

An Introduction to  
**ROBOTICS**

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# An Introduction to Robotics

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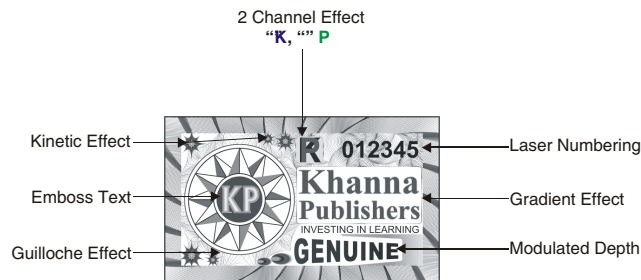
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# Preface

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This book is written at a time when there is a lot of discussion about the emergence of the fourth industrial revolution, popularly referred as “IR 4.0” or “Industry 4.0.” The Indian Express Group organised a conclave on December 15, 2021, on smart manufacturing that generated a lot of publicity about the program, particularly IR 4.0. AICTE took note of this event and announced a few areas of emerging technologies, of which robotics is one of them. With the announcement of emerging technologies, particularly robotics engineering, it has emerged as an important subject in view of Industry 4.0 or smart manufacturing. Automation in all walks of life, specifically in manufacturing, is inevitable, so much so that the factories of the future will be called “Smart Factories.” The manufacturing activities on the shop floor are challenged to be unmanned in view of the fourth industrial revolution. In view of this fact, robotics may be regarded as the backbone of manufacturing automation. Therefore, we, the authors, wrote this book with the contents suggested by AICTE. In fact, the authors are of the strong opinion that this subject, as a part of the academic curriculum, should be taught to the students of all the branches of engineering as a core subject. This would be a good beginning for AICTE to make a bandwagon of IR 4.0.

All those technologies that have been declared emerging technologies by AICTE, such as IoT, AI and ML, Cloud Computing, Blockchain, and Robotics are considered radically novel and relatively fast-growing technologies that need to be considered in academic curricula at an appropriate level and branch, making robotics engineering common to all branches.

This book, titled “An Introduction to Robotics”, has been crafted to cover all the topics as recommended by AICTE in six different units comprises of twenty chapters in all. The book is intended for undergraduate students to become familiar with the subject of robots and robotics. This deals with the subject in such a way that the students are able to design a robot and integrate it into appropriate applications, covering the necessary fundamentals of the subject however, if necessary, help of some other books may be taken as required. IoT, along with robotics, has become a game changer for the manufacturing industry. IR 4.0 has become particularly important as the pandemic has brought crucial changes to the manufacturing industry. This indicates that industry has to adopt digital communication channels over conventional ones. Communication between machine to machine may be made possible through the Industrial Internet of Things (IIoT). This has important relevance with regard to robots and interfacing machines for a complete robotised manufacturing environment. In this context, SaaS (Software as a Service) is a specific way of delivering applications over the internet. These facilities will simply allow access from machine to machine via the internet. Thus, it will free factory management from complex software-hardware supervision.

Following are the details of the six units, which consist of twenty chapters:

Chapter 1 is an introduction to the field of robotics. It introduces also covers historical background, robot characteristics and specifications, and fundamental terms related to robots. Chapter 2 covers the robot components, the classification of robots, and their functions and advantages. Chapter 3 covers the fundamentals of control systems with suitable examples. Chapter 4 deals with the robot kinematics, which includes the different robot geometries. Chapter 5 discusses various safety and social issues related to robots. Chapter 6 deals with the coordinate transformation and Denavit–Hartenberg representation. It also includes forward

and inverse Jacobians. Chapter 7 deals with the wrist and arm singularities, explaining what they are and how to avoid them. Chapter 8 explains the static forces acting on the robot link mechanism and how to determine equivalence of force. Chapter 9 deals with robot dynamics. In this chapter, the Lagrangian technique is used as the primary method for analysing a 2-dof manipulator. Chapter 10 covers the sensors and their characteristics. It also deals with the various sensors used in robotics and robotic applications. Chapter 11 explains the types of cameras and applications of CCD cameras in robots. Chapter 12 deals with transformation, *i.e.*, how a two-dimensional graphic sketch transforms when it is rotated through some angles. The vision system is covered in Chapter 13. It also includes different techniques for image processing. Chapter 14 covers robot control methods such as proportional, derivative, and integral control. Chapter 15 explains the non-linear control of the mechanisms of robot movement or any other machine. Chapter 16 covers actuators, including pneumatic and hydraulic devices. It also deals with the driving power or actuating power for robot mechanisms and includes the selection criteria for choosing a proper drive for a robotic system. Chapter 17 deals with the method and mechanism of transmission of power to move the links and end effectors of robots. Chapter 18 covers the fundamentals of embedded systems. Chapter 19 deals with an overview of different robot programming languages. Chapter 20 covers the future perspective of robotics in various fields.

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# Brief History and Concepts of Robotics

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## 1.1. BRIEF HISTORY

In ancient times, human slaves were used to accomplish dangerous, unpleasant, and repetitive tasks. As time passed, machines began to replace human beings in carrying out these undesirable tasks. With the growth and development of industrialization, machines were able to assume more and more of the hazardous, tedious work. Today, a new era in human history is beginning to unfold. Programmable machines, such as robots, are taking the place of human beings in these degrading jobs and hence are becoming the mechanical slaves of a more enlightened mankind.

The idea of robot labour has been around for a long time. In the Middle Ages, clockmakers assembled automations that moved about in a way that imitated human actions. Clockwork mechanisms tugged and pushed on pulley and gear systems to perform programmed dances to entertain people. Hence, the idea of programming is not new. Another example emerged during the Industrial Revolution in France, when automated looms were designed to replace human weavers. The program for these looms was punched into metal plates, and during operation the loom used programs to change the patterns in fabrics.

The term robot comes from the Czech word robotit, which means “to drudge or to do menial unpleasant work”. The word was coined in a play by the Czech dramatist Karl Capek in the early 1920s. The play was entitled R.U.R. (Rossum’s Universal Robots).

## 1.2. ROBOT GENERATIONS

Robot technology, like electronic technology, is developing in distinct phases or generations. At present three generations can be identified although the third is still largely at the research stage.

### 1.2.1. First-generation Robots

First-generation robots can be likened to devices that operate according to a strict, fixed sequence of events. They are known as *dumb* robots since they faithfully reproduce the programmed sequence whether work is present or not. They cannot detect any change (*i.e.*, the presence or absence of a component) in the surrounding environment, and cannot therefore modify their actions accordingly. Although they are programmable, programming is done by altering the physical positions of limit switches, re-setting stops on indexable drums, or replacing came to alter movements. The successful use of first generation robots depends, almost exclusively, on ensuring that the correct components are presented to the robot in the correct place, in the

correct orientation at the correct time. This usually entails the provision of support equipment (e.g., conveyors or feeders).

### 1.2.2. Second-generation Robots

Second-generation robots can be classed as ‘clever’ robots. They are equipped with a range of sensors, and the necessary computing power, to modify their actions in response to small detectable changes in the surrounding environment. For example, proximity sensors can differentiate between a number of different components and ‘instruct’ the robot to execute a different sequence of events depending on the component which has been identified—for instance, large components being transferred from a conveyor and placed into one bin, and small components being picked from the same conveyor and placed into a second bin. Second-generation robots (or more correctly their control systems) are necessarily more complex, and therefore more expensive. Since they have to be provided with a range of sensors and the associated control software. Latter developments enable such robots to be linked to host computers and have access to CAD databases.

### 1.2.3. Third-generation Robots

Third-generation robots are the ‘intelligent’ robots. They are at present only in the research stage. They will be characterised by their ability to plan, make strategic decisions and execute tasks ‘intelligently’. They are likely to be programmed to maximise (or minimise) some defined objectives. Development of third-generation robots will depend to a large extent on parallel developments being made in artificial intelligence (AI) software systems.

First-generation robots, whilst still in use, are being gradually superseded by second-generation robots. Second-generation robots are emerging in larger numbers and are finding greater application in all industrial tasks. They are however, under continual development and are destined to find even wider application. It should not necessarily be assumed that the ultimate industrial vision is one of third-generation robots assuming dominance in the manufacturing environment. The industrial application will continue to determine the means of achieving the desired goal. It may be entirely appropriate in those applications that do not necessarily require the flexibility of robots, to continue to apply hard automation techniques. In applications where small and medium batch quantities are the norm, readily programmable first or second-generation robots may continue to be entirely suitable.

## 1.3. CHARACTERISTICS OF THE ROBOT

A closer look at above definitions reveal unique features of the robot. First of all, the robot can be programmed to perform a particular task. If this is to be done, a human must first figure out how the task is to be done by thinking through the entire sequence of motions and operations, and then write a program that will allow the robot to carry out those motions. Second, the robot is not limited to one set of motions: it is reprogrammable. This means that when a specific operation is no longer needed, the robot can be moved to a different operation and programmed for it.

In addition, the robot is multifunctional, which means it may be used in different ways. The different tasks may even be a part of one program or operation. For example, the robot might move a work piece to a machine and load in into the machine. Then it might insert a cutting tool and control the cutting of the work piece. Finally, it might unload the piece and store it in an appropriate area.

This definition stresses the flexibility of the robot by pointing out how it can be changed to meet special needs. But this definition does not cover all aspects of robots, for people

view robots from their own unique perspectives and then define them based on those views. Businessmen see robots as providing the means of increasing productivity. Supporters of robots welcome these devices, since they take over the hazardous, tedious tasks that people have had to perform. Workers and labour leaders, however, tend to view robots as devices that put people out of jobs.

Whatever the individual's viewpoint may be, robots are devices that imitate human manipulation. Robots, however, are built by people, programmed by people, and maintained by people, hence, they are what people make them.

#### 1.4. DIFFERENCES BETWEEN THE HUMAN AND THE ROBOT

While home or personal robots move, talk, and grasp objects, the industrial robot generally consists only of one or two arms with grippers or tools at the end. Clearly, robots are very well-suited to a variety of tasks, particularly those tasks that are repetitive. However, there are many areas in which humans are superior and will probably always remain so. One of these areas consists of tasks requiring physical coordination and the ability to make many decisions based on a constantly changing environment. An example would be the ability to participate in a game of basketball, which requires the physical coordination of the entire body and the ability to make decisions about whether to pass, dribble, or shoot, based on the positions and movements of other players on the floor. While robots can react to their environment, the multitude and variety of conditions found in a basketball game call for responses that are clearly beyond the powers of robots and the computers that control them.

Robots also have difficulty with tasks that are artistic or creative. For a robot to function, it must be programmed, and for a program to work, the task must be broken down into discrete parts. All decisions to be made in each part must be capable of being reduced to equations. Therefore, humans will remain superiors in art, music, medicine, and other endeavors that cannot be expressed in purely mathematical terms.

Sensory capacities of robots continue to improve as technology improves, but the human's highly developed senses of sight, smell, hearing, and touch remain difficult to duplicate. Further, the combination of these senses gives human the capability of processing large amount of information simultaneously. As an example, humans are able to maneuver an automobile and avoid hazards because they are constantly receiving a variety of sensory messages.

Finally, the human brain is able to make decisions on experiences and stored information. Although the robot's computer can store large quantities of information, it cannot make decisions based on past experiences nor can it make intuitive judgements based on stored information and past experiences.

#### 1.5. ROBOT TERMINOLOGY

It is useful to consider the structure or the architecture of the machine. Doing this will require that we use some special terms and perhaps redefine some common ones. The study of the motion of a robot structure, without references to the forces involved, is called kinematics, and some of the following terms are regularly associated with this aspect of dynamics.

The following definitions are not meant to be rigorous. They are contrived to elicit the **CLEAR**EST understanding of the **THEIR** within your imagination.

**1. Axis:** An imaginary, straight line around which all parts of a solid body rotate (*see* Fig. 1.1).

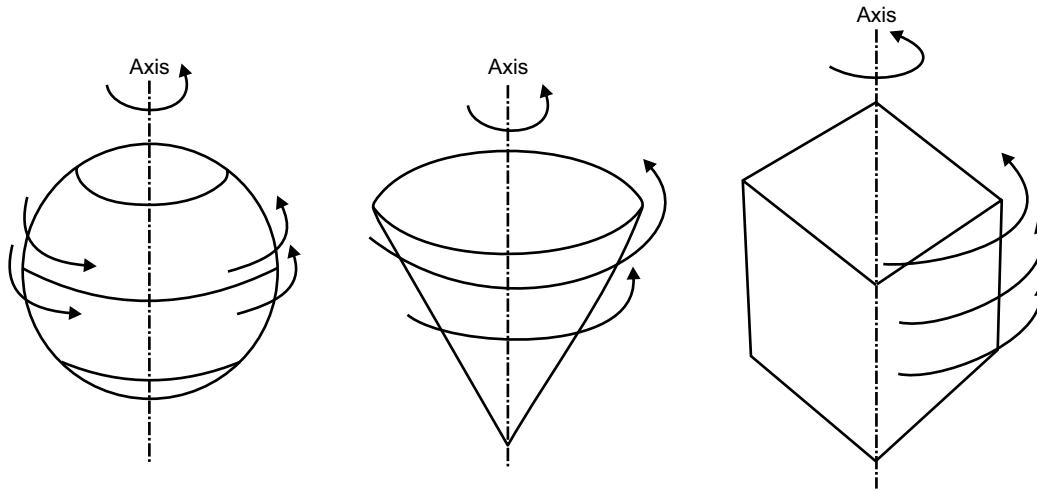


Fig. 1.1. Axes of various bodies.

**2. Cartesian Coordinates:** In this, position of any object can be described precisely by the intersection of three *orthogonal* (mutually perpendicular) planes, as shown in Fig. 1.2 (a). The result of such a configuration is a *coordinated* system of three mutually perpendicular axes Fig. 1.2 (b).

The *X*- and *Y*-axes are depicted at  $90^\circ$  to one another on a flat plane which touches the surface of the earth—perhaps at our feet. The third axis is constructed at  $90^\circ$  to this plane and conceivably passes right through this page as we look at it. Anyway, this axis, the *Z*-axis, rises vertically from the other two.

**3. Normal:** This is any line drawn at  $90^\circ$  to an axis or a plane, or expressed another way, any line perpendicular to an axis or a plane.

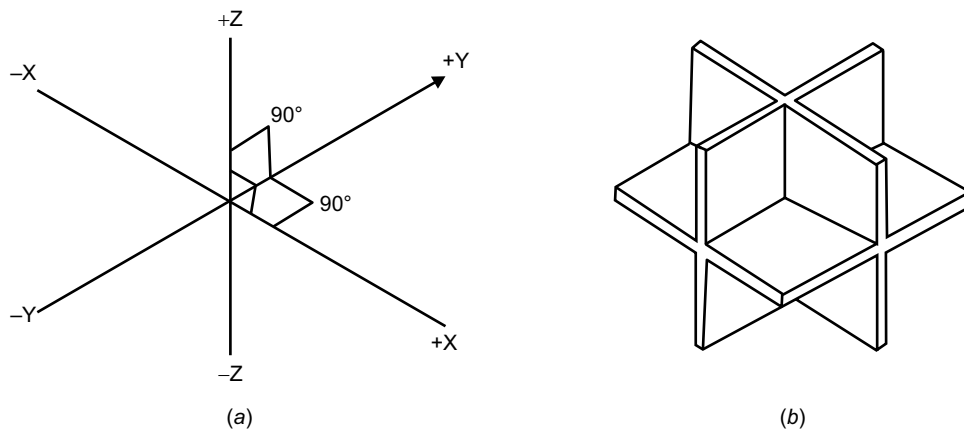
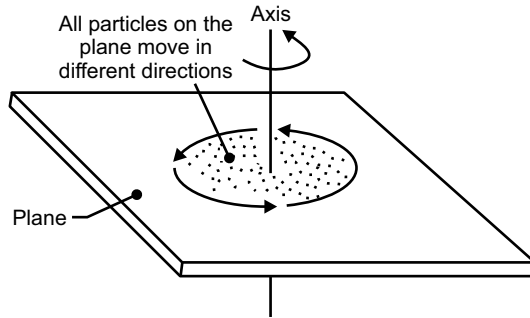
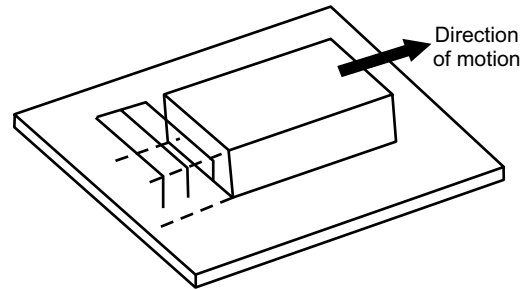


Fig. 1.2. (a) Orthogonal axes and (b) Orthogonal planes.

**4. Rotate:** The circular motion of each particle of a body around an axis. At any instant of time every particle of a body on a plane normal to the axis is moving in a different direction, as shown in Fig. 1.3.



**Fig. 1.3.** Particles on a plane. The plane is normal to the axis, and *vice-versa*.

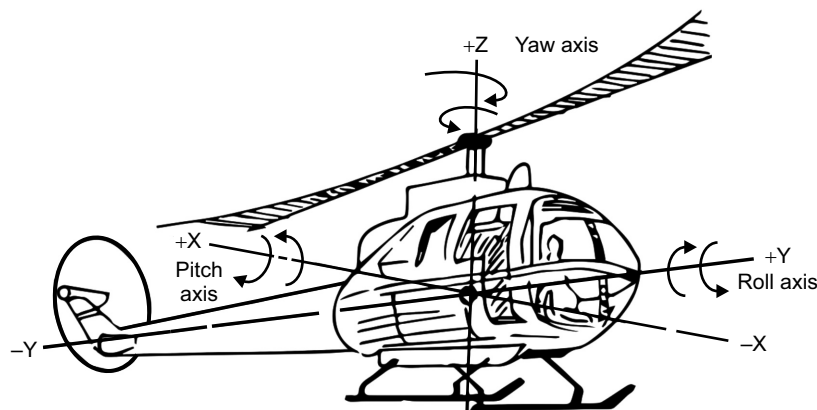


**Fig. 1.4.** Translational motion of a body.

**5. Translate:** The motions of all particles in a body are entirely in one direction. Consider the illustration in Fig. 1.4; all particles within the body are moving from left to right. The body is said to possess translational motion.

**6. Degrees of Freedom:** As a solid body can exhibit only two kinds of motion; rotational and translational and because there are only three mutually perpendicular planes or axes in space, as we usually perceive space, there can be only six possibilities of different motion of a solid object in that space. Figure 1.5 shows a familiar vehicle which is free to move (sometimes with difficulty) along and about these directions. In Fig. 1.5, the helicopter can move forward and backward in translation along the  $Y$ -axis. Forward is positive and backward is negative. It can move from side to side along the  $X$ -axis. To its right is positive and its left is negative in this case. It can, of course, move upward positively and downward negatively in translation along the  $Z$ -axis.

To this point we have considered three directions in which the helicopter is free to move, or have *three degrees* of freedom. There are also three other possibilities of free motion depicted in Fig. 1.5. It can rotate about the  $Y$ -axis, which is called *roll*; it can rotate about the  $X$ -axis, which is called *pitch*, and it is free to rotate about the  $Z$ -axis, which is called *yaw*. The positive and negative directions of rotation about these axes are defined aeronautically and are not necessarily Cartesian.



**Fig. 1.5.** A helicopter's six possible degrees of freedom.

The helicopter is therefore said to be capable of *six degrees of freedom*. This is the maximum number for any solid body.

**7. Global or World Coordinates:** The reference for such a coordinate system is the earth and because the earth beneath our feet stays reasonably immovable during our lifetime, this system is considered to be a *fixed* one. This system of coordinates has the *Y*-axis running north-south, the *X*-axis running east-west, and the *Z*-axis passing through both the center of the earth and the intersection of the *X*- and *Y*-axes, as shown in Fig. 1.6.

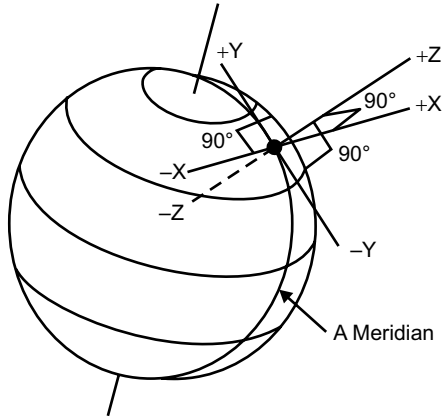


Fig. 1.6. Global coordinates.

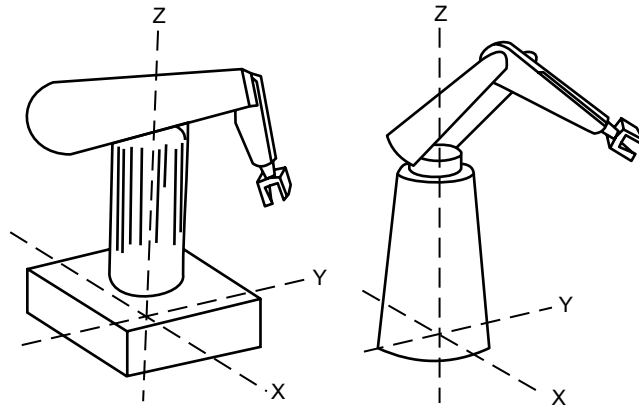


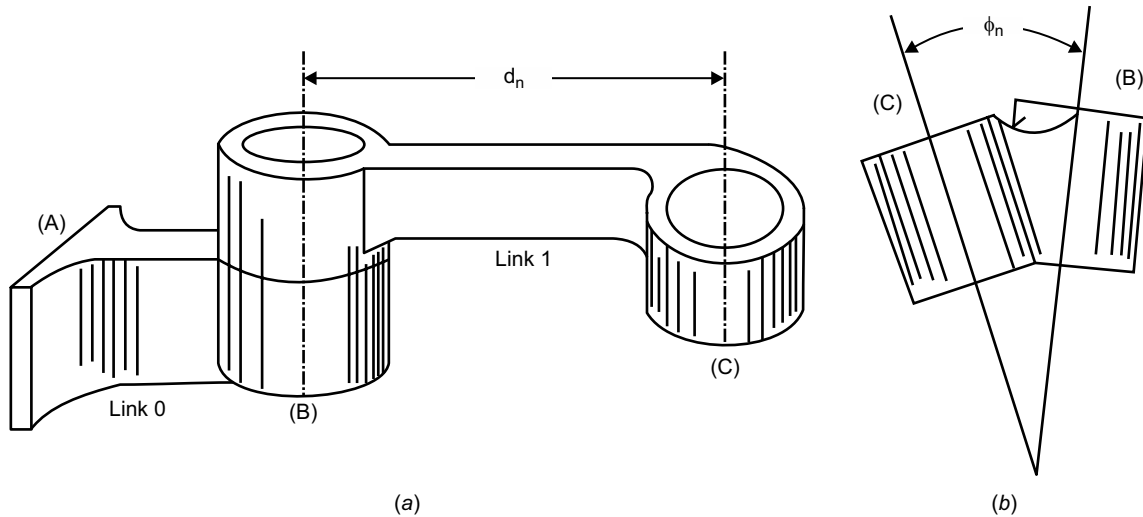
Fig. 1.7. Global coordinates for robots.

Global or world coordinates relative to a robot are usually fixed with reference to its base as indicated in Fig. 1.7 and hence the *X*- and *Y*-axes do not necessarily run east-west, north-south. Nevertheless, throughout the life of the robot (unless it is moved) they stay fixed in relation to the factory floor and walls.

**8. Home Position:** When a robot and its controller have been *powered-up* and the robot is waiting to be taught to execute a sequence of movements, it is usually at best at its *home position*. In this position each joint is oriented to  $0^\circ$  of rotation. Its general direction is usually facing along the *X*-axis of the global coordinate system as it refers to the factory floor and walls. Some robots return *home* every time a program of movements has been carried out, the result of which is to reset all joints to zero position awaiting a new set of commands. Home position is sometimes called the *calibrate position* because some robots are powered-up in what is called the *power-up calibration* mode.

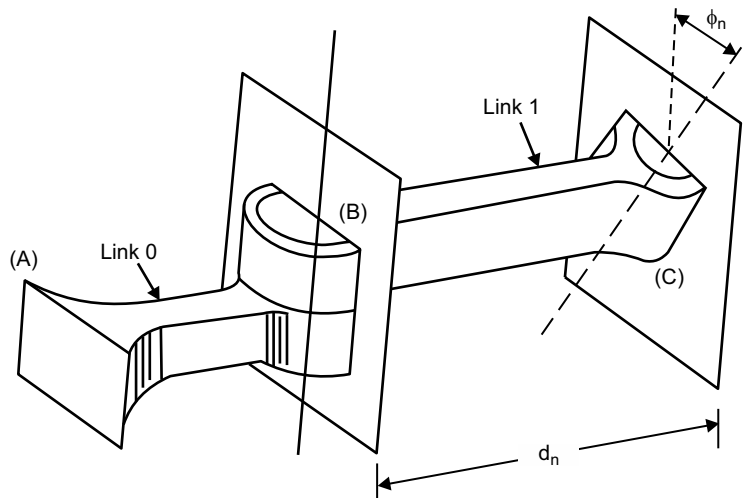
**9. Link:** A link is a rigid (the meaning of the word *rigid* is the condition of a solid which absolutely prohibits any movement at all. The meaning of *rigid* as used in the definition of a *link* means stiff, and permits the idea that the link will deform minutely under great stress. This is quite reasonable and does not compromise the definition) structure that connects two sites where motion may or may not take place. This simple definition is illustrated in Fig. 1.8. In the figure, link 0 is the connection between [A], where no motion takes place, and [B], where rotation can take place. Link 1 connects sites [B] and [C], where, at both of which motion can take place. The dimension  $d_n$  is considered to be the *common normal distance*. The common normal distance is the distance between the planes through which the axes at [B] and [C] passes. This is measured along the normal between the two planes. So Fig. 1.8(a) has two invisible parallel planes coming out of the page at us, whereas Fig. 1.8(b) shows the two axes at [B] and [C] displaced by the *twist angle*  $\phi_n$  and lying embedded in their respective planes, which, of course, are parallel to the page that we are looking at.

Figure 1.9 demonstrates another view of the linkages. This time the two parallel joint planes are shown.

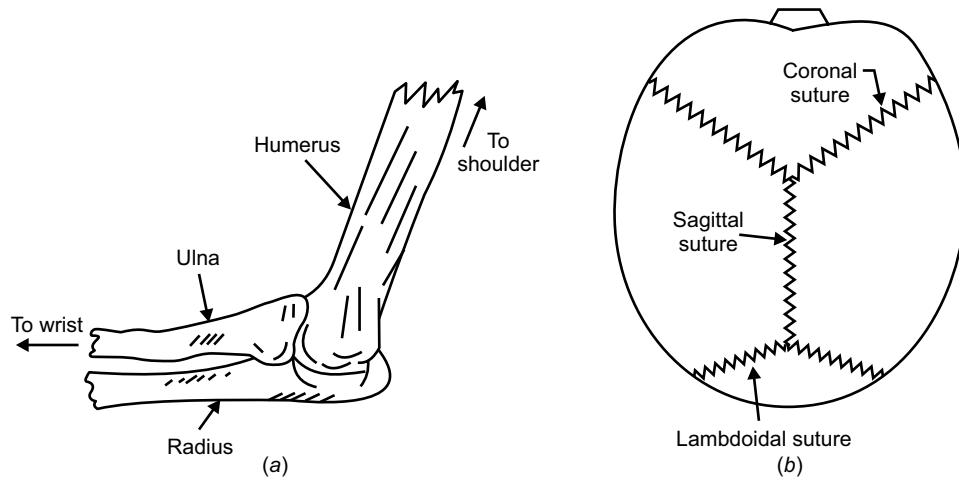


**Fig. 1.8.** Simple link configurations: (a) lateral view; (b) end-on view.

**10. Joint:** A joint is a site where two still bodies meet. At such a site there may be movement or there may not be movement. Considering Fig. 1.10(a): here the three bones of the arm that constitute the elbow are shown. The humerus, ulna, and radius hinge at the elbow and allow about  $160^\circ$  of movement. This type of joint is called a *revolute* joint. The joints at sites [B] and [C] in Fig. 1.8 and Fig. 1.9 are revolute joints. Referring to Fig. 1.10(b), this figure shows the joints of the skull sections that began to link together in the prenatal human. Osteologists call these joints *sutures*, and although they are real joints, they are not supposed to move. They are, in fact, *non-revolute* joints. The joint at site [A] in Fig. 1.8 and Fig. 1.9 is a non-revolute joint.

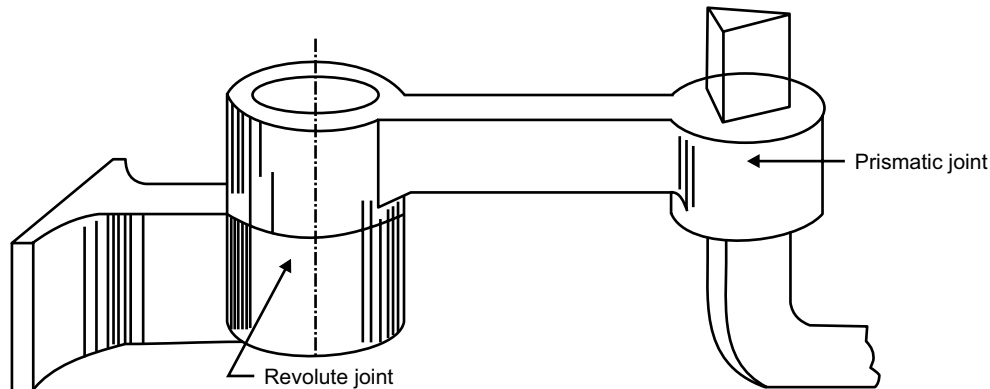


**Fig. 1.9.** Simple link configuration of Fig. 1.8, showing the two parallel planes between which normal distance  $d_n$  exists.



**Fig. 1.10.** Typical human body joints:  
(a) the revolute elbow joints, (b) the non-revolute skull sutures.

There is however, another type of joint, which is not associated with the human body. This joint is named *prismatic* and is shown in Fig. 1.11. Such a joint cannot rotate but can slide in and out of the end of the link. Hence it is only capable of translation motion.



**Fig. 1.11.** Prismatic joint capable only of translational motion.

**11. Work Envelope:** A work envelope is a volume of space surrounding a robot which is accessible to the tool or manipulator at the end of the arm and is therefore a local three-dimensional envelope in which work may be performed by the robot.

The work envelope of any robot is the result of the combinations of links and their twist angles together with the number of revolute and prismatic joints it possesses.

## 1.6. ROBOT SPECIFICATION

While determining the qualities of a robot and its ability to meet certain requirements several performance characteristics should be considered. Following are the important robot specifications that must be considered:

**1. Resolution:** Resolution is the ability of the robot to differentiate between two separator points. The smallest change in position that the axial feedback device can sense.

A resolution of one mm indicates that the robot can distinguish between two points that are one mm apart. A resolution of 0.01 mm means that the robot can distinguish between two points that are only 0.01 mm apart.

**2. Accuracy:** Accuracy identifies the manipulator to go to a pre-programmed point in space or its home position. Its usefulness as an indicator of robot capability is limited to robots which are programmed off-line. It measures the ability of the manipulator to reach the point that the off-line programming commands it to go.

**3. Repeatability:** Repeatability is the most important characteristic in determining the robot's ability to accurately perform a required task. It measures the ability of the manipulator to continuously return to the same point within the work envelope.

A repeatability of 0.25 mm indicates that once a manipulator has been taught to reach a certain point, it will continually return to that same point within 0.25 mm.

**4. Reliability:** Reliability identifies the percentage of time that the robot is expected to operate without being taken out of service for maintenance or repair. Manufacturers estimate the reliability of their robots to be between 96% and 98%. Although this estimate is not true in all cases, most robot users have found their robots to be very reliable.

**5. Mean Time Before Failure:** This measurement identifies the number of hours that the robot is expected to operate before a malfunction requires the robot to be temporarily taken out of service for repair and maintenance. These estimates range from 200 hours to over 2,000 hours. As with reliability, this measurement is an estimate by the manufacturer and may not always be accurate.

**6. Maximum Payload:** Payload identifies the amount of weight that the manipulator is able to handle. This weight includes the weight of the end effector (which is not considered to be a part of the robot by most manufacturers) and the weight of the workpiece or tool being handled. The figure given assumes that the robot is moving at slow or normal speed. Its ability to handle weight decreases as the speed of the manipulator increases.

**7. End-of-Arm Speed:** This measurement identifies the speed at which the manipulator can move an object. It depends upon several factors, including weight carried and path taken and should be used only when comparing characteristics of different robots.

**8. Memory Capacity:** Memory capacity determines the length and complexity of the operation that the manipulator is able to perform. It is usually given as the number of points that can be recorded in memory.

**9. Menu:** This is the list of program execution options appearing on the display, which the user may select according to the requirement.

The above characteristics of a robot's do help in classifying them.

## MULTIPLE CHOICE QUESTIONS

1. Robots may be considered as mechanical slaves of enlightened mankind because it is used to accomplish:
  - (a) dangerous, unpleasant and repetitive tasks
  - (b) programmed tasks to entertain people and programmed tasks
  - (c) automated industry
  - (d) all of the above.
2. Robot technology like electronics technology is developing in distinct generation similar to that of mobile, such that first generation robots are:
  - (a) are not programmable and work like hard automation.

- (b) designed on limit switches, cams and drum, they are called dumb robots.  
 (c) such robot designs work on support equipment.  
 (d) both (b) and (c).
3. Second generation robots are equipped with sensors and computing power such that:  
 (a) can response to small changes so as to modify their use.  
 (b) can respond to execute different sequence of changes.  
 (c) can identify the component to act for completing the task.  
 (d) all of the above.
4. Third generation robot are called intelligent robots and designed and characterised for specific tasks such:  
 (a) they can plan and execute the plan for completion of task.  
 (b) they have built-in re-programmable capability.  
 (c) robots are developed and available in the market.  
 (d) both (a) and (b).
5. Do you think whether or not robots would be acceptable as these may destroy the earth?  
 (a) These may emerge as androids' mechanical man.  
 (b) These may take over all kinds of human tasks.  
 (c) These may occupy as AI androids robotised man.  
 (d) None of these.
6. Robots are multidisciplinary designs consequently require high-calibre maintenance facility, which may not be possible as and when required to be named as 'Omnipresent'. As such it may not be possible everywhere. If so, it may result in the form of:  
 (a) self-destruction.  
 (b) taking over the humanity absolutely.  
 (c) finally, destruction of each as there may not possess cognitive intelligence.  
 (d) all of the above.
7. Which one of the following robots comes under first generation?  
 (a) Information robots. (b) Autonomous loading.  
 (c) Autonomous harvesting. (d) All of the above.
8. Design of a robot is derived from human body and it is the replica of:  
 (a) human arm hinged at shoulder (b) human body hinged at trunk  
 (c) entire human body (d) none of these.
9. For excellent performance of a robot, the most important parameter is its:  
 (a) resolution (b) accuracy  
 (c) repeatability (d) all of the above.
10. .... is up and down motion of wrist.  
 (a) Pitch (b) Yaw  
 (c) Roll (d) None of these

### ANSWERS

- |        |        |        |         |        |        |
|--------|--------|--------|---------|--------|--------|
| 1. (d) | 2. (d) | 3. (d) | 4. (d)  | 5. (c) | 6. (d) |
| 7. (a) | 8. (c) | 9. (d) | 10. (a) |        |        |

# An Introduction to ROBOTICS

## About the Book

This book on *"An Introduction to Robotics"* deals with the basic principles of the subject. All topics have been introduced in a simple manner. The book has been prepared to suit the requirements of students preparing for degree and diploma examinations in engineering. This book gives insight into the brief history and conceptual development of robotics, its components, and robot classification. It explains robot kinematics, its controlling system, differential motion, robot dynamics, homogeneous transformation, arm singularity effects, etc. in a comprehensive manner.

This book focuses on the use of various robotic sensors and robotic cameras for a variety of automated applications that are required by IR 4.0. The use of embedded systems and robotic vision has been suitably introduced in the book. Actuators are critical components of a robot, which are briefly explained along with the robot's programming and transformation.

## About the Authors



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