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Introduction

1.1 Introduction

There has been a rapidly growing and widespread interest in robots, mechanical manipulators and hands, mobile platforms, walking machines, and many other so-called robotic devices and 'intelligent' systems. These robotic technologies combined with rapid advances in electronics, controls, vision and other forms of sensing, and computing have been widely recognized for their potential applications in almost all areas where machines enter our society. In fact, it has been claimed that we are in the midst of a robotics revolution, and this revolution will have more influence on human society than had the Industrial Revolution of the 17th and 18th centuries. Although the number of robots and their applications are proliferating, the underlying science and, to some extent, the technology are moving at a much slower pace. In this chapter, we present a brief history of robots, the various types and classifications of robots, and the underlying science and technology in the field of robotics.

1.2 Brief History

The word 'robot' came into English language in 1923 from the translation of a 1921 Czech play *R.U.R (Rossum's Universal Robot)* by Karel Capek (Capek 1975). It is derived from the Czech word 'robota' meaning slave labour. The 'robots' in the play are designed to replace human workers and are depicted as very efficient and indistinguishable from humans except for their lack of emotions. In the play the robots rebel against their human masters and destroy the entire human race except one man so that he can continue making robots! Unfortunately, the formula gets lost in the destruction.

In contrast to the horrors of mechanization in Capek's play, in 1942, the science fiction writer Issac Asimov (Asimov 1970) in a story titled '*Runaround*' coined the word *'robotics'* to describe the study of robots and gave the three laws of robotics. In many of his stories dealing with robots,

Fig. 1.1 A PUMA 560 robot

always designed on the basis of these three laws, Asimov portrays robots as harmless and totally under the control of human beings.

The modern industrial robot, as it first appeared, bore little resemblance to the science-fiction-inspired vision of a robot. Figures 1.1 and 1.2 show a PUMA (Programmable Universal Machine for Assembly) and a $T3$ (The Tomorrow Tool) robot manufactured by Unimation Inc. and Cincinnati Milacron Inc., respectively, and seen extensively in textbooks, industry, and academic and research institutions. Clearly, these are not even remotely similar to the human-like robots depicted in science fiction. The modern industrial robot was patented by George C. Devol in 1954 and he called it a ‘programmable articulated transfer device’. J. Engelberger and George C. Devol founded the world’s first robot company, Unimation Inc., in 1956, and the first industrial robot, called Unimate, was purchased by General Motors and installed at an automobile plant in New Jersey, USA, in 1961.

What is a robot in the modern sense of the word? There are several definitions. The Webster dictionary defines a robot as ‘ .... an automatic device that performs functions normally ascribed to humans or a machine in the form of a human’. A more formal and restrictive definition from the

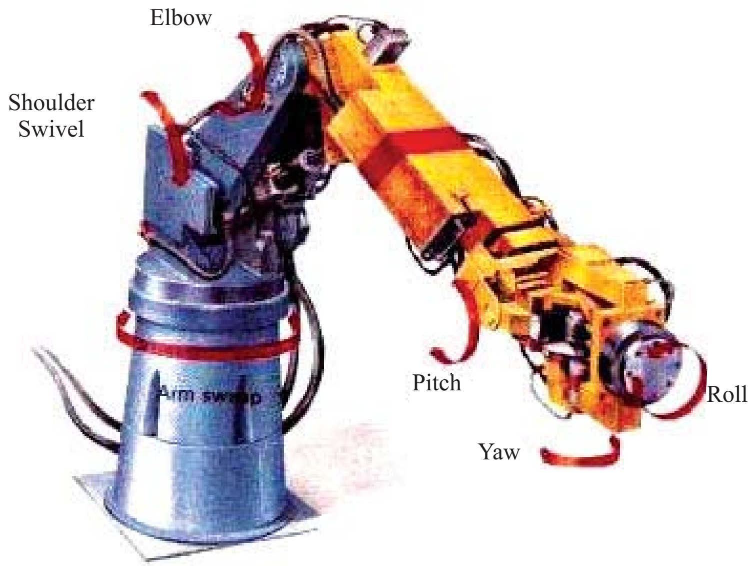

Fig. 1.2 A Cincinatti Milacron $T3$ robot

Robot Institute of America (1969) defines robot as '.... a re-programmable, multi-functional manipulator designed to move materials, parts, tools or specialized devices through various programmed motions for the performance of a variety of tasks'. The key word in the definition is 're-programmable' and this word has closely linked the development of robots to the rapid development of the digital computer and developments in the art and science of computing. A computer or a microprocessor that allows running of different robot programs for the various applications is an essential component of a robotic system. One of the first computers, ENIAC, was developed in the University of Pennsylvania in 1946 and in 1959 a programmable lathe was first demonstrated at MIT. It may be mentioned that the word 're-programmable' also distinguishes a robot from computer numerically controlled (CNC) machines since the level and sophistication of re-programmability is significantly higher in an industrial robot.

In addition to the digital computer, the other key ingredient in the development of the modern industrial robot is the concept and implementation of feedback control. Feedback control allows the execution of the programmed or desired motion (chosen by a robot operator or another program called a *task planner*) with the required accuracy in spite of 'small' changes in the robot or the environment, and thus improve the performance of robots. The first textbook on feedback control, *Cybernetics or Control and*

Communication in the Animal, describing control in mechanical, electronic, and biological systems, was written by Prof. Norbert Wiener of MIT in 1948. The use of feedback control is by no means limited to robots. Today a whole range of CNC machines, automobiles, airplanes, missiles, and spacecrafts, and an ever increasing number of consumer products such as washing machines and microwave ovens use feedback control.

In the late 1980s and early 1990s, the growth in the use of industrial robots slowed down significantly, except in Japan. One of the main reasons was the inability of robots to perform tasks that human operators could perform quite easily, such as avoiding obstacles in a cluttered workspace, recognizing and manipulating objects such as screws, bolts, and nuts, and adapting and reacting quickly to changes in the environment. It was realized that most of the existing industrial robots were essentially blind, deaf, and dumb, and a great deal of effort was made to equip robots with sensors and computing resources so that the robots could sense, quickly process data from sensors, and then interact intelligently with the environment. Present-day industrial robots are often equipped with sensors to detect the presence or absence of the object to be manipulated, measure applied forces and moments, and obtain the position and orientation of objects in its environment. Present-day industrial robots also come with a wide variety of end-effectors, hands, and grippers (which are often equipped with sensing elements) to grasp and manipulate a wide variety of tools and objects. With the advancement in sensing and computing, the modern industrial robot is easier to program and use, more flexible, and more intelligent. The late 1990s have seen a renewed interest in the use of robots.

Modern industrial robots are used in a variety of places and situations. These can be broadly classified into three categories. The first typical area is in an environment that is hazardous for humans to operate in, or an environment where the cost of protecting humans is very high. Examples are in handling of fuel and radioactive material in nuclear power plants, and in space and underwater operations. For example, the satellites and experimental payloads in the space shuttle are often removed from the cargo bay by a mechanical manipulator operated by an astronaut from the safety of the cabin. The pictures of the ocean liner *Titanic* and retrieval of portions of the Air India's Kanishka airplane, from great ocean depths, were taken by unmanned submersible robots. The exploration of Mars was done by mobile robots Sojourner in 1997 and Spirit and Opportunity in 2004, which not only beamed back spectacular pictures of the Martian landscape but also the data and the images sent by them allowed researchers to infer the presence of large amounts of water on the Martian surface in the past. Robots are also being used in environments not hazardous to human beings but where human beings are hazardous to the product—robots are being increasingly used in ultraclean rooms in the electronic industry as it is expensive to keep off dust and other foreign material carried and generated by human beings.

The second area where modern industrial robots have been employed in large numbers is in tasks that are repetitive, back-breaking, and also boring for human beings. In these tasks, human beings cannot maintain the required accuracy or quality because of the monotonous and tedious nature of the task. Typical applications can be seen in automotive industries where robots are often used for spray painting and welding of car bodies, in general manufacturing where robots are used for loading and unloading of material, parts, and tools from other machines, and more recently for assembly of components such as electric motors and computer peripherals.

The third area where robots are used is in manufacturing of consumer products where the number of items is not very large and the product or the model is frequently changing. Typical examples are television sets, cameras, and other audio/video consumer products. Robots are ideally suited for these industries because of their ease of re-programmability. Reprogramming the robots to handle different parts of newer models can be done more easily than expensive re-tooling and changes in the assembly line and this allows a manufacturer to keep pace with the changing consumer tastes and stay competitive.

With the maturing of the technology, robots are finding their way into many other areas of human activity. To name a few, robots are and have been used extensively for entertainment as evidenced by the *Star Wars* and *Terminator* series movies. The robot dog Aibo from Sony and the LEGO Mindstorms robot construction kit is very popular among children and adults. The humanoid robot P3 and Asimo from Honda have appeared in advertising for a variety of products. A robotic system called Da Vinci has been used for heart surgery, where it is programmed to follow the physician's hand movements very accurately and with no tremors (the tremors and unwanted movement can be removed with the help of a computer and the robot controller), and thus can be used to perform very delicate bypass and heart valve surgeries. Finally, robots are finding their way into human homes as robotic vacuum cleaners and lawn mowers which can clean the house or mow the lawns on their own when the occupant is away!

Japan, accounting for more than half the number of robots installed worldwide, is the largest user of robots, followed by the European Union and USA. To give an idea of the explosive growth in the use of robots in Japan, the number of robots in use in Japan went up from approximately 5,500 in 1980 to over 65,000 in 1985 and about 400,000 in 1995. Although the number of robots in use in Japan has not increased much during the last decade due to the retiring of older robots and the depressed economy, the number of robots in use have gone up in Europe and USA. It is forecast that there will be a dramatic increase, in tens of thousands, of robots for domestic and medical uses. In India (and other developing countries) too robots have found their way into a few industries such as for spray painting and spot welding of automobile bodies, handling of molten metals and other hazardous substances, and in nuclear waste handling. The use, however, is insignificant compared to that in Japan, USA, and Europe.

Some of the important dates in the history of robotics are given below.

- 1770—Mechanism-driven life-like machines that can draw, play instruments, and clocks made in Germany and Switzerland.
- 1830—Cam programmable lathe invented.
- 1923—Karel Capek's play *R.U.R.*
- 1942—Asimov coins the word 'robotics' and gives his three laws of robotics.
- 1946—ENIAC, the first electronic computer, developed at the University of Pennsylvania.
- 1947—The first servo electric-powered tele-operated robot at MIT.
- 1948—Book on feedback control, *Cybernetics*, written by Prof. Norbert Weiner of MIT.
- 1948—Transistor invented at Bell Laboratories.
- 1952—IBM's first commercial computer, IBM 701, marketed.
- 1954—First programmable robot patented and designed by Devol.
- 1955—Paper by J. Denavit and R. S. Hartenberg (Denavit and Hartenberg, 1955) provides a notation to describe links and joints in a manipulator.
- 1959—Unimation Inc. founded by Engelberger; CNC lathe demonstrated at MIT.
- 1961—General Motors buys and installs the first Unimate at a plant in New Jersey to tend a die casting machine.
- 1968—Shakey, the first mobile robot with vision capability, made at SRI.
- 1970—The Stanford Arm designed with electrical actuators and controlled by a computer.
- 1973—Cincinnati Milacron's ($T3$) electrically actuated, mini-computer controlled industrial robot.

- 1976—Viking II lands on Mars and an arm scoops Martian soil for analysis.
- 1978—Unimation develops PUMA, which can still be seen in many research labs.
- 1981—*Robot Manipulators* by R. Paul, one of the first textbooks on robotics.
- 1982—First educational robots introduced by Microbot and Rhino.
- 1983—Adept Technology, maker of SCARA robot, started.
- 1995—Intuitive Surgical formed to design and market surgical robots.
- 1997—Sojourner robot sends back pictures of Mars; the Honda P3 humanoid robot, started in 1986, unveiled.
- 2000—Honda demonstrates Asimo humanoid robot.
- 2001—Sony releases second generation Aibo robot dog.
- 2004—Spirit and Opportunity explore Mars surface and detect evidence of past water.

1.3 Types of Robots

Robots are generally classified according to their number of degrees of freedom or axes. The degrees of freedom (DOF) of a robot roughly indicate the capability of a robot. A general task consisting of arbitrarily positioning and orienting an object or a tool can be achieved only by a six-DOF or a six-axes robot. Painting and simple welding can be done by a five-axes robot, and often assembly robots have only four degrees of freedom. A five- or a six-DOF welding robot is often mounted on a three-axes gantry, giving rise to an eight- or nine-axes robotic system for larger operating volume and flexibility. We will discuss the concept of *degree of freedom* in detail in Chapter 3.

Based on its configuration, a robot may be a Cartesian, spherical, or cylindrical robot, since the motion of a point after the first three joints in the robot is best described by the use of Cartesian, spherical, or cylindrical coordinates. The term 'anthropomorphic' or 'articulate' is used for a robot because of its 'similarity' to a human arm, and a SCARA (selective compliance adaptive robot arm) design is based on a folding door. In most manipulators, there are two or three additional joints after the first three joints, which form a wrist. The first three joints are typically used to position an object or a tool in the workspace of the manipulator, whereas the wrist joints are used to orient the tool or the object being manipulated.

All the above configurations are called *serial* manipulators since they have one fixed end, a free end which carries the end-effector or tool, and no closed loops. Many present-day robots have one or more joints fixed to the ground and one or more closed loops. These are called *parallel* manipulators or robots.[1] The Stewart-Gough platform, shown in Fig. 1.3, is one of the most famous examples and has found use in many applications such as in a flight simulator, a six-DOF manipulator, and a six-component force–torque sensor. In Chapters 3 and 4, we present the kinematic analysis of serial and parallel manipulators.

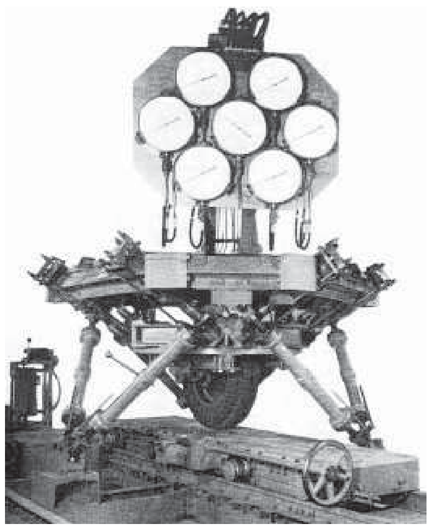

Fig. 1.3 The original Stewart-Gough platform (Stewart 1965)

According to the mode of operation in a playback robot, a robot is physically taken through each step of the desired motion by an operator and these recorded positions are simply played back by the robot on being signalled to do so. In a computer-controlled robot, the desired motion is obtained from a computer after computations according to specified algorithms. An intelligent robot is equipped with sensors and processors and is capable of performing tasks such as avoiding obstacles, taking simple decisions based on sensor inputs and even 'learn' about the environment in which it operates. The topics of feedback control of robots and sensors used in robots form the content of Chapter 8.

[1] Parallel manipulators are often further classified as fully parallel and hybrid. In a fully parallel manipulator, as shown in Fig. 2.22, all the connections between the end-effector and the ground are by means of two links and a single actuated joint. In a hybrid manipulator, as shown in Fig. 2.23, the end-effector can be connected to the ground by several links and actuated joints in a series. In this text, we will use the term 'parallel' for all configurations which are not serial, i.e., those having one or more closed loops.

In addition to the above classification, we also have other types of robots and robotic devices. To name a few, there exist multi-DOF walking machines, robots mounted on two- or three-DOF mobile platforms or automated guided vehicles (AGVs), and multi-DOF mechanical hands with fingers attached to a robot. In Chapter 10, we will discuss mobile robots in more details. For other kinds of robots, the reader is referred to the literature mentioned at the end of the chapter.

1.4 Technology of Robots

The technology and hardware of robots are changing continuously, and we can, at best, describe briefly and qualitatively some of the main components of a robot. A typical robot consists of mechanical components, actuators, power transmission devices, sensors, an electronic controller, and computers. The main mechanical components of a robot are links connected by joints. As mentioned earlier, in a serial manipulator, the links are arranged sequentially, starting from the base and ending in the end-effector with no loops. In a parallel manipulator, on the other hand, there can be one or more loops. Links are assumed to be rigid in most of this text (except in Chapter 9, where we discuss modelling and analysis of flexible link manipulators) and are generally made of metal such as steel or aluminium (cast or machined). It is desirable that links be as lightweight as possible so that torque (force) requirements from an actuator are low, and at the same time the links must have rigidity to achieve positioning accuracy. The joints allow relative rotation or translation between the connecting links, and various types of bearings are used to ensure relatively free and smooth motion. The end-effector carries the tool and is application specific. In painting or welding, the paint gun or the welding tool is fixed on the end-effector and the arrangement is made to continuously supply the paint or the welding wire. In material handling, often a two-fingered gripper is used to grasp objects, as shown in Fig. 1.4.

The links are moved by actuators, which are electric motors or pneumatic and hydraulic cylinders. Electric motors can be DC or AC servo-motors, or sometimes stepper motors. The motors required for robots should have ideally a low rpm (of less than 100), be lightweight and have high torque. Most lightweight DC servo-motors, however, run at a high speed of 3000 rpm or more[2] and a suitable transmission has to be used to bring down the speed. Usual speed reduction approaches using standard spur gears, chains, and

[2] Lightweight, high-torque, and low-rpm motors or direct drive motors are difficult to design and are expensive.

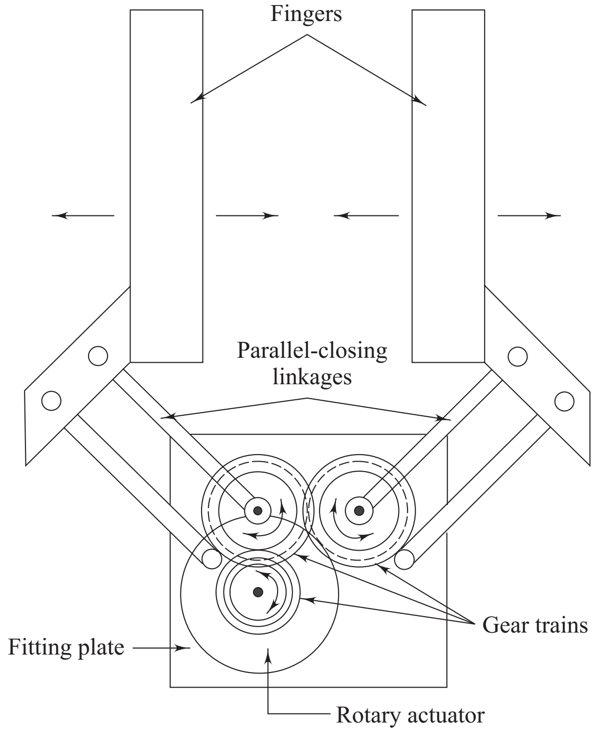

Fig. 1.4 A two-fingered gripper

sprockets or belts cannot be used since the accuracy is lost due to backlash or slippage. Special low-backlash gear sets, harmonic drives, and ball screws are used for transmission of power and to reduce speed. Often brakes are present to stop the motion or to hold the robot when it is not in motion.

The speed and repeatability requirement vary with the nature of the task and the load-carrying capacity. The tip of a large welding robot can move as fast as 2 m/sec (although the welding process speed is much smaller at about 1–5 m/min) carrying a payload of 5–10 kg, and can have a repeatability of less than 1 mm and a reach of 2–3 m. Typical speeds of material-handling robots are 1 m/sec carrying a payload of about 10 kg, with a repeatability of about 0.1 mm (thickness of a human hair) and a reach of 1–2 m. Finally, there are small electronic assembly robots which can have maximum speeds of more than 5 m/sec, a payload of less than 1 kg, a repeatability of 0.01 mm or less, and a reach less than 1 m.

Most robots have sensors at joints, which measure rotation or translation at joints for feedback control. The angular rotation at a joint is measured by optical encoders, and the angular velocity can be measured by tachometers. Translation and linear velocities can be measured by linear variable differential transformers (LVDTs) and video cameras. Force at the end-effector or at the links can be accurately measured by force–torque sensors, which use strain gauges.

Most controllers are implemented digitally using microprocessors and contain circuitry for analog to digital (A/D) and digital to analog (D/A) conversions, memory, and other electronics. Typically, the measured signals and the processing are digital ($0/5$ V and currents in milliamperes) whereas the input to the actuators are higher voltages (often 12 or 24 V) and currents (in amperes) in analog form, and hence carefully designed servo-amplifiers are used to drive actuators. The technology of controllers for robots is quite complex, difficult, and expensive to develop, and together with computers also makes up the bulk of the cost of a robotic system—the controller may cost as much as 60% of the entire robotic system.

In addition to the sensors required for control, most industrial robots have sensors required for the task and application for which the robot is being used. For example, an arc-welding robot will have sensors to maintain the arc length while the robot is moving along the required weld path. A few robots are equipped with simple vision systems. They are used to inspect or pick components not oriented in the desired way. Several research robots, at universities and research laboratories, have full-fledged vision systems or sonars which allow them to avoid obstacles and navigate in cluttered environments.

Two of the most important components in a robotic system are the computers and the software or the programs residing in them. Often there are two kinds of computers in a robotic system: one set performs the task of controlling the actuators in a robot and the other is a supervisory or a master computer where application programs can be developed and stored, fault detection, diagnosis, and corrective actions can be taken, or where a high-level task planner or an expert system can reside. At the actuator level, the programs are simple and the processing has to be very fast (typical sampling rates are about 50–100 Hz), and an assembly language programming is often used for achieving the fast processing requirements. At the supervisory level, the processing speed is much slower, but the programs are more complex. At this level, a user-friendly environment and a standard high-level language, such as C, or a robot programming language is available for developing application programs. There are two-way communication channels between the actuator control computers and the supervisory computer.

Finally, an industrial robot is a complex and expensive machine. It is important to provide a user-friendly operator interface so that the robot operator can learn to use it easily and quickly. The commands to the robot to accomplish a given task must be simple and straight forward to the operator. The operator interface is normally through a teach pendant or through a computer. A large amount of careful programming, often including graphics, is required to build this user interface.

1.5 Basic Principles in Robotics

To understand how and why robots work, we have to understand the scientific principles that form the basis of robotics. Robotics is an interdisciplinary subject drawing ideas and tools from mathematics, physics, engineering, and computing. We take a brief look at some of the ingredients of robotics, namely, kinematics, dynamics, controls, sensing, and intelligence.

Kinematics deals with the motion of rigid bodies (motion of the rigid links of a robot) in a three-dimensional (3D) space. A rigid body moving in a three-dimensional space has six degrees of freedom, or, in other words, a rigid body requires six independent parameters to be fully specified. Three of the six parameters specify the position of a point of interest, which could be a point on the end-effector, or the tip of the paint or welding tool, or the centre of gravity of the part being moved. Three other parameters are required to specify the orientation of the same object. In order to achieve these six degrees of freedom, a robot must have at least six independently actuated joints. In kinematics of robots we study the functional relationships between the motion at the joints and the motion of the end-effector or tool without reference to the cause (external forces and moments) of the motion. One can find and study, quantitatively, the motion at the end-effector for a given motion at the joints (the direct kinematics problem), the motion at the joints for a required motion of the end-effector (the inverse kinematics problem), the workspace or the volume in 3D space which a point of interest on the robot can reach, and other issues related to the time derivatives of the position and orientation of the links of a robot, i.e., the velocity and acceleration. In Chapter 2, we discuss in detail the representation of the rigid body position and orientation and the representation of links and joints of a serial or a parallel robot. In Chapters 3 and 4, we discuss the kinematics of serial and parallel robots, respectively, and in Chapter 5, we discuss velocity and acceleration.

In dynamics, we study the motion of the links and the end-effector under the action of external forces and torques from the actuators. The methodology is to first obtain the mass and inertia of the moving links and the end-effector, then obtain the dynamic equations of motion by the application of the well-known Newton's laws of motion, or by the Lagrangian formulation, or by the use of Kane's equations. There are two problems of interest. In the so-called direct problem, the differential equations of motion are solved for given initial conditions, and the time evolution of the variables which describe the motion of the complete robot system is obtained. The differential equations of motion are non-linear and coupled, and hence they can be solved only numerically on a computer. In the so-called inverse problem, we compute the actuator forces and torques required to achieve a desired motion of the robot. The direct problem is useful for simulation, whereas the inverse problem is useful for design (or choice) of actuators and links and for model-based control. Robot dynamics is discussed in detail in Chapter 6.

To ensure that a robot follows a desired motion, the paradigm of feedback control is used. In feedback control, as applied to a robot, the actual motion either at the joints or of the end-effector (or tool) is measured by means of sensors, and these measurements together with the known desired motions are used as inputs to a controller. The outputs of a controller are the torques and forces acting at the actuators, and they act in a way so as to reduce the errors between the desired and the actual motion. In a very common controller, the so-called proportional integral plus derivative (PID) controller, the output is proportional to the error (defined as the difference between the desired motion and the measured or estimated motion), the rate of change of the error and the integral of the error. One can show, for a linear system, that by a proper choice of the proportionality constants, also known as the controller gains, the errors can be driven to zero in an asymptotic manner. A PID controller also works reasonably well for common industrial robots in spite of them being non-linear systems. There are other advanced controllers which use a model (essentially the dynamic equations of motion) of the robot system to achieve better performance in terms of the accuracy and speed of response.

In many applications, in particular robotic assembly, position control is not suitable. In situations where the robot end-effector is in contact with the environment it is useful to control the force which the robot applies on the environment. Although force and position cannot be controlled in the same direction, there are advanced hybrid position/force control schemes which allow the user to switch between position and force control depending on the application. In Chapters 7 and 8, we deal with the generation of desired trajectories, position and force control in a robot, respectively.

A robot without sensors is like a human being without eyes, ears, and sense of touch or smell. It is also believed that to make robots more intelligent in interacting with the external environment and taking simple decisions, they need to be equipped with sensors. The single most important sensor in humans is the eye. It is also the most complex sensor and requires the maximum processing by the brain—to process the vast amount of information coming from the eyes quickly, unlike the other sense organs, the eye is directly connected to the brain by means of the optic nerve. Efforts have been made and are still continuing to endow robots with vision—a video camera acts as an eye and the processing is done by specialized electronic and high-speed computers.

Sensors which can measure force and simulate the sense of touch in humans have also been used in robots. These sensors use the phenomenon of change of electrical resistance of some material under pressure or contact forces. These sensors enable a robot to apply the correct amount of force to grip delicate objects, such as an egg or a paper cup, and detect objects and obstacles that come in its path. The reader interested in sensors used in robots is referred to Fu, Gonzalez, and Lee (1987) and other related refernces listed at the end of the chapter.

A robot equipped with vision and touch sensors that can adapt to various changes in its environment can be said to be intelligent. The foundation of this ability lies in the field of artificial intelligence or AI in short. The goal of AI is to produce systems that can imitate human performance in a large variety of tasks considered to be intelligent. A class of AI systems known as expert systems have a knowledge base consisting of 'if ..., then ...,' rules, rules of logic, heuristics and data about the current domain of interest, and algorithms to manipulate the data and the rules (it can learn and add new rules). These expert systems can obtain solutions to the problem at hand or extract useful information about the external world from sensory data, and serve as an interface with a human user or a robot. Other AI systems[3] for extracting useful data about a scene viewed by a TV camera, to avoid obstacles while moving in cluttered spaces, and to assemble blocks and other objects have been devised and used in robots. The present level of intelligence in a robot is minuscule—even an insect can move around with more agility and adapt to the changing environment with more ease than an advanced, expensive, state-of-the-art research robot. The topic of intelligence is outside the scope of this text, but interested readers can refer to some of the references listed at the end.

[3] AI systems are not restricted to robotics—they are used in widely varying areas such as in medicine to diagnose diseases, in organic chemistry to determine composition from spectroscopic data, prospecting of oils and minerals, and even in the design of computers.

1.6 Notation

The following notations will be used throughout the text.

Symbols such as a, x, P will be used to denote scalars. Boldfaced symbols such as $\mathbf{p}$, $\mathbf{q}$ will denote vectors. Often the components of a vector are required, and we will denote the components of a 3D vector $\mathbf{p}$ by $(p_x, p_y, p_z)^T$ or $(p_1, p_2, p_3)^T$. Vectors are described with respect to a coordinate system, and the leading superscript A as in ${}^A\mathbf{p}$ denotes the coordinate system in which $\mathbf{p}$ is described. The subscript with a vector is used for distinguishing one object out of many, for example, the vector ${}^0\mathbf{O}_1$ denotes a point $\mathbf{O}_1$ with respect to the coordinate system $\{0\}$. The first and second derivatives of vector $\mathbf{q}$ with respect to time will be denoted by $\dot{\mathbf{q}}$ and $\ddot{\mathbf{q}}$, respectively.

We will use several coordinate systems. The symbols such as $\{A\}$ or $\{Tool\}$ will be used to denote the coordinate system named A or $Tool$. The origin of the coordinate system $\{A\}$ will be denoted by O_A and it is located by a vector $\mathbf{O}_A$. The unit vectors along the three coordinate axes of $\{A\}$ will be denoted by $\widehat{\mathbf{X}}_A$, $\widehat{\mathbf{Y}}_A$, $\widehat{\mathbf{Z}}_A$. A rigid body i, in the context of kinematics, is equivalent to a coordinate system $\{i\}$, and will be used interchangeably.

Symbols enclosed in square brackets such as $[\mathbf{J}]$ or $[T]$ will denote matrices. Matrices are often associated with coordinate systems, for example, the orientation of a rigid body or a coordinate system with respect to another rigid body or a coordinate system can be defined with the help of a rotation matrix ${}^A_B[R]$. The matrix ${}^A_B[R]$ will be used to denote the rotation matrix describing $\{B\}$ relative to $\{A\}$. The inverse and transpose of a matrix $[R]$ will be denoted by the usual $[R]^{-1}$ and $[R]^T$, respectively. The identity matrix will be denoted by $[U]$ (for unitary) to differentiate from the inertia matrix $[I]$. Other matrices, as and when they appear, will be explained in the text.

We will use trigonometric functions $\sin(\cdot)$ and $\cos(\cdot)$ very frequently. For convenience, we will use the symbols c_1, s_{12}, etc. to denote $\cos\theta_1$ and $\sin(\theta_1 + \theta_2)$, etc., respectively, throughout the text.

Other symbols will be explained as and when they are introduced in the text.

1.7 Symbolic Computation and Numerical Analysis

Before we end this chapter, a word about computations is in order. In this text, we will be making significant use of computers in two main ways. Firstly, in this text, several problems and exercises are provided at the end of each chapter which enhance the understanding of the topics covered in that chapter. Some of the exercise problems require a significant amount of numerical computation, and a software such as MATLAB (Mathwork

1992) or MATHEMATICA (Wolfram 1999), on a PC or a Unix machine, is adequate. MATLAB or MATHEMATICA provide in-built and very easy to use functions and routines for almost all mathematical operations, plotting of numerical data, and other scientific computations. The use of MATLAB or MATHEMATICA is preferred over writing from scratch, in a language such as C or C++, error free codes for numerical computations.

Secondly, we have used extensive symbolic computations to derive and simplify many of the analytical results presented in this text. We have used the software MAPLE[4] (Heck 2003) which has an added advantage of being compatible with MATLAB, and symbolic expressions obtained in MAPLE can be easily ported to MATLAB for numerical computations and other post-processing. Several exercise problems at the end of the chapters require symbolic computations for derivations of analytical expressions. Readers are urged to obtain familiarity with MAPLE and MATLAB. Readers interested in knowing more about symbolic computations are referred to the book by Cohen (2002).

Exercises

1.1 Visit some of the websites mentioned in the text, for example *http://www.jpl.nasa.gov* and links to Mars Robots, and *http://world.honda.com/ASIMO/*, and learn about the robots.

1.2 From the Internet find out the most recent numbers of robots in use worldwide. What is the cost of a typical welding robot? What is the cost of a surgical robot? What is the largest robot in use? How much payload can it carry and what is its weight?

1.3 In later chapters, there will be many exercises where a computer will be necessary. We will use MAPLE or MATHEMATICA. Familiarize yourself with one of these software packages by
- Assignment of symbolic or numeric expressions to identifiers.
- Dot and cross-product of two vectors.
- Manipulating trigonometric expressions and simplification of expressions using known trigonometric and other identities.
- Symbolic multiplication of two 4×4 matrices.
- Symbolic inverse of a 3×3 matrix.

1.4 Test expressions obtained from symbolic computations numerically by choosing random numeric values for the variables.

1.5 Familiarize yourself with MATLAB by
- trying out mathematical operations on scalars, vectors, and matrices.
- plotting graphs for some common functions such as $x = \sin\theta, \theta \in [-\pi, \pi]$.
- writing and using a simple 'm'-functions.

[4] MATHEMATICA can also be used.

References and Suggested Additional Reading

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General Reference Journals and Magazines on Robotics

IEEE Transactions on Robotics (originally *Robotics and Automation*)

IEEE Transactions on System, Man and Cybernetics

International Journal of Robotics & Automation

Journal of Robotic Systems

Mechanism and Machine Theory

Robotics Today

The Industrial Robot

The International Journal of Robotics Research

Transactions of ASME, Journal of Dynamical Systems, Measurement and Control

Transactions of ASME, Journal of Mechanical Design

Some Useful and Interesting Robot Related Websites

http://www.jpl.nasa.gov and links to Mars Robots.

http://world.honda.com/ASIMO/

http://www.sony.net/Products/aibo/index.html

http://www.legomindstorms.com

http://www.howstuffworks.com

http://www.ai.mit.edu

http://robotics.stanford.edu

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