and generally move in a plane. Exoskeletal and humanoid robots, walking machines, and robots that mimic animals and insects have many DOF and may possess unique capabilities. However, the same principles we learn about manipulators apply to robot rovers too, whether kinematics, differential motions, dynamics, or control.

Robots are very powerful elements of today's industry. They are capable of performing many different tasks and operations, are accurate, and do not require common safety and comfort elements humans need, including in hazardous environments such as underwater, disaster areas, and space. However, it takes much effort and many resources to make a robot function properly. Most of the hundreds of companies that made robots in the mid-1980s are gone; and, with few exceptions, only companies that make real industrial robots have remained in the market (such as OMRON Adept, Stäubli, ABB, FANUC, KUKA, Epson, Motoman, DENSO, Fuji, Yaskawa, Kawasaki, and Universal Robots, as well as specialty robotic companies such as MAKO Surgical Corp., and Intuitive). Although there are several million robots working in factories, and the numbers are growing, early industrialists' predictions about the possible number of robots in industry never materialized because high expectations could not be met with the present robots. Innovations such as artificial intelligence embedded in robots, and new types of robots (such as parallel robots), have improved the situation and will continue to do so. However, robots are used where they are useful. Like humans, robots can do certain things but not others. As long as they are designed properly for the intended purposes, they are very useful and continue to be used. Current predictions indicate sustained growth in the number of robots used in industry in many different forms, from manufacturing and assembly to self-driving delivery robots, and from autonomous vehicles to domestic workers [1–4].

The subject of robotics covers many different areas. Robots alone are hardly ever useful: they are used together with peripheral devices 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 robot manipulator with a crane attached to, let's say, a utility or towing vehicle, you will notice that the robot manipulator is very similar to the crane. Both possess 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 placed in any desired location within the workspace of the system. Each one can carry a certain load, and in each, a central controller controls the actuators. However, one is called a *robot*, and the other is called a *manipulator* (or, in this case, a *crane*). Similarly, material-handling manipulators that move heavy objects in manufacturing plants look just like robots, but they are not robots. The fundamental difference between the two is that the crane and the manipulator are controlled by a human who operates and controls the actuators, whereas the robot manipulator is controlled by a computer or microprocessor that runs a program (Figure 1.1). This difference 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 under the supervision of the computer, which is running some type of program. Therefore, if the program is changed, the actions of the robot will change accordingly. The intention is to have a device that can perform many different tasks; consequently, it is very flexible in what it can do without having to be redesigned. Therefore, the robot is designed to be able to perform many tasks based on the running program(s) simply by changing the program. The simple manipulator (or the crane) cannot do this without an operator running it all the time.

Different countries have different standards for what they consider a robot. In American standards, a device must be easily reprogrammable to be considered a robot. Therefore, manual handling devices (devices that have multiple degrees of freedom and are actuated by an operator) and fixed-sequence robots (devices

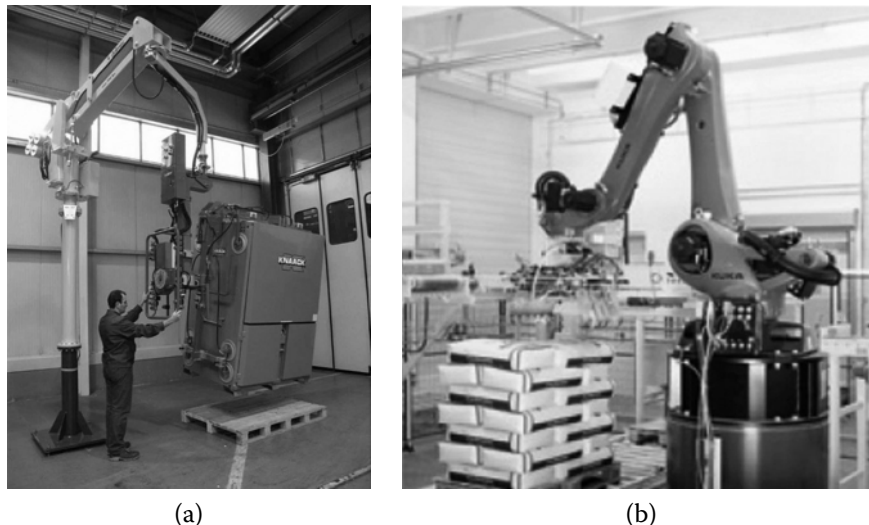


Figure 1.1 (a) A Dalmec manipulator; (b) a KUKA robot. Although they are both handling large loads, one is controlled by a human operator and the other is controlled by a controller. *Source:* Reproduced with permission from Dalmec USA and Kuka Robotics.

controlled by hard stops to control actuator motions on a fixed sequence, which is difficult to change) are not considered robots.

1.3 Classification of Robots

The following is a general list of classifications of devices that are considered robots. Different countries have different classifications, and, consequently, the number of robots in use in a country may be influenced by the definition:

- *Fixed-sequence robot*: A device that performs the successive stages of a task according to a predetermined, unchanging method that is hard to modify.
- *Playback robot*: A human operator performs a task manually by leading the robot, which records the motions for later playback. The robot repeats the same motions according to the recorded information.
- *Numerical-control robot*: The operator supplies the robot with a movement program rather than teaching it the task manually.
- *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.

1.4 What Is Robotics?

Robotics is the art, knowledge base, and 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. Robots may be used in manufacturing environments, in underwater and space exploration, in researching human and animal behavior, for aiding the disabled, for transportation and delivery, for military purposes, 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, cognitive sciences, 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 recent history, we can see a close relationship between the state of industry, the revolution in numeric and computer control of machinery, nuclear material handling, space exploration, and the vivid imagination of creative people. Starting with Karel Capek and his play *R.U.R. (Rossum's Universal Robots)* [5], and later, movies like *Flash Gordon*, *Metropolis*, *Lost in Space*, *The Day the Earth Stood Still*, and *Forbidden Planet* [6], the stage was set for a machine to be built to do a human's job (and, of course, R2D2, C3PO, Robocop, Transformers, the Bicentennial Man, and others continued the trend).

Capek dreamed of a scenario where a bioprocess could create human-like machines, devoid of emotions and souls, who were strong beyond 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 death would not matter. Eventually, the robots decided that they were actually superior to the humans, took over the whole world, and killed everyone. In this story, the word *rabota* or *worker* was coined, and it 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, multi-DOF manipulators were developed for work on nuclear materials. Integration

between the NC capability of machine tools and the manipulators created a simple robot. The first robots' movements were controlled using strips of paper with holes, which electric eyes could detect. As industry improved, the strip of paper gave way to magnetic tapes, memory devices, and personal computers and microprocessors. The following is a summary of events that have marked changes in the direction of this industry:

1922	Czech author Karel Capek wrote a story called <i>R.U.R. (Rossum's Universal Robots)</i> and introduced the word <i>rabota</i> (worker).
1946	George Devol developed the magnetic controller, a playback device. J. Presper Eckert and John Mauchly built the ENIAC computer at the University of Pennsylvania.
1952	The first numerically controlled machine was built at MIT.
1954	Devol developed the first programmable robot.
1955	Jacques Denavit and Richard Hartenberg developed kinematic notation for lower-pair mechanisms based on matrices.
1961	US patent 2,988,237 was issued to Devol for "Programmed Article Transfer," a basis for Unimate robots.
1962	Unimation was formed, the first industrial robots appeared, and GM installed its first robot from Unimation.
1967	Unimation introduced the Mark II robot. The first robot was imported to Japan for paint-spraying applications.
1968	An intelligent robot called Shakey was built at the 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.
1983	Robotics became a very popular subject, both in industry as well as academia. Many programs in the nation started teaching robotic courses.
2000	The first <i>ASIMO</i> humanoid robot was introduced by Honda.
2001	The FDA approved the use of the <i>da Vinci</i> surgical robot in the United States.
2008	Universal Robots made the first collaborative robot (cobot) available to the market, followed by Rethink in 2011.
2010–present	Many new robots, autonomous vehicles, drones, sensors, and associated devices have appeared and have become common.

1.6 Advantages and Disadvantages of Robots

- Robotics and automation can, in many situations, increase productivity, safety, efficiency, quality, and consistency of products.
- Robots can work in hazardous environments (such as radiation, darkness, hot and cold, ocean bottoms, space, and so on) without the need for life support, comfort, or concern for safety.

- Robots need no environmental comfort like lighting, air conditioning, ventilation, and noise protection.
- Robots work continuously without tiring or fatigue or boredom. They do not get mad, do not have hangovers, and need no medical insurance or vacation.
- Robots have repeatable precision at all times unless something happens to them, or unless they wear out.
- Robots can be much more accurate than humans. Typical linear accuracies are a few ten-thousandths of an inch. New wafer-handling robots have micro-inch accuracies.
- Robots and their accessories and sensors can have capabilities beyond those of humans.
- Robots can process multiple stimuli or tasks simultaneously. Humans can only process one active stimulus.
- Robots replace human workers, causing economic hardship, worker dissatisfaction and resentment, and the need for retraining the replaced workforce.
- Robots lack the 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 other machines that are working with them [7]. This includes:
 - Inappropriate or wrong responses
 - Lack of decision-making power
 - Loss of power
 - Damage to the robot and other devices
 - Injuries to humans
- Robots, although superior in certain senses, have limited capabilities in:
 - Cognition, creativity, decision making, and understanding
 - Degrees of freedom and dexterity
 - Sensors and vision systems
 - Real-time response
- Robots are costly due to:
 - Initial cost of equipment and installation
 - Need for integration into the manufacturing processes
 - 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, which consists of the links, joints, and other structural elements of the robot. Without other elements, the manipulator alone is not a robot. Figure 1.2 shows the manipulator part of an industrial 6-axis robot.

End effector. This is the part that is connected to the last joint (hand) of a manipulator and that generally handles objects, makes connection to other machines, or performs required tasks (Figure 1.3). 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 attaching specialty end effectors that are specifically designed for a purpose. It is the job of a company's engineers or outside consultants to select, or design and install, the end effector on the robot and to make it work for the given situation. Welding torches, paint spray guns, glue-laying devices, and parts handlers are but a few examples. In most cases, either the action of the end effector is controlled by the robot's controller (through the signals it sends to the end effector), or the controller communicates with the end effector's controlling device (such as a programmable logic controller [PLC]).



Figure 1.2 The 6-axis Yaskawa GP7 robot body. *Source:* Reproduced with permission from Yaskawa Electric.



(a)



(b)

Figure 1.3 End effectors: (a) A FANUC robot. *Source:* Courtesy of Fanuc America Corp. (b) A Sawyer robot. *Source:* Courtesy of Rethink Robotics GmbH.

Actuators. Actuators are the “muscles” of the manipulators. The controller sends signals to the actuators, which in turn move the robot’s joints and links. Common types are servomotors, stepper motors, pneumatic actuators, and hydraulic actuators. Other novel actuators are used in specific situations (this will be discussed later, in Chapter 9). Actuators are under the control of the controller.

Sensors. Sensors are used to collect information about the internal state of the robot or to communicate with the outside environment. The robot controller needs to know where each link of the robot is in order to know what the robot’s configuration is. It is similar for a human: when you wake up, even without opening your eyes, or when it is completely dark, you still know where your arms and legs are. This is because feedback sensors in your central nervous system, embedded in muscle tendons, send information to your brain. The brain uses this information to determine the length of your muscles and, consequently, the state of your arms, legs, and so on. The same is true for robots, where sensors, integrated into the robot, send information about each joint or link to the controller, which determines the configuration of the robot. Also, similar to your major senses of sight, touch, hearing, taste, smell, and speech, robots are equipped with external sensory

devices such as a vision system, touch and tactile sensors, a speech synthesizer, and so on, that enable the robot to communicate with the outside world.

Controller. The controller is rather similar to your cerebellum; although it does not have the power of the brain, it still controls your motions. The controller receives its data from the processor (the brain of the system), 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 sends a signal to the actuator (a current to an electric motor, air to a pneumatic cylinder, or a signal to a hydraulic servo valve), causing it to move. It then measures the change in the joint angle through the feedback sensor attached to the joint (a potentiometer, an encoder, and so on). When the joint reaches the desired value, the signal is stopped. In more sophisticated robots, the velocity of the end plate and the force exerted by the robot are also controlled by the controller.

Processor. The processor is the brain of the robot. It calculates the motions of the robot's joints based on the programs it runs, 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 this purpose. It requires an operating system, programs, and peripheral equipment like a monitor, and it has the same limitations and capabilities. In some systems, the controller and the processor are integrated together into one unit. In others, they are separate units. And in some, although the controller is provided by the manufacturer, the processor is not; the manufacturer expects the user to provide their own processor.

Software. Three groups of software programs are used in a robot. (i) The operating system operates the processor. (ii) Robotic software 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. (iii) A collection of application-oriented routines and programs are developed in order to use the robot or its peripherals for specific tasks, such as assembly, machine loading, material handling, and so on. This includes additional vision routines when the robot is equipped with a vision system.

1.8 Robot Degrees of Freedom

As you may already know, in order to locate a point in space, we need to specify three coordinates (such as x -, y -, and z -coordinates along the three Cartesian axes). Three coordinates are necessary and adequate to completely define the location of the point. Although different coordinate systems may be used to express this information, they are always necessary. However, neither two nor four will be possible; two is inadequate to locate a point in space, and four is illogical as there is simply too much information. For example, a device like a crane can move to any location within its workspace.

To locate a rigid body (a three-dimensional object rather than a point) in space, we first need to specify the location of a selected point on it, and therefore we require three pieces of information. Next, we also need to specify the orientation of the object to fully specify it in space. This means that six pieces of information are needed to fully specify the location and orientation of a rigid body. By the same token, there need to be 6 degrees of freedom (DOF) available to fully place the object in space and also orientate it as desired.

For this reason, robots need to have 6 DOF to be able to freely place and orientate objects within their workspace. A robot that has 6 DOF can be requested to place objects at any desired location and orientation. If a robot has fewer DOF, we cannot arbitrarily specify any location and orientation for the robot; it can only go to places and to orientations that the fewer joints allow. To demonstrate this, consider a robot with 3 DOF, 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 pick up a part and move it in space parallel to the reference axes. The orientation always remains the same. Now consider another robot with 5 DOF, 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 -, but not z -, axes. The same is true for any other robot configurations.

A system with 7 DOF would not have a unique solution. This means that if a robot has 7 DOF, there are infinite ways it can position a part and orient it at the desired location. In order for the controller to know what to do, there must be an additional decision-making routine that allows it to pick only one of the infinite solutions. As an example, we 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 7-DOF 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. In either case, the robot has an additional degree of freedom, which, based on the previous discussion, is impossible to control. The robot can be at a desired location and orientation from infinite distinct positions on the conveyor belt or mobile platform. However, in this case, the additional DOF are known, and there is no need to solve for them. When a robot is mounted on a conveyor belt or a track, as shown in Figure 1.4, 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 DOF is still 6 and, consequently, unique. As long as the location of the base of the robot on the belt or the location of the mobile platform is known (or selected by the user), there is no need to find it by solving the set of equations of robot motions; and as a result, the system can be solved.



Figure 1.4 The robot can move along a track, adding a degree of freedom to the system. *Source:* Reproduced with permission from Kuka Robotics.

Can you determine how many DOF the human arm has? This should exclude the hand (palm and fingers) but should include the wrist. Think about this before going on.

The human arm has three joint clusters: the shoulder, the elbow, and the wrist. The shoulder has 3 DOF, since the upper arm (humerus) can rotate in the sagittal plane (parallel to the midplane of the body), in 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 3 DOF. It can abduct and adduct, and flex and extend; and since the radius bone can roll over the ulna, it can rotate longitudinally (pronate and supinate). Consequently, the human arm

has a total of 7 DOF, even if the ranges of some movements are small. Since a 7-DOF system does not have a unique solution, how do you think we can use our arms?

Note that the end effector of the robot is never included in the DOF count. 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 DOF.

In some cases, the movements of a joint may not be fully controllable. For example, when a pneumatic actuator is used to move a joint, it can only be fully turned on or off (fully extended or fully retracted), but nothing in between. In this case, the convention is to assign only a half a 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 half 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 therefore it has a partial degree of freedom.

Many industrial robots possess fewer than 6 DOF. Robots with 3.5, 4, and 5 DOF are in fact very common. As long as there is no need for the additional DOF, these robots perform very well. As an example, suppose that you intend to insert electronic components into a circuit board. The circuit board is always laid flat on a known work surface; consequently, its height (z value) relative to the base of the robot is known. Therefore, there is only a need for 2 DOF along the x - and y -axes to specify any location on the board for insertion. Additionally, suppose that the components are to be inserted in any direction about the vertical axis. In that case, there is a need for one degree of freedom to rotate about the vertical axis (z) in order to orient the component above the surface. Since there is also a need for half a degree of freedom to fully extend the end effector to insert the part or to fully retract it to lift the end effector before moving, only 3.5 DOF are needed: 2 to move over the board, 1 to rotate the component, and 0.5 to insert or retract. Insertion robots are very common and are extensively used in electronic industry. Their advantage is that they are simple to program, less expensive, 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 DOF can achieve, but they can perform a variety of functions within this design limit.

1.9 Robot Joints

Robots may have different types of joints, such as linear, rotary, sliding, and spherical. Spherical joints are common in many systems, but they possess multiple DOF and therefore are difficult to control. Consequently, they are not common in robotics except in research [8]. Most robots have either a linear (*prismatic*) or a rotary (*revolute*) joint. Prismatic joints are linear; there is no rotation involved. They are either hydraulic or pneumatic cylinders or linear electric actuators. These joints are used in gantry, cylindrical, or spherical robots. Revolute joints are rotary, and although hydraulic and pneumatic rotary joints are common, most rotary joints are electrical, driven either by stepper motors or, more commonly, by servomotors.

1.10 Robot Coordinates

Robot configurations generally follow the common coordinate frames with which they are defined, as shown in Figure 1.5. 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, R, and/or S designations. 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 use three prismatic joints to position the end effector, usually followed by additional revolute joints that orient the end effector.

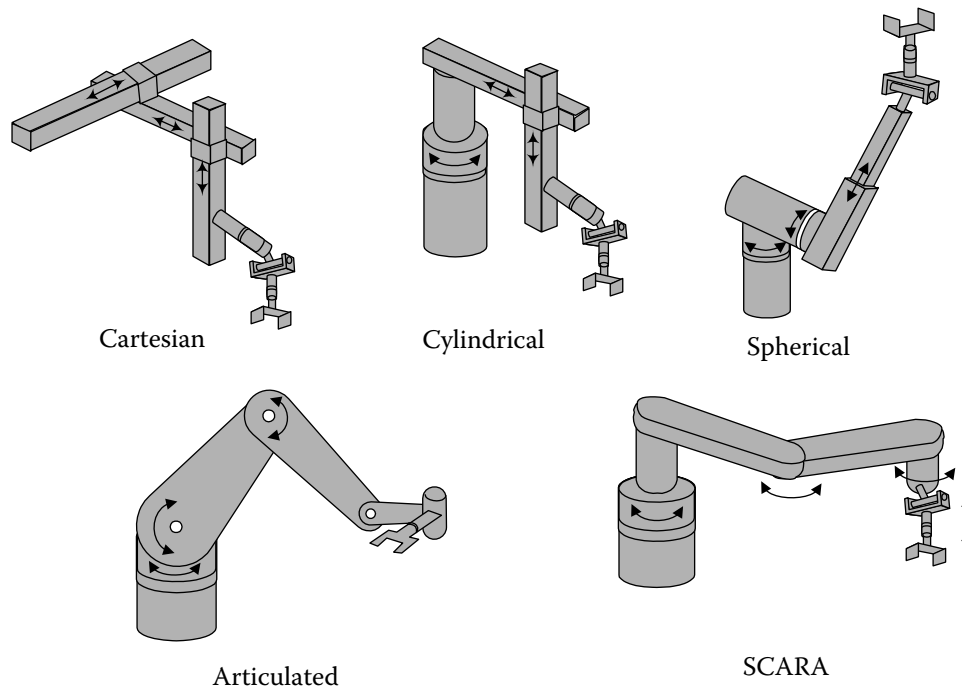


Figure 1.5 Common robot coordinate frames for serial robots.

- *Cylindrical (PRP)*: Cylindrical coordinate robots have two prismatic joints and one revolute joint for positioning the part, plus revolute joints for orientation.
- *Spherical (P2R)*: 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 the most common configuration for industrial robots.
- *Selective Compliance Assembly Robot Arm (SCARA)*: SCARA robots have two (or three) revolute joints that are parallel and allow the robot to move in a horizontal plane, plus an additional prismatic joint that moves vertically (Figure 1.6a). SCARA robots are very common in assembly operations.

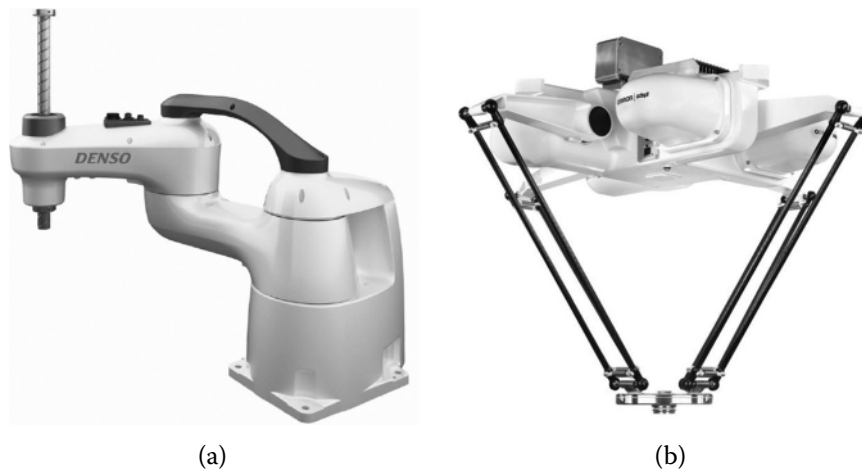


Figure 1.6 (a) A DENSO SCARA robot. *Source*: Courtesy of Denso Robotics. (b) The Adept Quattro s650H robot. *Source*: Omron Automation. © 2018 Omron. All Rights Reserved.

Their specific characteristic is that they are more compliant in the x - y plane but are very stiff along the z -axis, therefore providing selective compliance. This is an important issue in assembly, and will be discussed in Chapter 10.

- *Parallel robots:* Parallel robots differ in their configuration from serial robots and are discussed in Chapter 4. Figure 1.6b shows a typical parallel robot.

1.11 Robot Reference Frames

Robots may be moved relative to different coordinate frames as follows, resulting in different motions (Figure 1.7):

- *World reference frame:* This is a universal coordinate frame, as defined by x -, y -, and z -axes. In this case, the joints of the robot move simultaneously in a coordinated manner to create motions along the three major axes. In this frame, no matter where the arm is, a positive movement along the x -axis

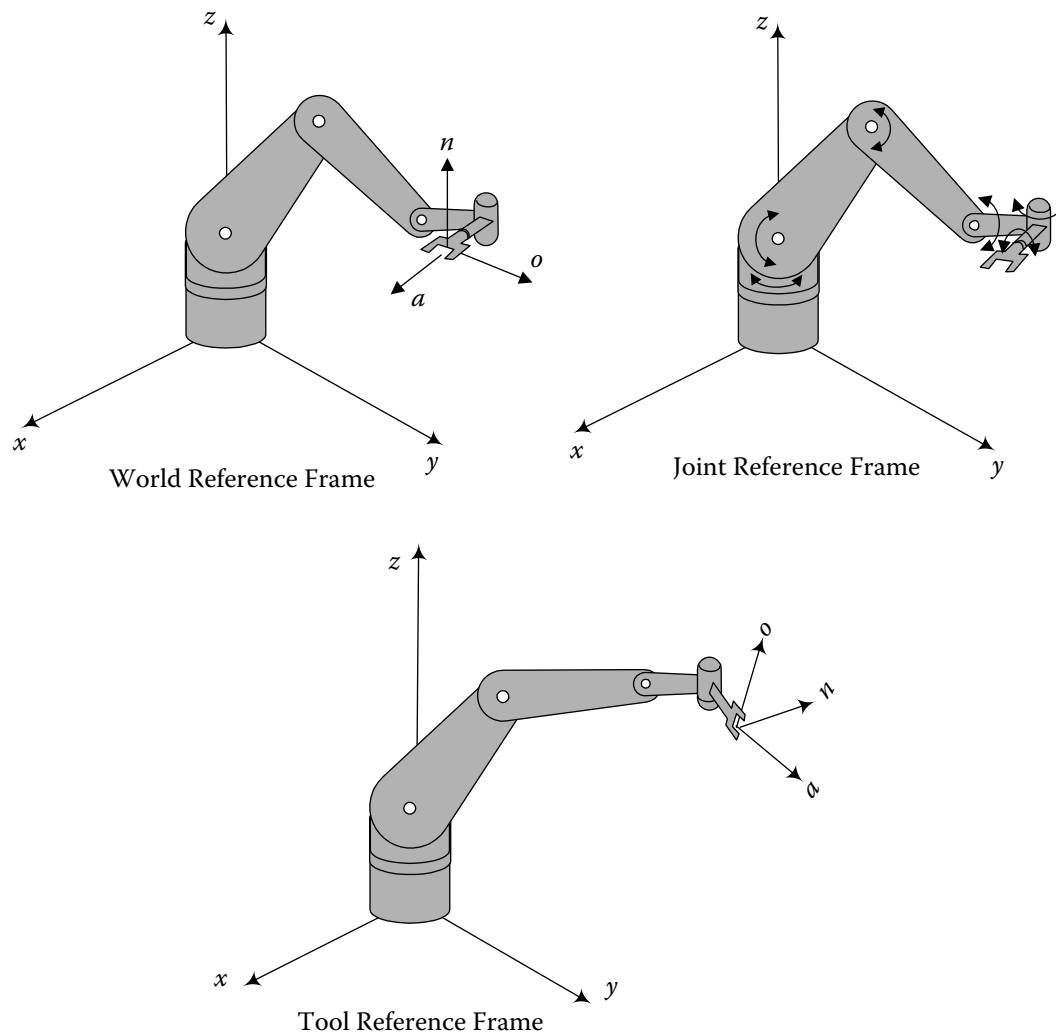


Figure 1.7 A robot's World, Joint, and Tool reference frames. Most robots may be programmed to move relative to any of these reference frames.

is always in the plus direction of the x -axis, and so on. The World reference frame is used to define the motions of the robot relative to other objects, define other parts and machines with which the robot communicates, and define motion trajectories.

- *Joint reference frame:* This is used to specify movements of individual joints of the robot. In this case, each joint is accessed and moved individually, and therefore only one joint moves at a time. Depending on the type of joint used (prismatic, revolute, or spherical) the motion of the robot hand is different. For instance, if a revolute joint is moved, the hand moves on a circle defined by the joint axis.
- *Tool reference frame:* This specifies movements of the robot's hand relative to a frame attached to the hand; consequently, all motions are relative to this local n,o,a -frame. Unlike the universal World frame, the local Tool frame moves with the robot. Suppose that the hand is pointed as shown in Figure 1.7. Moving the hand relative to the positive n -axis of the local Tool frame moves the hand along the n -axis of the Tool frame. If the arm were pointed elsewhere, the same motion along the local n -axis of the Tool frame would be completely different from the first motion. The same $+n$ -axis movement would be upward if the n -axis were pointed upward, and it would be downward if the n -axis were pointed downward. As a result, the Tool reference frame is a moving frame that changes continuously as the robot moves, and 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.

1.12 Programming Modes

Robots may be programmed in a number of different modes, depending on the robot and how sophisticated it is. The following programming modes are common:

- *Physical setup:* In this mode, an operator sets up switches and hard stops that control the motions of the robot. This mode is usually used along with other devices such as programmable logic controllers (PLCs).
- *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 location is entered (taught) into the controller. During playback, the controller moves the joints to the same locations and orientations. This mode is usually point-to-point, and as such, the motion between points is not specified or controlled. Only the points that are taught are guaranteed to be reached.
- *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 "wearing" the robot arm and moving it through its workspace. Painting robots, for example, may be programmed by skilled painters through this mode.
- *Software mode:* In this mode, a program is written offline or online 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 a working knowledge of the programming syntax 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*: This is the weight a robot can carry and still remain within its other specifications. As an example, a robot's maximum load capacity may be much larger than its specified payload, but at these levels, it may become less accurate, may not follow its intended path (trajectory) accurately, or may have excessive deflections. The payload of robots compared to their own weight is very small, usually only a few percent.
- *Reach*: This is the maximum distance a robot can reach within its work envelope. As will be seen later, much of the workspace of the robot may be reached with any desired orientation (called *dexterous* points). However, for other points close to the limit of the robot's reach capability, orientation cannot be specified as desired (called *non-dexterous* points). Reach is a function of the robot's joints and lengths of its linkages and its configuration. This is an important specification for industrial robots and must be considered before a robot is selected and installed.
- *Precision (validity)*: This is defined as how accurately a specified point can be reached. Precision is a function of the resolution of the actuators, as well as the robot's feedback devices. Most industrial robots can have precision in the range of 0.001 inches or better. The precision is a function of how many positions and orientations were used to test the robot, with what load, and at what speed. When the precision is an important specification, it is crucial to investigate these issues.
- *Repeatability (variability)*: This 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 exact same point every time, but be within a certain radius from the desired point. The radius of a circle that is formed by the repeated motions is called *repeatability*. Repeatability is much more important than precision. If a robot is not precise, it generally shows a consistent error, which can be predicted and, therefore, corrected through programming. As an example, suppose that a robot is consistently off by 0.05 inches to the right. In that case, all desired points can be specified at 0.05 inches to the left, thereby eliminating the error. However, if the error is random, it cannot be predicted, and, consequently, cannot be eliminated. Repeatability defines the extent of this random error. Repeatability is usually specified for a certain number of runs. A larger number of tests yields larger (bad for manufacturers) results, but 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 is different from when the arm is tested in a horizontal configuration. Most industrial robots have repeatability in the 0.001 inch range. It is crucial to find out about the details of repeatability if it is an important specification for the application.

1.14 Robot Workspace

Depending on their configuration and the size of their links and wrist joints, robots can reach a collection of points around them that constitute a *workspace*. The shape of the workspace for each robot is uniquely related to its design. The workspace may be found mathematically by writing equations that define the robot's links and joints, and which include their limitations such as ranges of motions for each joint [9]. Alternately, the workspace may be found empirically, by virtually moving each joint through its range of motions, combining all the space it can reach, and subtracting what it cannot reach. Figure 1.8 shows the

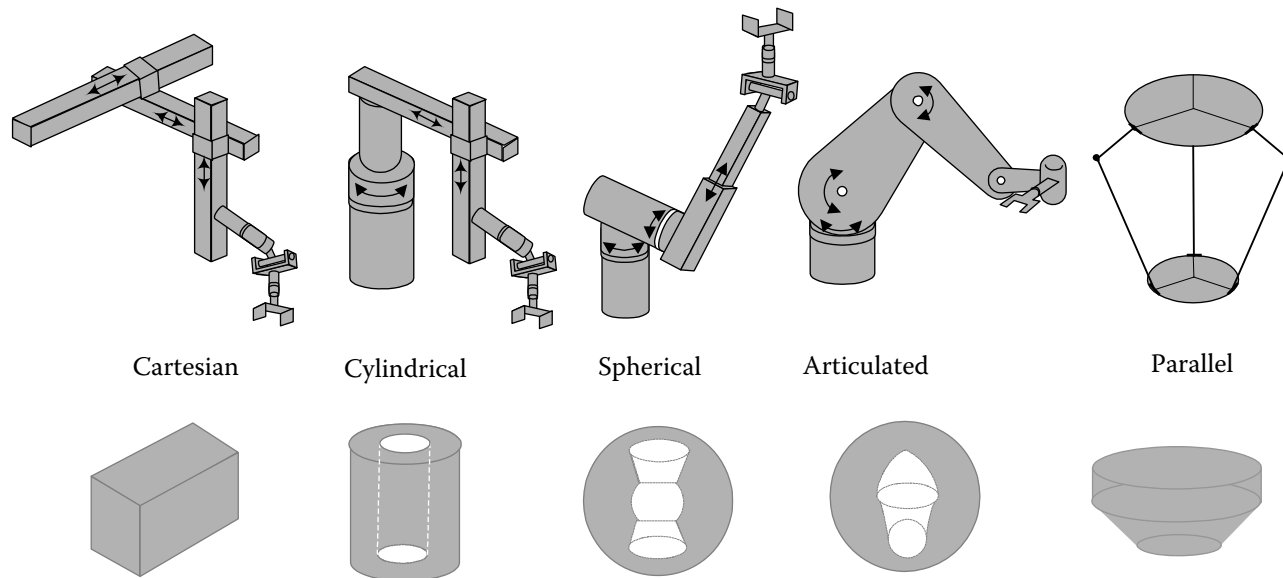


Figure 1.8 Typical approximate workspaces for common robot configurations.

approximate workspace for some common configurations. When a robot is considered for a particular application, its workspace must be studied to ensure that the robot is able to reach the desired points. Manufacturers' data sheets must be consulted for specific workspace information.

1.15 Robot Languages

There are perhaps as many robot languages as there are robot manufacturers. Each manufacturer designs its own robotic language, and therefore, in order to use any particular robot, its brand of the programming language must be learned. Many robot languages are based on common languages such as C++ and others. Other languages are stand-alone and do not relate 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 [10–13]. High-level languages are either interpreter-based or compiler-based.

Interpreter-based languages execute one line of the program at a time. Each line of the program has a line number. The interpreter interprets the line every time it is encountered (it converts the robot program to a machine language program 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, at which time execution stops. 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. As a result, debugging a program 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 OMRON Adept's V+ are interpreter-based.

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, 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 there are any syntax errors present, even before the logic of the program is tested. As a result, debugging a program is more difficult.

The following is a general description of different levels of robotic languages [11]:

- *Microcomputer machine language level:* At this level, programs are written in machine language. This level of programming is the most basic, and is very efficient, but it is difficult to understand and difficult for others 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 that is easier to follow and understand.
- *Point-to-point level:* At this level, 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 and is easy to use, but not very powerful. It also lacks branching, sensory information, and conditional statements.
- *Primitive motion level:* In these languages, it is possible to develop more-sophisticated programs, including sensory information, branching, and conditional statements. Most languages at this level are interpreter-based.
- *Structured programming level:* Most languages at this level are compiler-based, are powerful, and allow more sophisticated programming. However, they are also more difficult to learn.
- *Task-oriented level:* There are no actual languages in existence at this level – yet. AUTOPASS, proposed by IBM in the 1980s, never materialized. AUTOPASS was supposed to be task oriented, meaning that instead of programming a robot to perform a task by programming each and every step, the user would only mention the task, expecting that the controller would create the necessary sequence. Imagine that a robot is to sort three boxes by size. In all existing languages, the programmer has to specify every move and every step, including how to go to the largest box, how to pick up the box, where to place it, where to go to find the next box, and so on, even if a vision system or other sensory devices are used. In AUTOPASS, the user would only indicate “sort,” while the robot controller would create this sequence automatically. This never happened. With the advent of more-humanoid-type robots, robots are expected to understand conversations with humans. Although they are getting closer, they still need much direction.

Example 1.1 The following is an example of a program written in OMRON Adept’s V^+ , which is interpreter-based and allows for branching, sensory input and output communication, straight-line movements, and many other features. As an example, the user may define a distance “height” along the a -axis of the end effector Tool frame, which can be used with commands called APPRO (for approach) and DEPART in order to approach an object or depart from an object without collision. A command called MOVE allows the robot to move from its present location to the next specified location. However, MOVES does the same in a straight line. The difference is discussed in detail in Chapter 7. In the following listing, a number of different commands are described in order to show some of the capabilities of V^+ .

1	.PROGRAM TEST	Declares the program name.
2	SPEED 30 ALWAYS	Sets the speed of the robot.
3	height = 50	Specifies a distance for the lift-off and set-down points along the a -axis of the end effector Tool frame.

(Continued)

4	MOVES p1	Moves the robot in a 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 two 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 toward p6 but away from it a distance specified as “height” along the a -axis of the gripper (Tool frame). This is called a <i>lift-off point</i> .
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 a -axis of the gripper (Tool frame) a distance specified by “height.”
17	100 MOVE p1	Moves the robot to point p1.
18	TYPE “all done.”	Writes the message to the monitor.
19	.END	

Example 1.2 The following is an example of a program written in IBM’s AML (A Manufacturing Language). AML is no longer common. However, the example is provided to show how one language may differ from another one in its features and syntax. The program is written for a gantry 3P3R robot, with three prismatic positioning joints, three revolute orientation joints, and a gripper. Joints may be referred to by numbers <1, 2, 3, 4, 5, 6, 7>, where 1, 2, and 3 indicate the prismatic joints; 4, 5, and 6 indicate the revolute joints; and 7 indicates the gripper. The joints may also be referred to by index letters JX, JY, and JZ for motions along the x -, y -, and z - axes; JR, JP, and JY for rotations about the Roll, Pitch, and Yaw axes (used for orientation); and JG for the gripper. Note that since this robot is gantry, the path the robot takes is different from a revolute robot’s path. Therefore, the way it is programmed is also different. Instead of specifying a point, joint movements are specified, although all simultaneously.

There are two types of movements allowed in AML. MOVE commands are absolute. This means that the robot moves along the specified joint to the specified value. DMOVE commands are differential. This means that the joint moves the specified amount from wherever it is. Therefore, MOVE (1,10) means that the robot moves along the x -axis to 10 inches from the origin of the reference frame, whereas DMOVE (1,10) means that the robot moves 10 inches along the x -axis from its current position.

The following simple program directs the robot to pick an object from one location and place it at another. This is written to show you how a robotic program may be structured. Notice the differences between this and the previous program:

10	SUBR(PICK-PLACE);	Subroutine's name.
20	PT1: NEW <4, -24, 2, 0, 0, -13>;	Declares 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 the 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 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 the z-axis.
100	DMOVE (7,-1.5);	Closes the gripper by 1.5 inches
110	DMOVE (3, 1);	Moves up 1 inch along the 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 the z-axis to place the object.
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 for applications involving repetitive tasks, jobs requiring capabilities and precision beyond those of humans, and working in hazardous environments. Robots have already been used in many industries and for many purposes. They have excelled when they can perform better than humans or at lower costs. For example, a welding robot can probably weld better than a human welder in routine applications because it can move more uniformly and consistently along a prescribed path without needing protective goggles and clothing, ventilation, or other necessities. As a result, the robot can be more productive and better suited for the job as long as the task is set up for the robot, nothing happens to the setup, and the job is not too complicated. Similarly, a robot exploring the ocean floor requires far less attention than a human diver, can stay underwater for long periods of time, can go to very great depths and still survive the pressure, and yet does not require oxygen.

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

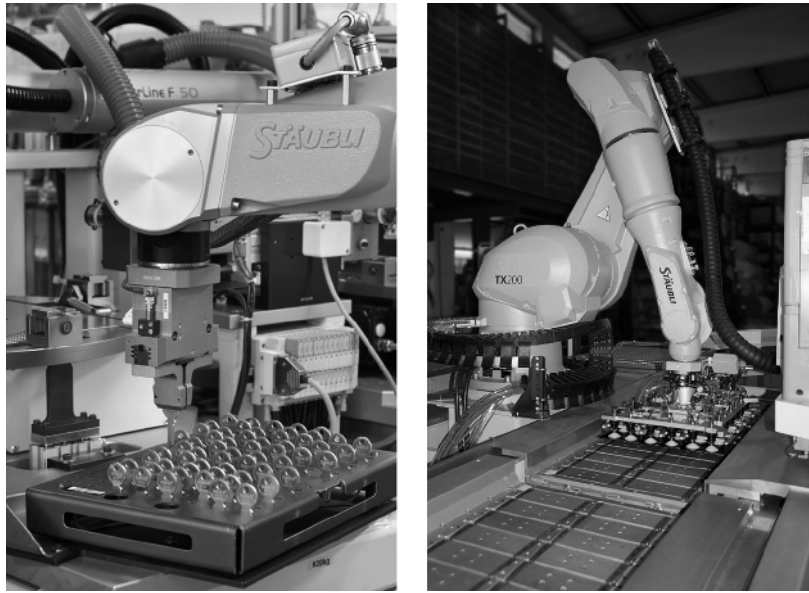


Figure 1.9 Robots performing loading and unloading of parts. *Source:* Reproduced with permission from Staubli.

Machine loading. Robots supply other machines with parts, or remove the processed parts from other machines (Figure 1.9). In this type of work, the robot may not even perform any operation on the part, but rather facilitates material and parts handling and loading other machines within the context of a task.

Pick and place operations. The robot picks up parts and places them elsewhere (Figure 1.10). This may include palletizing, placement of 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 parts from the oven, or other similar routines.

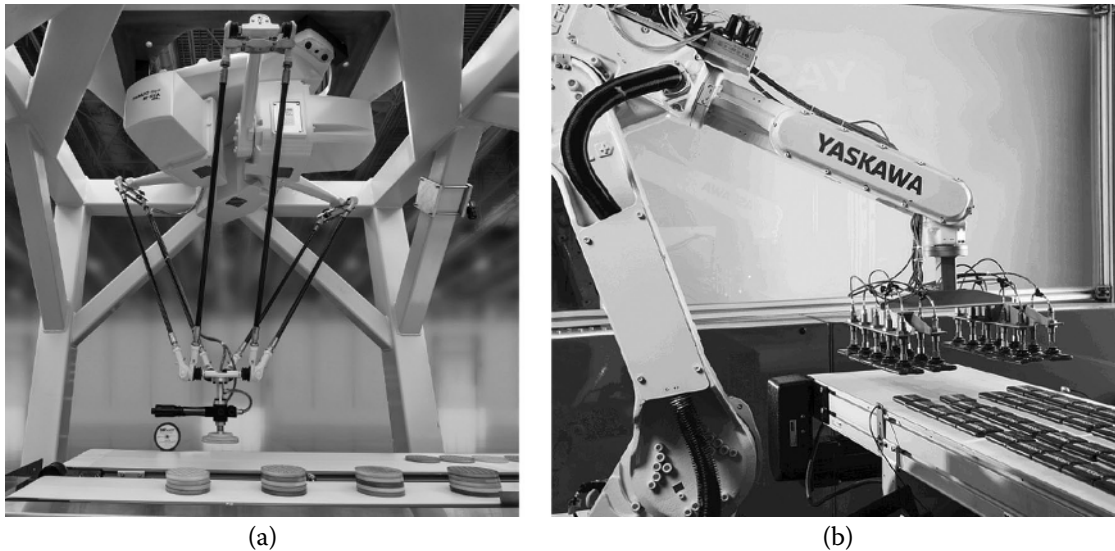


Figure 1.10 (a) A parallel robot stacking cookies. (b) A serial robot handling chocolate bars on a conveyor belt. *Source:* Reproduced with permission from Fanuc Robotics and Yaskawa Electric.

Welding. 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 their consistent movements, robotic welds are very uniform and accurate. Welding robots are usually large and powerful (Figure 1.11).

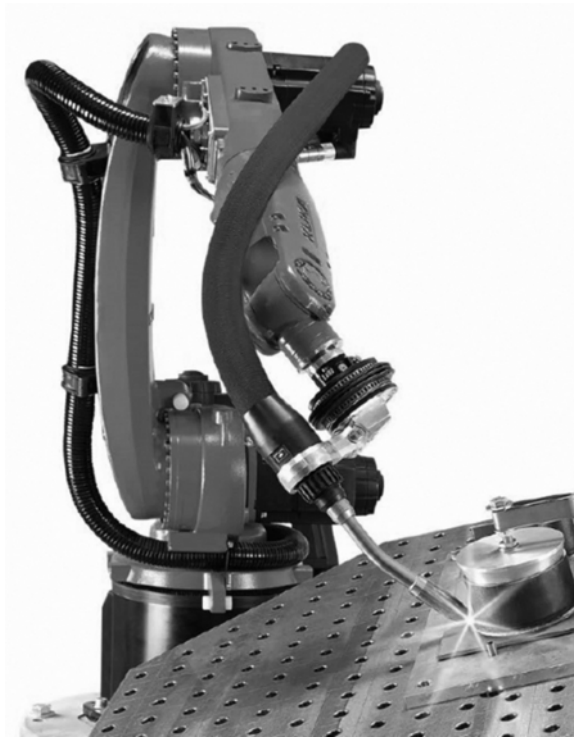


Figure 1.11 A robot welding parts together. *Source:* Reproduced with permission from Kuka Robotics.

Painting is another very common application of robots, especially in the automobile industry. Since maintaining a ventilated but clean paint area suitable for humans is difficult to achieve, and because compared to humans robotic operations are more consistent, painting robots are very well-suited for their job.

Inspection of parts, circuit boards, and other similar products is also a very common application for robots. In general, robots are one component of an inspection system that may include a vision system, an X-ray device, an ultrasonic detector, or other similar devices (Figure 1.12). In one application, a robot was equipped with an ultrasonic crack detector, was given the 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 would search for and find the location of each rivet, detect and mark the rivets with fatigue



Figure 1.12 A robot engaged in sorting and inspection of manufactured parts. *Source:* Reproduced with permission from Fanuc America Corporation.

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 applications like this, including part identification, the characteristics of the part (such as the circuit diagram of a board, the nameplate of a part, and so on) are stored in the system in a data library. The system uses this information to match the part with the stored data. Based on the result of the inspection, the part is either accepted or rejected.

Sampling with robots is used in the agriculture industry, as well as in many other industries. Sampling can be similar to pick-and-place and inspection, except that it is performed only on a certain number of products.

Assembly tasks usually involve many operations. For example, the parts must be located and identified, they must be carried in a particular order with many obstacles around the setup, and they must be fit together and then assembled. Many of the fitting and assembling tasks are complicated and may require pushing, turning, bending, wiggling, pressing, snapping tabs to connect the parts, and other operations. Slight variations in parts and their dimensions due to larger tolerances also complicate the process, since the robot has to know the difference between variations in parts and wrong parts. Figure 1.13 shows a Sawyer robot assembling an electronic circuit and a group of KUKA robots engaged in assembling a product.

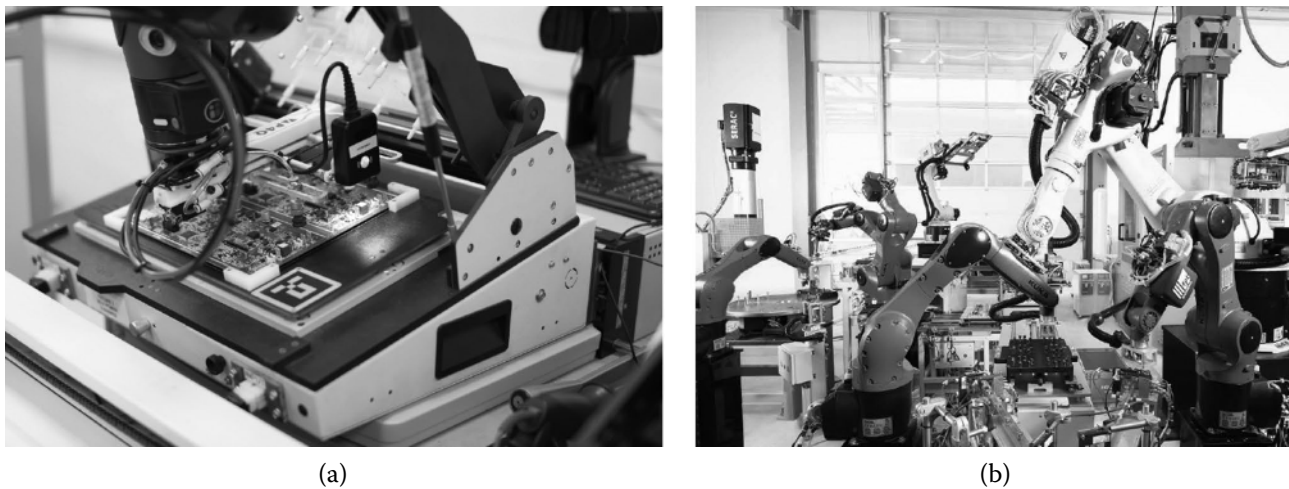


Figure 1.13 (a) A Sawyer robot inserting electronic parts into a circuit with its specialized end effector. *Source:* Courtesy of Rethink Robotics GmbH. (b) A group of KUKA robots on an assembly line. *Source:* Reproduced with permission from Kuka Robotics.

Manufacturing by robots may include many different operations, such as material removal, drilling, deburring, laying glue, cutting, and so on. It also includes insertion of parts, such as electronic components into circuit boards, installation of boards into electronic devices, and other similar operations. Insertion robots are very common and are extensively used in the electronic industry. Figure 1.14 shows a robot engaged in manufacturing.

Medical applications are also becoming increasingly common. Examples include Intuitive's *da Vinci* surgical robot, Stryker's Mako surgical robot, and many others under development at research universities [14–17]. Based on our earlier definition, surgical robots are not really robots because they are actually operated by a surgeon rather than operating on their own. No robot knows how to perform surgery, yet. However, these precision robots assist surgeons in performing surgery. Because of their accuracy, these robots can operate through much smaller incisions with more precise motions and can perform tasks such as cutting a bone, drilling holes, reaming for joint replacement, and much more. With the advanced haptic feedback provided by the robot, the surgeon can feel exactly as if they are doing the surgery. However, since the doctor does not have to be present in the operating room, conceivably they can operate remotely – an extremely important advantage that these robots provide. In addition, these robots have other capabilities that are



Figure 1.14 A robot engaged in a manufacturing task. *Source:* Reproduced with permission from Staubli Robotics.

beyond those of surgeons. For example, the CAT-scan image of a bone can be sent to the robot directly, allowing it to follow the bone's contour more precisely. The *da Vinci* robot possesses four arms: three that hold instruments (one more than a surgeon could) and one to hold a 3D imaging scope that displays the surgical area to a surgeon behind a monitor (Figure 1.15).

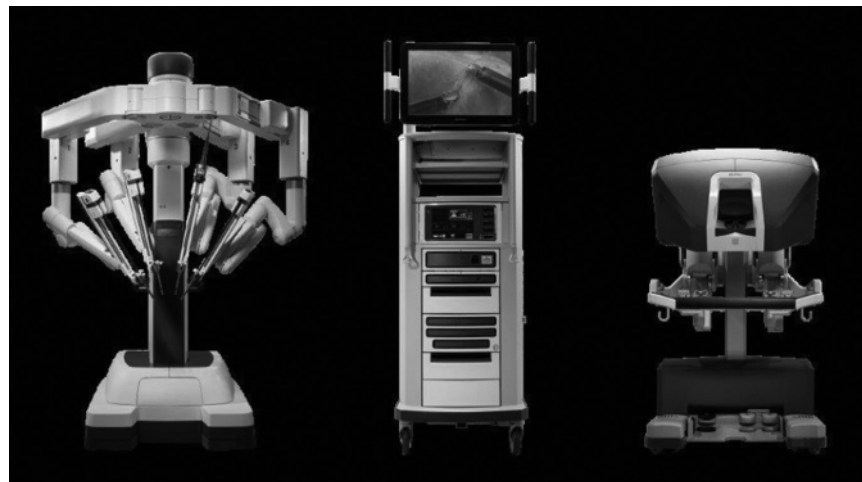


Figure 1.15 The *da Vinci* surgical system. *Source:* ©2019 Intuitive Surgical.

Assisting disabled individuals has also been tried with interesting results. Robots are well suited to help the disabled and elderly in many different ways, and many humanoid robots under development can be excellent choices for this purpose. In addition, many exoskeleton devices have been developed to help paraplegic persons walk. Examples include the ReWalk walker by ARGO Medical Technologies [18], which helps a paralyzed individual get up and walk, and the EksoGT suit that helps a patient with rehabilitation and correction of posture during recovery (Figure 1.16). Like surgical robots, these devices are not really robots, but they include much intelligence and autonomy. Work has also been done on reading brain signals to help a disabled person move with a robotic skeleton [19].

Another very different, and yet exceptional, application of robots is in providing a nurturing environment for kids with special needs. RoboKind's *Milo* robot and Blue Frog's *Buddy* robot are examples of robots that have been designed to have a "face" with changing expressions that can better relate to autistic children and adults and "make friends" with them in order to help them with social interactions [20, 21].

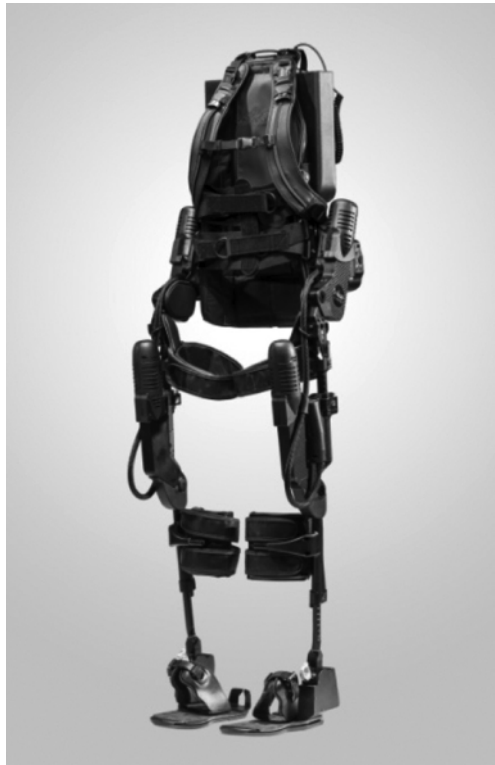


Figure 1.16 The *EksoGT* rehabilitation suit. *Source:* Reproduced with permission from EksoBionic.

The finger-spelling hand (Figure 1.17), designed for communication with deaf-blind individuals, is capable of making hand gestures that spell all the letters of the alphabet. With its 14 servomotors, the hand is mounted on an arm and can be held with one hand while the other hand reads the letters. Letters typed in a computer, emails, or text are coded and sent to the hand.



Figure 1.17 Finger-spelling hand for communication with deaf-blind individuals. Designed and built by Kendall Searing, Cal Poly, San Luis Obispo. Supported by the Smith Kettlewell Eye Research Institute.

Hazardous environments are well suited for robotics. Because of their inherent danger, in these environments humans must be well-protected. However, robots can access, traverse, maintain, and explore these areas without the same level of concern. Servicing a radioactive environment, for example, is easier with a robot than a human. In 1993, an eight-legged robot called Dante was supposed to reach the lava lake of the constantly erupting volcano of Mount Erebus in Antarctica and study its gases [22]. Robots were also used to clean up the Fukushima nuclear power plant in Japan after it was damaged by the tsunami of 2011.

A variety of mine-detecting and bomb-detonating robots have also been put to use with the idea that a robot may be expendable whereas a human is not. One such robot uses vibrating ultrasonic pods to identify underground mines, therefore eliminating the need for human searches [23]. Similarly, a crustacean-looking “lobster” robot was developed to search ocean bottoms for mines and other weapons [24].

Inaccessible locations, such as space, underwater, and mines can also be serviced or explored by robots. So far, it is still impractical to send a human to other planets, even Mars, but there have been a number of rovers (Figure 1.18) that have already landed and explored it [25]. In the last few years, underwater robots have also looked for, found, and explored sunken ships in deep oceans. Underwater robots have also been used to find crashed airplanes and to work on deep-water oil wells.



Figure 1.18 NASA Sojourner. *Source:* Courtesy NASA/JPL-Caltech.

In a project sponsored by the Defense Advanced Research Projects Agency (DARPA), the Aircrew Labor In-Cockpit Automation System (ALIAS) was tested to land a simulated Boeing 737 aircraft. The system, using its vision system and the aircraft’s autopilot, fully actuated the landing procedure [26].

Robots in agriculture can be very useful, especially in places where labor shortage or environmental conditions are important issues. Robotic pickers have been developed and tested around the world and are becoming more common. This includes orange pickers, strawberry pickers, and so on. [27]. Geneticists have developed dwarf trees and long-stem strawberries that hang on the side to facilitate robotic picking.

1.17 Other Robots and Applications

Since the first edition of this book was published, many new robots and issues have appeared. Such is the nature of this active field. Therefore, you should expect that there will be applications and robots that are not included in this edition either. However, the following are just a sample of some systems that show a trend and future possibilities.

A large number of humanoid robots have been developed that are meant to mimic humans in different ways for many different purposes, from domestic maids to factory workers to assisting military personnel. Robots such as Honda's *ASIMO*, BlueBotics' *Gilbert*, Nestle's *Nesbot*, Anybots's *Monty*, Aldebaran *NAO*, Boston Dynamics's *Atlas* (Figure 1.19) and many others are intelligent humanoid robots with human-like features and behavior. *Atlas* includes an advanced control-and-balance system that enables it to coordinate the motions of its extremities and torso in whole-body mobile manipulation, to keep its balance when jostled, and to get up if tipped over. It also includes a stereo vision system, range finders, and other sensors that enable it to see its environment and traverse rough terrain. *ASIMO* walks, runs, walks up and down a staircase, and interacts with people. *Nesbot* brings coffee to workers who have ordered it online [28]. *Monty* loads a dishwasher and does other chores, while *Robomower* mows your lawn while you read [29].



Figure 1.19 Atlas humanoid robot. *Source:* Image courtesy of Boston Dynamics.

A number of different robots have also been designed and used for emergency services during natural and human-caused disasters [30]. These robots, equipped with special sensors, are capable of looking for live humans and animals buried under rubble and reporting their locations to rescuers. Yaskawa Electric SDA10 dual-arm robots (Figure 1.20) have 15 axes of motion. The two arms can move independently or in a coordinated manner. They can transfer a part from one gripper to the other without the need to set it down. The Kawasaki *duAro* robot's dual arms are SCARA type and move in a coordinated manner; they can transfer and handle parts together or move independently. In addition, they are designed to be the size of



Figure 1.20 Dual-arm robots. *Source:* Reproduced with permission from Yaskawa Electric and from Kawasaki Robotics (USA), Inc.

a human. Therefore, they can be integrated into an assembly line or workspace without the need to change anything (this robot is also a collaborative robot; see Section 1.18).

Exoskeletal assistive devices, although not robots, are enablers. They enable a human to carry large loads for extended periods of time or to exert large forces in awkward positions. In fact, there is a certain synergy between these devices and assistive devices to help disabled individuals walk. Figure 1.21 shows *EksoVest*, a non-powered upper-body exoskeleton device that is worn by an individual: it elevates and supports the



Figure 1.21 The *EksoVest* suit. *Source:* Reproduced with permission from Ekso Bionic.

arm and assists in tasks above the chest and overhead (teachers know about shoulder problems caused by writing on the board in this manner). Other devices also help military personnel carry large loads for extended periods of time [31].

Figure 1.22 shows a large-scale, quadruped, all-terrain exoskeletal “anti-robot suit” called *Prosthesis*, by Furrion, designed to augment human skill and strength, with applications ranging from competitive sports to search and rescue to materials handling and more. As discussed earlier, based on the strict definition of a robot, *Prosthesis* is not really a robot because it is driven by an operator (pilot). But like other non-robots (such as surgical robots and exoskeletons), it is based on the same analysis and design principles.



Figure 1.22 The *Prosthesis* exoskeletal suit. Source: Jonathan Tippet, *Prosthesis*’s designer and inventor, produced by Furrion Exo-Bionic, of which Tippet is co-founder and CTO. Photo credit: Sam Carter.

Prosthesis has 12 actuators with 8 DOF in the legs (4 legs with 2 joints each), controlled by the pilot through the exoskeletal interface; and 4 DOF for the big tusks fore and aft, which are controlled independently from the cockpit using 2 joysticks. The tusks can be deployed or retracted to guard against falling over or to right the machine after falling.

The pilot wears an exoskeletal suit with which *Prosthesis* is driven. The pilot’s shoulders control the swing of the outer legs at the outer hips. The elbows control the bend of the outer legs at the knees. The pilot’s hips control the swing of the inner legs at the hips, and the knees control bend of the inner legs at the knees. The motions of *Prosthesis* make it feel like a gorilla moving on its four legs. The pilots state that, “With enough practice, it just starts to feel like you have an eight and a half thousand pound body and a 200 horsepower heart.” *Prosthesis* weighs nearly 3900 kg (8600 lbs). It is 4 m high, 5.5 m wide, and 5.1 m long, and it has about 200 kg (440 lbs) of lithium ion batteries that can power it for up to an hour. The actuators are hydraulic with electronically controlled valves. Its proprietary control system includes a human-in-the-loop element with 1:1 positional parity between the pilot and *Prosthesis* and 50–100 times amplification of pilot strength [32].

Other monster-sized devices include a humanoid bipedal robot called *Method-2*, a 13 ft, 1.5 ton robot that walks like a human, driven by an operator inside of it [33]; and NASA’s robotic titan, which is designed to help in the manufacture of massive composite parts for rockets, where exaggerated sizes and weights play important role [34].

There are also more humanoid-type robots on the factory floor, interacting and working with others. As time goes on, better robots, better communication skills, and more-sophisticated artificial intelligence will make coexistence between workers and robots more realistic [35, 36]. This includes a robot takeover of infrastructure maintenance and inspection duties such as the use of drones for offshore oil-platform inspection and robotic interior pipeline inspection [37].

In addition, many companies are testing simple mobile robots to do mundane and routine tasks, from moving items in warehouses and delivering to workstations, to more-sophisticated package delivery to customers

[38]. These are primarily 2D mobile robots with the capability to pick up and place items from shelves and tables, but with the intelligence to know their way around a warehouse or factory environment and to find items by codes such as a barcode (Figure 1.23).



Figure 1.23 A mobile transport robot. *Source:* Reproduced with permission from Locus Robotics.

At the other end of the spectrum, there are also some very tiny robots for other applications. For example, *RoboFly* is a flying robot slightly larger than a real fly, weighing about 190 mg, which can fly on its own without a battery. It develops its power from a solar panel powered by a laser beam that is projected on it [39]. A cell-sized robot that can sense its environment is meant to travel through the body or a pipeline and look for problems [40]. Researchers at the University of Texas in San Antonio are developing a nanoscale spherical robot that is 120 nanometers in size and is controlled remotely through electromagnetic fields. The intention is for the robot to deliver drugs or perform operations at the cellular scale in places where larger robots or drugs cannot reach [41].

As mentioned earlier, in addition to humanoid robots, other life-form robots such as insects, creatures, animals, and fish have been used for a variety of purposes. Some of these are designed and studied for their robotic aspects, others for specific applications, and yet others for the study of the animal's behavior. For example, in one study, small robotic roaches were doused with the roach's sex hormone. Real roaches that cannot see very well follow the robotic roach. Normally, they tend to congregate in dark places; however, researchers could alter the behavior of roaches by sending the robotic roach to unexpectedly lighter places. The real roaches would follow the robotic roaches against their instinct [42].

Other insect robots have also been designed for applications from pure research to entertainment and from civilian to military uses. They mimic six-legged insects, eight-legged insects, flying insects, swarms of insects, and more [43–45]. Developed at Ben-Gurion University and inspired by Spider-Man, *Spiderbot* is an insect robot that launches four (magnetic) grapples that stick to the ceiling, by which it pulls itself

up. It then releases the magnets one at a time, retracts them, and launches again to a new point [46]. Other application-oriented life-forms include worm-like robots; snake-like robots; robots that swim like fish; a lobster-like robot; a honey-bee robot; bird-like robots; “dinosaur” robots; a reconfigurable robot that flies, crawls, and navigates; as well as unidentified life forms [47–52]. Figure 1.24 shows *Spot*, a 30 kg robot in the form of a dog. It has the ability to pick up and handle objects with its 5-DOF arm and comes with perception sensors including stereo vision, depth cameras, and position and force sensors that help it with its navigation and manipulation. It can open doors and balance itself if pushed around. Unlike its predecessor *BigDog*, which had an onboard engine, *Spot* is all electric and can go for about 1.5 hours on a charge.



Figure 1.24 Boston Dynamics’ *Spot* robot. *Source:* Image courtesy of Boston Dynamics.

Animatronics refers to the design and development of systems used in animated robotic figures and machines that look and behave like humans and animals. Examples include animatronic lips, eyes, and hands [53, 54]. As more-sophisticated animatronic components become available, the action figures they replace become increasingly real.

Micro-electro-mechanical-systems (MEMS) have also been integrated into robotic design for different tasks. As an example, a micro-level 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. One device, so far only tested on animals, releases insulin from a post that pops out after it clings to the wall of an empty stomach; it is eventually eliminated by the user. If this device is approved for human use, it has the potential to relieve diabetics from their daily injections.

1.18 Collaborative Robots

Collaborative robots (also called *cobots*) are designed to safely work and collaborate with humans. Therefore, it is necessary that these robots have sensors and the intelligence needed to work safely around humans (or other robots and machines), to prevent injuries, damage, or mishaps. The first cobots were introduced to the market by Universal Robotics in 2008, followed by Rethink Robotics’s dual-armed *Baxter* and later *Sawyer*

robots. Today, many other companies also make collaborative robots, including established companies such as FANUC America [55].

Most initial cobots were designed to move at slower speeds, to reduce impact forces, afford the robot ample time to respond and stop when necessary, and enable it to work with humans or other robots. Consequently, these robots were generally less productive, but obviously safer, and they did not have to be in a cage. Some current cobots work either at higher speeds like a regular robot or at lower speeds as a cobot. However, due to industrial demand for speed and productivity, newer cobots have speeds almost similar to those of regular robots even in collaborative mode.

The ISO 10218-2 and ISO/TS 15066 standards define what is needed for safe robots as well as for collaborative robots. This ranges from requiring robots to be in cages with sensors that shut down the robot in the presence of a human to collaborative robots that simply stop when they touch other objects, including a human, or that can be manipulated (moved around) by humans who are teaching them.

Cobots are designed to be able to determine the presence of a human around them. This can be accomplished by a vision system and a camera that is mounted on the arm and can see the workspace of the robot while it moves, by sensors that monitor the current to the actuating motors and measuring the increase when there is resistance against the motion, by sensors in the joint axes that measure loads on the joint, or other similar devices (Figure 1.25). For dual-arm robots, the arms are designed to work together to prevent collision, dropping a part when it is handled by both arms, and damage to the part while transporting it (see Section 2.15). They can also take advantage of the kinematic and kinetic equations we will develop and study later in this book to control real-time torques at the joints to prevent injuries and damage. One other feature of these robots is that they are generally rounder, to allow better detection and dissipation of impact forces with flat surfaces (indicating other objects or humans). Their actuating motors are generally completely covered, and there are no pinch points. Due to these characteristics, it is easier to guide the cobots and teach them a path or trajectory that they repeat later.

We will discuss cobots later, in other chapters.



Figure 1.25 Collaborative robots are designed to detect the presence of humans around them and to collaborate with them. *Source:* Reproduced with permission from Fanuc America Corporation.

1.19 Social Issues

We must always remember the social consequences of using robots. Although there are many applications of robots where they are used because no workers can do the same job, there are many other applications in which a robot replaces a human worker. The worker who is replaced by a robot may lose their income. If the trend continues without consideration, it is conceivable that most products can be made by robots, without the need for any human workers. The result will be fewer workers with jobs who have the money to buy the

products the robots make. Of importance is the issue of social problems that arise as increasingly more workers are out of jobs as well as its economic consequences. One of the important points of negotiations between automobile manufacturers and the United Auto Workers (UAW) is how many human jobs may be replaced by robots, and at what rate.

Although no solution is presented in this book, many references are available for further study of the problem [56, 57]. However, as engineers who strive to make better products at lower costs and who may consider using robots to replace human workers, we must always remember the consequences of this choice. Our academic and professional interest in robotics must always be intertwined with its social and economic considerations.

On the other end of the spectrum, some are raising the issue of legal rights for robots and whether or not they deserve it [58], especially when more-sophisticated humanoid robots become a reality. In Hollywood's *The Bicentennial Man*, a household domestic robot is continually improved over a long period of time until it has feelings, emotions, and thoughts just like a human, and eventually is granted the status of being a human just before dying. We may still be some distance from this reality, but there is no doubt it will be an issue in the future.

1.20 Summary

Many people who are interested in robotics have background information about robots and may even have interacted with robots, too. However, it is necessary that certain ideas are understood by everyone. In this chapter, we discussed some fundamental ideas about robotics that enable us to better understand what they are for, how they can be used, and what they can do. Robots can be used for many purposes, including industrial applications, entertainment, and other specific and unique applications such as in space and underwater exploration and in hazardous environments. Obviously, as time goes on, robots will be used for other unique applications. The remainder of this book will discuss the kinematics and kinetics of robots; their components, such as actuators and sensors and vision systems; and robot applications.

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Problems

- 1.1 Draw the approximate workspace for the following robot. Assume the dimensions of the base and other parts of the structure of the robot are as shown.

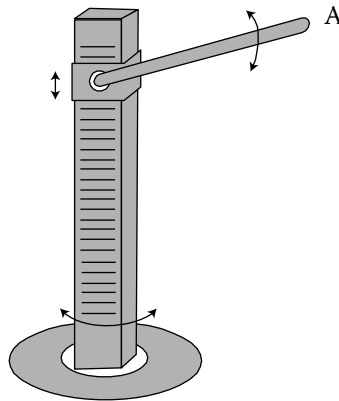


Figure P.1.1

- 1.2 Draw the approximate workspace for the following robot. Assume the dimensions of the base and other parts of the structure of the robot are as shown.

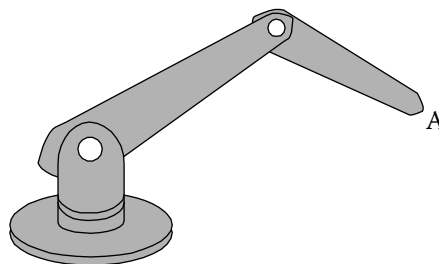


Figure P.1.2

- 1.3** Draw the approximate workspace for the following robot. Assume the dimensions of the base and other parts of the structure of the robot are as shown.

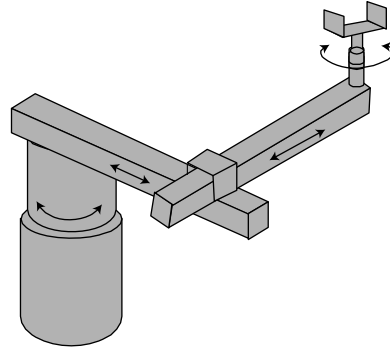


Figure P.1.3

