Playback robot: a manipulator that is able to perform an operation by reading off the memorized information for an operating sequence, which is learned beforehand.

Intelligent robot: a robot that can determine its own behaviour and conduct through its functions of sense and recognition.

The British Robot Association (BRA) has defined the industrial robot as:

"A reprogrammable device with minimum of four degrees of freedom designed to both manipulate and transport parts, tools, or specialized manufacturing implements through variable programmed motions for performance of specific manufacturing task."

The Robotics Industries Association (RIA) of USA defines the robot as:

"A reprogrammable, multifunctional manipulator designed to move material through variable programmed motions for the performance of a variety of tasks."

The definition adopted by International Standards Organization (ISO) and agreed upon by most of the users and manufacturers is:

"An industrial robot is an automatic, servo-controlled, freely programmable, multipurpose manipulator, with several areas, for the handling of work pieces, tools, or special devices. Variably programmed operations make the execution of a multiplicity of tasks possible."

Despite the fact that a wide spectrum of definitions exist, none covers the features of a robot exhaustively. The RIA definition lays emphasis on programmability, whereas while the BRA qualifies minimum degrees of freedom. The JIRA definition is fragmented. Because of all this, there is still confusion in distinguishing a robot from automation and in describing functions of a robot. To distinguish between a robot and automation, following guidelines can be used.

For a machine to be called a robot, it must be able to respond to stimuli based on the information received from the environment. The robot must interpret the stimuli either passively or through active sensing to bring about the changes required in its environment. The decision-making, performance of tasks and so on, all are done as defined in the programs taught to the robot. The functions of a robot can be classified into three areas:

"Sensing" the environment by external sensors, for example, vision, voice, touch, proximity and so on, "decision-making" based on the information received from the sensors, and "performing" the task decided.

1.4 PROGRESSIVE ADVANCEMENT IN ROBOTS

The growth in the capabilities of robots has been taking rapid strides since the introduction of robots in the industry in early 1960s, but there is still a long way to go to obtain the super-humanoid anthropomorphic robot depicted in fiction. The growth of robots can be grouped into *robot generations*, based on characteristic breakthroughs in robot's capabilities. These generations are overlapping and include futuristic projections.

1.4.1 First Generation

The first generation robots are repeating, nonservo, pick-and-place, or point-to-point kind. The technology for these is fully developed and at present about 80% robots in use in the industry are of this kind. It is predicted that these will continue to be in use for a long time.

1.4.2 Second Generation

The addition of sensing devices and enabling the robot to alter its movements in response to sensuary feedback marked the beginning of second generation. These robots exhibit path-control capabilities. This technological breakthrough came around 1980s and is yet not mature.

1.4.3 Third Generation

The third generation is marked with robots having human-like intelligence. The growth in computers led to high-speed processing of information and, thus, robots also acquired artificial intelligence, self-learning, and conclusion-drawing capabilities by past experiences. On-line computations and control, artificial vision, and active force/torque interaction with the environment are the signifjcant characteristics of these robots. The technology is still in infancy and has to go a long way.

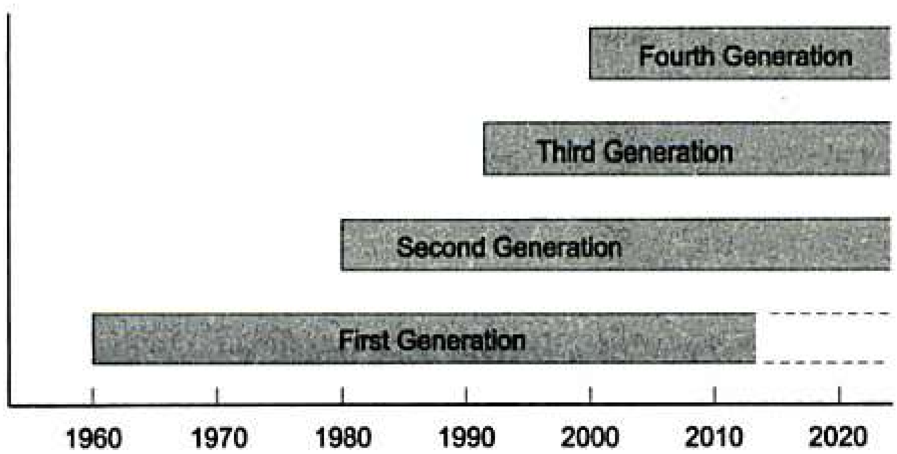

Fig. 1.4 *The four generations of robots*

1.4.4 Fourth Generation

This is futuristic and may be a reality only during this millennium. Prediction about its features is difficult, if not impossible. It may be a true android or an artificial biological robot or a super humanoid capable of producing its own clones. This might provide for fifth and higher generation robots.

A pictorial visualization of these overlapping generations of robots is given in Fig. 1.4.

1.5 ROBOT ANATOMY

As mentioned in the introduction to the chapter, the manipulator or robotic arm has many similarities to the human body. The mechanical structure of a robot is like the skeleton in the human body. The robot anatomy is, therefore, the study of skeleton of robot, that is, the physical construction of the manipulator structure.

The mechanical structure of a manipulator that consists of rigid bodies (links) connected by means of articulations (joints), is segmented into an *arm* that ensures mobility and reachability, a *wrist* that confers orientation, and an end-effector that performs the required task. Most manipulators are mounted on a base fastened to the floor or on the mobile platform of an autonomous guided vehicle (AGV). The arrangement of base, arm, wrist, and end-effector is shown in Fig. 1.5.

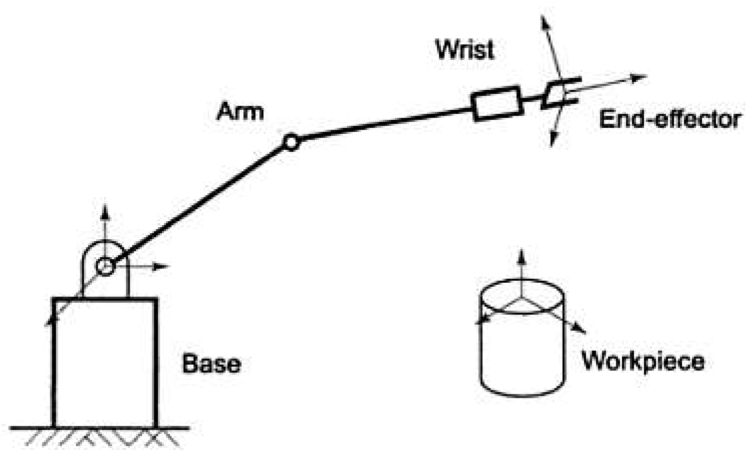

Fig. 1.5 *The base, arm, wrist, and end-effector forming the mechanical structure of a manipulator*

1.5.1 Links

The mechanical structure of a robotic manipulator is a mechanism, whose members are rigid links or bars. A rigid link that can be connected, at most, with two other links is referred to as a *binary link*. Figure 1.6 shows two rigid binary links, 1 and 2, each with two holes at the ends A, B, and C, D, respectively to connect with each other or to other links.

Two links are connected together by a joint. By putting a pin through holes B and C of links 1 and 2, an *open kinematic chain* is formed as shown in Fig. 1.7. The joint formed is called a *pin joint* also known as a *revolute* or *rotary joint*. Relative rotary motion between the links is possible and the two links are said to

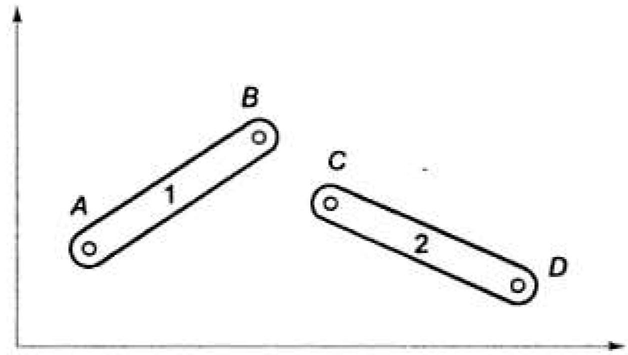

Fig. 1.6 *Two rigid binary links in free space*

be paired. In Fig. 1.7 links are represented by straight lines and rotary joint by a small circle.

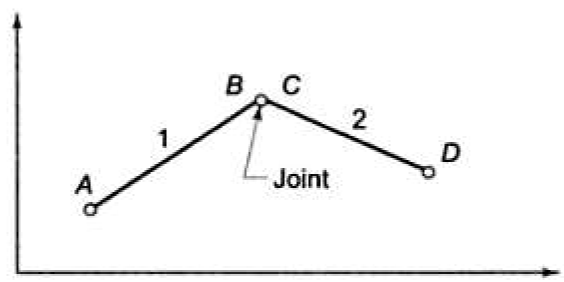

Fig. 1.7 *An open kinematic chain formed by joining two links*

1.5.2 Joints and Joint Notation Scheme

Many types of joints can be made between two links. However, only two basic types are commonly used in industrial robots. These are

- Revolute (R) and
- Prismatic (P).

The relative motion of the adjoining links of a joint is either rotary or linear depending on the type of joint.

Revolute joint: It is sketched in Fig. 1.8(a). The two links are jointed by a pin (pivot) about the axis of which the links can rotate with respect to each other.

Prismatic joint: It is sketched in Fig. 1.8(b). The two links are so jointed that these can slide (linearly move) with respect to each other. Screw and nut (slow linear motion of the nut), rack and pinon are ways to implement prismatic joints.

Other types of possible joints used are: planar (one surface sliding over another surface); cylindrical (one link rotates about the other at 90° angle, Fig. 1.8(c)); and spherical (one link can move with respect to the other in three dimensions). Yet another variant of rotary joint is the 'twist' joint, where two links remain aligned along a straight line but one turns (twists) about the other around the link axis, Fig. 1.8(d).

At a joint, links are connected such that they can be made to move relative to each other by the actuators. A rotary joint allows a pure rotation of one link

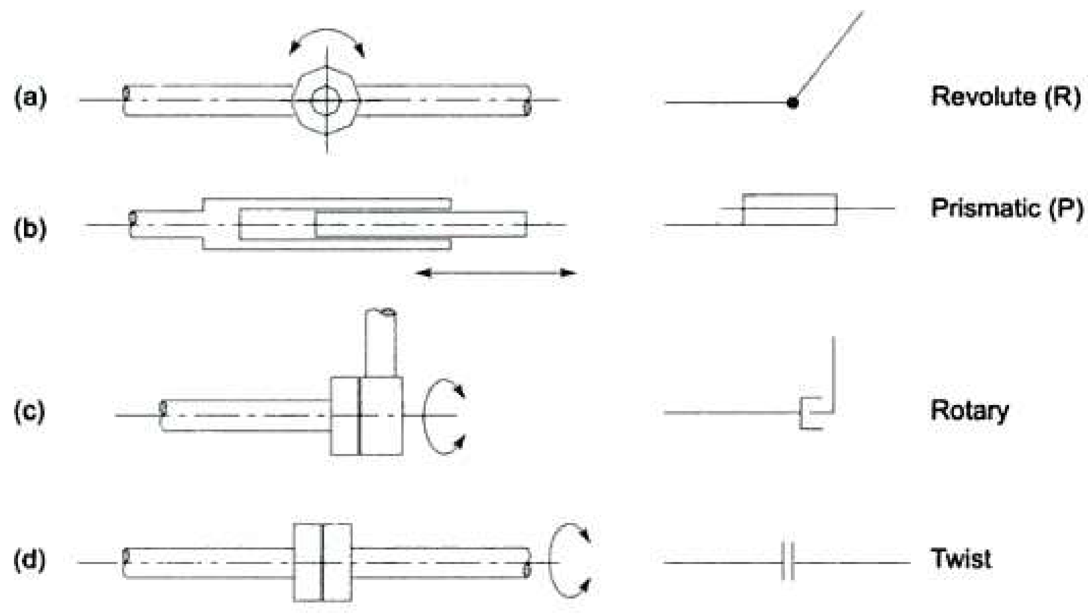

Fig. 1.8 *Joint types and their symbols*

relative to the connecting link and prismatic joint allows a pure translation of one link relative to the connecting link.

The kinematic chain formed by joining two links is extended by connecting more links. To form a manipulator, one end of the chain is connected to the base or ground with a joint. Such a manipulator is an open kinematic chain. The end-effector is connected to the free end of the last link, as illustrated in Fig. 1.5. Closed kinematic chains are used in special purpose manipulators, such as parallel manipulators, to create certain kind of motion of the end-effector.

The kinematic chain of the manipulator is characterized by the degrees of freedom it has, and the space its end-effector can sweep. These parameters are discussed in next sections.

1.5.3 Degrees of Freedom (DOF)

The number of independent movements that an object can perform in a 3-D space is called the number of *degrees of freedom* (DOF). Thus, a rigid body free in space has six degrees of freedom—three for position and three for orientation. These six independent movements pictured in Fig. 1.9 are:

(i) three translations (T_1, T_2, T_3), representing linear motions along three perpendicular axes, specify the position of the body in space.

(ii) three rotations (R_1, R_2, R_3), which represent angular motions about the three axes, specify the orientation of the body in space.

Note from the above that six independent variables are required to specify the location (position and orientation) of an object in 3-D space, that is, $2 \times 3 = 6$. Nevertheless, in a 2-D space (a plane), an object has 3-DOF—two translatory and one rotational. For instance, link 1 and link 2 in Fig. 1.6 have 3-DOF each.

Consider an open kinematic chain of two links with revolute joints at A and B (or C), as shown in Fig. 1.10. Here, the first link is connected to the ground by a

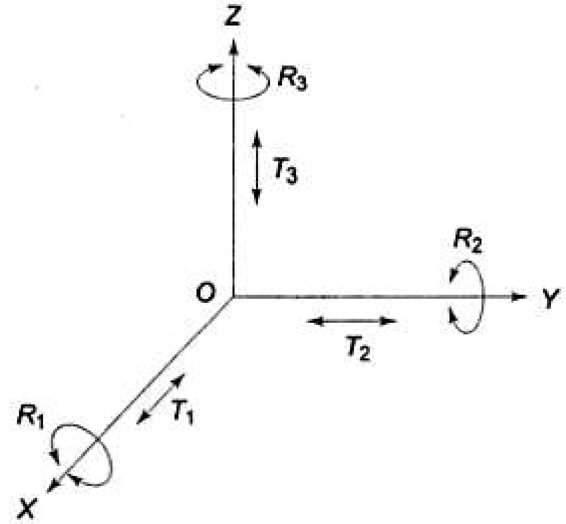

Fig. 1.9 *Representation of six degrees of freedom with respect to a coordinate frame*

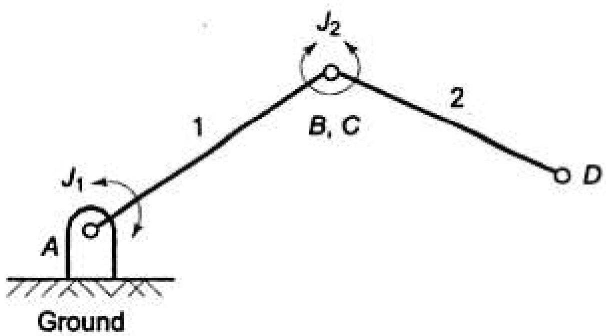

Fig. 1.10 *A two-DOF planar manipulator–two links, two joints*

joint at *A*. Therefore, link 1 can only rotate about joint 1 (J_1) with respect to ground and contributes one independent variable (an angle), or in other words, it contributes one degree of freedom. Link 2 can rotate about joint 2 (J_2) with respect to link 1, contributing another independent variable and so another DOF. Thus, by induction, conclude that an open kinematic chain with one end connected to the ground by a joint and the farther end of the last link free, has as many degrees of freedom as the number of joints in the chain. It is assumed that each joint has only one DOF.

The DOF is also equal to the number of links in the open kinematic chain. For example, in Fig. 1.10, the open kinematic chain manipulator with two DOF has two links and two joints.

The variable defining the motion of a link at a joint is called a *joint-link variable*. Thus, for an ***n***-DOF manipulator ***n*** independent joint-link variables are required to completely specify the location (position and orientation) of each link (and joint), specifying the location of the end-effector in space. Thus, for the two-link, in turn 2-DOF manipulator, in Fig. 1.10, two variables are required to define location of end-point, point *D*.

1.5.4 Required DOF in a Manipulator

It is concluded from Section 1.5.3 that to position and orient a body freely in 3-D space, a manipulator with 6-DOF is required. Such a manipulator is called a *spatial manipulator*. It has three joints for positioning and three for orienting the end-effector.

A manipulator with less than 6-DOF has constrained motion in 3-D space. There are situations where five or even four joints (DOF) are enough to do the required job. There are many industrial manipulators that have five or fewer DOF. These are useful for specific applications that do not require 6-DOF. A *planar manipulator* can only sweep a 2-D space or a plane and can have any number of degrees of freedom. For example, a planar manipulator with three joints (3-DOF)— may be two for positioning and one for orientation —can only sweep a plane.

Spatial manipulators with more than 6-DOF have surplus joints and are known as *redundant manipulators*. The extra DOF may enhance the performance by adding to its *dexterity*. Dexterity implies that the manipulator can reach a subspace, which is obstructed by objects, by the capability of going around these. However, redundant manipulators present complexities in modelling and coordinate frame transformations and therefore in their programming and control.

The DOF of a manipulator are distributed into subassemblies of *arm* and *wrist*. The arm is used for positioning the end-effector in space and, hence, the three positional DOF, as seen in Fig. 1.9, are provided to the arm. The remaining 3-DOF are provided in the wrist, whose task is to orient the end-effector. The type and arrangement of joints in the arm and wrist can vary considerably. These are discussed in the next section.

1.5.5 Arm Configuration

The mechanics of the arm with 3-DOF depends on the type of three joints employed and their arrangement. The purpose of the arm is to position the wrist in the 3-D space and the arm has following characteristic requirements.

- Links are long enough to provide for maximum reach in the space.
- The design is mechanically robust because the arm has to bear not only the load of workpiece but also has to carry the wrist and the end-effector.

According to joint movements and arrangement of links, four well-distinguished basic structural configurations are possible for the arm. These are characterized by the distribution of three arm joints among prismatic and rotary joints, and are named according to the coordinate system employed or the shape of the space they sweep. The four basic configurations are:

(i) Cartesian (rectangular) configuration – all three *P* joints.
(ii) Cylindrical configuration – one *R* and two *P* joints.
(iii) Polar (spherical) configuration – two *R* and one *P* joint.
(iv) Articulated (Revolute or Jointed-arm) Configuration – all three *R* joints.

Each of these arm configurations is now discussed briefly.

(i) Cartesian (Rectangular) Configuration This is the simplest configuration with all three prismatic joints, as shown in Fig. 1.11. It is constructed by three perpendicular slides, giving only linear motions along the three principal axes. There is an upper and lower limit for movement of each link. Consequently, the *endpoint* of the arm is capable of operating in a cuboidal space, called *workspace*.

The workspace represents the portion of space around the base of the manipulator that can be accessed by the arm endpoint. The shape and size of the workspace depends on the arm configuration, structure, degrees of freedom, size of links, and design of joints. The physical space that can be swept by a manipulator (with wrist and end-effector) may be more or less than the arm endpoint workspace. The volume of the space swept is called *work volume*; the surface of the workspace describes the *work envelope*.

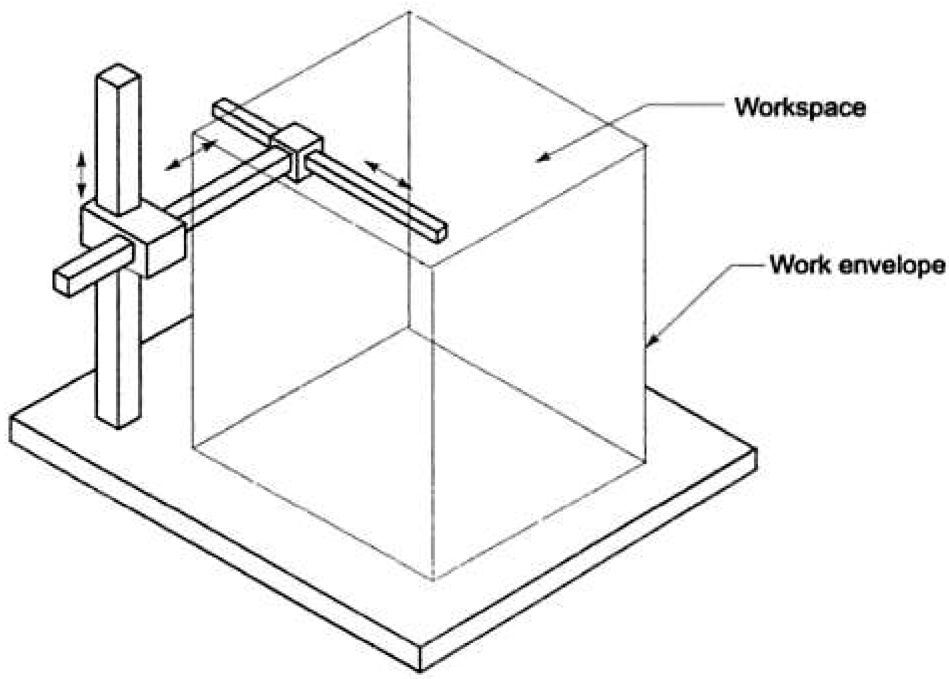

Fig. 1.11 *A 3-DOF Cartesian arm configuration and its workspace*

The workspace of Cartesian configuration is cuboidal and is shown in Fig. 1.11. Two types of constructions are possible for Cartesian arm: a *Cantilevered Cartesian*, as in Fig. 1.11, and a *Gantry* or *box Cartesian*. The latter one has the appearance of a gantry-type crane and is shown in Fig. 1.12. Despite the fact that Cartesian arm gives high precision and is easy to program, it is not preferred for many applications due to limited manipulatability. Gantry configuration is used when heavy loads must be precisely moved. The Cartesian configuration gives large work volume but has a low dexterity.

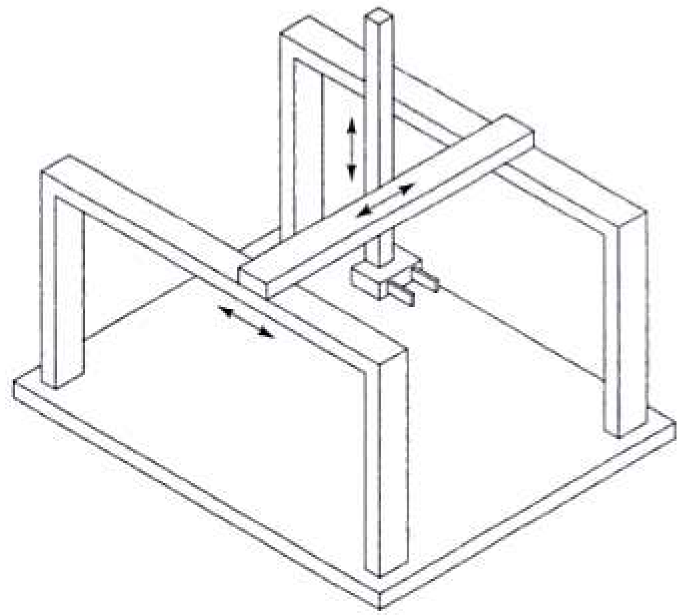

Fig. 1.12 *Gantry or box configuration Cartesian manipulator*

(ii) Cylindrical Configuration The cylindrical configuration pictured in Fig. 1.13, uses two perpendicular prismatic joints, and a revolute joint. The difference from the Cartesian one is that one of the prismatic joint is replaced with a revolute joint. One typical construction is with the first joint as revolute. The rotary joint may either have the column rotating or a block revolving around a stationary vertical cylindrical column. The vertical column carries a slide that can be moved up or down along the column. The horizontal link is attached to the slide such that it can move linearly, in or out, with respect to the column. This results in a RPP configuration. The arm endpoint is, thus, capable of sweeping a cylindrical space. To be precise, the workspace is a hollow cylinder as shown in Fig. 1.13. Usually a full 360° rotation of the vertical column is not permitted due to mechanical restrictions imposed by actuators and transmission elements.

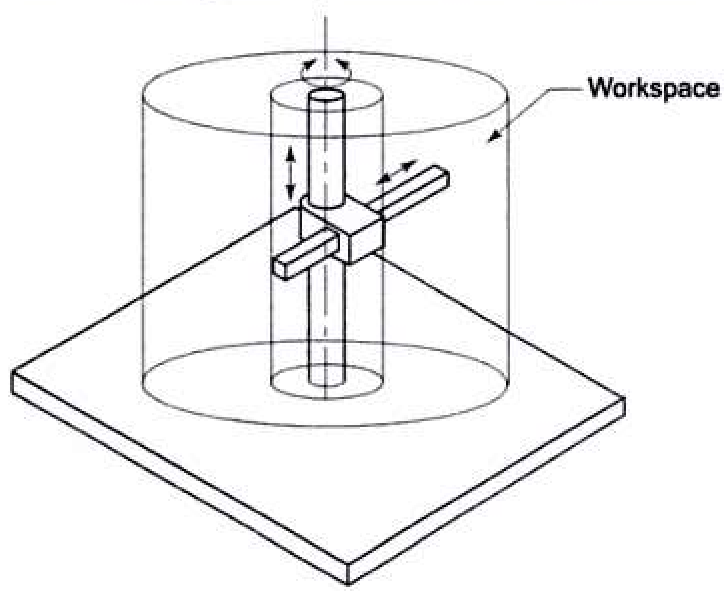

Fig. 1.13 *A 3-DOF cylindrical arm configuration and its workspace*

Many other joint arrangements with two prismatic and one rotary joint are possible for cylindrical configuration, for example, a PRP configuration. Note that all combinations of 1R and 2P are not useful configurations as they may not give suitable workspace and some may only sweep a plane. Such configurations are called *nonrobotic configurations*. It is left for the reader to visualize as to which joint combinations are robotic arm configurations.

The cylindrical configuration offers good mechanical stiffness and the wrist positioning accuracy decreases as the horizontal stroke increases. It is suitable to access narrow horizontal cavities and, hence, is useful for machine-loading operations.

(iii) Polar (Spherical) Configuration The polar configuration is illustrated in Fig. 1.14. It consists of a telescopic link (prismatic joint) that can be raised or lowered about a horizontal revolute joint. These two links are mounted on a rotating base. This arrangement of joints, known as RRP configuration, gives the capability of moving the arm end-point within a partial spherical shell space as work volume, as shown in Fig. 1.14.

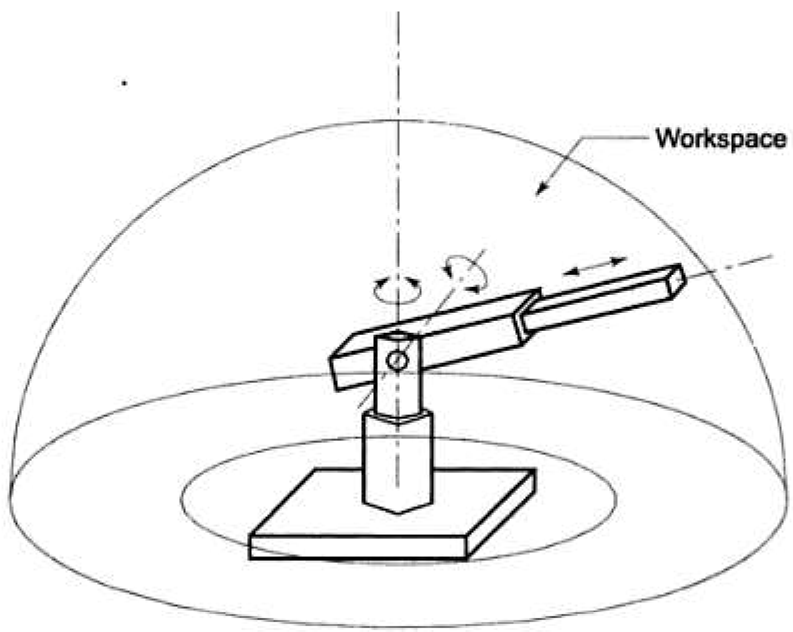

Fig. 1.14 *A 3-DOF polar arm configuration and its workspace*

This configuration allows manipulation of objects on the floor because its shoulder joint allows its end-effector to go below the base. Its mechanical stiffness is lower than Cartesian and cylindrical configurations and the wrist positioning accuracy decreases with the increasing radial stroke. The construction is more complex. Polar arms are mainly employed for industrial applications such as machining, spray painting and so on. Alternate polar configuration can be obtained with other joint arrangements such as RPR, but PRR will not give a spherical work volume.

(iv) Articulated (Revolute or Jointed-arm) Configuration The articulated arm is the type that best simulates a human arm and a manipulator with this type of an arm is often referred as an *anthropomorphic manipulator*. It consists of two straight links, corresponding to the human "forearm" and "upper arm" with two rotary joints corresponding to the "elbow" and "shoulder" joints. These two links are mounted on a vertical rotary table corresponding to the human waist joint. Figure 1.15 illustrates the joint-link arrangement for the *articulated arm*.

This configuration (RRR) is also called revolute because three revolute joints are employed. The work volume of this configuration is spherical shaped, and with proper sizing of links and design of joints, the arm endpoint can sweep a full spherical space. The arm endpoint can reach the base point and below the base, as shown in Fig. 1.15. This anthropomorphic structure is the most dexterous one, because all the joints are revolute, and the positioning accuracy varies with arm endpoint location in the workspace. The range of industrial applications of this arm is wide.

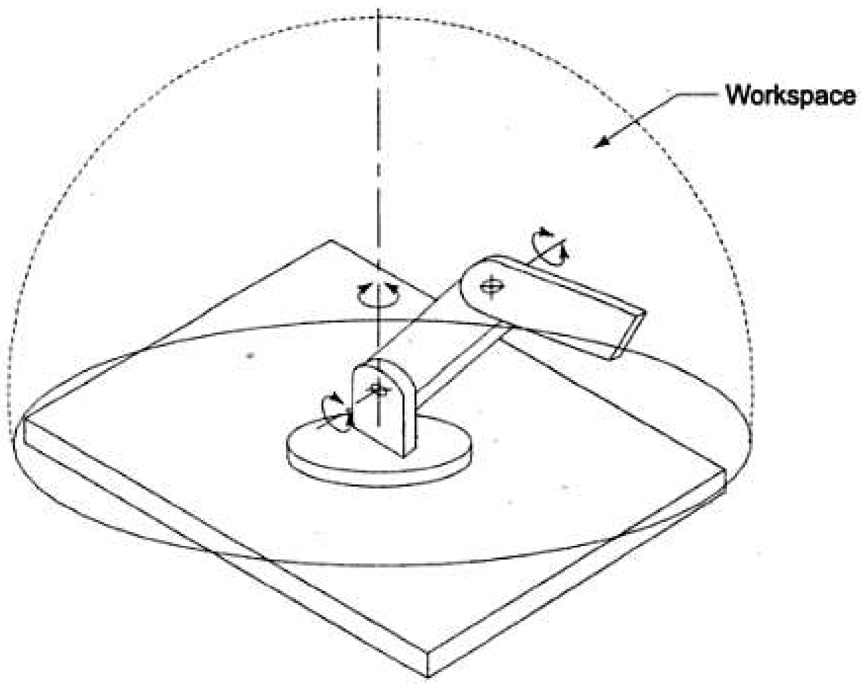

Fig. 1.15 *A 3-DOF articulated arm configuration and its workspace*

(v) Other Configurations New arm configurations can be obtained by assembling the links and joints differently, resulting in properties different from those of basic arm configurations outlined above. For instance, if the characteristics of articulated and cylindrical configurations are combined, the result will be another type of manipulator with revolute motions, confined to the horizontal plane. Such a configuration is called SCARA, which stands for Selective Compliance Assembly Robot Arm.

The SCARA configuration has vertical major axis rotations such that gravitational load, Coriolis, and centrifugal forces do not stress the structure as much as they would if the axes were horizontal. This advantage is very important at high speeds and high precision. This configuration provides high stiffness to the arm in the vertical direction, and high compliance in the horizontal plane, thus making SCARA congenial for many assembly tasks. The SCARA configuration and its workspace are presented pictorially in Fig. 1.16.

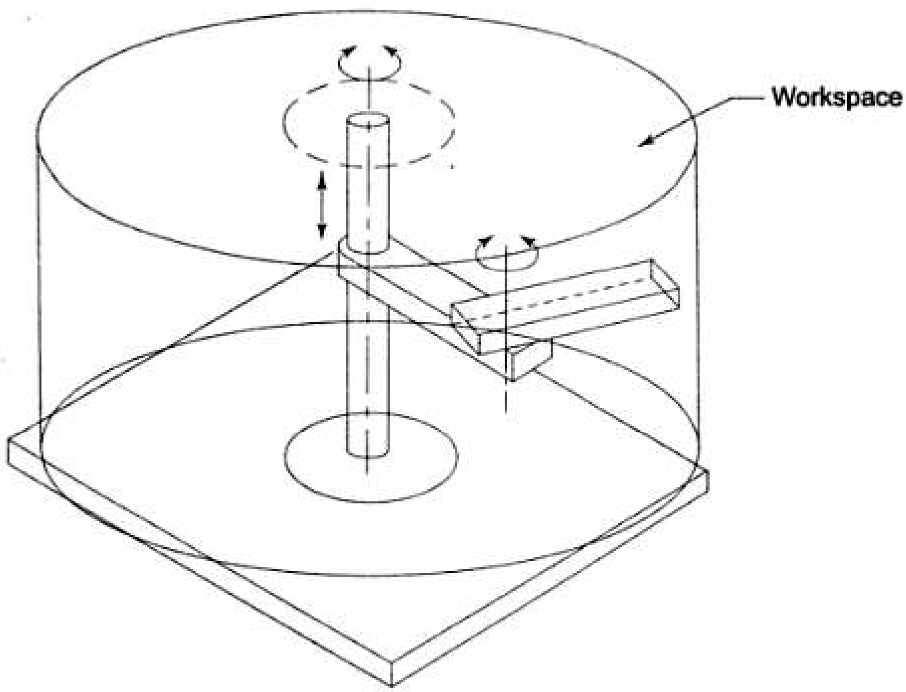

Fig. 1.16 *The SCARA configuration and its workspace*

1.5.6 Wrist Configuration

The arm configurations discussed above carry and position the wrist, which is the second part of a manipulator that is attached to the endpoint of the arm. The wrist subassembly movements enable the manipulator to orient the end-effector to perform the task properly, for example, the gripper (an end-effector) must be oriented at an appropriate angle to pick and grasp a workpiece. For arbitrary orientation in 3-D space, the wrist must possess at least 3-DOF to give three rotations about the three principal axes. Fewer than 3-DOF may be used in a wrist, depending on requirements. The wrist has to be compact and it must not diminish the performance of the arm.

The wrist requires only rotary joints because its sole purpose is to orient the end-effector. A 3-DOF wrist permitting rotation about three perpendicular axes provides for *roll* (motion in a plane perpendicular to the end of the arm), *pitch* (motion in vertical plane passing through the arm), and *yaw* (motion in a horizontal plane that also passes through the arm) motions. This type of wrist is called *roll-pitch-yaw* or *RPY* wrist and is illustrated in Fig. 1.17. A wrist with the highest dexterity is one where three rotary joint axes intersect at a point. This complicates the mechanical design.

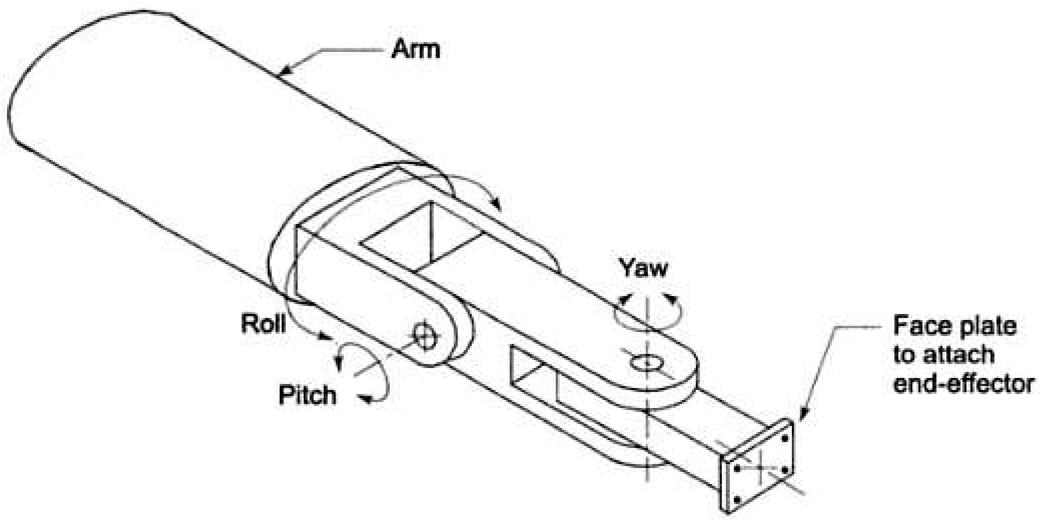

Fig. 1.17 *A 3-DOF RPY wrist with three revolute joints*

1.5.7 The End-effector

The end-effector is external to the manipulator and its DOF do not combine with the manipulator's DOF, as they do not contribute to manipulatability. Different end-effectors can be attached to the end of the wrist according to the task to be executed. These can be grouped into two major categories:

1. Grippers
2. Tools

Grippers are end-effectors to grasp or hold the workpiece during the work cycle. The applications include material handling, machine loading-unloading, palletizing, and other similar operations. Grippers employ mechanical grasping or other alternative ways such as magnetic, vacuum, bellows, or others for holding objects. The proper shape and size of the gripper and the method of holding are determined by the object to be grasped and the task to be performed. Some typical mechanical grippers are shown in Fig. 1.18.

For many tasks to be performed by the manipulator, the end-effector is a *tool* rather than a gripper. For example, a cutting tool, a drill, a welding torch, a spray

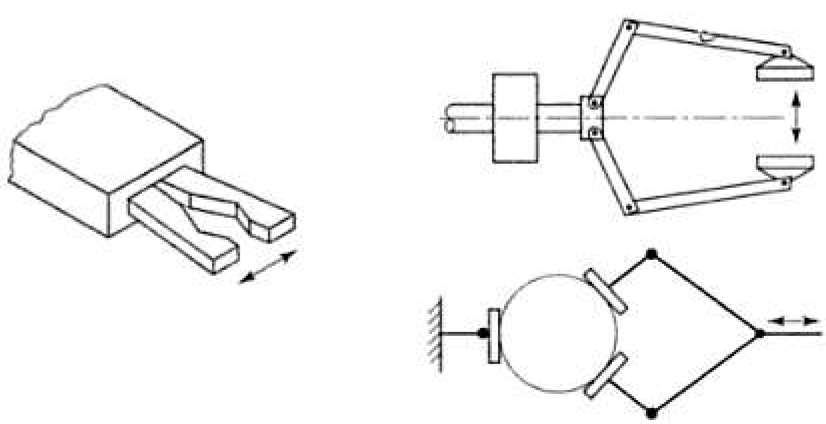

Fig. 1.18 *Some fingered grippers for holding different types of jobs*

gun, or a screwdriver is the end-effector for machining, welding, painting, or assembly task, mounted at the wrist endpoint. The tool is usually directly attached to the end of the wrist. Sometimes, a gripper may be used to hold the tool instead of the workpiece. *Tool changer* devices can also be attached to the wrist end for multi-tool operations in a work cycle.

1.6 HUMAN ARM CHARACTERISTICS

The inaustrial robot, though not similar to human arm, draws inspiration for its capabilities from the latter. The human arm and its capabilities make the human race class apart from other animals. The design of the human arm structure is a unique marvel and is still a challenge to replicate. Certain characteristics of the human arm are a far cry for today's manipulators. It is, therefore, worth considering briefly, human arm's most important characteristics as these serve as a benchmark for the manipulators.

The human arm's basic performance specifications are defined from the *zero reference position*, which is the stretched right arm and hand straight out and horizontal with the palm in downward direction. The three motions to orient the hand, which is the first part of human arm, are approximately in the following range.

$$-180^\circ \leq \text{Roll} \leq +90^\circ$$
$$-90^\circ \leq \text{Pitch} \leq +50^\circ$$
$$-45^\circ \leq \text{Yaw} \leq +15^\circ$$

Note that to provide the roll motion to the hand, forearm, and the upper-arm, both undergo a twist, while pitch and yaw are provided by the wrist joint. The second part of the human arm consists of upper arm and forearm with shoulder and elbow joints. It has 2-DOF in the shoulder with a ball and socket joint, 1-DOF in the elbow between forearm and upper-arm, with two bones in the forearm and one in upper arm. The 2-DOF shoulder joint provides an approximately hemispherical sweep to the elbow joint. The elbow joint moves the forearm by approximately 170° (from –5° to 165°) in different planes, depending on the orientation of two forearm bones and the elbow joint. For the zero reference position defined above, the forearm and the wrist can only sweep an arc in the horizontal plane.

Another important feature of the human arm is the ratio of the length of the upper arm to that of the forearm, which is around 1.2. Any ratio other than this results in performance impairment. A mechanical structure identical to the human arm, with 2-DOF shoulder joint, three-bones elbow joint, eight-bones wrist joint with complicated geometry of each bone and joint, is yet to be designed and constructed. The technology has to go a long way to replicate human arm's bone shapes, joint mechanisms, mechanism to power and move joints, motion control, safety, and above all, self repair.

The human hand, at the end of arm, with four fingers and a thumb, each with 4-DOF, is another marvel with no parallel. The finger and thumb joints can act independently or get locked, depending on the task involved, offering a very high dexterity to zero dexterity. This, coupled with the joint actuation and control mechanism and tactile sensing provided by the skin makes the human hand a marvel. In contrast, the robot gripper with two or three fingers has almost no dexterity. The human arm's articulation, and to the same extent, the human leg's locomotion are challenges yet to be met.

1.7 DESIGN AND CONTROL ISSUES

Robots are driven to perform more and more variety of highly skilled jobs with minimum human assistance or intervention. This requires them to have much higher mobility, manipulatability, and dexterity than conventional machine tools. The mechanical structure of a robot, which consists of rigid cantilever beams connected by hinged joints forming spatial mechanism, is inherently poor in stiffness, accuracy, and load carrying capacity. The errors accumulate because joints are in a serial sequence. These difficulties are overcome by advanced design and control techniques.

The serial-spatial linkage geometry of a manipulator is described by complex nonlinear transcendental equations. The position and motion of each joint is affected by the position and motion of all other joints. Further, each joint has to be powered independently, rendering modeling, analysis, and design to be quite an involved issue.

The weight and inertial load of each link is carried by the previous link. The links undergo rotary motion about the joints, making centrifugal and Coriolis effects significant. All these make the dynamic behaviour of the robot manipulator complex, highly coupled, and nonlinear. The kinematic and dynamic complexities create unique control problems that make control of a robot a very challenging task and effective control system design a critical issue. The robot control problem has added a new dimension in control research.

The environment in which robots are used poses numerous other complexities as compared to conventional machine tools. The work environment of the latter is well-defined and structured and the machine tools are essentially self-contained to handle workpieces and tools in well-defined locations. The work environment of the robot is often poorly structured, uncertain, and requires effective means to identify locations, workpieces and tools, and obstacles. The robot is also required to interact and coordinate with peripheral devices.

Robots being autonomous systems, require to perform additional tasks of planning and generating their own control commands. The detailed procedure, control strategy, and algorithm must be taught in advance and coded in an appropriate form so that the robot can interpret these and execute these accurately. Effective means to store the data, commands, and manage memory are also needed. Thus, programming and command generation become critical issues in robotics. To monitor it's own motions and to adapt to disturbances and unpredictable environments, robot requires interfacing with internal and external sensors. To utilize the sensory information, effective sensor-based algorithms and advanced control systems are required, in addition to a thorough understanding of the task.

1.8 MANIPULATION AND CONTROL

This section briefly describes the topics, which will be covered in this text, and introduces some terminology in the robotics field.

In the analysis of spatial mechanisms (manipulators), the location of links, joints, and end-effector in 3-D space is continuosly required. Mathematical description of the position and orientation of links in space and manipulation of these is, naturally, one topic of immediate importance.

To describe position and orientation of a body in space, a frame is attached to the body. The position and orientation of this frame with respect to some reference coordinate frame, called *base frame*, mathematically describes the location of the body. Frames are attached to joints, links, end-effector, and workpieces in the environment of the robot to mathematically describe them, as illustrated in Fig. 1.19.

Often, the description of a body in one frame is known, while requirement is the description of the body with respect to another frame. This requires *mapping* or *transforming* or changing the description of its attributes from one frame to another. Conventions and methodologies for description of position and orientation, and the mathematics of transforming these quantities are first discussed in this text.

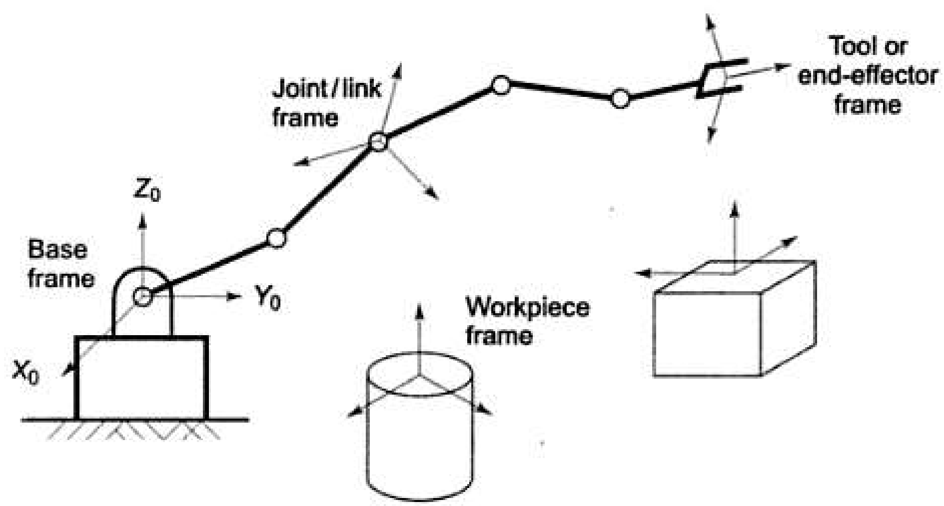

Fig. 1.19 *Attachment of frames for manipulator modelling*

Consider the simplest nontrivial two-link planar manipulator of Fig. 1.20 with link lengths (L_1, L_2) and assume that the joint angles are (θ_1, θ_2) and the coordinates of end-effector point P are (x, y). From simple geometrical analysis for this manipulator, it is possible to compute coordinates (x, y) from the given joint angles (θ_1, θ_2) and for a given location of point P (x, y), joint angles (θ_1, θ_2) can be computed.

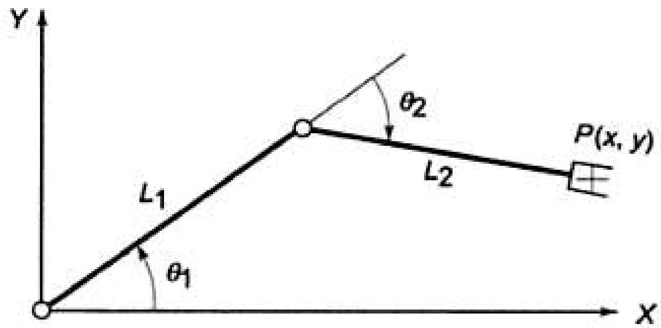

Fig. 1.20 *The 2-DOF two-link planar manipulator*

The basic problem in the study of mechanical manipulation is of computing the position and orientation of end-effector of the manipulator when the joint angles are known. This is referred to as *forward kinematics* problem. The *inverse kinematics* problem is to determine the joint angles, given the position and orientation of the end-effector.

A problem that can be faced in inverse kinematics is that the solution for joint angles may not be unique; there may be multiple solutions. This is illustrated for the simple planar 2-DOF manipulator in Fig. 1.20.

If the 2-DOF manipulator in Fig. 1.20 is used to position some object held in its end-effector to a specified position P_1 (x_1, y_1), the joint angles θ_1 and θ_2 that make the end point coincide with desired location must be found. This is the *inverse kinematics* problem. For the manipulator in Fig. 1.20, there are two sets of joint angles θ_1 and θ_2 that lead to the same endpoint position, as illustrated in Fig. 1.21.

The inverse kinematics problem is, thus, to calculate all possible sets of joint angles, which could be used to attain a given position and orientation of the end-effector of the manipulator. The inverse kinematics problem is not as simple as the forward kinematics, as it requires the solution of the kinematics equations which are nonlinear, involving several transcendental terms. The issues of existence and nonexistence of solutions and of multiple solutions are to be considered in detail. It may also be stated here that not all points in space are reachable by a given manipulator. The space covered by the set of reachable points defines the *workspace* of a given manipulator. For example, the workspace of the 2-DOF planar manipulator in Fig. 1.21 is shown in Fig. 1.22.

Another important problem of a manipulator is to find the end-effector velocity for given joint velocities and its inverse problem of calculating the joint velocities for specified end-effector velocity. These two problems, direct and inverse need the manipulator Jacobian (matrix), which is obtained from the kinematic parameters.

An identical problem of the static force analysis can also be solved through the Jacobian. This problem is stated as: given a desired contact force and moment,

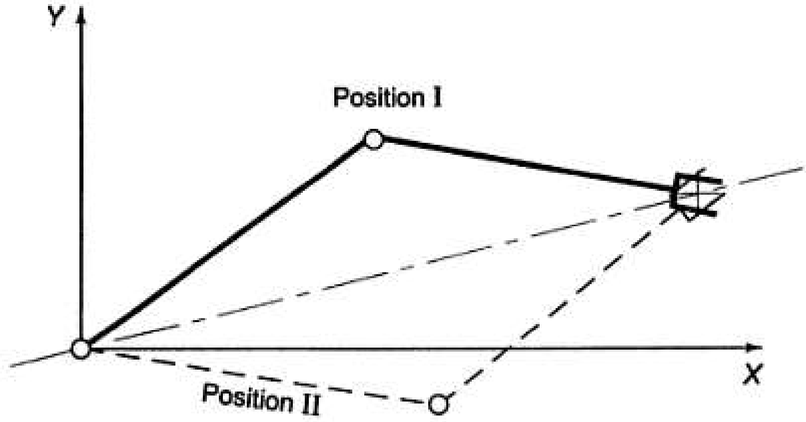

Fig. 1.21 *Two possible joint positions for a given end point position*

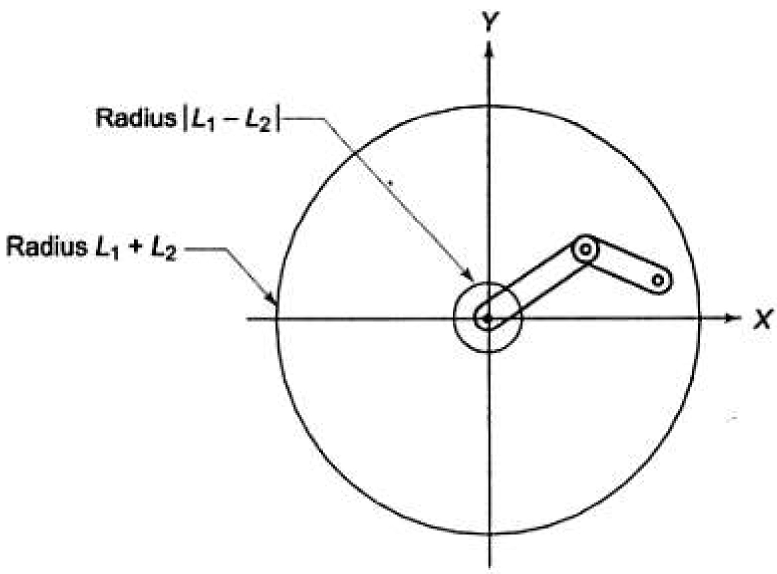

Fig. 1.22 *The workspace of a 2-DOF planar manipulator*

determine the set of joint torques to generate them or vice-versa. Figure 1.23 illustrates the interaction of a manipulator at rest with the environment; the manipulator is exerting a force $\boldsymbol{F}$ on the body.

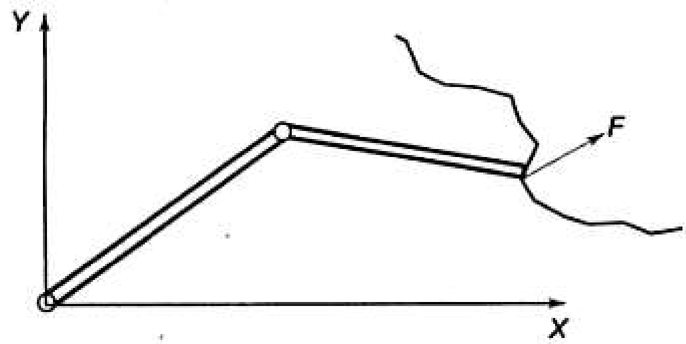

Fig. 1.23 *Manipulator exerting a force on the environment*

To perform an assigned task or to attain a desired position, a manipulator is required to accelerate from rest, travel at specified velocity, traverse a specified path, and finally decelerate to stop. To accomplish this, the trajectory to be followed is computed. To traverse this trajectory, controlling torques are applied by the actuators at the manipulator joints. These torques are computed from the *equations of motion* of the manipulator, which describe the *dynamics* of the manipulator. The *dynamic model* is very useful for mechanical design of the structure, choice of actuator, computer simulation of performance, determination of control strategies, and design of control system.

During the work cycle, the motion of each joint and end-effector must be smooth and controlled. Often the end-effector path is described by a number of intermediate locations, in addition to the desired destination. The term *spline* is used to refer to a smooth function, which passes through a set of specified points. The motion of end-effector through space from point A to point C via point B is illustrated in Fig. 1.24. The goal of *trajectory planning* is to generate time laws for the manipulator variables for a given description of joint or end-effector motion.

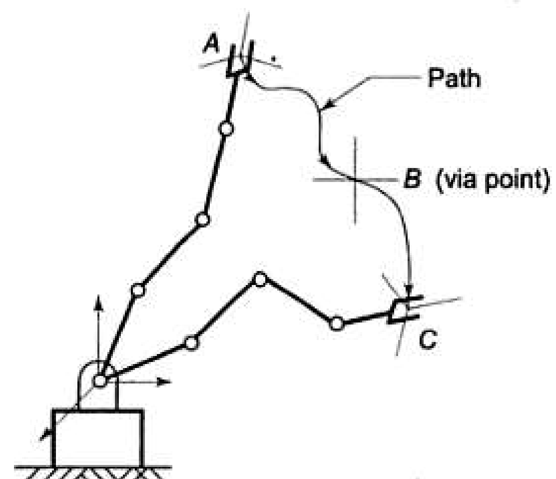

Fig. 1.24 *Trajectory generation for motion from A to C via B*

The dynamic model and the generated trajectory constitute the inputs to the motion-control system of the manipulator. The problem of manipulator control is to find the time behaviour of the forces and torques delivered by the actuators for executing the assigned task. Both the manipulator motion control and its force interaction with the environment are monitored by the control algorithm. The above exposed problems will lead to the study of control systems for manipulator and several control techniques.

The tasks to be performed by the manipulator are: (i) to move the end-effector along a desired trajectory, and (ii) to exert a force on the environment to carry out the desired task. The controller of manipulator has to control both tasks, the former is called *position control* (or *trajectory control*) and the latter *force control*. A schematic sketch of a typical controller is given in Fig. 1.25. The positions, velocities, forces, and torques are measured by *sensors* and based on these measurements and the desired behaviour, the controller determines the inputs to the actuators on the robot so that the end-effector carries out the desired task as closely as possible.

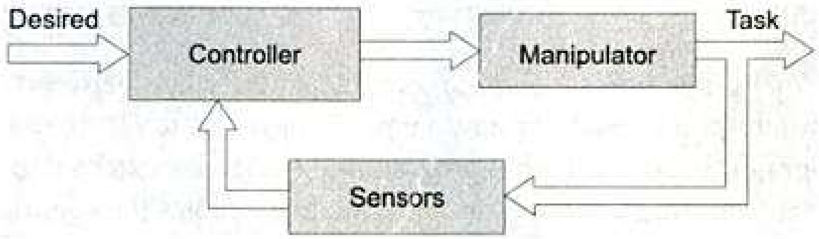

Fig. 1.25 *A schematic sketch of a manipulator control system*

1.9 SENSORS AND VISION

The control of the manipulator demands exact determination of parameters of interest so that the controller can compare them with desired values and accordingly command the actuators of the manipulator. Sensors play the most important role in the determination of actual values of the parameters of interest. For manipulator motion control, joint-link positions, velocities, torques, or forces are required to be sensed and the end-effector position and orientation is required for determining actual trajectory being tracked. The force control requires sensing of joint force/torque and end-effector force/torque.

Sensors used in robotics include simple devices such as a potentiometer as well as sophisticated ones such as a *robotic vision system*. Sensors can be an integral part of the manipulator (*internal sensors*) or they may be placed in the robot's environment or workcell (*external sensors*) to permit the robot to interact with the other activities and objects in the workcell.

The task performance capability of a robot is greatly dependent on the sensors used and their capabilities. Sensors provide intelligence to the manipulator. Sensors used in robotics are *tactile sensors* or *nontactile sensors*; *proximity or range sensors*; *contact* or *noncontact sensors*, or a vision system.

A robotic vision system imparts enormous capabilities to a robot. The robotic vision or vision sensing provides the capability of viewing the workspace and interpreting what is seen. Vision-equipped robots are used for inspection, part recognition, and identification, sorting, obstacle avoidance, and other similar tasks.

1.10 PROGRAMMING ROBOTS

Robots have no intelligence to learn by themselves. They need to be "taught" what they are expected to do and "how" they should do it. The teaching of the workcycle to a robot is known as *robot programming*. Robots can be programmed in different ways. One is " teach-by-showing" and the other is using textual commands with a suitable interface.

The manipulator is required to execute a specified workcycle and, therefore, must know where to move, how to move, what work to do, where and so on. In teach-by-showing method of programming, the manipulator is made to move through the desired motion path of the entire workcycle and the path and other parameters are saved in the memory. This method is also known as *lead through programming*.

A *robot programming language* serves as an interface between the human user (the programmer) and the robot manipulator for textual programming. The textual programming using a robot programming language can be done on-line or off-line. In on-line programming, the manipulator executes the command as soon as it is entered and the programmer can verify whether the robot executes the desired task. Any discrepancy is, therefore, corrected immediately.

In off-line programming, the robot is not tied-up and can continue doing its task, that is, there is no loss of production. The programmer develops the program and tests it in a simulated graphical environment without the access to the manipulator. After the programmer is satisfied with the correctness of the program, it is uploaded to the manipulator. In off-line and on-line programming, after the program is complete, it is saved and the robot executes it in the 'run' mode relentlessly.

The robot programming languages are built on the lines of conventional computer programming languages and have their own 'vocabulary', 'grammar', and 'syntaxes'. A typical vocabulary includes command verbs for (i) definition of points, paths, frames and so on, (ii) motion of joints-links and end-effector, (iii) control of end-effector, say grippers to open, close and so on; and (iv) interaction with sensors, environment, and other devices.

Each robot-programming language will also require traditional commands and functions for: arithmetic, logical, trigonometric operations; condition testing and looping operations; input-output operations; storage, retrieval, update, and debugging and so on.

The robot programming encompasses all the issues of traditional computer programming or software development and computer programming languages. This is an extensive subject itself and is not included in this book.

1.11 THE FUTURE PROSPECTS

The use of robots in industries has been increasing at the rate of about 25% annually. This growth rate is expected to increase rapidly in the years to come with more capable robots being available to the industry at lesser costs. The favourable factors for this prediction are:

(i) More people in the industry are becoming aware of robot technology and its potential benefits.

(ii) The robotics technology will develop rapidly in the next few years and more user-friendly robots will be available.

(iii) The hardware, software interfacing, and installations will become easier.

(iv) The production of industrial robots will increase and will bring down the unit cost, making deployment of robots justifiable.

(v) The medium and small-scale industries will be able to beneficially utilize the new technology.

All these will increase the customer base and, therefore, demand for the industrial robots and manpower geared with robot technology.

Robot is the technology for the future and with a future. The current research goals and trends indicate that the industrial robots of the future will be more robust, more accurate, more flexible, with more than one arm, more mobile, and will have many more capabilities. The robots will be human friendly and intelligent, capable of responding to voice commands and will be easy to program.

1.11.1 Biorobotics and Humanoid Robotics

A new research field in robotics inspired by biological systems has arisen. The technological developments have made it possible for engineers and robot designers to look for solutions in nature and look forward to achieving one of their most attractive goals to develop a humanoid robot.

Conventional viewpoint in robot design is dominated by its industrial applications, where emphasis is on mechanical properties that go beyond human performance, such as doing stereotype work tirelessly, carrying heavy loads, working in hostile environment, or giving high precision and consistent performance.

The biorobotics is historically connected to service robotics. These robots are conceptualized in a different manner than industrial robots. Their task is usually to help humans in diverse activities from house cleaning to carrying out a surgery, or playing the piano to assisting the disabled and the elderly.

The motion abilities of biological systems, their intelligence, and sensing are far ahead of all the achievements in manmade things till date. Progress in robot technology, rapid technological developments through the remarkable achievements in computer-aided technology in recent years have opened an entirely new research area, where the objective is to analyze and model biological systems behaviour, intelligence, sensing, and motions in order to incorporate properties of biological systems in robots. The ultimate objective is to produce a humanoid robot. The aspirations are not to limit these to service robots but these are to be extended to the industrial robots. It is expected that humanoid robots will be able to communicate with humans and other robots; facilitate robot programming; increase their flexibility and adaptability for executing different tasks; learn from experience; and adapt to different tasks and environments or change of place.

In the implementation of biological behavioural systems, the replication of anthropomorphic characteristics is possibly the answer in every context of development in robotics. The research in anthropomorphic robotics has advanced to development of anthropomorphic components for humanoid robots like anthropomorphic visual and tactile sensors, anthropomorphic actuators and anthropomorphic computing techniques. Replicating the functionality of the human brain is one of the hardest challenges in the biorobotics and in general still one of the most difficult objectives.

1.12 NOTATIONS

In a subject of interdisciplinary nature like robotics encompassing mechanical, electrical and many other disciplines, use of clear and consistent notations is always an issue. In this text we have used the following notations and conventions:

1. Vectors and matrices are written in upper case-bold-italic. Unit vectors are lower case-bold-italic, as an exception. Lower case italic is used for scalars. Vectors are taken as column vectors. Components of a vector or matrix are scalars with single subscript for vector components and double subscripts for matrix components. For example, components of a vector are a_i or b_z and elements of a matrix are a_{ij}.
2. Coordinate frames are enclosed in curved parenthesis { }, for example coordinate frame with axes XYZ is $\{x\ y\ z\}$ or coordinate frame 1 is {1} and square parenthesis [ ] are used for elements of vectors and matrices.
3. The association of a vector to a coordinate frame is indicated by a leading superscript. For example, ${}^0\boldsymbol{P}$ is a position vector $\boldsymbol{P}$ in frame {0}.
4. A trailing subscript on a vector is used, wherever necessary to indicate what the vector represents. For example, $\boldsymbol{P}_{tool}$, represents the tool position vector and $\boldsymbol{v}_i$ represents velocity vector for link i.
5. Matrices used for transformation from one coordinate frame to another, have a leading superscript and a trailing subscript. For example, ${}^0\boldsymbol{T}_1$ denotes the coordinate transformation matrix, which transforms coordinates from frame {1} to frame {0}.
6. Trailing superscripts on matrices are used for inverse or transpose of a matrix, for example, $\boldsymbol{R}^{-1}$ or $\boldsymbol{R}^T$ and on vectors for transpose of a vector, for example, if $\boldsymbol{P}$ is a column vector $\boldsymbol{P}^T$ is a row vector.
7. Many trigonometric functions are required in mathematical models. The sines and cosines of an angle θ_i can take any of the forms: $\cos\theta_i = C\theta_i = C_i$ and $\sin\theta_i = S\theta_i = S_i$. Some more shortened forms are $V\theta_i$ for $(1 - \cos\theta_i)$ and S_{ij} for $\sin(\theta_i + \theta_j)$.

A complete list of symbols used in the text is available in Appendix E.

1.13 BIBLIOGRAPHICAL REFERENCE TEXTS

Literature production in the nascent field of robotics has been conspicuous in the last twenty years, both in terms of research monographs and textbooks. The number of scientific and technical journals dedicated to robotics are also few, though the robotics field has simulated an ever-increasing number of scholars and has established a truly respectable international research community.

This chapter, therefore, includes a selection of journals, reference texts and monographs related to the field. The bibliography references cited here are