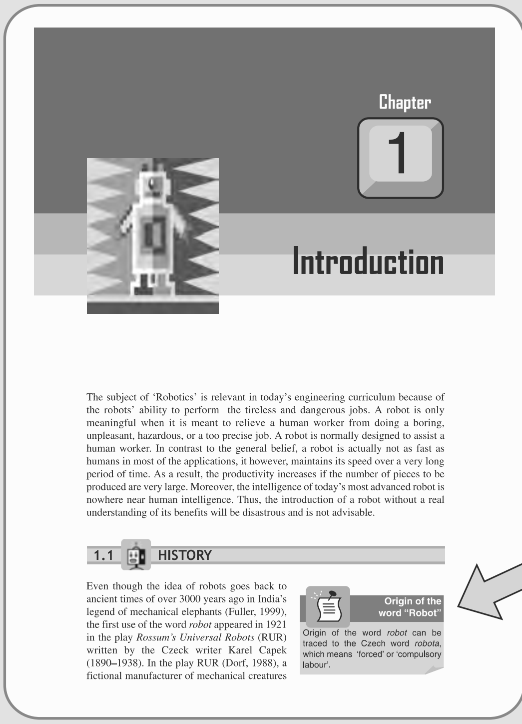
WALK THROUGH



Chapter

1

Introduction

The subject of 'Robotics' is relevant in today's engineering curriculum because of the robots' ability to perform the tireless and dangerous jobs. A robot is only meaningful when it is meant to relieve a human worker from doing a boring, unpleasant, hazardous, or a too precise job. A robot is normally designed to assist a human worker. In contrast to the general belief, a robot is actually not as fast as humans in most of the applications, it however, maintains its speed over a very long period of time. As a result, the productivity increases if the number of pieces to be produced are very large. Moreover, the intelligence of today's most advanced robot is nowhere near human intelligence. Thus, the introduction of a robot without a real understanding of its benefits will be disastrous and is not advisable.

1.1 HISTORY

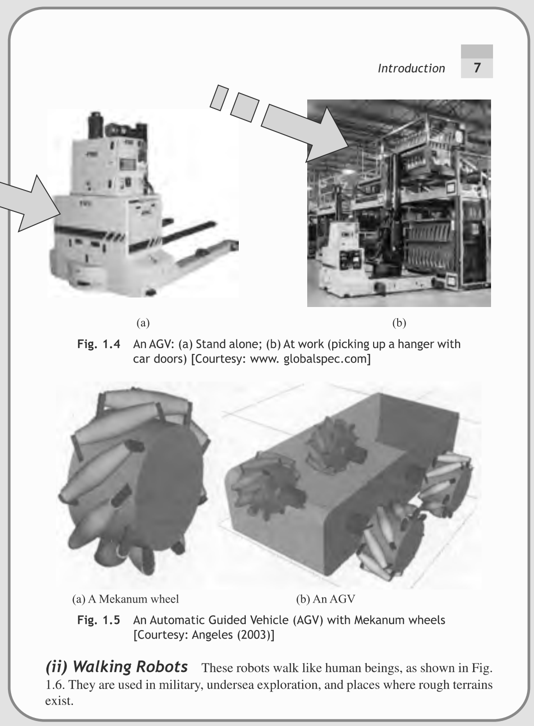
Even though the idea of robots goes back to ancient times of over 3000 years ago in India's legend of mechanical elephants (Fuller, 1999), the first use of the word *robot* appeared in 1921 in the play *Rossum's Universal Robots* (RUR) written by the Czeck writer Karel Capek (1890–1938). In the play RUR (Dorf, 1988), a fictional manufacturer of mechanical creatures

Origin of the word "Robot"

Origin of the word *robot* can be traced to the Czech word *robota*, which means 'forced' or 'compulsory labour'.

Textboxes in each chapter provide historical facts and topic-related information to complement the knowledge gained through the text of the book.

Photos of practical robots and their real applications give true understanding and utility of the subject covered in this book.



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(a) (b)

Fig. 1.4 An AGV: (a) Stand alone; (b) At work (picking up a hanger with car doors) [Courtesy: www. globalspec.com]

(a) A Mekanum wheel (b) An AGV

Fig. 1.5 An Automatic Guided Vehicle (AGV) with Mekanum wheels [Courtesy: Angeles (2003)]

(ii) Walking Robots These robots walk like human beings, as shown in Fig. 1.6. They are used in military, undersea exploration, and places where rough terrains exist.

country to country and are essential to ensure that any installation complies with the local legislation. Mostly safety is about isolating personnel from the robot's work envelope and ensuring that the movements can be easily halted in an emergency. To this end robots have in-built dual safety chains or run-chains. These are two parallel circuits that when broken will prevent the robot from moving. External connections including emergency stops are also catered for. It should also be noted that almost all robots have electrically operated disc brakes on each axis. These are on whenever power is not applied to release them. Therefore, in the event of a power failure or if the emergency stop is applied the robot stops dead, within a split second, in its position. It does not collapse and it retains positional and program data.

SUMMARY

Robots, their history, definitions, categories, applications, and populations are presented in this chapter. The laws of robotics, and when to use robots are also presented.

Summary at the end of each chapter gives a glimpse of what has been explained in that chapter.

EXERCISES

1.1 What is a robot?
1.2 What are the types of robots?
1.3 Name a few typical applications of an industrial robot.
1.4 What are the differences between a robot and a CNC machine tool?
1.5 How to decide the introduction of a robot for a particular job?
1.6 What are the four D's of robotics?
1.7 What is RUR?
1.8 What are the "Laws of Robotics?"
1.9 Write down the differences between serial and parallel robots.
1.10 What are the safety issues in robot usage?

WEB BASED EXERCISES

Based on web searches find the answers to the following questions:

1.11 Find names of different robot manufacturers.
1.12 How an industrial robot is specified?
1.13 What is the robot population in the world?

Web-based exercises will keep the readers up-to-date with the latest developments in this area.

Selection of components (Motors in this page) and necessary calculations give a student a practical approach to the subject, and provide a practicing engineer useful information for real product applications.

3.4 SELECTION OF MOTORS

For any application of robots, one must decide which of the available actuators is most suitable. Positioning accuracy, reliability, speed of operation, cost, and other factors must be considered.

Electric motors are inherently clean and capable of high precision if operated properly. In contrast, pneumatic systems are not capable of high precision for a continuous-path operation and hydraulic actuators require the use of oil under pressure. Hydraulic systems can generate greater power in a compact volume than the electric motors. Oil under pressure can be piped to simple actuators capable of extremely high torque and rapid operations. Also, the power required to control an electro-hydraulic valve is small. Essentially, the work is done in compressing the oil and delivering it to the robot arm drives. All the power can be supplied by one powerful, efficient electric motor driving the hydraulic pump at the base of the robot or located some distance away. Power is controlled in compact electro-hydraulic valves. However, high-precision electro-hydraulic valves are more expensive and less reliable than the low-power electric amplifiers and controllers. On the other hand, electric motors must have individual controls capable of controlling their power. In large robots, this requires switching of 10 to 50 amperes at 20 to 100 volts. Current switching must be done rapidly; otherwise there is a large power dissipation in the switching circuit that will cause it heat excessively. Small electric motors use simple switching circuits and are easy to control with the low-power circuits. Stepper motors are especially simple for open-loop operation. The single biggest advantage of a hydraulic system is their intrinsically safe operation.

As a thumb rule hydraulic actuators are preferred where rapid movement at high torques is required, at power ranges of approximately over 3.5 kW unless the slight possibility of an oil leakage cannot be tolerated. Electric motors are preferred at power levels under about 1.5 kW unless there is a danger due to possible ignition of explosive materials. At ranges between 1–5 kW the availability of a robot in a particular coordinate system with specific characteristics or at a lower cost may determine the decision. Reliability of all types of robots made by reputable manufacturers is sufficiently good. Hence this is not a major determining factor.

3.4.1 Calculations

Simple mathematical calculations are needed to determine the torque, velocity, and power characteristics of an actuator or a motor for different applications. Torque is defined in terms of a force times distance or moment. A force—f, at distance—a, from the center of rotation has a moment or torque—τ, i.e. $\tau = fa$. In general terms, power—P, is transmitted in a drive shaft is determined by the torque—τ, multiplied by the angular velocity—ω. Power P is expressed as—$P = \tau\omega$. For an example, a calculation can tell one what kilowatt or horsepower is required in a motor used to

The 'position' of any point, P, on a rigid body in motion with respect to the fixed reference frame can be described by the 3-dimentional Cartesian vector—**p**, as indicated in Fig. 5.12. If the coordinates of point P or the components of vector **p** are, p_x, p_y, p_z, in the fixed frame F, it is denoted as

$$[\mathbf{p}]_F \equiv \begin{bmatrix} p_x \\ p_y \\ p_z \end{bmatrix} \tag{5.8}$$

where the subscript F stands for the reference frame where the vector **p**, is represented. The subscripts, x, y and z, represent the projections of the position vector **p**, onto the coordinate axes of the fixed reference frame, namely, along X, Y and Z, respectively. Vector **p** can alternatively be expressed as

$$\mathbf{p} = p_x\mathbf{x} + p_y\mathbf{y} + p_z\mathbf{z} \tag{5.9}$$

where **x**, **y** and **z** denote the unit vectors along the axes, X, Y and Z of the frame F, respectively, as indicated in Fig. 5.12. Their representations in frame F, namely $[\mathbf{x}]_F$, $[\mathbf{y}]_F$ and $[\mathbf{z}]_F$, are as follows:

$$[\mathbf{x}]_F \equiv \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}, [\mathbf{y}]_F \equiv \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix}, \text{ and } [\mathbf{z}]_F \equiv \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \tag{5.10}$$

Substituting eq. (5.10) into eq. (5.9), it can be shown that the expression of vector **p** in frame F, i.e. $[\mathbf{p}]_F$, is same as that of given in eq. (5.8). Note that if vector **p** is represented in another fixed frame different from frame F then the vector **p,** will have different components along the new coordinate axes even though the actual position of point P has not changed. Thus, a vector will normally be written without

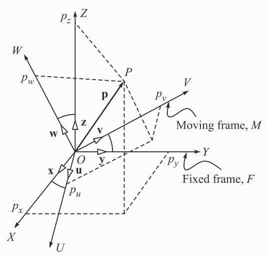

Fig. 5.12 Spatial description

Complex concepts like rotations are explained with detailed diagrams and mathematical expressions.

$$\mathbf{T}_\alpha = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & C\alpha_i & -S\alpha_i & 0 \\ 0 & S\alpha_i & C\alpha_i & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{5.49d}$$

The resulting coordinate transformation between the frames connected with bodies $i-1$ and i namely, $\mathbf{T}_i$, is then obtained by post-multiplying the above four elementary transformations, as done in Eq. (5.31d) i.e.,

$$\mathbf{T}_i = \mathbf{T}_b\mathbf{T}_\theta\mathbf{T}_a\mathbf{T}_\alpha \tag{5.50a}$$

The expression, $\mathbf{T}_i$, can also be read as the transformation matrix of the frame attached to body i, i.e. frame $i+1$, as represented in the frame attached to the body $i-1$, i.e. frame i. Substituting the matrix expressions from eqs. (5.49a–d) to eq. (5.50a), the following expression is obtained:

$$\mathbf{T}_i = \begin{bmatrix} C\theta_i & -S\theta_i C\alpha_i & S\theta_i S\alpha_i & a_i C\theta_i \\ S\theta_i & C\theta_i C\alpha_i & -C\theta_i S\alpha_i & a_i S\theta_i \\ 0 & S\alpha_i & C\alpha_i & b_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{5.50b}$$

MATLAB programming examples help a student to master solving complex problems with ease.

Example 5.24 ***Obtain Eq. (5.50b) using MATLAB***

In order to obtain eq. (5.50b), the symbolic operations have to be performed in MATLAB. For that the following commands are used:

```
>syms bi thi ai ali;
>tbm=[1,0,0,0;0,1,0,0;0,0,1,bi;0,0,0,1];
>tthm=[cos(thi),-sin(thi),0,0;sin(thi),cos(thi),0,0;0,0,1,0;0,0,0,1];
>tam=[1,0,0,ai;0,1,0,0;0,0,1,0;0,0,0,1];
>talm=[1,0,0,0;0,cos(ali),-sin(ali),0; 0,sin(ali),cos(ali),0; 0,0,0,1];
>tim=tbm*tthm*tam*talm
tim =
[     cos(thi), -sin(thi)*cos(ali),  sin(thi)*sin(ali),  cos(thi)*ai]
[     sin(thi),  cos(thi)*cos(ali), -cos(thi)*sin(ali),  sin(thi)*ai]
[            0,           sin(ali),           cos(ali),           bi]
[            0,                  0,                  0,            1]
```

where command 'syms' are used to define the symbolic variables, 'bi,' 'thi,' 'ai,' and 'ali,' for the DH parameters, b_i, θ_i, a_i, and α_i, respectively. Moreover, the notations, 'tbm,' 'tthm,' 'tam,' and 'talm' are used to represent the matrices, $\mathbf{T}_b$, $\mathbf{T}_\theta$, $\mathbf{T}_a$, and $\mathbf{T}_\alpha$, given by eqs. (5.49a–d), respectively. Finally, the resultant matrix $\mathbf{T}_i$, denoted as 'tim' in the MATLAB environment, is evaluated above, which matches with eq. (5.50b).

the joint torque space maps onto a 6-dimensional cylinder in the end-effector force space. Thus, the mechanical advantage of the manipulator becomes infinitely large in some direction.

SUMMARY

Torques required to exert a force and a moment by the end-effector are derived in this chapter while the robot is in static equilibrium. It is shown how the velocity Jacobian comes into picture in static analysis. Finally, physical interpretations of the Jacobian matrix in force domain are given.

EXERCISES

7.1 What is a static equilibrium in robotics?
7.2 How are wrench and twist propagation matrices related?
7.3 Define virtual displacement and work.
7.4 How does velocity Jacobian matrix comes into picture in static analysis?
7.5 What would happen to the end-effector forces upon application of joint torques while the associated Jacobian is singular?
7.6 Extract the Jacobian matrix for the revolute-prismatic (RP) planar arm in Example 7.2.
7.7 Find the expression of the above Jacobian matrix in the fixed frame.
7.8 Why is the concept of force ellipsoid important in the study of statics?
7.9 What happens if one of the principal axes of force ellipsoid vanishes.
7.10 Derive the torque and force expressions for the prismatic-revolute (PR) planar arm shown in Fig. 5.26 while the end-effector force $\mathbf{f}_e$ is applied and no link weights are considered.

MATLAB BASED EXERCISES

7.11 Verify the results of Exercise 7.7 using a MATLAB program.
7.12 Verify the results of Exercise 7.10.
7.13 Find the torque expressions for the SCARA robot shown in Fig. 5.28.
7.14 Find out the torques for the anthropomorphic arm of Example 7.6 while $\theta_1 = \theta_2 = 0$ and $\theta_3 = \pi/2$.
7.15 What are the torque values for the spherical wrist shown in Fig. 5.30 while only a moment $\mathbf{n}_e$ is applied at its end-effector.

MATLAB-based exercises enhance the problem-solving skill with ease.

In-house developed software usage not only allows the reader to get results for complex problems but also provides the possibility of writing new programs based on the existing ones.

Fig. 9.5 MS-Windows interface of RIDM

of the robot under study, which are defined in Chapter 5, namely, in Section 5.4. They are b_i, a_i, α_i, for a revolute joint, and θ_i, a_i, α_i, for a prismatic joint. The parameters b_i, θ_i, a_i, and α_i, are referred to as the joint offset, joint angle, link length, and twist angle, respectively.

2. Time history of the variable DH parameter, i.e. θ_i, for a revolute pair, and b_i, for a prismatic joint, and their first and second time derivatives, i.e. $\dot{\theta}_i$, $\dot{b}_i$, and $\ddot{\theta}_i$, $\ddot{b}_i$, respectively.
3. Mass of each body, m_i.
4. Vector denoting the distance of the $(i+1)$st joint from the ith mass center C_i in $(i+1)$st frame, i.e. $[\mathbf{r}_i]_{i+1}$.
5. Inertia tensor of the ith link about its mass center C_i in the $(i+1)$st frame, $[\mathbf{I}_i]_{i+1}$.

Note that RIDM has following features:

- It can handle manipulators with both revolute and prismatic pairs or joints;
- Gravity is taken into account by providing negative acceleration due to the gravity denoted by $\mathbf{g}$, to the first body, #1, as shown in eq. (9.32).

Example 9.3 Inverse Dynamics of Three-DOF Planar Manipulator

The three-link manipulator under study, as shown in Fig. 9.6, whose DH and inertial parameters are shown in Table 9.2. It is assumed that the manipulator moves in the X-Y plane, where the gravity is working in the negative Y

Table A.1 Evaluation of 'Atan2' function

x	*Atan2(y, x)*
+ve	Atan(z)
0	Sgn(y) $\pi/2$
−ve	Atan(z) + Sgn(y)π

Atan2(−1, 1) = $-\pi/4$ and Atan2(1, −1) = $3\pi/4$, whereas the Atan(−1) returns $-\pi/4$ in both the cases.

A.2 VECTORS

Unless otherwise stated, vectors will be defined as column vectors and denoted with lower-case bold letters. Thus, an n-dimensional vector **a** is defined as

$$\mathbf{a} \equiv \begin{bmatrix} a_1 \\ \vdots \\ a_n \end{bmatrix} \quad \text{(A.2)}$$

where $a_1, \ldots, a_n$ are the elements of vector **a.** The vector **a**, can also be represented as

$$\mathbf{a} \equiv [a_1, \ldots, a_n]^T \quad \text{(A.3)}$$

in which superscript T denotes transpose. The magnitude or length or norm of the vector **a**, denoted with italics letter a, is given by

$$a = \sqrt{\mathbf{a}^T\mathbf{a}} = \sqrt{a_1^2 + \ldots + a_n^2} \quad \text{(A.4)}$$

A.2.1 Unit Vectors

A unit vector is defined as a vector with unit magnitude. Hence, the unit vector along the vector **a**, denoted with $\bar{\mathbf{a}}$ can be defined as

$$\bar{\mathbf{a}} = \frac{\mathbf{a}}{a} \quad \text{(A.5)}$$

where a is given by eq. (A.4), Hence, the magnitude of the unit vector $\bar{\mathbf{a}}$ is $\bar{a} = 1$. Now, if **i**, **j**, and **k**, denote the unit vectors along the axes, X, Y, and Z, respectively, of a coordinate frame, as shown in Fig. A.1, any 3-dimensional Cartesian vector shown in Fig. A.1, say, $\mathbf{a} \equiv [a_1 \quad a_2 \quad a_3]^T$, can be expressed as

$$\mathbf{a} = a_1\,\mathbf{i} + a_2\,\mathbf{j} + a_3\,\mathbf{k} \quad \text{(A.6)}$$

Mathematical Fundamentals quickly revise the basics of mathematics required for the topics covered in the book without the need of referring other books immediately.

Robots built by the students give readers the confidence to build their own robots that will certainly enhance their knowledge about the subject.

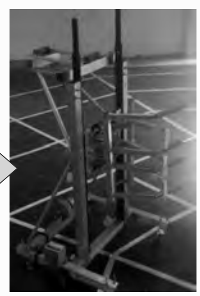

Fig. C.2 Automatic robot 2007

Fig. C.3 Manual robot 2007

latter can extend almost about half a meter in front of the robot to be able to place the block inside the boundary line of the 10-sided polygon. Once the design is done, the next level of challenge is to fabricate, assemble, program, and make them run successfully.

From the experiences of the author, typically, the following aspects should be looked into to successfully complete such projects:

1. Proper planning keeping in mind 5P's (Proper Planning Prevents Poor Performance).
2. Maintaining a project diary by each student to record day-to-day activity, sketches, information, etc.
3. Strictly follow a well-planned Gantt Chart. A typical Gantt Chart is shown in Fig. C.4. In case the deadlines are not met, reasons are to be found out and measures are to be taken without redefining the Gantt-Chart. In fact, the actual schedule can be put below the planned one.
4. It is extremely important that the students learn how to work in a group. Particularly, the coordinators of different heads, e.g. Mechanical, Electrical, Fabrication, etc., should know how to distribute the work amongst other members of his or her group. Otherwise, they may end up doing most of the jobs themselves, while others have no job. The latter group may get frustrated, and even