# ROHINI COLLEGE OF ENGINEERING AND TECHNOLOGY

Kanyakumari Main Road, Near Anjugramam, Palkulam, Tamil Nadu 629401

## Department of Mechanical Engineering

VALUE ADDED COURSE ON ROBOTICS

# SYLLABUS

# Chapter 1

## Introduction

Many definitions have been suggested for what we call a robot. The word may conjure up various levels of technological sophistication, ranging from a simple material handling device to a humanoid. The image of robots varies widely with researchers, engineers, and robot manufacturers. However, it is widely accepted that today's robots used in industries originated in the invention of a programmed material handling device by George C. Devol. In 1954, Devol filed a U.S. patent for a new machine for part transfer, and he claimed the basic concept of teach-in/playback to control the device. This scheme is now extensively used in most of today's industrial robots.

### 1.1 Era of Industrial Robots

Devol's industrial robots have their origins in two preceding technologies: numerical control for machine tools, and remote manipulation. Numerical control is a scheme to generate control actions based on stored data. Stored data may include coordinate data of points to which the machine is to be moved, clock signals to start and stop operations, and logical statements for branching control sequences. The whole sequence of operations and its variations are prescribed and stored in a form of memory, so that different tasks can be performed without requiring major hardware changes. Modern manufacturing systems must produce a variety of products in small batches, rather than a large number of the same products for an extended period of time, and frequent changes of product models and production schedules require flexibility in the manufacturing system. The transfer line approach, which is most effective for mass production, is not appropriate when such flexibility is needed When a major product change is required, a special-purpose production line becomes useless and often ends up being abandoned, despite the large capital investment it originally involved.

Another origin of today's industrial robots can be found in remote manipulators. A remote manipulator is a device that performs a task at a distance. It can be used in environments that human workers cannot easily or safely access, e.g. for handling radio-active materials, or in some deep sea and space applications. The first master-slave manipulator system was developed by 1948. The concept involves an electrically powered mechanical arm installed at the operation site, and a control joystick of geometry similar to that of the mechanical arm (Figure 1-2). The joystick has position transducers at individual joints that measure the motion of the human operator as he moves the tip of the joystick. Thus the operator's motion is transformed into electrical signals, which are transmitted to the mechanical arm and cause the same motion as the one that the human operator performed. The joystick that the operator handles is called the master manipulator, while the mechanical arm is called the slave manipulator, since its motion is ideally the replica of the operator's commanded motion. A master-slave manipulator has typically six degrees of freedom to allow the gripper to locate an object at an arbitrary position and orientation. Most joints are revolute, and the whole mechanical construction is similar to that of the human arm. This analogy with the human arm results from the need of replicating human motions. Further, this structure allows dexterous motions in a wide range of workspaces, which is desirable for operations in modern manufacturing systems.

## 1.2 Creation of Robotics

The merge of numerical control and remote manipulation created a new field of engineering, and with it a number of scientific issues in design and control which are substantially different from those of the original technologies have emerged.

Robots are required to have much higher mobility and dexterity than traditional machine tools. They must be able to work in a large reachable range, access crowded places, handle a variety of work pieces, and perform flexible tasks. The high mobility and dexterity requirements result in the unique mechanical structure of robots, which parallels the human arm structure. This structure, however, significantly departs from traditional machine design. A robot mechanical structure is basically composed of cantilevered beams, forming a sequence of arm links connected by hinged joints. Such a structure has inherently poor mechanical stiffness and accuracy, hence is not appropriate for the heavy-duty, high-precision applications required of machine tools. Further, it also implies a serial sequence of servoed joints, whose errors accumulate along the linkage. In order to exploit the high mobility and dexterity uniquely featured by the serial linkage, these difficulties must be overcome by advanced design and control techniques.

The serial linkage geometry of manipulator arms is described by complex nonlinear equations. Effective analytical tools are necessary to understand the geometric and kinematic behavior of the manipulator, globally referred to as the manipulator kinematics. This represents an important and unique area of robotics research, since research in kinematics and design has traditionally focused upon single-input mechanisms with single actuators moving at constant speeds, while robots are multi-input spatial mechanisms which require more sophisticated analytical tools.

The dynamic behavior of robot manipulators is also complex, since the dynamics of multi-input spatial linkages are highly coupled and nonlinear. The motion of each joint is significantly affected by the motions of all the other joints. The inertial load imposed at each joint varies widely depending on the configuration of the manipulator arm. Coriolis and centrifugal effects are prominent when the manipulator arm moves at high speeds. The kinematic and dynamic complexities create unique control problems that are not adequately handled by standard linear control techniques, and thus make effective control system design a critical issue in robotics.

Finally, robots are required to interact much more heavily with peripheral devices than traditional numerically-controlled machine tools. Machine tools are essentially self-contained systems that handle work pieces in well-defined locations. By contrast, the environment in which robots are used is often poorly structured, and effective means must be developed to identify the locations of the work pieces as well as to communicate to peripheral devices and other machines in a coordinated fashion. Robots are also critically different from master-slave manipulators, in that they are autonomous systems. Master-slave manipulators are essentially manually controlled systems, where the human operator takes the decisions and applies control actions. The operator interprets a given task, finds an appropriate strategy to accomplish the task, and plans the procedure of operations. He/she devises an effective way of achieving the goal on the basis of his/her experience and knowledge about the task. His/her decisions are then transferred to the slave manipulator through the joystick. The resultant motion of the slave manipulator is monitored by the operator, and necessary adjustments or modifications of control actions are provided when the resultant motion is not adequate, or when unexpected events occur during the operation.

The human operator is, therefore, an essential part of the control loop. When the operator is eliminated from the control system, all the planning and control commands must be generated by the machine itself. The detailed procedure of operations must be set up in advance, and each step of motion command must be generated and coded in an appropriate form so that the robot can interpret it and execute it accurately. Effective means to store the commands and manage the data file are also needed. Thus, programming and command generation are critical issues in robotics. In addition, the robot must be able to fully monitor its own motion. In order to adapt to disturbances and unpredictable changes in the work environment, the robot needs a variety of sensors, so as to obtain information both about the environment (using external sensors, such as cameras or touch sensors) and about itself (using internal sensors, such as joint encoders or joint torque sensors). Effective sensor-based strategies that incorporate this information require advanced control algorithms. But they also imply a detailed understanding of the task.

### 1.3. Manipulation and Dexterity

Contemporary industrial needs drive the applications of robots to ever more advanced tasks. Robots are required to perform highly skilled jobs with minimum human assistance or intervention. To extend the applications and abilities of robots, it becomes important to develop a sound understanding of the tasks themselves.

In order to devise appropriate arm mechanisms and to develop effective control algorithms, we need to precisely understand how a given task should be accomplished and what sort of motions the robot should be able to achieve. To perform an assembly operation, for example, we need to know how to guide the assembly part to the desired location, mate it with another part, and secure it in an appropriate way. In a grinding operation, the robot must properly position the grinding wheel while accommodating the contact force. We need to analyze the grinding process itself in order to generate appropriate force and motion commands.

A detailed understanding of the underlying principles and "know-how" involved in the task must be developed in order to use industrial robots effectively, while there is no such need for making control strategies explicit when the assembly and grinding operations are performed by a human worker. Human beings perform sophisticated manipulation tasks without being aware of the control principles involved. We have trained ourselves to be capable of skilled jobs, but in general we do not know what the acquired skills are exactly about. A sound and explicit understanding of manipulation operations, however, is essential for the long-term progress of robotics. This scientific aspect of manipulation has never been studied systematically before, and represents an emerging and important part of robotics research.

### 1.4 Locomotion and Navigation

Robotics has found a number of important application areas in broad fields beyond manufacturing automation. These range from space and under-water exploration, hazardous waste disposal, and environment monitoring to robotic surgery, rehabilitation, home robotics, and entertainment. Many of these applications entail some locomotive functionality so that the robot can freely move around in an unstructured environment.

Most industrial robots sit on a manufacturing floor and perform tasks in a structured environment. In contrast, those robots for non-manufacturing applications must be able to move around on their own. See Figure 1-8.

Locomotion and navigation are increasingly important, as robots find challenging applications in the field. This opened up new research and development areas in robotics. Novel mechanisms are needed to allow robots to move through crowded areas, rough terrain, narrow channels, and even staircases. Various types of legged robots have been studied, since, unlike standard wheels, legs can negotiate with uneven floors and rough terrain. Among others, biped robots have been studied most extensively, resulting in the development of humanoids, as shown in Figure 1-9. Combining leg mechanisms with wheels has accomplished superior performance in both flexibility and efficiency. The Mars Rover prototype shown below has a rocker-buggy mechanism combined with advanced wheel drives in order to adapt itself to diverse terrain conditions.

Navigation is another critical functionality needed for mobile robots, in particular, for unstructured environment. Those robots are equipped with range sensors and vision system, and are capable of interpreting the data to locate themselves. Often the robot has a map of the environment, and uses it for estimating the location. Furthermore, based on the real-time data obtained in the field, the robot is capable of updating and augmenting the map, which is incomplete and uncertain in unstructured environment. As depicted in Figure 1-10, location estimation and map building are simultaneously executed in the advanced navigation system. Such Simultaneous Location and MApping (SLAM) is exactly what we human do in our daily life, and is an important functionality of intelligent robots.

The goal of robotics is thus two-fold: to extend our understanding about manipulation, locomotion, and other robotic behaviors and to develop engineering methodologies to actually perform desired tasks. The goal of this book is to provide entry-level readers and experienced engineers with fundamentals of understanding robotic tasks and intelligent behaviors as well as with enabling technologies needed for building and controlling robotic systems.

## Chapter 2
## Actuators and Drive Systems

Actuators are one of the key components contained in a robotic system. A robot has many degrees of freedom, each of which is a servoed joint generating desired motion. We begin with basic actuator characteristics and drive amplifiers to understand behavior of servoed joints.

Most of today's robotic systems are powered by electric servomotors. Therefore, we focus on electromechanical actuators.

### 2.1 DC Motors

Figure 2-1 illustrates the construction of a DC servomotor, consisting of a stator, a rotor, and a commutation mechanism. The stator consists of permanent magnets, creating a magnetic field in the air gap between the rotor and the stator. The rotor has several windings arranged symmetrically around the motor shaft. An electric current applied to the motor is delivered to individual windings through the brush-commutation mechanism, as shown in the figure. As the rotor rotates the polarity of the current flowing to the individual windings is altered. This allows the rotor to rotate continually.

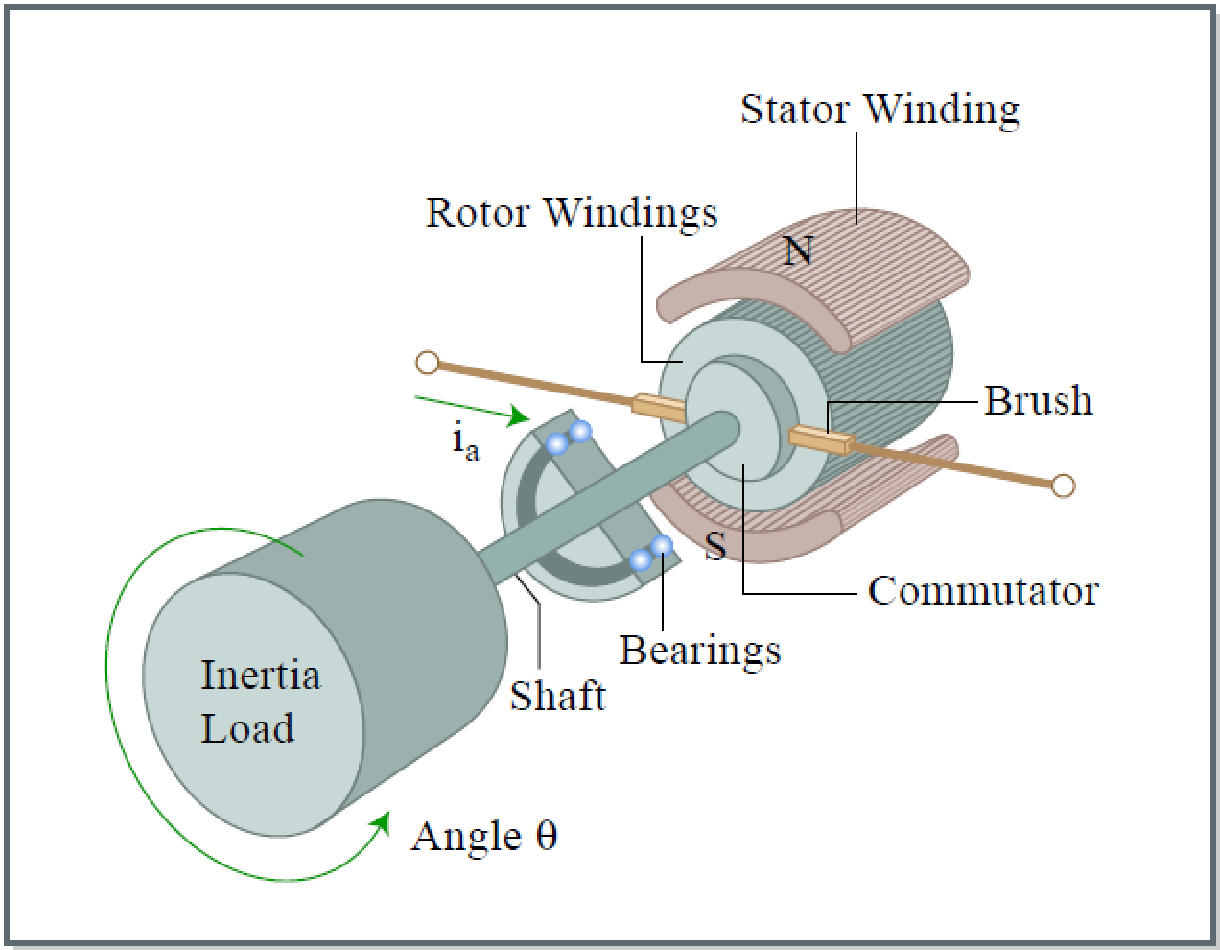
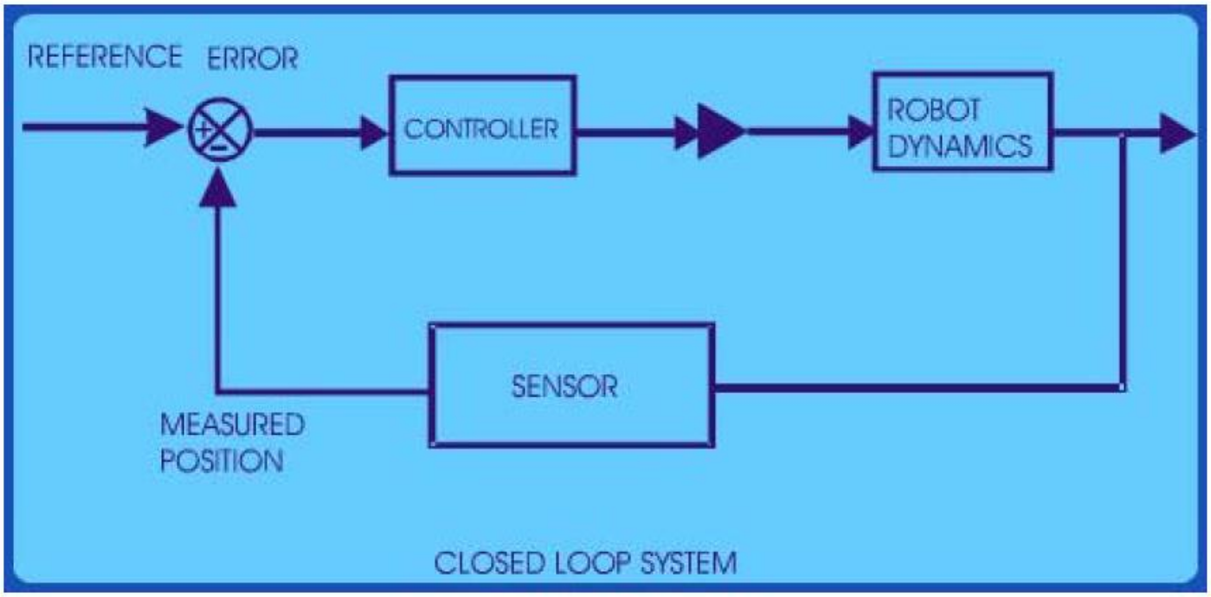


Figure 2.1.1 Construction of DC motor

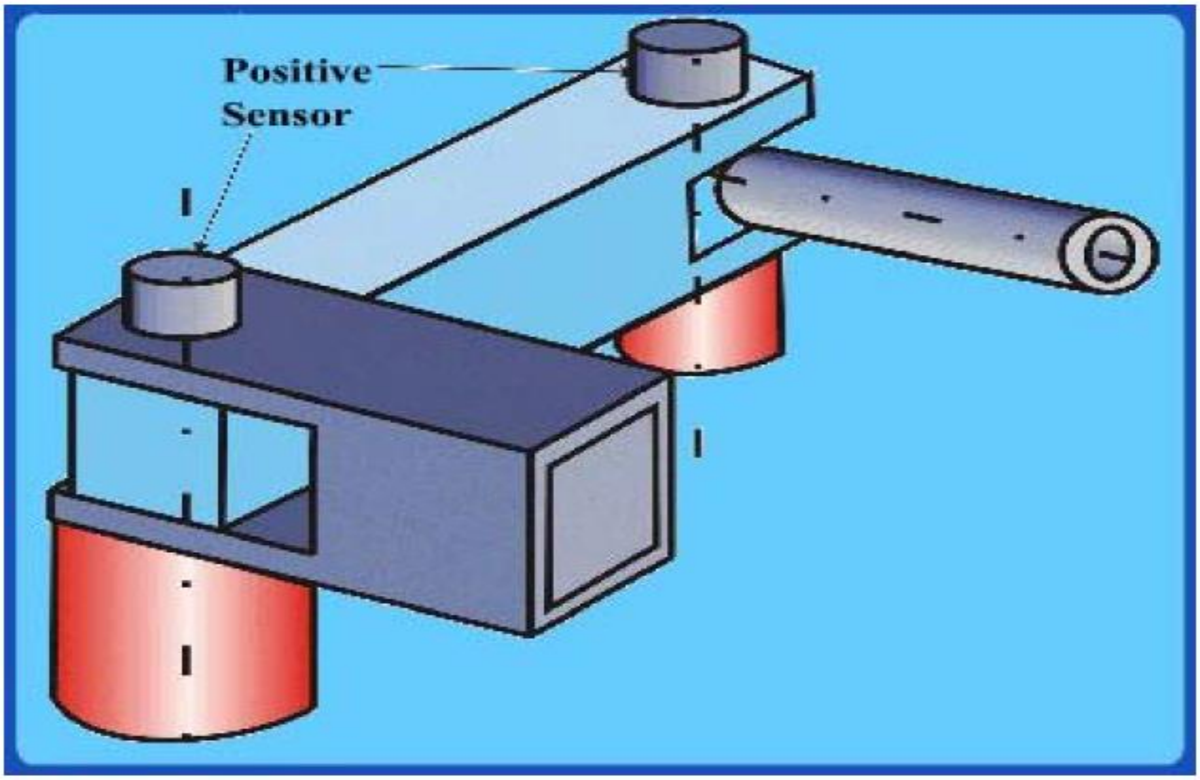
**Sensors and Controllers in robots**
Sensors and controllers (sensor types)
Objectives
In this course you will learn about

- Actuators: Stepper Motors, Electric DC motors, Hydraulic & Pneumatic Actuators
- Temperature, Bearing Forces, Frequency response
- Brawn Vs. Brain
- Sensors
- Internal State / External State
- Basic Movements – Position, Velocity, Acceleration
- Interaction with environment – Torques, Forces, Touch, Slip, Range, Vision

**CLOSED LOOP SYSTEM**




**VELOCITY SENSOR**

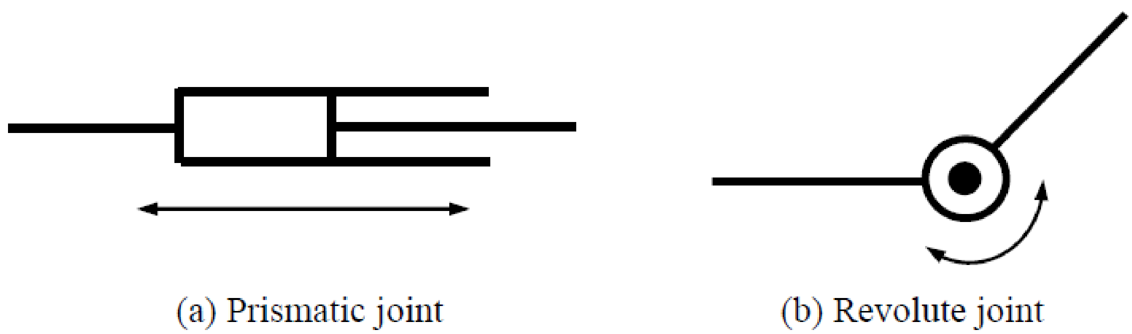



**Chapter 3**
**Robot Mechanisms**

A robot is a machine capable of physical motion for interacting with the environment. Physical interactions include manipulation, locomotion, and any other tasks changing the state of the environment or the state of the robot relative to the environment. A robot has some form of mechanisms for performing a class of tasks. A rich variety of robot mechanisms has been developed in the last few decades. In this chapter, we will first overview various types of mechanisms used for generating robotic motion, and introduce some taxonomy of mechanical structures before going into a more detailed analysis in the subsequent chapters.

**3.1 Joint Primitives and Serial Linkages**

A robot mechanism is a multi-body system with the multiple bodies connected together. We begin by treating each body as rigid, ignoring elasticity and any deformations caused by large load conditions. Each rigid body involved in a robot mechanism is called a link, and a combination of links is referred to as a linkage. In describing a linkage it is fundamental to represent how a pair of links is connected to each other. There are two types of primitive connections between a pair of links, as shown in Figure 3.1.1. The first is a prismatic joint where the pair of links makes a translational displacement along a fixed axis. In other words, one link slides on the other along a straight line. Therefore, it is also called a sliding joint. The second type of primitive joint is a revolute joint where a pair of links rotates about a fixed axis. This type of joint is often referred to as a hinge, articulated, or rotational joint.1




Combining these two types of primitive joints, we can create many useful mechanisms for robot manipulation and locomotion. These two types of primitive joints are simple to build and are well grounded in engineering design. Most of the robots that have been built are combinations of only these two types. Let us look at some examples.

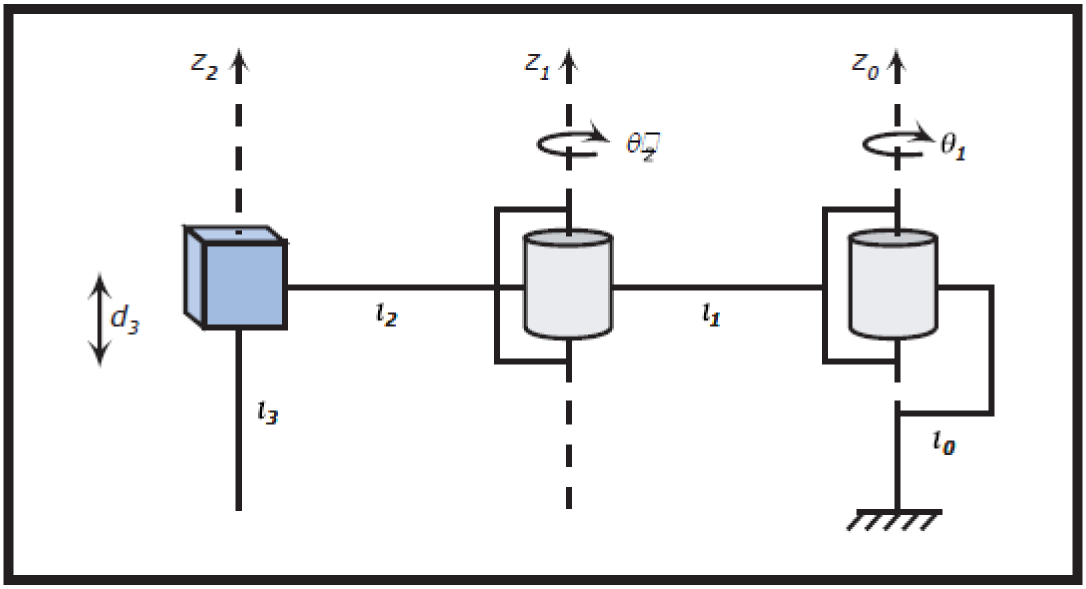
Robot mechanisms analogous to coordinate systems

One of the fundamental functional requirements for a robotic system is to locate its end-effecter, e.g. a hand, a leg, or any other part of the body performing a task, in three-dimensional space. If the kinematic structure of such a robot mechanism is analogous to a coordinate system,

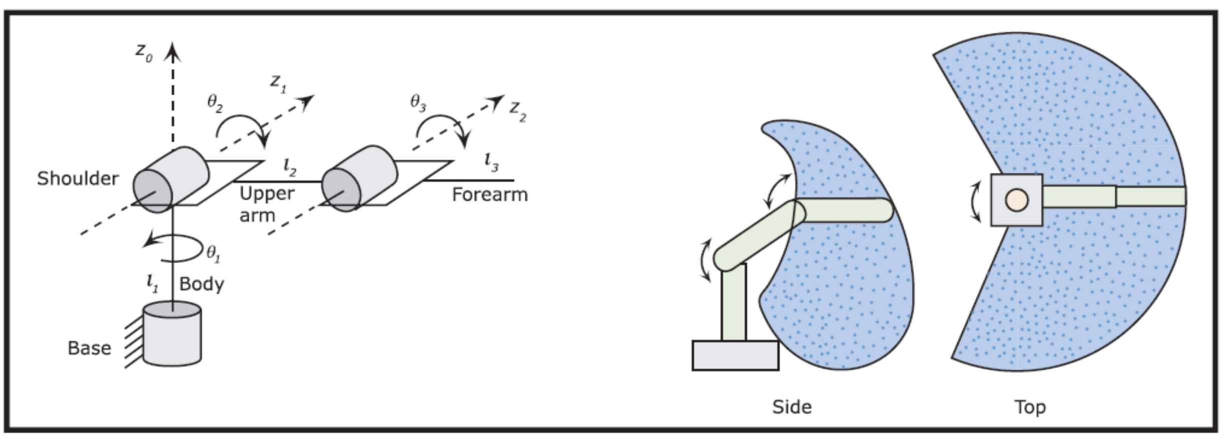
1 It is interesting to note that all biological creatures are made of revolute type joints; there are no sliding joints involved in their extremities. It may suffice this positioning requirement. system, the cylindrical coordinate system, and the spherical coordinate system respectively.

There are many other ways of locating an end-effecter in three-dimensional space. Figure 3.1.5 ~ 7 show three other kinematic structures that allow the robot to locate its end-effecter in three-dimensional space. Although these mechanisms have no analogy with common coordinate systems, they are capable of locating the end-effecter in space, and have salient features desirable for specific tasks.

The first one is a so-called SCALAR robot consisting of two revolute joints and one prismatic joint. This robot structure is particularly desirable for assembly automation in manufacturing systems, having a wide workspace in the horizontal direction and an independent vertical axis appropriate for insertion of parts.




The second type, called an articulated robot or an elbow robot, consists of all three revolute joints, like a human arm. This type of robot has a great degree of flexibility and versatility, being the most standard structure of robot manipulators. The third kinematic structure, also consisting of three revolute joints, has a unique mass balancing structure. The counter balance at the elbow eliminates gravity load for all three joints, thus reducing toque requirements for the actuators. This structure has been used for the direct-drive robots having no gear reducer.




Note that all the above robot structures are made of serial connections of primitive joints. This class of kinematic structures, termed a serial linkage, constitutes the fundamental makeup of robot mechanisms. They have no kinematic constraint in each joint motion, i.e. each joint displacement is a generalized coordinate. This facilitates the analysis and control of the robot mechanism. There are, however, different classes of mechanisms used for robot structures. Although more complex, they do provide some useful properties. We will look at these other mechanisms in the subsequent sections.

### 3.2 Parallel Linkages

Primitive joints can be arranged in parallel as well as in series. Figure 3.2.1 illustrates such a parallel link mechanism. It is a five-bar-linkage consisting of five links, including the base link, connected by five joints. This can be viewed as two serial linkage arms connected at a particular point, point A in the figure. It is important to note that there is a closed kinematic chain formed by the five links and, thereby, the two serial link arms must conform to a certain geometric constraint. It is clear from the figure that the end-effecter position is determined if two of the five joint angles are given. For example, if angles 1? And 3? Of joints 1 and 3 are determined, and then all the link positions are determined, as is the end-effecter's. Driving joint 1 and 3 with two actuators, we can move the end-effecter within the vertical plane. It should be noted that, if more than two joints were actively driven by independent actuators, a conflict among three actuators would occur due to the closed-loop kinematic chain. Three of the five joints should be ***passive joints***, which are free to rotate. Only two joints should be ***active joints,*** driven by independent actuators.

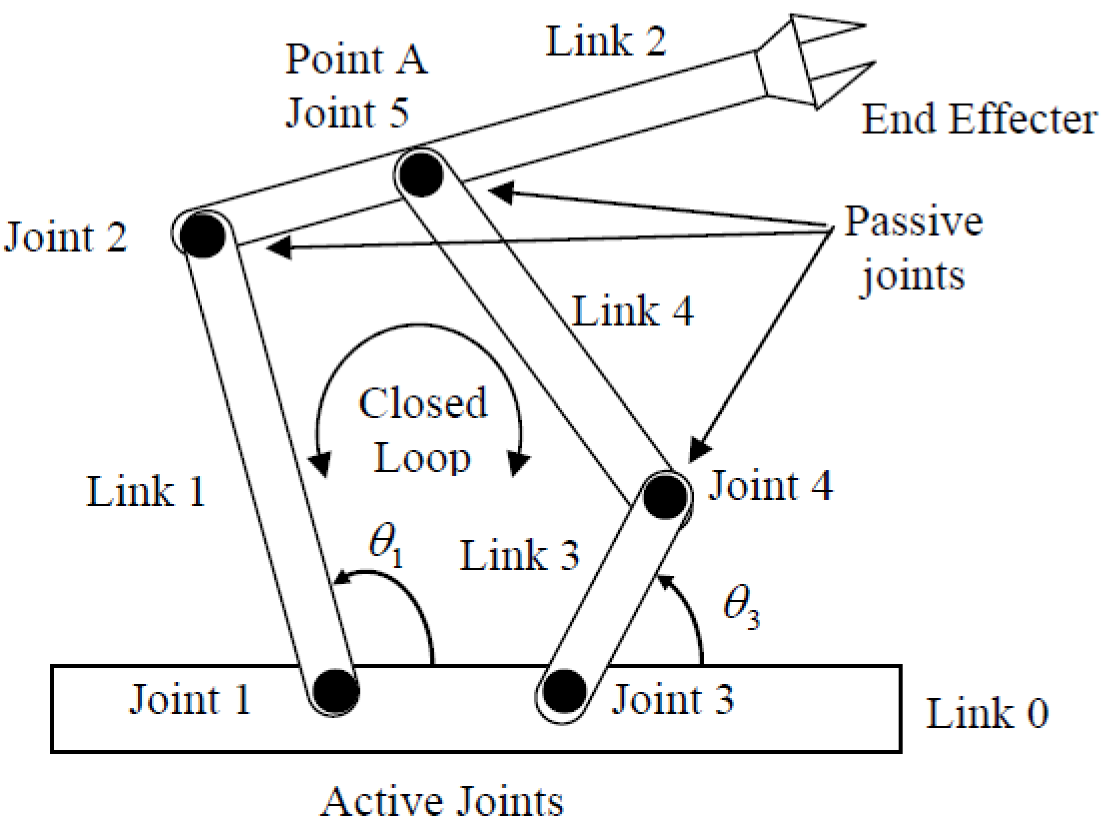



Figure 3.2.1 Five-bar-link parallel link robot

This type of parallel linkage, having a closed-loop kinematic chain, has significant features. First, placing both actuators at the base link makes the robot arm lighter, compared to the serial link arm with the second motor fixed to the tip of link 1. Second, a larger end-effecter load can be born with the two serial linkage arms sharing the load.

Kinematics is Geometry of Motion. It is one of the most fundamental disciplines in robotics, providing tools for describing the structure and behavior of robot mechanisms. In this chapter, we will discuss how the motion of a robot mechanism is described, how it responds to actuator movements, and how the individual actuators should be coordinated to obtain desired motion at the robot end-effecter. These are questions central to the design and control of robot mechanisms.

To begin with, we will restrict ourselves to a class of robot mechanisms that work within a plane, i.e. Planar Kinematics. Planar kinematics is much more tractable mathematically, compared to general three-dimensional kinematics. Nonetheless, most of the robot mechanisms of practical importance can be treated as planar mechanisms, or can be reduced to planar problems. General three-dimensional kinematics, on the other hand, needs special mathematical tools, which will be discussed in later chapters.

## 4.1 Planar Kinematics of Serial Link Mechanisms

Example 4.1 Consider the three degree-of-freedom planar robot arm shown in Figure 4.1.1. The arm consists of one fixed link and three movable links that move within the plane. All the links are connected by revolute joints whose joint axes are all perpendicular to the plane of the links. There is no closed-loop kinematic chain; hence, it is a serial link mechanism.

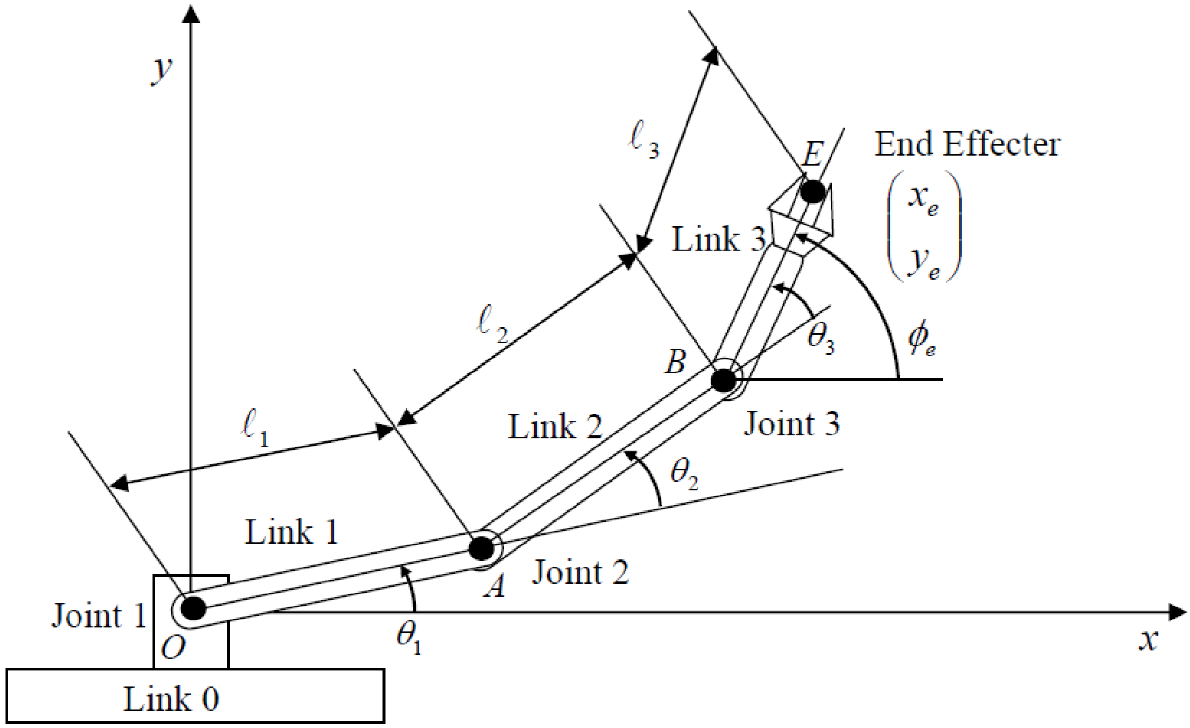



Figure 4.1.1 Three dof planar robot with three revolute joints

To describe this robot arm, a few geometric parameters are needed. First, the length of each link is defined to be the distance between adjacent joint axes. Let points *O, A,* and *B* be the locations of the three joint axes, respectively, and point E be a point fixed to the end-effecter. Then the link lengths are link 1 is fixed to the base link (link 0), generating angle θ1, while Actuator 2 driving link 2 is fixed to the tip of Link 1, creating angle θ2 between the two links, and Actuator 3 driving Link 3 is fixed to the tip of Link 2, creating angle θ3, as shown in the figure. Since this robot arm performs tasks by moving its end-effecter at point E, we are concerned with the location of the end-effecter. To describe its location, we use a coordinate system, O-xy, fixed to the base link with the origin at the first joint, and describe the end-effecter position with coordinates e and e. We can relate the end-effecter coordinates to the joint angles determined by the three actuators by using the link lengths and joint angles defined above:

$$x_e = \ell_1 \cos\theta_1 + \ell_2 \cos(\theta_1 + \theta_2) + \ell_3 \cos(\theta_1 + \theta_2 + \theta_3)$$
$$y_e = \ell_1 \sin\theta_1 + \ell_2 \sin(\theta_1 + \theta_2) + \ell_3 \sin(\theta_1 + \theta_2 + \theta_3)$$

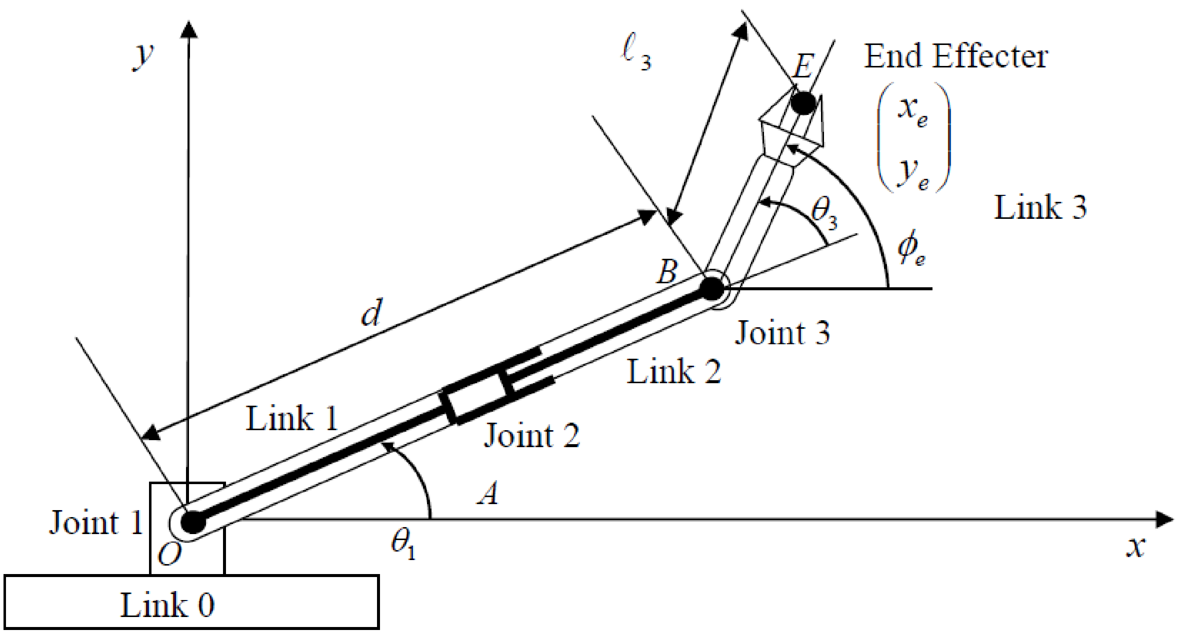
This three dof robot arm can locate its end-effecter at a desired orientation as well as at a desired position. The orientation of the end-effecter can be described as the angle the centerline of the end-effecter measured from the positive x coordinate axis. This end-effecter orientation φe is related to the actuator displacements as

$$\phi_e = \theta_1 + \theta_2 + \theta_3$$

The above three equations describe the position and orientation of the robot end-effecter viewed from the fixed coordinate system in relation to the actuator displacements. In general, a set of algebraic equations relating the position and orientation of a robot end-effecter, or any significant part of the robot, to actuator or active joint displacements, is called Kinematic Equations or more specifically, Forward Kinematic Equations in the robotics literature.

Exercise 4.1

Shown below in Figure 4.1.2 is a planar robot arm with two revolute joints and one prismatic joint. Using the geometric parameters and joint displacements, obtain the kinematic equations relating the end-effecter position and orientation to the joint displacements.




Now that the above Example and Exercise problems have illustrated kinematic equations, let us obtain a formal expression for kinematic equations. As mentioned in the previous chapter, two types of joints, prismatic and revolute joints, constitute robot mechanisms in most cases. The displacement of the i-th joint is described by distance di if it is a prismatic joint, and by angle iθ for a revolute joint. For formal expression, let us use a generic notation: qi. Namely, joint displacement qi represents either distance di or angle iθdepending on the type of joint.

$$q_i = \begin{cases} d_i & \text{Prismatic joint} \\ \theta_i & \text{Revolute joint} \end{cases}$$

We collectively represent all the joint displacements involved in a robot mechanism with a column vector: , where n is the number of joints. Kinematic equations relate these joint displacements to the position and orientation of the end-effecter. Let us collectively denote the end-effecter position and orientation by vector p. For planar mechanisms, the end-effecter location is described by three variables:

$$p = \begin{bmatrix} x_e \\ y_e \\ \phi_e \end{bmatrix}$$

Using these notations, we represent kinematic equations as a vector function relating p to q:

$$p = f(q), \quad p \in \Re^{3x1}, q \in \Re^{nx1}$$

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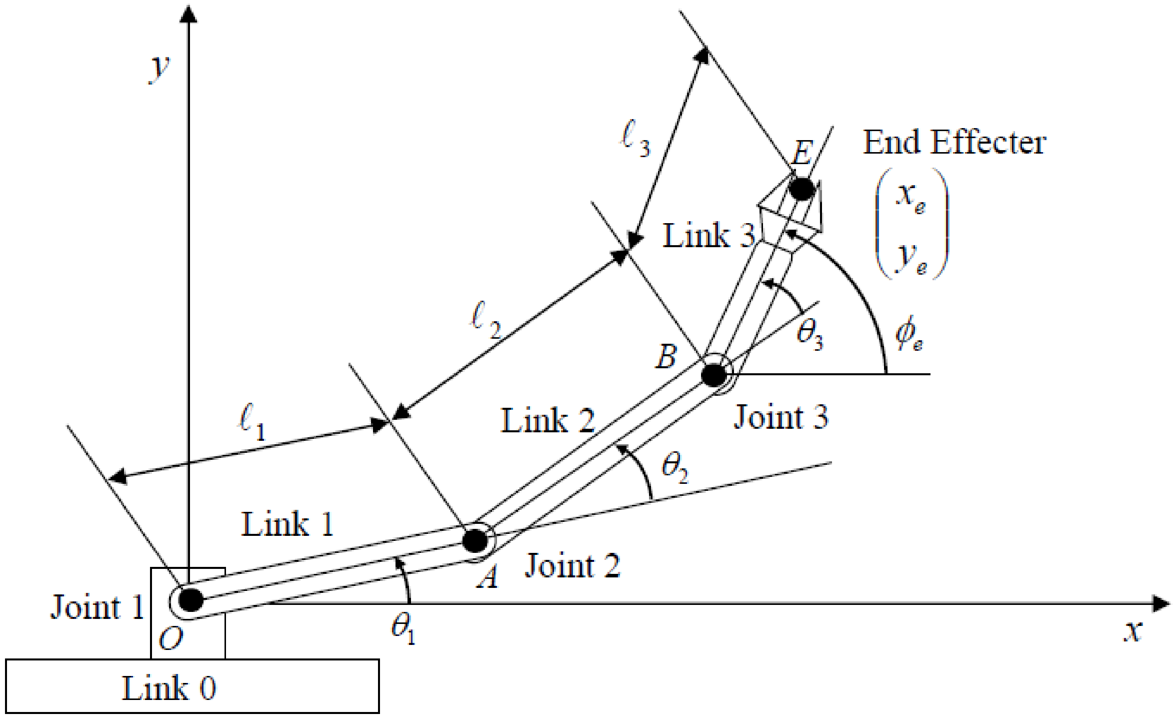


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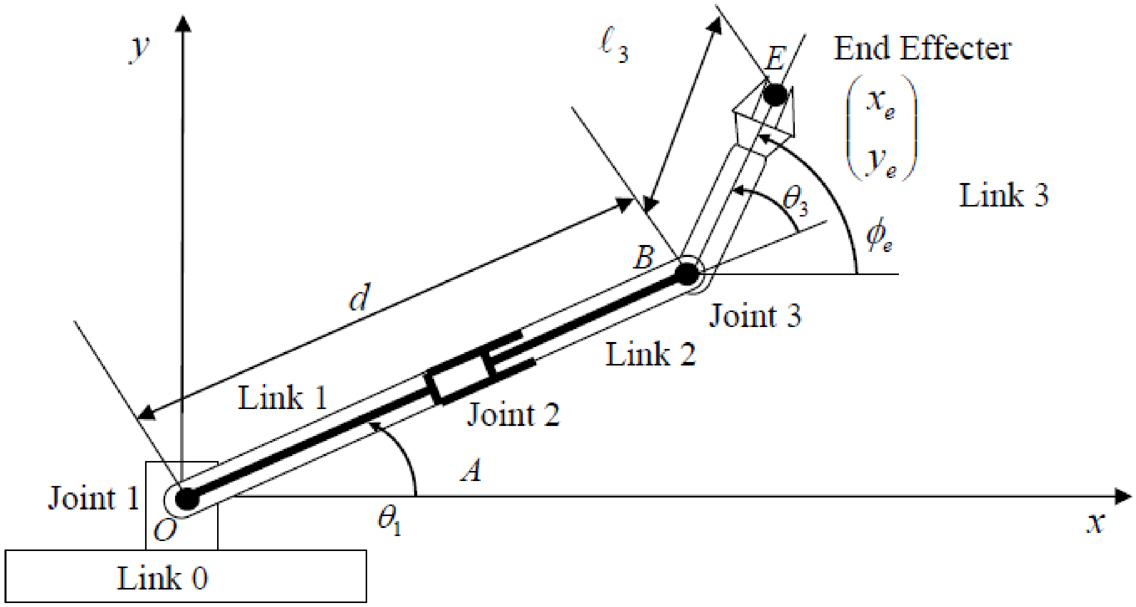



4.1.2 Planar robot arm with two revolute joints

## 4.2 Inverse Kinematics of Planar Mechanisms

The vector kinematic equation derived in the previous section provides the functional relationship between the joint displacements and the resultant end-effecter position and orientation. By substituting values of joint displacements into the right-hand side of the kinematic equation, one can immediately find the corresponding end-effecter position and orientation. The problem of finding the end-effecter position and orientation for a given set of joint displacements is referred to as the direct kinematics problem. This is simply to evaluate the right-hand side of the kinematic equation for known joint displacements. In this section, we discuss the problem of moving the end-effecter of a manipulator arm to a specified position and orientation. We need to find the joint displacements that lead the end-effecter to the specified position and orientation. This is the inverse of the previous problem, and is thus referred to as the inverse kinematics problem.

The kinematic equation must be solved for joint displacements, given the end-effecter position and orientation. Once the kinematic equation is solved, the desired end-effecter motion can be achieved by moving each joint to the determined value.

In the direct kinematics problem, the end-effecter location is determined uniquely for any given set of joint displacements. On the other hand, the inverse kinematics is more complex in the sense that multiple solutions may exist for the same end-effecter location. Also, solutions may not always exist for a particular range of end-effecter locations and arm structures. Furthermore, since the kinematic equation is comprised of nonlinear simultaneous equations with many trigonometric functions, it is not always possible to derive a closed-form solution, which is the explicit inverse function of the kinematic equation. When the kinematic equation cannot be solved analytically, numerical methods are used in order to derive the desired joint displacements.

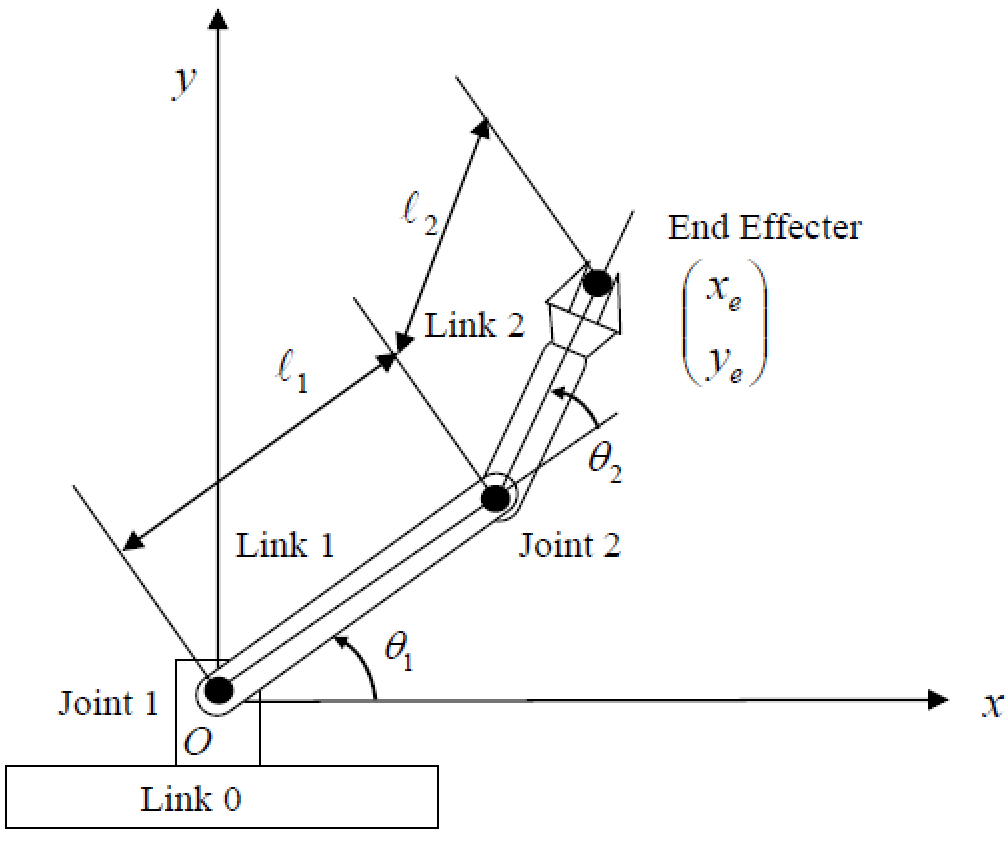
# Chapter 5
# Differential Motion

In the previous chapter, the position and orientation of the manipulator end-effecter were evaluated in relation to joint displacements. The joint displacements corresponding to a given end-effecter location were obtained by solving the kinematic equation for the manipulator. This preliminary analysis permitted the robotic system to place the end-effecter at a specified location in space. In this chapter, we are concerned not only with the final location of the end-effecter, but also with the velocity at which the end-effecter moves. In order to move the end-effecter in a specified direction at a specified speed, it is necessary to coordinate the motion of the individual joints. The focus of this chapter is the development of fundamental methods for achieving such coordinated motion in multiple-joint robotic systems. As discussed in the previous chapter, the end-effecter position and orientation are directly related to the joint displacements. Hence, in order to coordinate joint motions, we derive the differential relationship between the joint displacements and the end-effecter location, and then solve for the individual joint motions.

## 5.1 Differential Relationship

We begin by considering a two degree-of-freedom planar robot arm, as shown in Figure 5.1.1. The kinematic equations relating the end-effecter coordinates and to the joint displacements e x ye θ1 and 2θ are given by

$$x_e(\theta_1, \theta_2) = \ell_1 \cos\theta_1 + \ell_2 \cos(\theta_1 + \theta_2)$$
$$y_e(\theta_1, \theta_2) = \ell_1 \sin\theta_1 + \ell_2 \sin(\theta_1 + \theta_2)$$




5.1.1 2 DOF planar robot arm

We are concerned with "small movements" of the individual joints at the current position, and we want to know the resultant motion of the end-effecter. This can be obtained by the total derivatives of the above kinematic equations:

$$dx_e = \frac{\partial x_e(\theta_1, \theta_2)}{\partial \theta_1} d\theta_1 + \frac{\partial x_e(\theta_1, \theta_2)}{\partial \theta_2} d\theta_2$$

$$dy_e = \frac{\partial y_e(\theta_1, \theta_2)}{\partial \theta_1} d\theta_1 + \frac{\partial y_e(\theta_1, \theta_2)}{\partial \theta_2} d\theta_2$$

where are variables of both eeyx,1θand 2θ, hence two partial derivatives are involved in the total derivatives. In vector form the above equations reduce to

$$d\mathbf{x} = \mathbf{J} \cdot d\mathbf{q}$$

Where

$$d\mathbf{x} = \begin{pmatrix} dx_e \\ dy_e \end{pmatrix}, \quad d\mathbf{q} = \begin{pmatrix} d\theta_1 \\ d\theta_2 \end{pmatrix}$$

and **J** is a 2 by 2 matrix given by

$$\mathbf{J} = \begin{pmatrix} \frac{\partial x_e(\theta_1, \theta_2)}{\partial \theta_1} & \frac{\partial x_e(\theta_1, \theta_2)}{\partial \theta_2} \\ \frac{\partial y_e(\theta_1, \theta_2)}{\partial \theta_1} & \frac{\partial y_e(\theta_1, \theta_2)}{\partial \theta_2} \end{pmatrix}$$

The matrix J comprises the partial derivatives of the functions 2),( θ1, θe and 2 x ),( θ1 θe with respect to joint displacements 2y1 and θθ. The matrix J, called the Jacobean Matrix, represents the differential relationship between the joint displacements and the resulting end-effecter motion. Note that most robot mechanisms have a multitude of active joints, hence a matrix is needed for describing the mapping of the vectorial joint motion to the vectorial end-effecter motion.
For the two-dof robot arm of Figure 5.1.1, the components of the Jacobian matrix are computed as

$$\mathbf{J} = \begin{pmatrix} -\ell_1 \sin\theta_1 - \ell_2 \sin(\theta_1 + \theta_2) & -\ell_2 \sin(\theta_1 + \theta_2) \\ \ell_1 \cos\theta_1 + \ell_2 \cos(\theta_1 + \theta_2) & \ell_2 \cos(\theta_1 + \theta_2) \end{pmatrix}$$

coordinates to individual joint displacements. This sensitivity information is needed in order to coordinate the multi dof joint displacements for generating a desired motion at the end-effecter.
Consider the instant when the two joints of the robot arm are moving at joint velocities , and let be the resultant end-effecter velocity vector. The Jacobian provides the relationship between the joint velocities and the resultant end-effecter velocity. Indeed, dividing eq.(5) by the infinitesimal time increment dt yields

$$\frac{d\mathbf{x}_e}{dt} = \mathbf{J}\frac{d\mathbf{q}}{dt}, \quad \text{or} \quad \mathbf{v}_e = \mathbf{J} \cdot \dot{\mathbf{q}}$$

Thus the Jacobian determines the velocity relationship between the joints and the end-effecter.

**5.2 Properties of the Jacobian**

The Jacobian plays an important role in the analysis, design, and control of robotic systems. It will be used repeatedly in the following chapters. It is worth examining basic properties of the Jacobian, which will be used throughout this book.

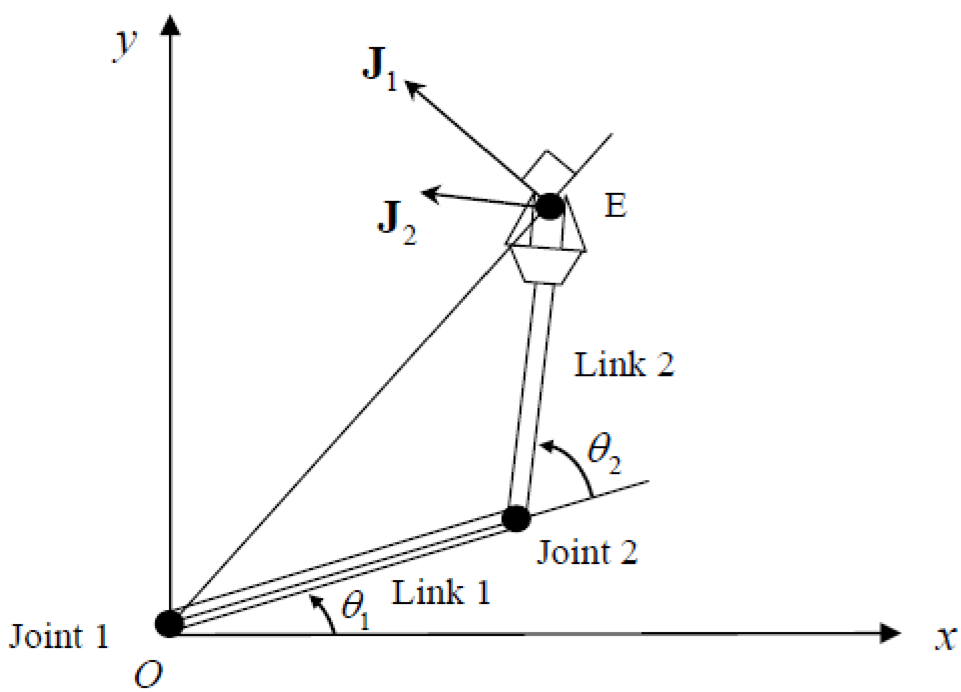
We begin by dividing the 2-by-2 Jacobian of eq.(5.1.8) into two column vectors:

$$\mathbf{J} = (\mathbf{J}_1, \mathbf{J}_2), \quad \mathbf{J}_1, \mathbf{J}_2 \in \Re^{2\times 1}$$

$$\mathbf{v}_e = \mathbf{J}_1 \cdot \theta_1 + \mathbf{J}_2 \cdot \theta_2$$

The first term on the right-hand side accounts for the end-effecter velocity induced by the first joint only, while the second term represents the velocity resulting from the second joint motion only. The resultant end-effecter velocity is given by the vectorial sum of the two. Each column vector of the Jacobean matrix represents the end-effecter velocity generated by the corresponding joint moving at a unit velocity when all other joints are immobilized.

Figure 5.2.1 illustrates the column vectors 21of the 2 dof robot arm in the two-dimensional space. Vector 2J, given by the second column of eq.(5.1. 8), points in the direction perpendicular to link 2. Note, however, that vector 1is not perpendicular to link 1 but is perpendicular to line OE, the line from joint 1 to the endpoint E. This is because 1 represents the endpoint velocity induced by joint 1 when joint 2 is immobilized. In other words, links 1 and 2 are rigidly connected, becoming a single rigid body of link length OE, and is the tip velocity of the link OE.




5.2.1 2 DOF robot arm

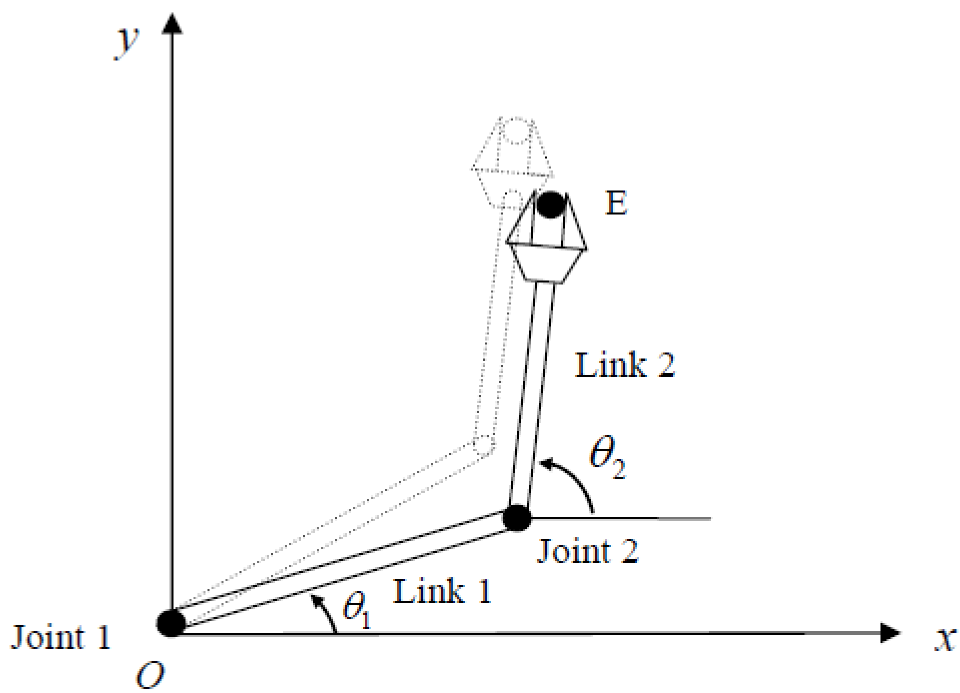
In general, each column vector of the Jacobian represents the end-effecter velocity and angular velocity generated by the individual joint velocity while all other joints are immobilized. Let be the end-effecter velocity and angular velocity, or the end-effecter velocity for short, and iJbe the i-th column of the Jacobian. The end-effecter velocity is given by a linear combination of the Jacobian column vectors weighted by the individual joint velocities.

$$\dot{\mathbf{p}} = \mathbf{J}_1 \cdot \dot{q}_1 + \cdots + \mathbf{J}_n \cdot \dot{q}_n$$

where n is the number of active joints. The geometric interpretation of the column vectors is that is the end-effecter velocity and angular velocity when all the joints other than joint i are immobilized and only the i-th joint is moving at a unit velocity.

**Exercise**

Consider the two-dof articulated robot shown in Figure 5.2.1 again. This time we use "absolute" joint angles measured from the positive x-axis, as shown in Figure 5.2.2. Note that angle 2θ is measured from the fixed frame, i.e. the x-axis, rather than a relative frame, e.g. link 1. Obtain the 2-by-2 Jacobian and illustrate the two column vectors on the xy plane. Discuss the result in comparison with the previous case shown in Figure 5.2.1.




Two dimensional articulated arm

Note that the elements of the Jacobian are functions of joint displacements, and thereby vary with the arm configuration. As expressed in eq the partial derivatives, i.e dx/dy , are functions of 21andθθ. Therefore, the column vectors 21vary depending on the arm posture. Remember that the end-effecter velocity is given by the linear combination of the Jacobian column vectors 21.

Therefore, the resultant end-effecter velocity varies depending on the direction and magnitude of the Jacobian column vectors 21 spanning the two dimensional space. If the two vectors point in different directions, the whole two-dimensional space is covered with the linear combination of the two vectors. That is, the end-effecter can be moved in an arbitrary direction with an arbitrary velocity. If, on the other hand, the two Jacobian column vectors are aligned, the end-effecter cannot be moved in an arbitrary direction. As shown in Figure 5.2.3, this may happen for particular arm postures where the two links are fully contracted or extended. These arm configurations are referred to as singular configurations. Accordingly, the Jacobian matrix becomes singular at these positions. Using the determinant of a matrix, this condition is expressed as

$$\det \mathbf{J} = 0$$

### 5.3 Inverse Kinematics of Differential Motion

Now that we know the basic properties of the Jacobian, we are ready to formulate the inverse kinematics problem for obtaining the joint velocities that allow the end-effecter to move at a given desired velocity. For the two dof articulated robot, the problem is to find the joint velocities , for the given end-effecter velocity . If the arm configuration is not singular, this can be obtained by taking the inverse of the Jacobian matrix in eq.(5.1.9),

$$\dot{\mathbf{q}} = \mathbf{J}^{-1} \cdot \mathbf{v}_\mathbf{e}$$

Note that the solution is unique. Unlike the inverse kinematics problem discussed in the previous chapter, the differential kinematics problem has a unique solution as long as the Jacobian is non-singular.

The above solution determines how the end-effecter velocity ve must be decomposed, or resolved, to individual joint velocities. If the controls of the individual joints regulate the joint velocities so that they can track the resolved joint velocities q, the resultant end-effecter velocity will be the desired ve. This control scheme is called Resolved Motion Rate Control, attributed to Daniel Whitney (1969). Since the elements of the Jacobian matrix are functions of joint displacements, the inverse Jacobian varies depending on the arm configuration. This means that although the desired end-effecter velocity is constant, the joint velocities are not.

## INDUSTRIAL ROBOT APPLICATIONS

Industrial Robot Applications:

a. Material Handling Applications

b. Processing Operations

c. Assembly and Inspection

One of the earliest installations of an industrial robot was around 1961 in a die casting operation [5].The robot was used to unload castings from the die casting machine. The typical environment in die casting is not pleasant for humans due to the heat and fumes emitted by the casting process. It seemed quite logical to use a robot in this type of work environment in place of a human operator. Work environment is one of several characteristics that should be considered when selecting a robot application. The general characteristics or industrial work situations that tend to promote the substitution of robots for human labor are the following:

Hazardous work environment for humans. When the work environment is unsafe, unhealthful, hazardous, uncomfortable, or otherwise unpleasant for humans, there is reason to consider an industrial robot for the work. In addition to die casting, there are many other work situations that are hazardous or unpleasant for humans, in eluding forging, spray painting, continuous arc welding, and spot welding. Industrial robots ue utilized in all of these processes

Repetitive work cycle. A second characteristic that tends to promote the use of robotics is a repetitive work cycle. If the sequence of elements in the cycle is the same, and the elements consist of relatively simple motions. a robot is usually capable of performing the work cycle with greater consistency and repeatability than a human worker Greater consistency and repeatability are usually manifested as higher product quality than can he achieved in a manual operation.

Difficult handling for humans. If the task involves the handling of parts or tools that are heavy or otherwise difficult to manipulate, it is likely that an industrial robot is available that can perform the operation. Parts or tools that are too heavy for humans to handle conveniently arc well within the load carrying capacity of a large robot

Multi shift operation. In manual operations requiring second and third shifts, substitution of a robot will provide a much faster financial payback than a single shift operation. Instead of replacing one worker, the robot replaces two or three workers.

Infrequent changeovers, most batch or job shop operations require a changeover of the physical workplace between one job and the next. The time required to make the changeover is nonproductive time since parts are not being made. In an industrial robot application, not only must the physical setup be changed, but the robot must also be reprogrammed, thus adding to the downtime. Consequently, robots have traditionally been easier to justify fur relatively long production runs where changeovers arc infrequent. As procedures for offline robot programming improve, it will be possible to reduce the time required to perform the reprogramming procedure. This will permit shorter production runs to become more economical.

Part position and orientation art' established in the work cell. Most robots in today's industrial applications are without vision capability. Their capacity to pick up an object during each work cycle relies on the fact that the part is in a known position and orientation. A means of presenting the part to the robot at the same location each cycle must be engineered

These characteristics are summarized in Table 7.2, which might be used as a checklist of features to look for in a work situation to determine if a robot application is feasible. The more check marks jailing in the "YES" column, the more likely that an industrial robot is suitable for the application. .

Robots arc being used in a wide field of applications in industry, Most of the current applications of industrial robots are in manufacturing. The applications can usually be classified into one of the following categories: (1) material handling, (2) processing operations, and (3) assembly and inspection. At least some of the work characteristics discussed in Table 7.2 must be present in the application to make the installation of a robot technically and economically feasible

**Material Handling Applications**

Material handling applications are those in which the robot moves materials or parts from one place to another. To accomplish the transfer. the robot is equipped with a gripper type end effectors. The gripper must be designed to handle the specific part or parts that are to be moved in the application, Included within this application category are the following

Cases: (1) material transfer and (2) machine loading and/or unloading. In nearly all material handling applications, the parts must be presented to the robot in a known position and orientation. This requires some form of material handling device to deliver the parts into the work cell in this defined position and orientation

Material Transfer. These applications are ones in which the primary purpose of the robot is to pick up parts at one location and place them at a new location. In many cases, reorientation of the part must be accomplished during the relocation. The basic application in this category is the relatively simple pick-and-place operation, where the robot picks up a part and deposits it at a new location. Transferring parts from one conveyor to another is an example. The requirements of the application are modest: a low technology robot. (e.g., limited sequence type) is usually sufficient. Only two, three, or four joints are required for most of the applications. Pneumatically powered robots are often used.

A more-complex example of material transfer is palletizing, in which the robot must retrieve parts. Cartons, or other objects from one location and deposit them onto a pallet or other container with multiple positions.

**Machine loading and unloading by industrial robots**

In machine loading and unloading process, a robot will be used to move the work parts to or/and from the production machine. This application comes under the category of material handling operations.

The machine loading and unloading application includes the following three processes:

Machine loading
Machine unloading
Machine load and unload

Machine loading and machine unloading
In this operation, the robot loads raw work parts in the machine, and some other systems are used to unload the finished work parts from the machine.
Example: In a press working process, a robot is used to load the sheet metal in the press, and the finished work parts are removed from the press with the help of gravity.
Machine Loading and/or Unloading. In machine loading and/or unloading applications, the robot transfers parts into and/or from a production machine. The three possible cases are'

Machine loading. This is the case in which the robot loads paris into the production machine, but the parts arc unloaded from the machine by some other means

Machine unloading. In this case. The raw materials are fed into the machine without using the robot, and the robot unloads the finished parts.

Machine loading and unloading. This case involves both loading or the raw workpart and unloading of the finished part by the robot

Industrial robot applications of machine loading and/or unloading include the following processes:

Die casting. The robot unloads parts from the die casting machine. Peripheral operations sometimes performed by the robot include dipping the parts into a water bath for cooling.

Plastic molding. Plastic molding is a robot application similar to die casting. The robot is used to unload molded parts from the injection molding machine.

Mew! Machining operations, The robot is used to load raw blanks into the machine tool and unload finished parts from the machine. The change in shape and size of the part before and after machining often presents a problem in end effectors design. And dual grippers (Section 7.3.1) are often used to deal with this issue.

Forging. The robot is typically used to load the raw hot billet into the die, hold it during the forging blows, and remove it from the forge hammer. The hammering action and the risk of damage to the die or end effectors are significant technical problems. Forging and related processes are difficult as robot applications because of the severe conditions under which the robot must operate

Press working. Human operators work at considerable risk in sheet-metal pressworking operations because of the action of the press. Robots are used as substitutes for the human workers to reduce the danger. In these applications, the robot loads the blank into the press, the stamping operation is performed, and the part fails out the back of the machine into a container. In high production runs, press working operations can be mechanized by using sheetmetal coils instead of individual blanks. These operations require neither humans nor robots to participate directly in the process

Hear treating, these are often relatively simple operations in which the robot loads and/or unloads parts from a furnace

In machine unloading, the finished work parts are unloaded from the machine by a robot, while the loading of raw materials are done without any robot support.
Example: Plastic modeling and die casting.

Machine load and unload:
In this process, a robot performs both loading and unloading of work parts in and from the machine.

Example: Machining operation.

The machine loading and unloading process performed by industrial robots is very well characterized by the robot-centered work cell. This cell includes a robot, production machine, and other devices like part delivery system. It helps in increasing the usage of a robot by making it to service more than a production machine. As a result, the productivity in the cell is also increased to a larger extent. This robot cell can be preferred when a robot is in the idle state for a long time.

Moreover, the robots are largely used to carry out loading and unloading process in some production operations like forging, die casting, plastic modeling, stamping press, and machining operations.

**Processing Operations**

Processing application are those in which the robot performs a proccss.ing operation on a work part. A distinguishing feature of this category IS that the robot 1, equipped with some type of to a! as its end effecter (Section 7.3.2). To perform the process. the robot must manipulate the tool relative to the part during the work cycle. In some processing applications, more than one tool must be used during the work cycle. In these instances. a fast-change tool holder is used to exchange tools during the cycle. Examples of industrial robot applications in the processing category include spot welding. Continuous arc welding, spray painting, and various machining and other rotating spindle processes.

Spot Welding. Spot welding is a metal joining process in which two sheet metal parts are fused together at localized points of contact. Two copper-based electrodes are used to squeeze the metal parts together and then apply a large electrical current across the contact point to cause fusion to occur. The electrodes, together with the mechanism that actuates them, constitute the welding gun in spot welding. Because of its widespread use in the automobile industry for car body fabrication, spot welding represents one of the most common applications of industrial robots today. The end effectors are the spot welding gun used to pinch the car panels together and perform the resistance welding process. The welding gun used for automobile spot welding is typically heavy. Prior to the use of robots in this application, human workers performed this operation, and the heavy welding tools were difficult for humans to manipulate accurately. As a consequence, there were many instances of missed welds, poorly located welds, and other defects. Resulting in overall low quality of the finished product. The use of industrial robots in this application has dramatically improved the consistency of the welds.

Robots used for spot welding are usually large, with sufficient payload capacity to wield the heavy welding gun. Five or six axes are generally required to achieve the required positioning and orientation of the welding gun. Playback robots with point-to-point arc used. Jointed arm coordinate robots are the most common anatomies in automobile spot welding lines, which may consist of several dozen robots.

Continuous Arc Welding. Continuous arc welding is used to provide continuous welds rather than individual welds at specific contact points as in spot welding. The resulting arc welded joint is substantially stronger than in spot welding. Since the weld is continuous, it can be used to make airtight pressure vessels and other elements in which strength and continuity are required. There are various forms of continuous arc welding, but they all follow the general description given here.

The working conditions [or humans who perform arc welding are not good. The welder must wear a face helmet for eye protection against the ultraviolet radiation emitted by the arc welding process. The helmet window must be dark enough to mask the ultraviolet. However, the window is so dark that the worker cannot see through it unless the arc is on. High electrical current is used in the welding process, and this creates a hazard for the welder. Finally, there is the obvious danger from the high temperatures in the process, high enough to melt the steel, aluminum, or other metal that is being welded. A significant amount of hand-eye coordination is required by human welders to make sure that the arc follows the desired path with sufficient accuracy to make a good weld. This, together with the conditions described above, results in a high level of worker fatigue. Consequently, the welder is only accomplishing the welding process for perhaps 20-30% of the time. This percentage is called the arc-on time, defined as the proportion of time during the shift when the welding arc is on and performing the process. To assist the welder, a second worker, called the fitter, is usually present at the work site to set up the parts to be welded and to perform other similar chores in support of the welder.

Because of these conditions in manual arc welding, automation is used where technically and economically feasible. For welding jobs involving long continuous joints that are accomplished repetitively, mechanized welding machines have been designed to perform the process. These machines are used for long straight sections and regular round parts. such as pressure vessels tank", and pipes

Industrial robots can also be used to automate the continuous arc welding process The economics of robot arc welding suggest that the application should involve a relatively long production run. The cell consists of the robot, the welding apparatus (power unit. controller, welding 1001,and wire feed mechanism), and a fixture that positions the components for the robot. The fixture might be mechanized with one or two degrees-of-freedom so that it can present different portions of the work to the robot for welding. For greater productivity, a double fixture is often used so that a human helper can be unloading the completed job and loading [he components for the next work cycle while the robot is simultaneously welding the present job. Figure 7.12 illustrates this kind of workplace arrangement

The robot used in arc welding jobs must be capable of continuous path control. Jointed arm robots consisting of five or six joints are frequently used. In addition. A fixture consisting of one or two more degrees-of-freedom is often used to hold the parts during welding. The fixture must be designed specifically for the job. Programming for arc welding is usually costly. Therefore. most applications require a large batch size to justify the robot cell. In the future, as quick-change fixtures are developed and programming effort is reduced, shorter production runs will be possible in robot arc welding applications.

Spray Coating. Spray coating makes use of a spray gun directed at the object to be coated. Fluid (e.g., paint) flows through the nozzle of the spray gun to be dispersed and applied over the surface of the object. Spray painting is the most common application in the category. The term spray coating indicates a broader range of applications that includes painting.

The work environment for humans who perform this process is filled with health hazards. These hazards include noxious fumes in the air, risk of flash fires, and noise from the spray gun nozzle. The environment is also believed to pose a carcinogenic risk for workers. Largely because of these hazards, robots are being used with increasing frequency for spray coating tasks.

Robot applications include spray coating of appliances, automobile car bodies, engines, and other parts, spray staining of wood products, and spraying of porcelain coatings on bathroom fixtures. The robot must he capable of continuous path control to accomplish the smooth motion sequences required in spray painting. The most convenient programming method is manual leadthrough (Section 7.6.1). Jointed arm robots seem to be the most common anatomy for this application. The robot must possess a long reach to access the areas of the work part to be coated in the application.

The use of industrial robots for spray coating applications offers a number of benefits in addition to protecting workers from a hazardous environment. These other benefits include greater uniformity in applying the coating than humans can accomplish, reduced use of paint (less waste), lower needs for ventilating the work area since humans are null present during the process, and greater productivity.

Other Processing Applications. Spot welding, arc welding, and spray coating are the most familiar processing applications of industrial robots. The list of industrial processes that are being performed by robots is continually growing. Among these processes are the following:

Drilling, routing, and other machining processes. These applications use a rotating spindle as the end effectors. Mounted in the spindle chuck is the particular cutting tool. One of the problems with this application is the high cutting forces encountered in machining. The robot must be strong enough to withstand these cutting forces and maintain the required accuracy of the cut.

Grinding, wire brushing, and similar operations. These operations also usc a rotating spindle to drive the tool (grinding wheel, wire brush, polishing wheel, etc.] at high rotational speed to accomplish finishing and deburring operations on the work.

Water jet cutting. This is a process in which a high pressure stream of water is forced through a small nozzle at high speed to cut plastic sheets, fabrics, cardboard, and other materials with precision. The end effector is the waterjet nozzle that is directed over the desired cutting path by the robot.

Loser culling. The function of the robot in this application is similar to its function in waterjet cutting. The laser tool is attached to the robot as its end effector. Laser beam welding is a si~i1ar application

Riveting. Some work has been done in using robots to perform riveting operations in sheet metal fabrication. A riveting tool with a feed mechanism for feeding the rivets is mounted on the robot's wrist. The function of the robot is to place the riveting tool at the proper hole and actuate the device

**Assembly and Inspection**

In some respects. Assembly and inspection are hybrids of the previous two application categories: material handling and processing. Assembly and inspection applications can involve either the handling of materials or the manipulation of a tool. For example, assembly operations typically involve the addition of components to build a product. This requires the movement of components from a supply location in the workplace to the product being assernbled, which is material handling. In some cases, the fastening of the components re quires a tool to be used by the robot (e.g. staking, welding. driving a screw). Similarly. Some robot inspection operations require that parts be manipulated, while other applications require that an inspection tool be manipulated.

Assembly and inspection are traditionally labor-intensive activities. They are also highly repetitive and usually boring. For these reasons, they are logical candidates for robotic applications. However. assembly work typically involves diverse and sometimes difficult tasks, often requiring adjustments to be made in parts that don't quite fit together. A sense of feel is often required to achieve a dose fitting of parts. Inspection work requires high precision and patience. and human judgment is often needed to determine whether a product is within quality specifications or not. Because of these complications in both types of work, the application of robots has not been easy. Nevertheless, the potential rewards are so great chat substantial efforts are being made to develop the necessary technologies to achieve success in these applications.

Assembly. Assembly involves the addition of two or more parts to form a new entity, called a subassembly (or assembly). The new subassembly is made secure by fastening two or more part, together using mechanical fastening techniques (such as screws, nuts, and rivets) or joining processes (e.g .. welding. brazing, soldering, or adhesive bonding). We have already discussed robot applications in welding, which are often considered separately from mechanical assembly applications (as we have separated them in our (overage here).

Because of the economic importance of assembly, automated methods are often applied. Fixed automation (Chapter 1) is appropriate in mass production of relatively simple products, such as pens, mechanical pencils, cigarette lighters, and garden hose nozzles. Robots are usually at a disadvantage in these high production situations because they cannot operate at the high speeds that fixed automated equipment can.

The most appealing application of industrial robots for assembly is where a mixture of similar products or models are produced in the same work cell or assembly line. Examples of these kinds of products include electric motors, small appliances, and various other small mechanical and electrical products. In these instances. the basic configuration of the different models is the same. but there are variations in size, geometry, options, and other features. Such products are often made in batches on manual assembly lines. However, the pressure to reduce inventories makes mixed model assembly lines (Section 17.2) more attractive. Robots can be used to substitute for some or all of the manual stations on these lines. what makes robots viable in mixed model assembly is their capability to execute programmed variations in the work cycle to accommodate different product configurations.

Industrial robots used for the types of assembly operations described here are typically small. with light load capacities. An internal study at General Motors revealed that a large proportion of assembly tasks require a robot capable of lifting parts weighing Sib or less [7]. The most common configurations arc jointed arm, SCARA, and Cartesian coordinate. Accuracy requirements in assembly work are often more demanding than in other robot applications, and some of the more, precise robots in this category have repeatabilities as dose as :B105 mm (±O.OO2 in j, In addition to the robot itself, the requirements of the end effector are often demanding, The end effector may have to perform multiple functions at a single workstation to reduce the number of robots required in the cell. These multiple functions can include handling more than one part geometry and performing both as a gripper and an automatic assembly tool

Inspection. There is often a need in automated production and assembly systems to inspect the work that is supposed to be done. These inspections accomplish the following functions: (1) making sure that a given process has been completed. (2) ensuring that parts have been added in assembly as specified. and (3) identifying flaws in raw materials and finished parts. The topic of automated inspection is considered in more detail in Chapter 22. Our purpose here is to identify the role played by industrial robots in inspection. Inspection tasks performed by robots can be divided into the following two cases:

The robot performs loading and unloading tasks to support an inspection or testing machine. This case is really machine loading and unloading, where the machine is an inspection machine. The robot picks parts (or assemblies) that enter the cell, loads and unloads them to carry out the inspection process, and places them at the cell output. In some cases. the inspection may result in parts sortation that must be accomplished by the robot. Depending on the quality level, the robot places the parts in different containers or on different exit conveyors,

The robot manipulates an inspection device. such as a mechanical probe, to test the product. This case is similar to a processing operation in which the end effector attached to the robot's wrist is the inspection probe. To perform the process, the part must be presented at the workstation in the correct position and orientation, and the robot manipulates the inspection device as required.