Mechanical Engineering

Mechatronics and Robotics

Comprehensive Theory

with **Solved Examples** and **Practice Questions**

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CHAPTER 5

Robotics

5.1 INTRODUCTION

- Word robot was coined by a Czech novelist Karel Capek in a 1920 play titled Rassum's Universal Robots (RUR).
- Robot in Czech is a word for worker or servant.
- Robot is an automatically controlled material handling unit that is widely used in the manufacturing industry. It is generally used for high volume production and better quality. Implementation of robot technology with integration of automatic system can contribute to increase in productivity of the company and enhances its profitability.
- Another definition from Robot Institute of America is that the robot is a programmable multi function manipulator designed to move and manipulate material, parts, tools or specialized devices through variable programmed motions for the performance of a variety of specified tasks.

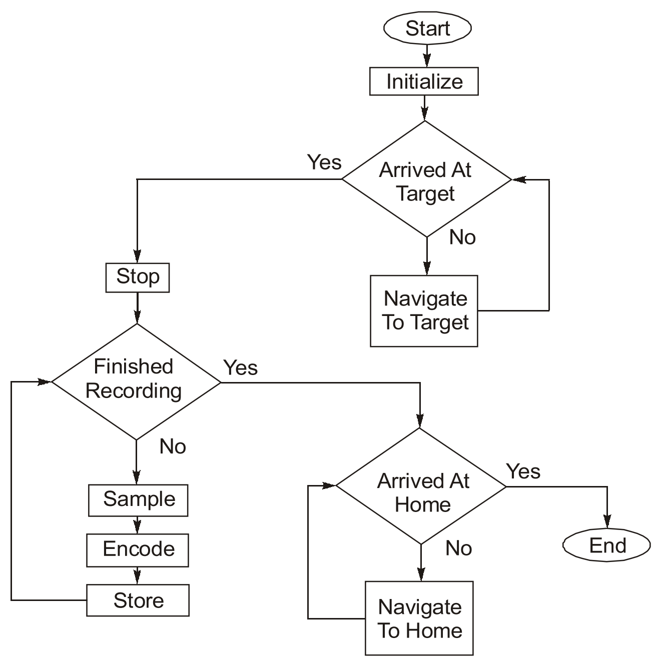


Fig. 5.1: The simple robotic flow chart

- There are a number of successful examples of robot applications such as the following:

  Robots perform more than 98 percent of the spot welding on Ford's Taurus and Sable cars in USA. A robot drills holes in the vertical tail fins at general dynamics compared to man when the job was done manually. Robots insert disk drives into personal computers and snap keys onto electronic type writer keyboards.

5.4 Robot Types

5.4.1 Types of Robots by Applications

Now-a-days, robots do a lot of different tasks in different fields and the number of jobs entrusted to robots is growing steadily. That's why one of the best ways to classify robots is by their applications:

- Industrial robots: Industrial robots are robots used in an industrial manufacturing environment. Usually these are articulated arms specifically developed for such applications as welding, material handling, painting and others. If we judge purely by application this type could also include some automated guided vehicles and other robots.
- Domestic or household robots: These are the robots used at home or for domestic purposes. This type of robots includes several different devices such as robotic vacuum cleaners, robotic pool cleaners, sweepers, gutter cleaners and other robots that can do different chores. Also, some surveillance and telepresence robots could be regarded as household robots if used in that environment.
- Medical robots: Robots used in medicine and medical institutions. First and fore most-surgery robots. Also, some automated guided vehicles and may be lifting aides.
- Military robots: Robots used in military. This type of robots includes bomb disposal robots, different transportation robots, reconnaissance drones. Often robots initially created for military purposes can be used in law enforcement, search and rescue operations.
- Service robots: Robots that don't fall into other types by usage. These could be different data gathering robots, robots made to show off technologies, robots used for research, etc.

5.4.2 Types of Robots by Locomotion and Kinematics

As you can understand, robot's application alone does not provide enough information when talking about a specific robot. So they can also be classified as:

1. Stationary robots (Including robotic arms with a global axis of movement)

- Cartesian/Gantry robots
- Cylindrical robots
- Spherical robots
- SCARA robots
- Articulated robots (robotic arms)
- Parallel robots

2. Wheeled robots

- Single wheel (ball) robots
- Two-wheel robots
- Three and more wheel robots

3. Legged robots

- Bipedal robots (humanoid robots)
- Tripedal robots
- Quadrupedal robots
- Hexapod robots
- Robot with other number of legs

4. Swimming robots

5. Flying robots

6. Mobile spherical robots (robotic balls)

7. Swarm robots

5.4.3 On the Basis of Configuration

5.4.3.1 Cartesian co-ordinates Robots

A Cartesian coordinate robot (also called linear robot) is an industrial robot whose three principal axis of control are linear (i.e. they move in a straight line rather than rotate) and are at right angles to each other. The three sliding joints correspond to moving the wrist up-down, in-out, back-forth. Among other advantages, this mechanical arrangement simplifies the robot control arm solution. Cartesian coordinate robots with the horizontal member supported at both ends are sometimes called Gantry robots. They are often quite large.

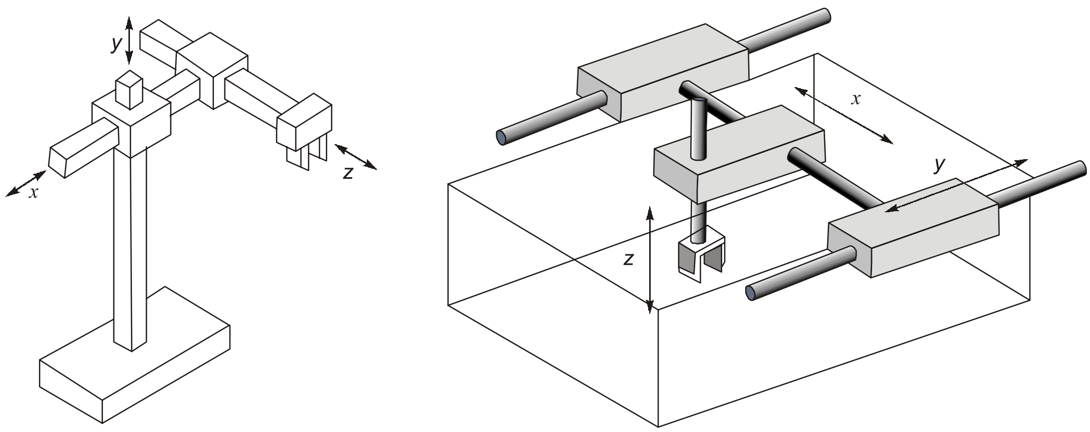


Fig. 5.2: Cartesian Robot Configurations

Positioning may be done by linear motion along three principal axes: left and right, in and out and up and down. These axes are known, respectively, as the Cartesian axes *X*, *Y* and *Z* shows a typical manipulator arm for a Cartesian co-ordinates robots. This is one of the simplest types of robots.

5.4.3.2 Spherical or Polar Coordinate Robots

In this type of robot there are mostly rotational axes. The axes for the spherical co-ordinates are θ, the rotational axis, *R*, the reach axis and β, the bend-up and down axis. The work area serviced by a polar co-ordinate robot is the space between two concentric hemispheres. The reach of the arm is de-concentric hemispheres. The reach of the arm defines the inner hemisphere when it is fully retracted along the *R*-axis.

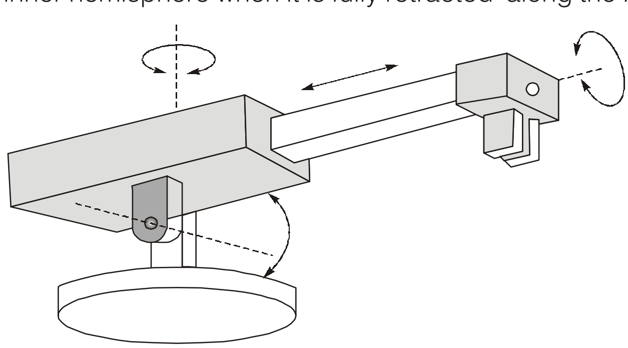


Fig. 5.3: Spherical or polar coordinate Robot

5.4.3.3 Cylindrical Coordinate Robots

A cylindrical robot has two linear axes and one rotary axis. The robot derives its name from the operating envelope (the space in which a robot operates that is created by moving the axes from limit to limit).

The *Z*-axis is located inside the base, resulting in a compact end-of-arm design that allows the robot to "reach" into tight work envelopes without sacrificing speed or repeatability.

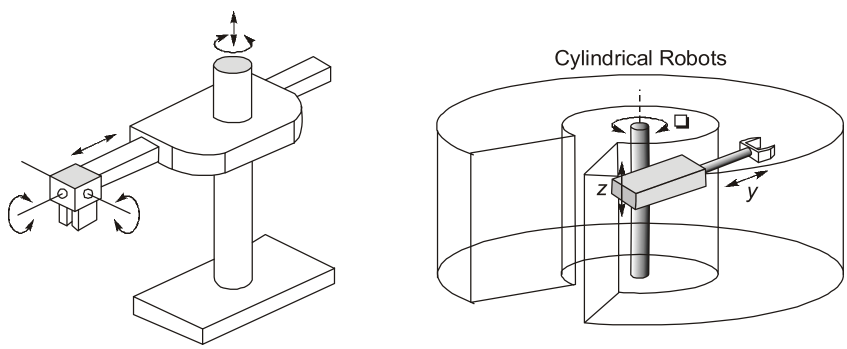


Fig. 5.4: Cylindrical Robot configurations

5.4.3.4 Jointed Arm Robot

It consists of three straight members connected by two rotational joints and mounted on rotary base. This type of configuration is similar to the human arm. The three members connected by rotational joints are analogous to the human shoulder, elbow and wrist. Here the arm can rotate about all three axes, hence the robot is called a revolute Co-ordinates, articulate or jointed arm robot. This type of configuration has low resolution which depends upon arm length however it can move at high speeds.

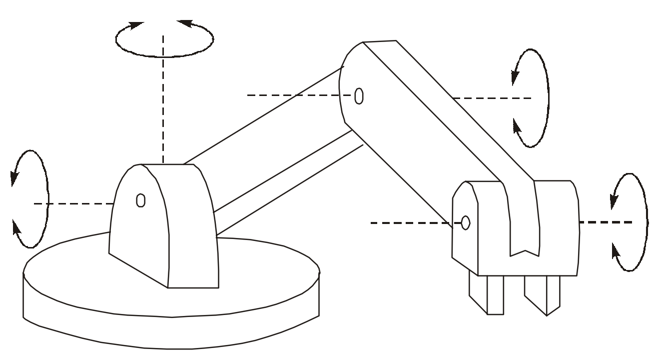


Fig. 5.5: Jointed Arm Robot Configuration

5.4.3.5 Articulate or Revolute Robot

An articulated robot uses rotary joints to access its work space. Usually the joints are arranged in a "chain", so that one joint supports another further in the chain. Articulated robots range from simple two-jointed structures to robots with 10 or more interacting joints. They are powered by a variety of means, like electric motors etc.

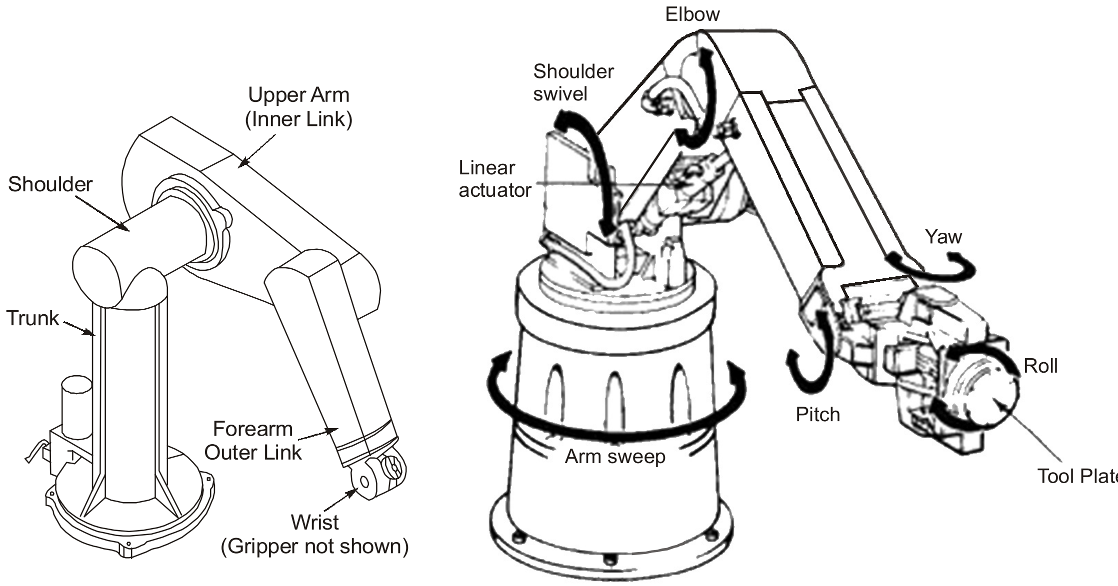


Fig. 5.6: Articulated Robots

5.4.3.6 Parallel Robot

The robot manipulators can be either serial or parallel. In a parallel robot, the end-effector is connected to the base through several chains of interconnected links. Therefore, a parallel robot has at least two legs or arms. Most of its joints are not actuated, and many of these passive joints have several degrees-of-freedom (DOFs) (e.g. spherical, universal and planar joints).

Two of the most popular parallel robots are the telescoping-leg hexapod used in most motion simulators (often called "motion platforms") and the "Delta robot", generally used for rapid pick-and-place. While there are fewer parallel robots than serial robots in use, the variety of parallel robots is larger.

A typical application of parallel robot is a mobile platform handling cockpit flight simulators. It is a robot whose arms have concurrent prismatic or rotary joints.

Fig. 5.7: Parallel Robot

(a) **Linear joint (type L joint):** The relative movement between the input link and the output link is a translational sliding motion, with the axes of the two links being parallel.

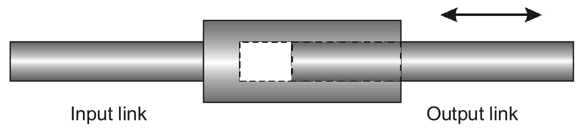


Fig. 5.12: Linear Joint

(b) **Orthogonal joint (type U joint):** This type of joint also have translational sliding motion, but the input and output links are perpendicular to each other during the move.

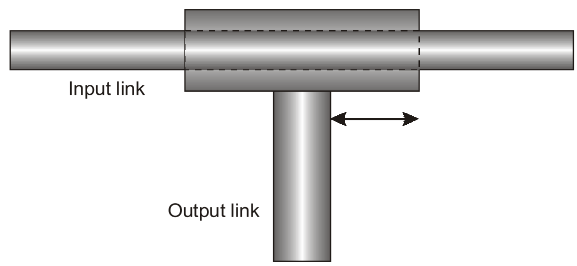


Fig. 5.13: Orthogonal Joint

(c) **Rotational joint (type R joint):** This type of joint provides rotational relative motion, with the axis of rotation perpendicular to the axes of the input and output links.

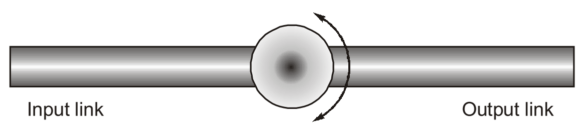


Fig. 5.14: Rotational Joint

(d) **Twisting joint (type T joint):** This joint also involves rotary motion, but the axis or rotation is parallel to the axes of the two links.

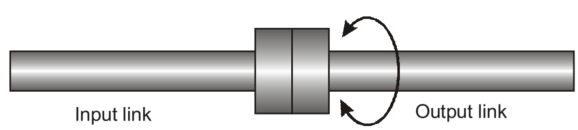


Fig. 5.15: Twisting Joint

(e) **Revolving joint (type V-joint, V from the "v" in revolving):** In this type, axis of input link is parallel to the axis of rotation of the joint. However the axis of the output link is perpendicular to the axis of rotation.

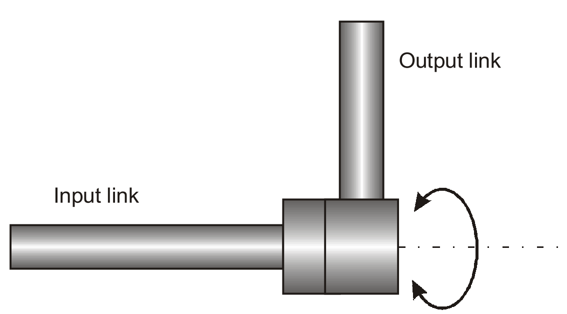


Fig. 5.16: Revolving Joint

5.6.2 End Effectors

End effectors are the devices attached to the robot's wrist to perform a specific task. The end effectors are two types: Gripers and Tools.

Grippers

- Mechanical Grippers
- Magnetized grippers
- Scoops (to carry fluids)
- Suction cups or vacuum cups
- Hooks

5.6.3 Tools

Tools are used when the robot is required to perform some processing operation on the work piece. Here the robot manipulate the tool relative to the work piece. The tools used as end effectors by robot to perform processing operations like

- Arc welding tool
- Spot welding gun
- Rotating spindle for drilling, grinding etc.
- Spray painting gun
- Assembly tool like automatic screwdriver

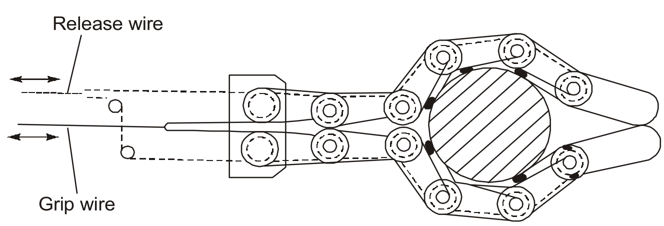


Fig. 5.17: Robot Gripper

5.6.4 Sensors in Robotics

- Robot sensors: measure robot configuration/condition and its environment and send such information to robot controller as electronic signals (e.g., arm position, presence of toxic gas)
- Robots often need information that is beyond 5 human senses (e.g., ability to: see in the dark, detect tiny amounts of invisible radiation, measure movement that is too small or fast for the human eye to see)

Type of Sensors

- Force Sensor: e.g., parts fitting and insertion, force feedback in robotic surgery.
- Vision Sensor: e.g., to pick bins, perform inspection, etc.
- Tilt sensors: e.g., to balance a robot
- Tactile sensors (touch sensors, force sensors, tactile array sensors).
- Proximity and range sensors (optical sensors, acoustical sensors, electromagnetic sensors).
- Miscellaneous sensors (transducers and sensors which sense variables such temperature, pressure, fluid flow, thermocouples, voice sensors).
- Machine vision systems.

Application of Sensors

- Safety monitoring
- Interlocks in work cell control
- Part inspection for quality control
- Determining positions and related information about objects

$l_1 = \overline{OA}, l_2 = \overline{AB}, l_3 = \overline{BE}$ Let us assume that Actuator 1 driving link 1 is fixed to the base link (link 0), generating angle θ_1, while Actuator 2 driving link 2 is fixed to the tip of Link 1, creating angle θ_2 between the two links, and Actuator 3 driving Link 3 is fixed to the tip of Link 2, creating angle θ_3, 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 x_e and y_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:

$$x_e = l_1 \cos\theta_1 + l_2 \cos(\theta_1 + \theta_2) + l_3 \cos(\theta_1 + \theta_2 + \theta_3) \tag{4.1.1}$$

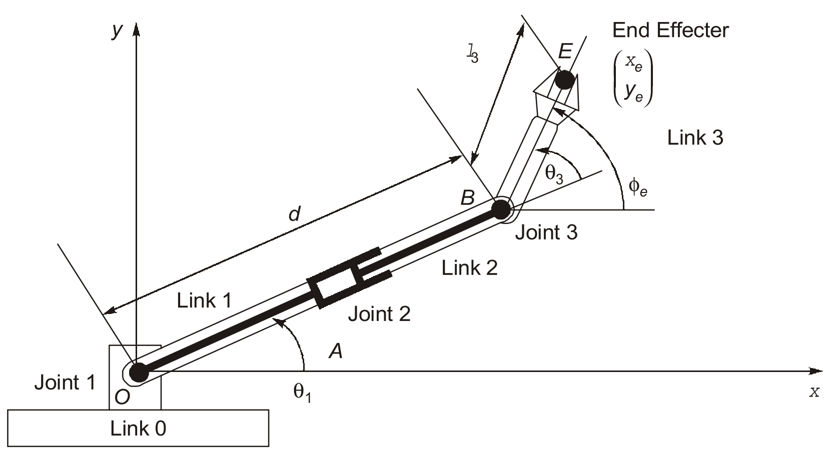
$$y_e = l_1 \sin\theta_1 + l_2 \sin(\theta_1 + \theta_2) + l_3 \sin(\theta_1 + \theta_2 + \theta_3) \tag{4.1.2}$$

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 ϕ_e is related to the actuator displacements as

$$\phi_e = \theta_1 + \theta_2 + \theta_3 \tag{4.1.3}$$

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.

Example - 5.1 **As shown below in figure 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.**



Solution:

Let us obtain a formal expression for kinematic equations. As we know 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 d_i if it is a prismatic joint, and by angle θ_i for a revolute joint. For formal expression, let us use a generic notation: q_i. Namely, joint displacement q_i represents either distance d_i or angle θ_i depending 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: $q = [q_1 \;\; q_2 \;\; \cdots \;\; q_n]^T$, 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:

$$p = f(q),\; p \in [p]_{3 \times 1},\; q \in [q]_{1 \times n}$$

NOTE

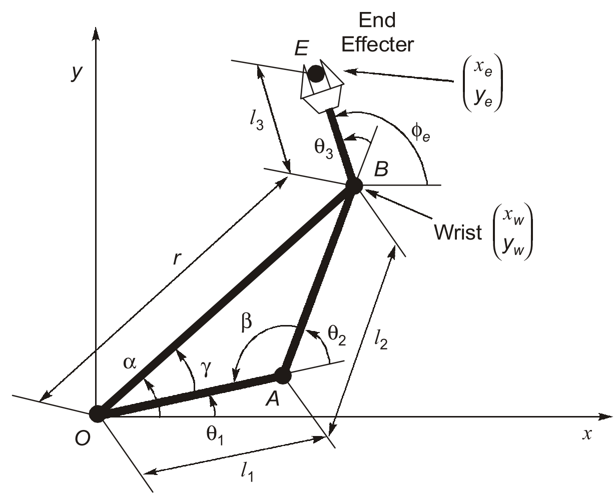
For a serial link mechanism, all the joints are usually active joints driven by individual actuators. Except for some special cases, these actuators uniquely determine the end-effecter position and orientation as well as the configuration of the entire robot mechanism. If there is a link whose location is not fully determined by the actuator displacements, such a robot mechanism is said to be *under-actuated*. Unless a robot mechanism is under-actuated, the collection of the joint displacements, i.e. the vector q, uniquely determines the entire robot configuration. For a serial link mechanism, these joints are independent, having no geometric constraint other than their stroke limits. Therefore, these joint displacements are *generalized coordinates* that locate the robot mechanism uniquely and completely. Formally, the number of generalized coordinates is called *degrees of freedom*. Vector q is called joint coordinates, when they form a complete and independent set of generalized coordinates.

5.8.2 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.

Example - 5.2 Consider the three dof planar arm shown in figure below again. To solve its inverse kinematics problem, the kinematic structure is redrawn in figure below. The problem is to find three joint angles θ_1, θ_2, θ_3 that lead the end effecter to a desired position and orientation, x_e, y_e, ϕ_e. We take a two-step approach. First, we find the position of the wrist, point B, from x_e, y_e, ϕ_e. Then we find θ_1, ϕ_2 from the wrist position. Angle θ_3 can be determined immediately from the wrist position.



Solution:

Let x_w and y_w be the coordinates of the wrist. As shown in above figure, point B is at distance l_3 from the given end-effecter position E. Moving in the opposite direction to the end effecter orientation ϕ_e, the wrist coordinates are given by

$$x_w = x_e - l_3 \cos \phi_e \quad ...(1)$$
$$y_w = y_e - l_3 \sin \phi_e$$

Note that the right hand sides of the above equations are functions of x_e, y_e, ϕ_e alone. From these wrist coordinates, we can determine the angle α shown in the figure.

$$\alpha = \tan^{-1}\frac{y_w}{x_w} \quad ...(2)$$

Next, let us consider the triangle OAB and define angles β, γ, as shown in the figure. This triangle is formed by the wrist B, the elbow A, and the shoulder O. Applying the law of cosines to the elbow angle β yields

$$l_1^2 + l_2^2 - 2l_1l_2\cos\beta = r^2 \quad ...(3)$$

where $r^2 = x_w^2 + y_w^2$, the squared distance between O and B. Solving this for angle β yields

$$\theta_2 = \pi - \beta = \pi - \cos^{-1}\frac{l_1^2 + l_2^2 - x_w^2 - y_w^2}{2l_1l_2} \quad ...(4)$$

Similarly, $$r^2 + l_1^2 - 2rl_1\cos\gamma = l_2^2 \quad ...(5)$$

Solving this for γ yields

$$\theta_1 = \alpha - \gamma = \tan^{-1}\frac{y_w}{x_w} - \cos^{-1}\frac{x_w^2 + y_w^2 + l_1^2 - l_2^2}{2l_1\sqrt{x_x^2 + y_w^2}} \quad ...(6)$$

From the above ϕ_1, ϕ_2 we can obtain

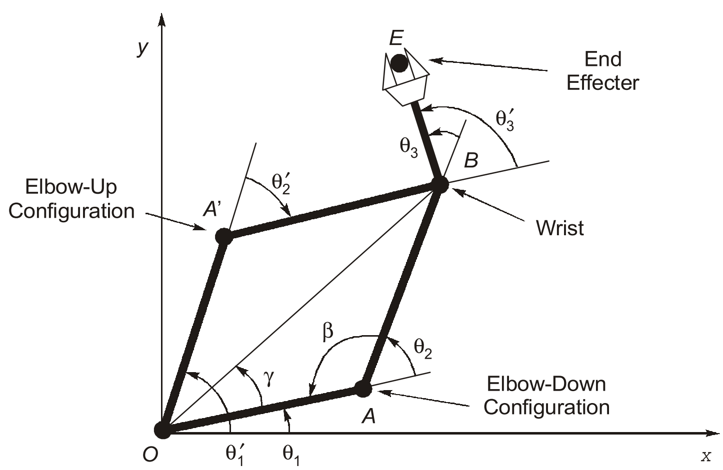
$$\theta_3 = \phi_e - \theta_1 - \theta_2 \quad \text{...(7)}$$

Eqs. (4), (6), and (7) provide a set of joint angles that locates the end-effecter at the desired position and orientation. It is interesting to note that there is another way of reaching the same end-effecter position and orientation, i.e. another solution to the inverse kinematics problem. Figure shows two configurations of the arm leading to the same end-effecter location: the elbow down configuration and the elbow up configuration. The former corresponds to the solution obtained above. The latter, having the elbow position at point *A*', is symmetric to the former configuration with respect to line *OB*, as shown in the figure below. Therefore, the two solutions are related as

$$\theta_1' = \theta_1 + 2\gamma$$

$$\theta_2' = -\theta_2$$

$$\theta_3' = \phi_e - \theta_1' - \theta_2' = \theta_3 + 2\theta_2 - 2\gamma$$



NOTE

Inverse kinematics problems often possess multiple solutions, like the above example, since they are nonlinear. Specifying end-effecter position and orientation does not uniquely determine the whole configuration of the system. This implies that vector *p*, the collective position and orientation of the end-effecter, cannot be used as generalized coordinates.

The existence of multiple solutions, however, provides the robot with an extra degree of flexibility. Consider a robot working in a crowded environment. If multiple configurations exist for the same end-effecter location, the robot can take a configuration having no interference with the environment. Due to physical limitations, however, the solutions to the inverse kinematics problem do not necessarily provide feasible configurations. We must check whether each solution satisfies the constraint of movable range, i.e. stroke limit of each joint.

PRACTICE QUESTIONS

1. Single wheel robots are called as
(a) Legged robots (b) Arm robots
(c) Ball robots (d) 4-axis robots

2. Maximum possible number of degrees of freedom for a rigid body in a plane motion is
(a) 6 (b) 3
(c) 2 (d) 5

3. An android takes the form of:
(a) An insect
(b) A simple robot with human appearance
(c) Binocular vision
(d) A human body

4. An automotive robot might best keep itself traveling down a specific lane of traffic by using:
(a) Binaural hearing
(b) Epi-polar navigation
(c) Edge detection
(d) A second-generation end effector

5. A rule-based system is also known as:
(a) Artificial intelligence (b) An expert system
(c) An analytical engine (d) An automated guided vehicle

6. According to motion of the arms which of following is a type of robot?
(a) Physical manipulator
(b) Continuous path robot
(c) Fixed sequence robot
(d) Intelligent robot

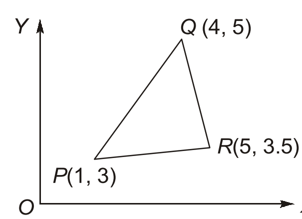
7. In which year, one of the first humanoid robots was exhibited at the annual exhibition of the model engineers society in London?
(a) 1930 (b) 1920
(c) 1928 (d) 1924

8. Who invented first humanoid robots?
(a) Czech (b) Josef capek
(c) W.H.Richards (d) None of the above

9. Who created the first electronic autonomous robots with complex behaviour?
(a) Gakutensoku
(b) Archibald Low
(c) William Grey Walter
(d) Rodon Brooks

10. The first palletizing robot was introduced in which year?
(a) 1947 (b) 1940
(c) 1936 (d) 1963

11. The figure below represents a triangle *PQR* with initial coordinates of the vertices as *P*(1,3) *Q*(4,5) and *R*(5,3.5). The triangle is rotated in the X-Y plane about the vertex *P* by angle q in clockwise direction. If $\sin\theta = 0.6$ and $\cos\theta = 0.8$, the new coordinates of the vertex *Q* are:



(a) (4.6, 2.8) (b) (3.2, 4.6)
(c) (7.9, 5.5) (d) (5.5, 7.9)

12. There are two points *P* & *Q* on a planar rigid body. The relative velocity between the two points
(a) should always be along *PQ*.
(b) can be oriented along any direction.
(c) should always be perpendicular to *PQ*.
(d) should be along *QP* when the body undergoes pure translation.

13. Who invented the first robot in the world?
(a) George Devol (b) Czech
(c) Archibald low (d) None of the above

14. The scara robot was developed under the guidance of
(a) Sankyo Seiki
(b) Hiroshi Makino
(c) William Grey Walter
(d) None of the above

15. In contrast with expensive big robots which robots are cheap and simple?
(a) Virtual robots (b) Stationary robots
(c) Beam robots (d) Mechanical robots

16. A manipulator is also known as a:
(a) Track drive (b) Robot arm
(c) Vision system (d) Robot controller

17. Spherical coordinates can uniquely define the position of a point in up to:
(a) One dimension
(b) Two dimensions
(c) Three dimensions
(d) Four dimensions

18. The physical structure of Robot which moves around is called?
(a) Manipulator (b) End-effectors
(c) Joints (d) Links

19. The kinematic part of the robot or manipulator is called
(a) Links (b) Joints
(c) End-effectors (d) None of the above

20. The Tripedal Robot is which type of Robot?
(a) Wheeled robot (b) Legged Robot
(c) Stationary Robot (d) None of the above

■■■■

ANSWERS

1. (c)	**2.** (b)	**3.** (d)	**4.** (c)	**5.** (b)	**6.** (b)	**7.** (c)
8. (c)	**9.** (c)	**10.** (d)	**11.** (a)	**12.** (c)	**13.** (a)	**14.** (a)
15. (c)	**16.** (b)	**17.** (c)	**18.** (a)	**19.** (b)	**20.** (b)	