1. Robotics: History, Present Status and Future Trends

1.1. PHILOSOPHICAL CONSIDERATIONS

Modern science has grown by leaps and bounds in this century. Man has expanded his horizon beyond the natural environment by devising means to protect himself and by making machines for operation in extreme conditions to meet varied demands and necessities.

Today's changes in every aspect of life and global activity are not independent of one another. Nor are they random. Seemingly unrelated events, they are not isolated—they are, in fact, the components of a much larger phenomenon, the rise of a completely new concept of civilization.

The very first stage was the invention of tools. That was the starting of mechanization and the beginning of the technological evolution of implements. This evolution naturally was very slow throughout the first wave of agricultural civilization. Man started exploiting nature without doing any harm to it.

The industrial renaissance brought in the second stage of development with the advent of steam and IC engines. Life style, family bondage, state economy and politics, interstate relations started changing; as also the degree of exploitation of nature disturbing the ecology unavoidably to a large extent and deliberately in some cases. Demand for consumable inputs and outputs compelled invention of large machinery and process complexes from manually operable stages to semiautomatic and fully automatic stages relieving man from working under hazardous conditions. Technical inventions backed by technological innovations marked the second wave of industrial revolution.

Man's destiny was reshaped in the post world war period, when began the third stage of technological development. Every industry felt the necessity for having machinery and components with exacting tolerances and specifications on materials, shape and size, machines becoming more and more dependable than man himself. Thus in the early 1950s there came into existence the brand of numerically controlled (NC) machines.

The fourth stage of development began with the advent of computers after the invention of transistors which revolutionized the total concept of controls in the industry. Computer numerically controlled (CNC) machines edged out many predecessors on the arrival of the microprocessors. It provided the greatest technological boost to industry backed up by the latest developments in microelectronics, advances in computer technology and the availability of reliable electromechanical and hydromechanical servomechanisms.

The final stage has led to the concept of robotics. Startling advances in science and technology and their innovative application in production and manufacturing industries have lifted the limitations of previous concepts in the industrial scenario, consequently widening the capabilities of robots.

Conceptually, robotics differs from conventional automation, in its ability to perform on its own, going to the extent of unmanning many operations. It has enabled man to be relieved of tedious and mindless, repetitive and hazardous jobs. Increased flexibility, low cost in the long run, and reliability are the three main advantages of robotics.

Recent developments in robot technology have made its presence inevitable in the industry. Robots are being endowed with more capabilities such as rudimentary sensory perceptions like touch, smell (!) and audiovision, and advanced technology for artificial intelligence and decision-making under conditions of uncertainty, speech recognition and many more similar qualities.

Robots, for better or worse, have already taken over many factory jobs in Japan and the USA. The robot population is on the increase in all the advanced countries. However, the impact it would have on the socio-economic and political structure of a nation is of grave concern and consequence. That is more so in the case of the developing and underdeveloped countries. The rising problem of unemployment, even in the developed countries, not to mention the technologically backward nations, would certainly limit the immediate application of robots except in very specific hazard-prone industries. Nevertheless, research work in the frontiers of robotics continues.

It is important for India—recently declared a developed country by the United Nations—not to lag behind other nations in the sphere of technology. In this perspective, it would be relevant to introduce this fascinating subject, where knowledge of many other fields interact, to the engineering community.

1.2. ROBOTICS AND PROGRAMMABLE AUTOMATION

Robotics is the science of designing and building robots suitable for real-life applications in automated manufacturing and other nonmanufacturing environments. Robots are the means of performing multifarious activities for man's welfare in the most planned and integrated manner, maintaining their own flexibility to do any work, effecting enhanced productivity, guaranteeing quality, assuring reliability and ensuring safety to the workers. When the early men, started settling in villages, they invented many innovative implements and left behind inscriptions to communicate many of their ideas. Around 5000 B.C., history of the Indian civilization indicates that the people of Mohen-jo-Daro and Harappa in the Indus Valley had many toys that could move their heads and duplicate motions of wild animals. In the Vedic period as depicted in the great epics *Ramayana* and *Mahabharata*, there were flying chariots like the present-day aeroplanes; there existed in concept many missile-like tools and arrows which could perform a variety of miraculous tasks like firing and igniting, creating smoke screens, extinguishing fire by bringing down rains and digging wells in the earth to obtain water and so on. Those were fantasies, no doubt. But there is enough indication that the early people discovered certain principles and knew simple mechanisms to create those wonders. Later the Chinese, Greek and Roman civilizations designed and constructed many devices which were similar to the present-day machines and robots. These early fabricated devices were probably meant for the purpose of entertaining common people, and taming wild animals and sometimes for terrorizing or controlling unruly people by the most powerful group of the society. Mostly, the king, the priests and the rulers of the land practised those fascinating ideas and created many working models imitating many creatures on the earth. From these ideas, models and mechanisms, grew the concept of early mechanization.

Another merit of further mechanization was to multiply human energy—both physical and mental—to harness the abundant natural resources for man's welfare. That was how the idea of employing machines grew to produce more consumable products and services and to replace the culture of direct slavery.

To facilitate the manufacture of products, attempts were made to reduce human and animal labour, and to employ efficient machines run by exploiting other direct or converted natural energy sources. Meanwhile, the economic rule of demand and supply became operative. To produce more goods in a reasonably shorter period of time, the speed of production emerged as a factor of paramount importance. For the given five-M inputs (man, machines, materials, money and motivation), more outputs at faster speed became imperative to raise the level of productivity. Gradually, the degree of mechanization in real life increased by employing more machines in place of direct labour. Higher heights of mechanization achieved every century, decade or year rendered the newer machines indispensable.

Man is imaginative. He has fine sensory organs and possesses the highest level of intelligence. With his imagination, he can conceive innovative ideas. But the same man when asked to produce goods in bulk through repetitive procedures is unable to produce products having identical shape and size, desired degree of accuracy and surface quality in spite of his best efforts. A man even with his learning ability is inconsistent in repetitive jobs. In man, flexibility is very much present, which acts as an instinct to change over to a different course for pleasure and satisfaction of the mind. As a result, mechanical motions being mindless, lack of concentration creeps in and there is no consistency in producing goods in bulk. The history of industrial revolution tells us how El Whitney introduced the concept of interchangeability in order to maintain consistency in producing components on a large scale.

Attempts were therefore made to develop versatile machines to manufacture products of different shapes, sizes and quality.

General-purpose machine tools and other equipment were developed where machines could be made more productive by labour intensive skill-based manual operations. These machines were developed according to the skills involved in the jobs giving rise to the concept of piece production where conventional, general purpose and standalone machines could be employed. In piece production, consistency could be maintained only at a lower level of productivity as this depended on the skill of human operators. But when the production volume became quite high, conventional and standalone machines were not the appropriate choice. Semiautomatic machines tools appeared on the scene where the workpieces had to be loaded and unloaded manually. All the required tools needed setting in and change, if any, only by manual means. For a fixed set of tools, the machines performed automatically all the sequential steps of operations. Fully automatic or dedicated machines came later, and the age of hard automation began. Dedicated machines or fixed equipment were custom-made machines tailored to perform a significant part of their functions without direct human intervention so as to cope with higher volume of production of the components with consistency, but at the same time losing a great deal of flexibility.

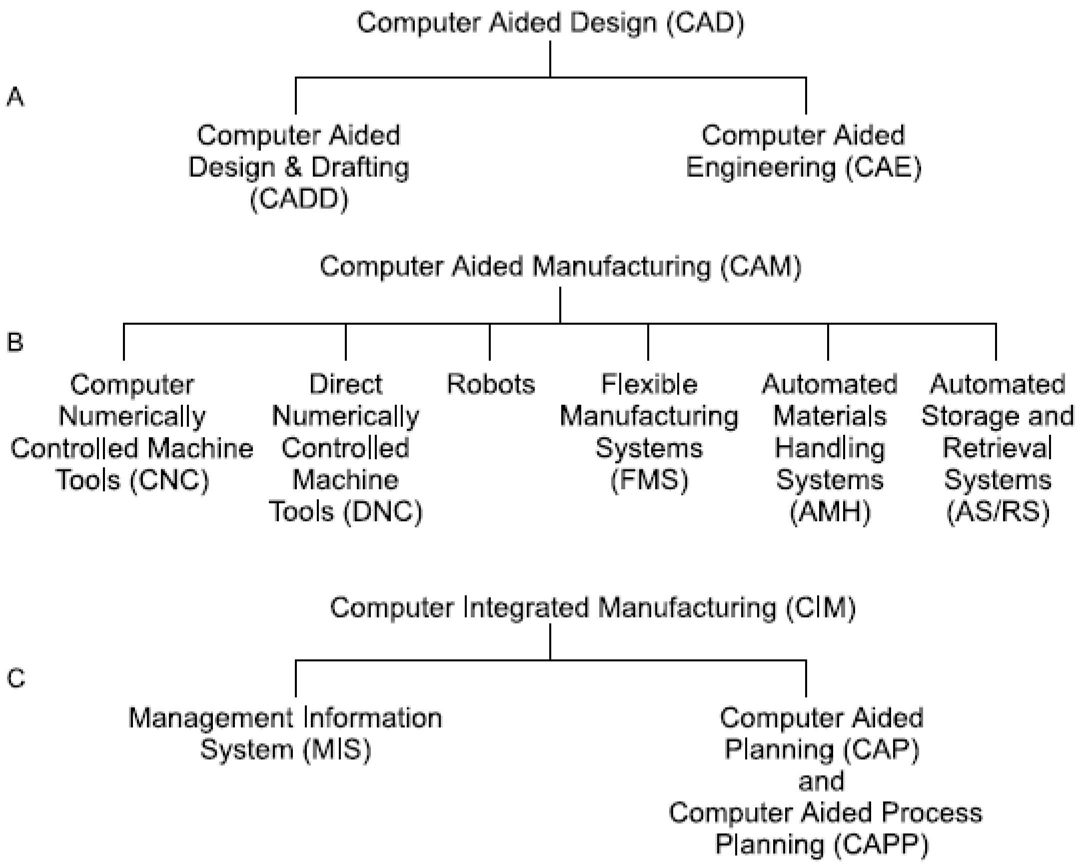
There is a growing demand for new consumer products nowadays. A new product entails a change in design. To manufacture such low-volume new products with individual custom-made machines or fixed equipment is economically prohibitive because of the increased changeover cost. Therefore, a new system of workpiece classification was developed. Products or components had for long been identified by their functional requirements and produced on machines following either a product layout or a process layout. In the new system, these workpieces are identified as a 'group' or a class on the basis of similarity in geometric shape, dimension and technology. The components are codified according to the groups in the classification system and those belonging to one category are processed at the same work-station. Thus, components with different functional requirements belong to a homogeneous family for which better machines and tooling layouts and a better 'cell system' of production can be designed. The classification of operations into groups of similar processes and codification of workpieces is termed *Group Technology*. It is an important step in discrete manufacturing, especially batch manufacturing.

In order to cope with batch manufacture, where the quantity is in small and medium lots, a new type of automation technology has become available. This is adjustable, adaptable and flexible enough not only to the change in design of the products, but also to the change in the process of manufacture of the products. This type of automation is termed as *Programmable Automation.* The word programmable means that one set of tasks can be easily switched over to another set by changing the computerized instructions. In programmable automation, attempts have been made to combine consistency and flexibility. Programmable automation consequentially reduces the very high costs involved in the changeover to another custom-made capital intensive machine.

The birth of flexible automation has been possible with the advent of microelectronics, microcomputers and programmable controllers. When a machine is made to act or perform tasks similar to those done by a human being in sub-human working environment, it has to be flexible. Around 1950, automation took a new turn with the introduction of numerical controlled (NC) machines. But NC machines are hardware based machines. To make these more compatible with the software based system, computer numerically controlled (CNC) machines have been evolved. Each NC machine is provided with a minicomputer or a microcomputer. They are easily programmable through their software. They are suitable for batch quantity production where products often undergo either design change or process change. Software packages are developed to accommodate different programmes or routines in the storage medium of magnetic tape or disc and thus various tasks can be performed according to the sequence laid down in the process sheets.

Programmable automation uses information technology and numerical engineering to provide coordination, machine control and communication through computers in the most effective way. It attempts to bridge the gap between consistency and flexibility. The principal programmable automation technologies are shown in Table 1.1.

Table 1.1



An example of the programmable automation technology is the robot. The robot is an essential component of CAM and CIM technologies. The name *robot* came from the Czechoslovakian word *Robota* which means a worker or a slave doing heavy work. In 1921–22, Karel Capek, a Czechoslovakian playwright wrote a play called 'Rossum's Universal Robots' or briefly 'RUR'. In this play, Rossum thinks of a robot meant for serving humanity, but unfortunately his time and energy to build such a robot are in vain. Finally, Rossum's robot, as depicted in the play, becomes a dreadful creature. In the play, the robots dreamt of by Rossum and his son are humanoid creations, but the present-day robots as used in industry are unlike the humanoid shape, though some toy robots look like giant human beings. However, the concept of 'robotics'—a term introduced and popularized by Isaac Asimov, the great science fiction writer—has come a long way from the pages of science fiction to reality in a relatively short period of time. This is due to the sincere effort of many robotocists and robotics schools of repute. Development of industrial robots by a successful team led by Joseph Engelberger and George Devol in 1960 was the turning point in the history of robots.

The protoplasm of modern industrial robots is formed of hydraulics, pneumatics, electrical drives and silicon chips. Today's robots are therefore, to a great extent, as smart and intelligent as the robots conceived in fiction. Present-day industrial robots can work efficiently in both structured and unstructured environments. So, robots with their sensory capabilities and artificial intelligence (AI) are more advanced than the conventional and automated machines in all respects.

1.3. HISTORICAL BACKGROUND

Robots have their historical past though they came into existence only in 1961 when Unimation Inc., USA introduced the first servo-controlled industrial robots. The background, however, can broadly be divided into three stages, namely, (i) ancient and post historic ages, (ii) post-industrial renaissance age and (iii) microelectronics and microprocessor age, lying distinctly in the three waves of civilization in the conceptual frame of Alvin Toffler.

Early discoveries in the ancient historic age dated back to 5000 B.C. when during the Indus-Valley civilization (Indian–Pakistan), many human and animal-like figures and automatic puppets were made to imitate the movements of wild animals and birds. In the period around 3000 B.C., water clocks were built by the Egyptians. Around the same time, the Chinese also built many amusing devices that depicted sequential motions. About 500 B.C. Herodotus recorded how a bonded labourer lost his feet and later his feet had been replaced by prosthetic wooden feet. In the later period, the Romans also made some prosthetic hands for the victims of war. In 400 B.C., Archytas of Tarentum made a wooden pigeon which could fly, and during the Middle Ages, numerous instances of constructing automata were recorded. German astronomer Johann Müller made an iron fly, able to flutter around the room and return to his hand; later he fabricated an eagle that flew before the Emperor Maximilian when he entered Nurnbery. The early men discovered many mechanisms and exhibited their innovative skill in building ships and introduced looms to weave cloth and patterns. The most striking event in the early age was, perhaps, the invention of the mechanism of the clock. In its march towards progress, mankind gradually approached the age of the industrial revolution.

In the age of the industrial revolution, steam power became the main source of energy. Invention of the first commercial steam engine by James Watt, introduction of the interchangeability concepts by El Whitney, development of many new highly productive machines in textile industry, creation of other machine tools like lathes, drilling and boring machines, and milling machines in the period between 1769 and 1818 gave a new thrust to the concept of mechanization. In 1805, J.M. Jacquard introduced an automatic loom with punched card control mechanism. Though the use of cams already provided a sort of mechanical memory, the mechanism for the control to punched card paved the way for a new concept of store programs. Later, in 1823, Charles Babbage's attempt to build a machine for calculating mathematical tables brought a scientific outlook to the existing technological skill. In the subsequent periods, many automation elements were invented and introduced with the prime object of providing relief to man in his struggle against painful and strenuous work. Some of the ideas were to relieve man from the hazards involved in handling heavy and odd jobs. Automation found wide applications in spray painting and many spray painting machines were invented in the early part of this century.

In the 1940s, a great many inventions were made and new ideas brought in. Remote teleoperated master–slave manipulators were developed around 1944 by Roy C. Goertz at the Argonne National Laboratory in the USA. The atomic age accelerated the growth of teleoperators. In teleoperated systems, the slave manipulator was actuated by the master arm to handle radioactive materials from a safe distance. Later, force feedback and kinesthetic sensory elements were added to the teleoperated manipulators for facilitating the operator to have better control as he would have a sense of 'feeling'. Teleoperated devices found useful applications later in the exploration of Mars in 1976 when Viking-II landed on the planet. In the 1940s, the first electronic computer ENIAC was developed by the University of Pennsylvania. In 1948, the embryo of the third wave civilization, i.e. the transistor was invented at the Bell Laboratories, USA. In 1952, IBM's first commercial computer IBM 701 was introduced. Then came the numerically controlled machine tools in which various slides of the machines were displaced by numerical commands through suitable hardware. The development of NC machine tools has, therefore, been a turning point in the development of robotics.

Popularization of robots as an 'artificial mechanical man' or 'humanoids' capable of doing wonders has been due to novels and movies. In reality they do not exist. However, a battery-operated mechanical man—a computer controlled walking robot—was made in the Stanford University, USA. This man could move from room to room, identify some of the items with its 'vision' (TV camera), and when its battery voltage went down below some threshold value, it searched for an electric socket, plugged in to recharge its battery before moving to its next destination.

The Planet Corporation, in 1959, introduced a pick and place robot. In 1961, the first industrial robot was commercialized by Unimation Inc. Microprocessor technology was brought by INTEL in 1961. The real robot development process continued between 1968 and 1982 when various models of robots were developed by many leading robotocists in different Universities, national laboratories and different industrial houses of the USA, Japan, France, Sweden, West Germany, USSR, Italy, UK and other European countries. Some of the robot models of historical interest are the Versatran by AMF, developed in 1963 and Cincinnati Milacron T^3 introduced in 1974. While Unimation, the pioneering robot model, stands for the words 'Universal automation', Versatran is the abbreviated form of the word chain 'versatile for transfer of materials'. Similarly, T^3 robot which was the first computer controlled industrial robot symbolizes 'the tomorrow tool'. Developmental work in robotics has been done by the ASEA in introducing its model IRb-6 in 1978. The Kawasaki and Hitachi groups in Japan have also contributed a lot in developing various sensors to make the robots 'think' intelligently.

Since 1978, attempts have been made to make intelligent robots with various tactile and non-tactile sensors including vision systems. Walking robots have also been developed. Great attention has been paid to develop robotic organs for prostheses and orthoses applications. Prostheses are meant to replace human body organs or limbs by artificial ones and orthoses are used by paralytic patients.

Various robot institutions propagate the ideas and ideologies of the robotics to the profession. Some of the pioneering institutions like Japan Industrial Robot Association (JIRA, 1971), Robot Institute of America (RIA, 1975), British Robot Association (BRA, 1977) and Robotics International/SME, 1981 are worth mentioning.

The scientific temperament of ancient Indians is evident from their understanding of mathematics, astronomy, the biological response to herbal medicines and technological attainments confirmed in mining of ores, metal extraction and alloying techniques and in the erection of a large number of old monuments and temples, architecture and town planning, ship building technology etc. India, however, failed to catch up with the progressive and scientific ideas since the industrial revolution, due to political and socio-economic reversals. Nevertheless, after independence, new scientific policies were framed; India set up and expanded its industrial base in the 1950's. Various centres of industrial growth with a mixed economy came into being. India took a leading role among the developing countries to build up the modem machine tool industry as the backbone and set up big industries like Hindustan Machine Tools Ltd. (HMT), Heavy Engineering Corporation (HEC) in the government sector; many leading private industrial houses were encouraged to build up infrastructures for manufacturing activities including machine building plants. There has been tremendous growth in machine tool and metal working industry in India between 1955 and 1980.

In the 70's, manufacture of numerically controlled (NC) machine tools was started in both the public and private sector industries. In the late 70's, computer numerically controlled (CNC) machine tools and other process controllers were manufactured. In the 1980s a new range of manufacturing tehnologies like Computer-Aided Design (CAD), Computer-Aided Manufacturing (CAM) and Flexible Manufacturing System (FMS) were developed. Different universities and higher technological institutions remodelled their courses and introduced CAD, CAM, FMS, Robotics and Computer Integrated Manufacturing (CIM) technologies in their curricula.

In 1981, a microprocessor-based pneumatically operated pick-and-place robot was indigenously developed by the author in the Production Engineering Department at Jadavpur University. Later in 1982, an Automation and Robotics Laboratory was set up in the same department at Jadavpur University to have organized robotic research. In 1985, the first National Convention of Production Engineers on 'Robotics and Robot Applications' was organized by the Institution of Engineers (India) in Calcutta.

A survey on the use of robots in Indian industries revealed that the Bhabha Atomic Research Centre has developed a 6-axes multipurpose robot around 1984. This robot weighs about 300 kg and can move an end-of-arm load of 10 kg including that of the end effector. The robot has electric dc-servo drives on all arm axes and has positional accuracy of ± 2 mm; movement of the end effector in a desired spatial continuous path (CP) profile can be effected by the teach mode or by programming. BARC has also set up separately a Division of Robotics and Remote Handling for this purpose.

A microprocessor-based pick and place robot is reported to have been designed in the Military College of Electronics and Mechanical Engineering, Hyderabad in 1984. This robot is capable of working in its assigned workspace of 2600 cm^2. It can be operated independently from a front panel as well as from a remotely placed video terminal. It has the capability of limited search also.

The survey further reveals that some of the potential manufacturing industries, besides the nuclear power generating stations, have already opted for and installed robotic manipulators; many more are planning to install robots, subject to cost–benefit analysis. It is now certain that Indian industries, despite unemployment, are eager to catch up with the latest techniques and technologies of all kinds of manufacturing processes.

A brief chronology of the major events in the history of industrial robots is given in Table 1.2.

Table 1.2

1720's	In the wake of the industrial revolution the first programmable loom controlled by punch cards was developed in France.
1801	Card programmable Jacquard loom was introduced in France for mass production.
1822	Babbage completed the difference engine for automatic computation of tables in England.
1830's	The Automat, a cam programmable lathe was invented by Spencer in the USA.
1892	Motor operated crane with a gripper for removing ingots from a furnace was patented by Babbitt in the USA.
1921	Karel Capek's play, R.U.R. was staged in London when the word robot was popularized.
1938/39	A programmable paint-spraying machine was developed by Pollard in the USA. Spray guns movable through predetermined paths were developed by Roselund also in the USA.
1944	Howard Aiken developed the Mark 1 computer, an electro-mechanical automatic sequence control calculator, a joint venture of IBM and Harvard, at Harvard.
1946	Eckert and Mauchly developed the ENIAC, the first large electronic computer, at the University of Pennsylvania, in collaboration with the US Army. A general-purpose analogue storage device with Magnetic Process Control was developed by Devol in the USA.
1947	Servomechanisms Lab was opened at MIT, Massachusetts, USA.
1948	"Cybernetics"—An integrated concept of communication and control (feedback) was introduced by Norbert Weiner.
1951	A general-purpose digital program storage device for controlling Automatic Machine Tools was developed by Lippel in the USA. A remote controlled teleoperator with an articulated arm called Electrical Manipulation Device was developed by Goertz, under the auspices of the US Atomic Energy Commission.
1952	IBM's first commercial computer, the 701, was marketed. The first NC machine tool was developed jointly by the MIT Servomechanism Lab and the US Air Force.
1954	Another remote controlled teleoperator with an articulated arm called Remote Station Manipulator was developed by Bergsland. The first robot with point to point control and an electronic playback memory was developed by Devol in the USA.
1956	The idea of Artificial Intelligence was floated at the Dartmouth Conference.
1957	Cam programmable "pick and place" robot was developed by Brown, at the Planet Corporation in the USA.
1959	First commercially available robot was sold by Planet Corporation, USA.
1960	The Unimate robot was developed from Devol's original device. First mobile, two armed manipulator remotely controlled by an operator was built by Huges Aircraft to work in radioactive environment.
1962/63	Devol developed a "teachable" mechanical program controlled system providing a quick and accurate way of making robot programs. He coordinated a robot and conveyor line and introduced a micromanipulator as well as a force-sensing system for his robots.
1964	Devol developed continuous path control for robots. Remington Rand released the UMAC control, the first commercially available general-purpose controller.

1964–67	Different Robotics research labs were established at MIT, Stanford Research Institute, Stanford, and the University of Edinburgh.
1966	Cincinatti Milacron developed Direct Numerical Control of Machine Tools.
1968/71	The first and second versions of the SHAKEY—an "intelligent" mobile robot were built at Stanford Research Institute.
1968	A robot controlled by a general purpose PDP-6 computer was built by Max Ernst at MIT.
1968/70	Scheinman built his first hydraulically powered arm at Stanford and the first electrically powered arm at MIT.
1971	"Structured Light" vision system was developed at Stanford and IBM. WAVE—the first robot programming language to automatically plan smooth trajectories and which could use rudimentary force and touch sensing to control a manipulator was developed at Stanford.
1972	Force Vector Assembly Concept—using forces as inputs to a servo controller to guide parts assembly was developed at Charies Stark Draper Labs, in Cambridge, Massachusetts.
1973	Device for controlling automation along *a* predetermined path—the control system for the T3, the first commercially available mini-computer controlled robot was developed at Cincinatti Milacron. First computer integrated assembly robot was developed at Stanford.
1974	First version of AL—a robot programming language for real-time control of concurrent multiple devices with sensory/motor control was developed at Stanford. Three legged walking machine was built at the University of Wisconsin. Scheinman developed First Vicarm robot arm controlled by a minicomputer. Olivetti built a minicomputer controlled robot.
1975	The LSI-11 microprocessor was commercialized by Digital Equipment Corporation.
1976	Space hunting of robots started Viking 1 robot rover, built by NASA, landed on Mars. First Scheinman arm robot controlled by a LSI-11 microprocessor was built by Vicarm. Remote Center Compliance Device—a compliant robot wrist used to make non compliant parts was developed at Draper Labs. Vision system and AL programming language were interfaced at Stanford. BARPY speech understanding system was completed at Carnegie Mellon by Reddy.
1977	Al-Stanford Robot Programming Language was completed by Schamano and Taylor. Vision module was developed at Stanford Research Institute and subsequently commercialized by Machine Intelligence Corporation. General Motors issued specification for a Programmable Universal Machine for Assembly—the PUMA robot. Unimation acquired Vicarm and won the PUMA bid, ASEA commercialized a microprocessor-controlled robot, and Olivetti developed the Sigma robot.
1978	First PUMA prototype, based on Scheinman's MIT model arm was built for General Motors. Improved version of the RCC device was developed at Draper Labs.
1979	First version of ACRONYM-a vision system using "reasoning about geometry" was developed at Stanford.
1980	The largest academic robot lab in the US, the Robotics Institute at Carnegie Mellon was established.

1980	First robot to pick randomly stacked connecting rods out of a bin was developed at the University or Rhode Island. Mobile robot which could move through a simple obstacle course was developed by Moravec at Stanford.
1981	Direct drive manipulator using rare earth motors eliminating mechanical linkages was developed at Carnegie Mellon by Asada and Kanede.
1983–84	Southerland's hexapod of Carnegie Mellon University—the first man-carrying computer-controlled walking machine by Raibert (1983) and Southerland and Ullner (1984). BIPER-4—A two-legged walking machine designed by Miura–Shimoyana.
1986	LEGO and MIT Media Lab collaborate to bring the first LEGO-based educational product.
1989	Genghis, a walking robot, was developed at MIT.
1990	ABB of Switzerland acquires Cincinnati Milacron.
1992	Dr. J. Adler came up with the concept of a Cyberknife, a robot that images the patient with X-rays for tumor and plans for a right dose of radiation.
1993	Carnegie Mellon University developed an eight-legged walking robot for Antarctica; Seiko Epson develops a microrobot, called Monsieur.
1994	Carnegie Mellon University developed DANTA-II robot that descended into volcano, Mt. Spurr to sample volcanic gases.
1995	A surgical robotic system was developed in collaboration with SRI, IBM, and MIT.
1996	A Robotuna fish robot was developed by David Barrett at MIT. The University of South Florida, Tampa, USA, developed Gastrobot, a robot that digests organic mass to produce CO_2 used later for power. This engine is known as 'Chew Chew'.
1997	G. Kasparov loses to IBM's Deep Blue Supercomputer in Chess. NASA's Pathfinder Mission, the Robotic Rover Sejourner lands on Mars.
1998	MIT starts work on Kismit Robot that can mime the emotional range of a baby.
1999	Sony builds Albo, K9 the next generation intended for consumer market and reacting on sounds. Personal Robots releases the Cye robot performing a variety of household chores.
2000	Honda builds a humanoid robot ASHIMO, walking like a human being and reacting. Sony unveils humanoid robots, Sony Dream Robots (SDR), at Robodex S. Mussa-Invaldi, a computational neurologist hooks up a lamprey brain to sensors to control a robot.
2001	LEGO releases the Mindstorms Unimate Builder's set after the first and second releases in 1999 and 2000, respectively. MD Robotics of Canada developed the space station Remote Manipulator (SSRMS) for assembly of International Space Station. Honda's ASHIMO robot walks smoothly and climbs the stairs. It rings the opening bell at NY Stock Exchange.
2003	Sony releases the AIBO ERS-7 third-generation robotic pet. Epson unveils the Monsieur II-P—a microrobot and Micro Flying Robot (10 g and measuring 70 mm), the smallest robot helicopter.
2004	The Robot rovers 'Spirit' lands on Mars and 'Opportunity' safely lands on Meridium Planum.

2005	Cornell University developed the first self-replicating robot. Fish robots were developed in London to test robotic navigation.

1.4. LAWS OF ROBOTICS

Sir Isaac Asimov dealing on the subject of robotics framed three basic laws which the robotocists still obey with respect. The laws are philosophical in nature. They are as follows:

First Law:	A robot must not harm a human being or, through inaction, allow one to come to harm.
Second Law:	A robot must always obey human beings unless it is in conflict with the first law.
Third Law:	A robot must protect itself from harm unless that is in conflict with the first and/or the second laws.

1.5. ROBOT DEFINITIONS

A question of perpetual interest is to define a robot. The origin of the word 'robot' as already mentioned is in the Czech word 'robota' meaning either a slave or a mechanical item that would help its master. During the first quarter of this century, a gyrocompass used in a ship and a governor used for controlling the speed of steam locomotives or automobiles had also been termed as robots. In the 70's, automatic machines with the capability of lifting materials, tools, etc. and performing tasks as instructed by the master had also been called robots. A robot therefore carries out the tasks done by a human being. A robot may do assembly work where some sort of intelligence or decision-making capability as expected from a man is needed. A robot sometimes does heavy work and automatically performs the same task repetitively like a machine. Is then a robot an automated machine? Is robotics an automation only?

In (hard) automation, the machine performs a particular job only in the designed sequence, while a robot can be made to do different jobs at different times and in different sequences. This can be done by programming. A robot can be reprogrammed to change the sequence of tasks while a fixed machine set to perform certain tasks in sequence cannot be programmed. A fixed automated machine cannot take any decision if any change is required in the environment. An automated machine does not have sensory feedback to reprogram the predetermined path. An automated machine has neither a "knowledge base" nor intelligence. At best, an automated machine can be made to adapt to slight changes in a known environment, as in the case of a few NC machine tools. So a robot is more than an automated machine or equipment. Hence, since the beginning of the study of robotics, there has been some controversy in the definition of a robot. So long as the evolution of robotics continues, the definition of the robot will change from time to time-depending on the technological advances in its sensory capability and level of intelligence.

However, the definition that has been accepted as reasonable in the present state-of-the-art is given by the Robotics Industries Association (formerly the Robotics Institute of America) in November, 1979. (An industrial robot has been defined as "... a reprogrammable multifunctional manipulator designed to move material, parts, tools or specialized devices through various programmed motions for the performance of a variety of tasks").

A closer examination of this definition indicates that a robot is a manipulator that is reprogrammable and multifunctional. The reprogrammability has got its meaning only when a computer or a microprocessor is interfaced with it; it is through this computer that programmed instructions can be written and fed, and also if necessary, it can be edited to have a new program and information. It is multifunctional in the sense of its versatility. It can perform various activities; sometimes it can use an end effector to move raw materials for further processing into the final product; it can transfer or handle parts; it can also actuate some of the tools like painting gun for spray painting, welding gun for welding and drill or reamers for machining and finishing operations. It may also hold some specialized devices for working in an unstructured environment, handling radioactive materials or assembling components of a job. The robot has a mechanical configuration called the manipulator arm with a gripper at its free end to move from point to point or in a continuous path following some trajectory with or without feedback sensing elements. A robot by virtue of its reprogrammability and versatility is productive, dynamic and flexible to an extent.

1.6. ROBOTICS SYSTEMS AND ROBOT ANATOMY

A system is an integrated whole of parts or subsystems. A system has a specified goal or output for a given set of inputs; a system may have many goals as well. A robot is a system as it combines many subsystems that interact among themselves as well as with the environment in which the robot works.

A robot has many components which include:

1. A base—fixed or mobile.
2. A manipulator arm with several degrees of freedom (DOF).
3. An end-effector or gripper holding a part or a tool.
4. Drives or actuators causing the manipulator arm or end-effector to move in a space.
5. Controller with hardware and software support for giving commands to the drives.
6. Sensors to feed back the information for subsequent actions of the arm or gripper as well as to interact with the environment in which the robot is working.
7. Interfaces connecting the robotic subsystems to the external world.

A robot has some specific objective. It may be designed for simply picking up and placing the workpieces. It may be employed to interact with and work load a lathe, a milling machine or any equipment, or it may also perform some assembly work. To accomplish the job, a robot must have a suitable manipulator arm with specified coordinate systems to attain a designed reach in the working space. It should have a suitable gripper to match the geometry of the workpiece to be handled; a suitable control system with or without servo mechanisms for sending signals to the drives, or permitting storage of programmes and data for desired path planning with adequate speed and good accuracy. The robot may have some sensors to feed back information for modifying the motion or path. The controller is provided with interfacing units connected to external equipment in the outside world.

Figure 1.1 indicates a scheme of a robotic system. It consists of a manipulator arm, a gripper, a controller, and a power source.

Figure 1.1 A robotic system

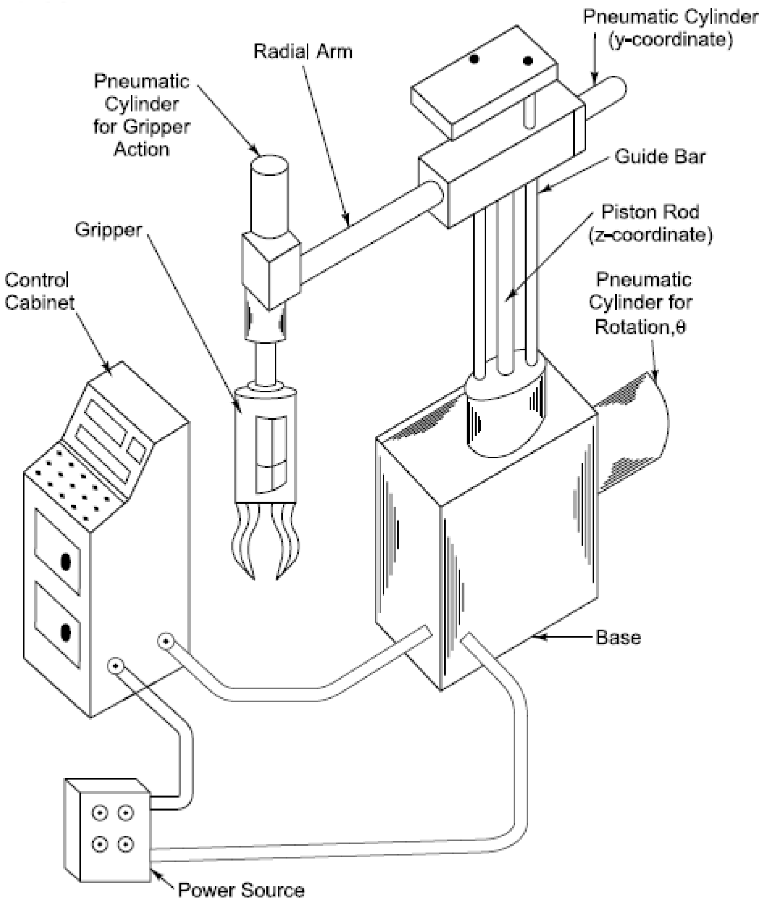


Figure 1.2 indicates the basic components of a microprocessor-based pneumatic robot system.

Figure 1.2 Basic components of a microprocessor-based robotic system

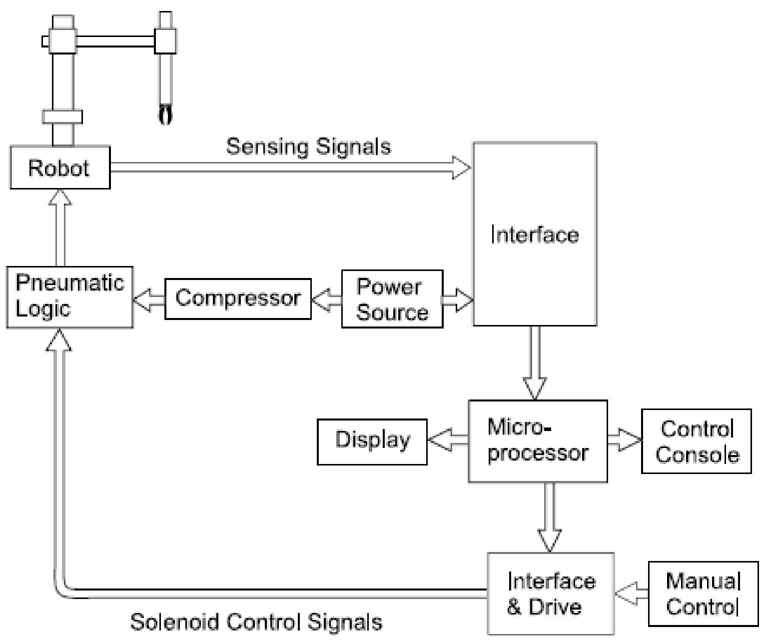


Figure 1.3 shows a popular model of computer-controlled Unimation–Puma robot.

Figure 1.3(a) Six axes Puma manipulator

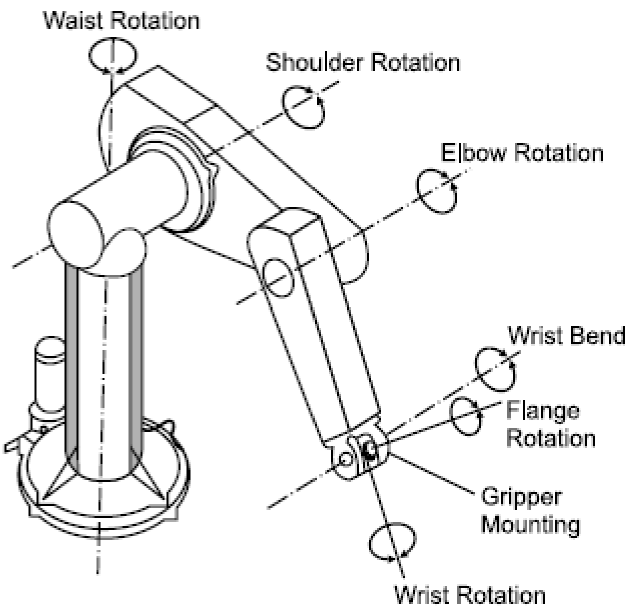


Figure 1.3(b) A scheme of computer controlled Puma robotic system

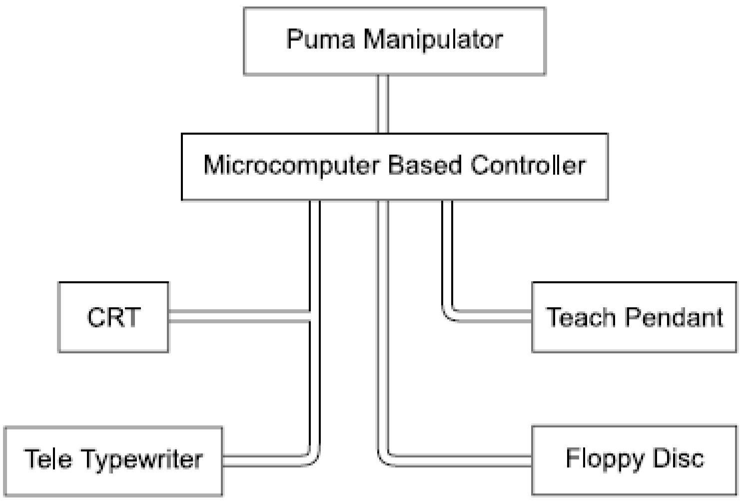
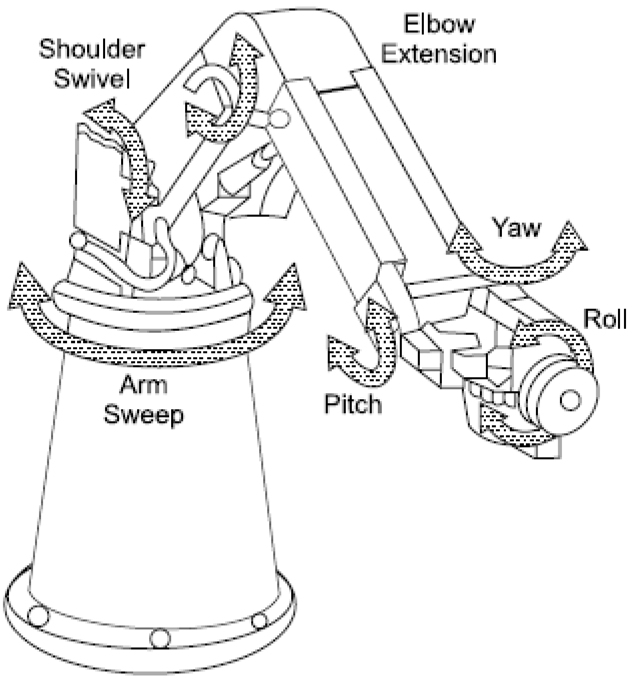


Figure 1.4 shows Cincinnati Milacron T^3 robotic manipulator indicating six degrees of freedom—arm sweep, shoulder swivel, elbow extension, wrist pitch, wrist yaw and wrist roll.

Figure 1.4 The Cincinnati Milacron T^3 robot



1.6.1. Robot Manipulator and Wrist

1.6.1.1. Robotic Manipulator Arm

The most obvious mechanical configuration of the robot is the manipulator arm. There are several designs of the arm to facilitate movement within the work envelope with maximum possible load and speed with high precision and repeatability. The simplest robot may be a two or three-axes arm. The axis is meant to understand independent movement or degree of freedom.

Figure 1.5 indicates a simple blacksmith's tong that can be used as an end of arm tooling attached to a manipulator to provide three degrees of freedom (DOF) to locate or translate an object and three degrees of freedom to orient it. P_1, P_2 and P_3 are the three DOFs indicating translation or location of hand and R_1, R_2 and R_3 are the three DOFs of orientation of the object. Robots are built with several degrees of freedom that may vary from two to ten. Most of the industrial robots have, of course, five or six degrees of freedom. A typical robotic manipulator arm suitable for remote purpose operations is illustrated in Fig. 1.6. It has 3 degrees of freedom for locating or positioning the object and 3 degrees of freedom for orienting the same.

Figure 1.5 A blacksmith's tong indicating 6-degrees of freedom

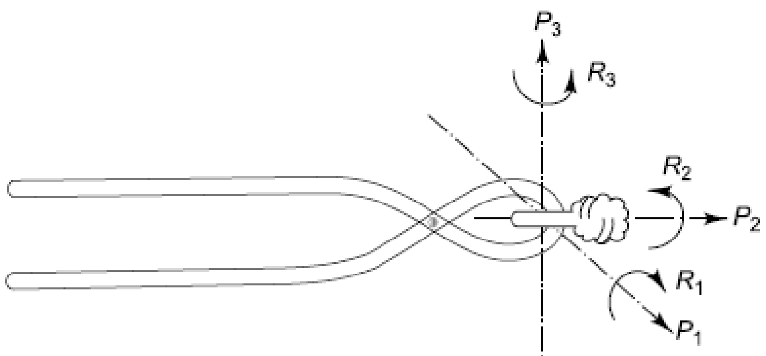
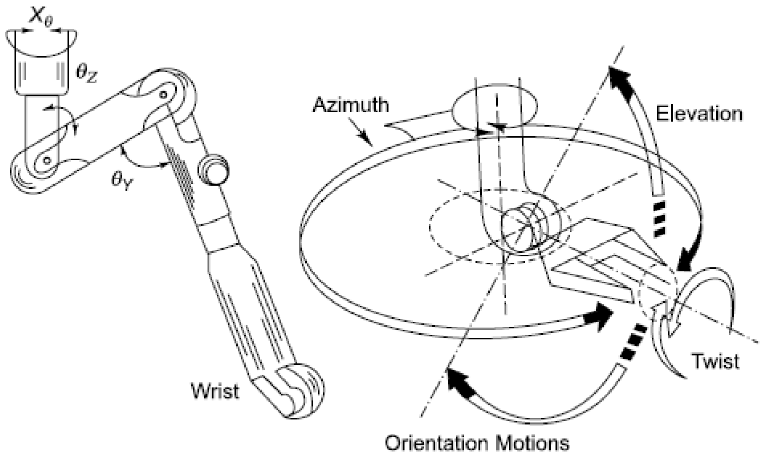


Figure 1.6 A manipulator arm for remote purpose operations



A robotic manipulator arm consists of several separate links making a chain. The manipulator is located relative to the ground on either a fixed base or on a movable base. The base may be a mobile one and may have some transportation system. The manipulator arm has a free-end where an end-effector or gripper or sometimes a specialized tool holder (for holding, say, a welding gun) or any powered device (say, a drill) is attached. In a fixed base, 6 degrees of freedom robot, the first three links of the manipulator constitute the body and they help to place the end-effector at a desired location inside its work environment or working volume. The remaining three links make up the wrist of the manipulator and are used to define the orientation of the manipulator end points. It is therefore important to know the types of the linkages used in the base-body-wrist-end effector complex in the manipulator work environment system.

A robot is essentially a movable open chain of successively coupled bodies with one end fixed to the ground and the free end containing an end effector. The bodies of the open chain are usually links which are joined together by some lower pair connectors. The most common types of lower pair connectors are:

- Revolute pair (1 DOF)
- Prismatic pair (1 DOF)
- Cylindric pair (2 DOF)
- Spherical pair (3 DOF)
- Hooke joint (2 DOF)

Figures 1.7–1.11 illustrate the various types of elemental pairs or joints. The revolute pair (R) as shown in Fig. 1.7 permits relative rotation about a unique pair axis and has a single degree of freedom.

Figure 1.7 *Revolute pair (R)*

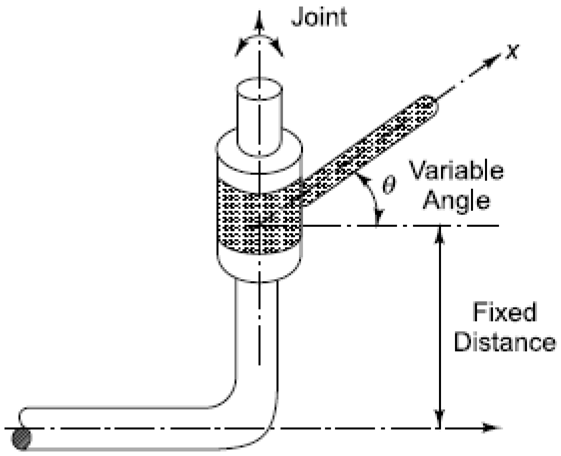


Figure 1.8 *Prismatic pair (P)*

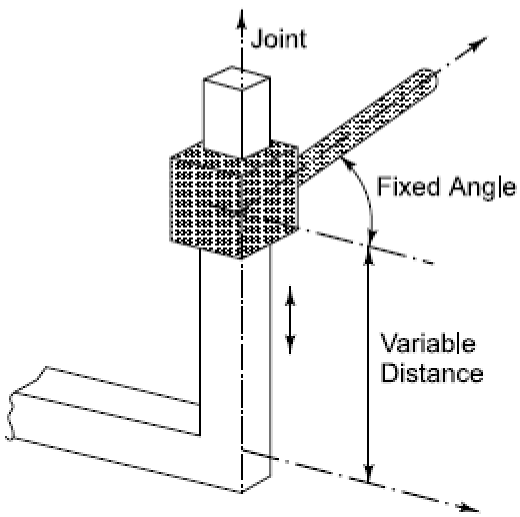


Figure 1.9 *Cylindrical pair (C)*

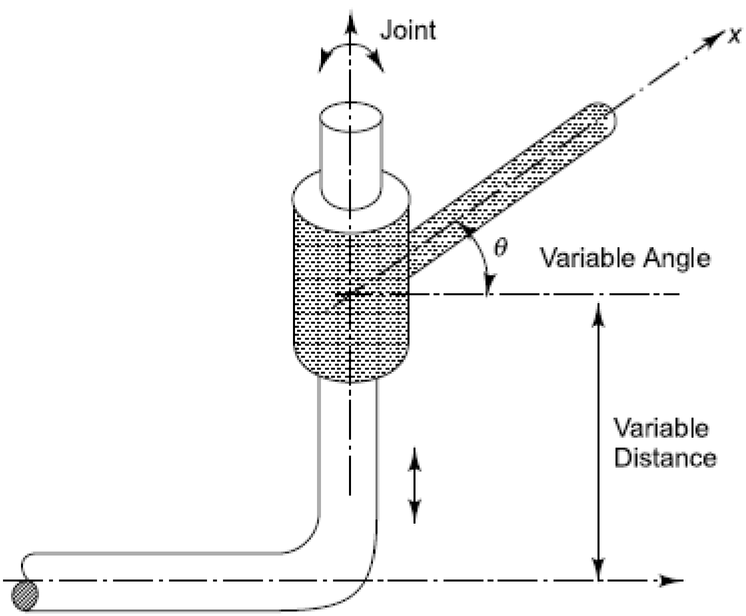


Figure 1.10 *Spherical pair (S)*

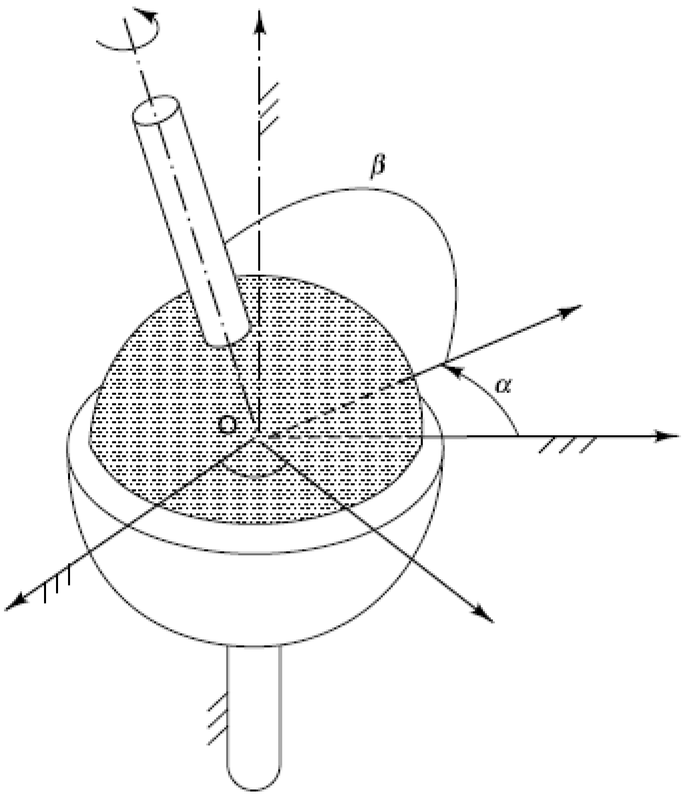
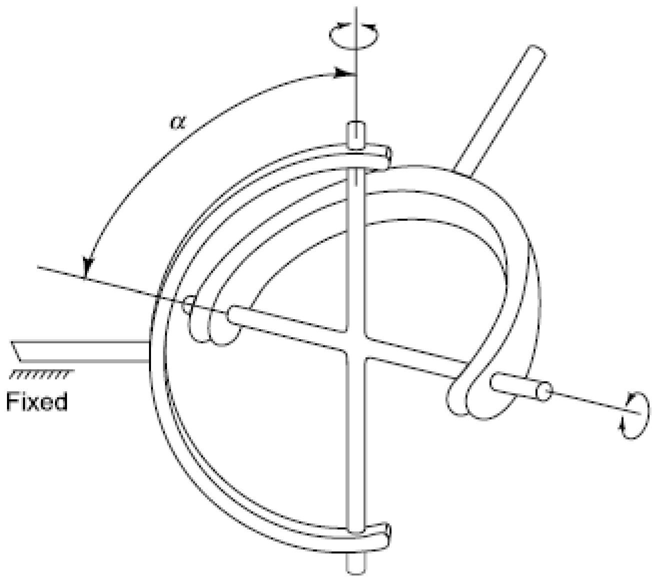


Figure 1.11 *Hooke's joint (T)*



The prismatic pair (P) as shown in Fig. 1.8 allows relative sliding parallel with a unique pair axis and has one degree of freedom.

The cylindrical pair (C) illustrated in Fig. 1.9 permits independent relative rotation about and relative sliding parallel to a pair axis and it has two degrees of freedom.

The spherical pair (S) as shown in Fig. 1.10 is a ball and socket joint that permits relative rotation about three non-coplanar interacting axes and has three degrees of freedom.

Hooke's joint (T) as shown in Fig. 1.11 permits independent rotation about two intersecting axes offset by an angle α and has two degrees of freedom.

However, the most basic joints are the one-DOF revolute pair (R) and one-DOF prismatic pair (P) and these two pairs are extensively used in combination in the robotic manipulators.

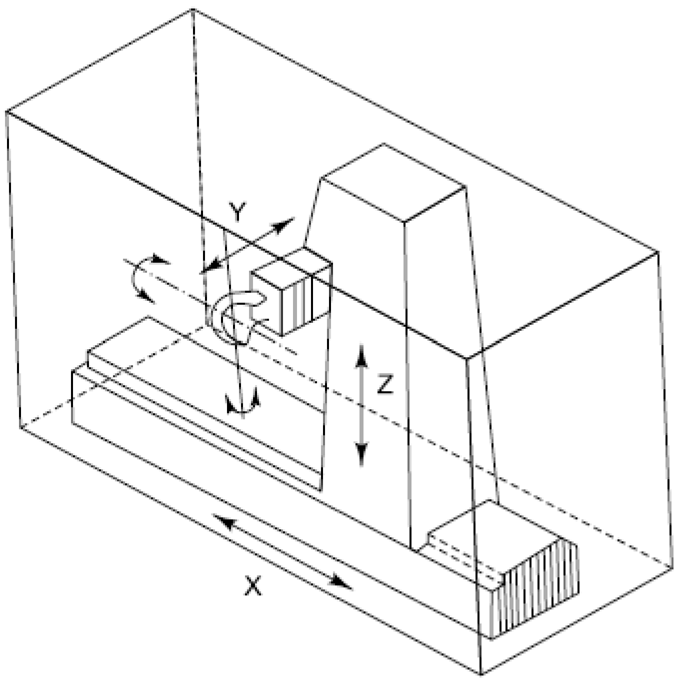
1.6.1.2. Robot Coordinate System

There are some major coordinate systems based on which robots are generally specified. The common designs of robot coordinates are

- Cartesian coordinate system
- Cylindrical coordinate system
- Polar or spherical coordinate system
- Revolute coordinate system

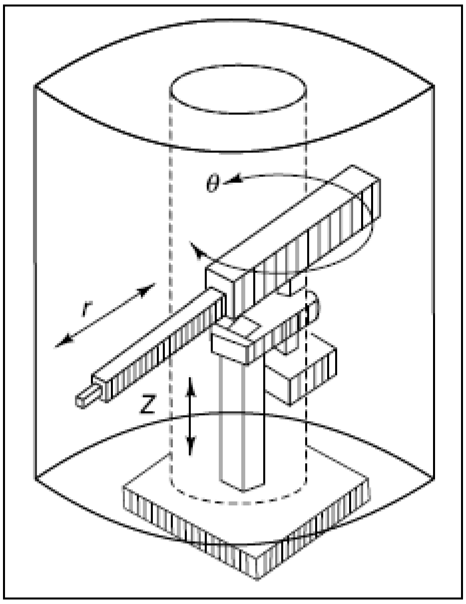
In the cartesian coordinate configuration shown in Fig. 1.12, the three orthogonal directions are X, Y and Z. X-coordinate axis may represent left and right motion; Y-coordinate axis may describe forward and backward motion; Z-coordinate axis may be used to represent up and down motions. Motion in any coordinate axis can be imparted independently of the other two. The manipulator can reach any point in a cubic volume of space. It allows three DOFs (x, *y, z)* in translation only.

Figure 1.12 Cartesian coordinates



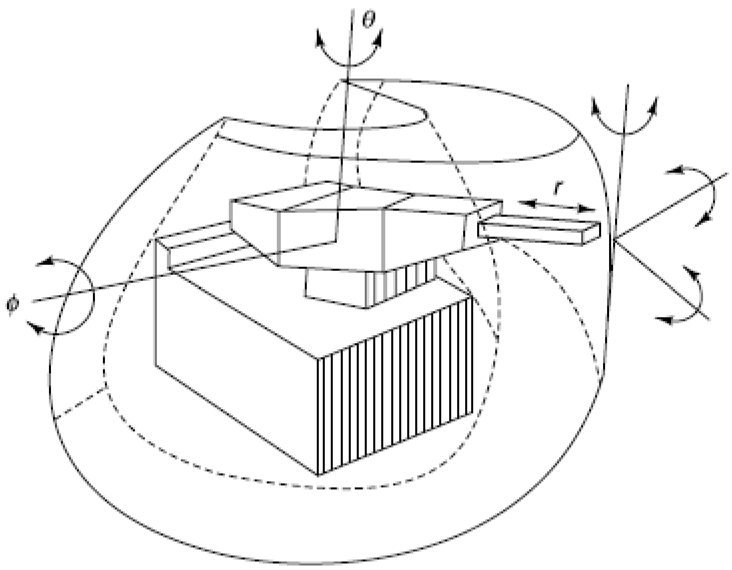
In cylindrical coordinate configuration shown in Fig. 1.13, the three degrees of freedom—two linear motions and one rotational—correspond to a radial in or out translation *r*, an angular motion, θ about the vertical axis, and *z*, a translation in the z-direction that corresponds to the up or down motion. The manipulator can ideally reach any point in a cylindrical volume of space. In reality, the robot cannot rotate through a complete circle in the space bounded between two cylinders.

Figure 1.13 *Cylindrical coordinates*



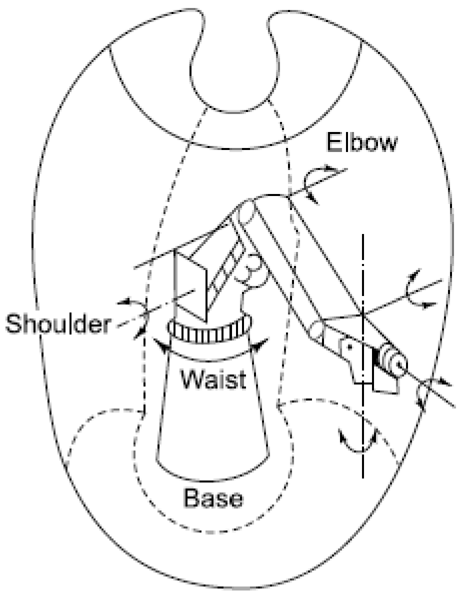
In the spherical coordinate configuration shown in Fig. 1.14 the robot has one linear and two angular motions. The linear motion, *r* corresponds to a radial in or out translation, the first angular motion corresponds to a base rotation, θ about a vertical axis, and the second angular motion, φ is the one that rotates about an axis perpendicular to the vertical through the base and is sometimes termed as elbow rotation. The two rotations along with the in or out motion enable the robot to reach any specified point in the space bounded by an outer and inner hemisphere. Sometimes, the spherical coordinate system is referred to as the polar coordinate system.

Figure 1.14 *Spherical coordinates*



In the revolute coordinate, that is, anthropomorphic or jointed arm configuration as illustrated in Fig. 1.15, a robot uses three rotations. The anthropomorphic design corresponds to the design of a human arm having waist, shoulder and elbow joints. The link of the arm mounted on the base joint can rotate around the base about the Z-axis and the two links, namely the shoulder and the elbow. The shoulder can rotate about a horizontal axis and the elbow motion may either be a rotation about a horizontal axis or may be at any locationin space depending on the rotational motions of the base and the shoulder. The anthropomorphic robot can move in a space bounded between a spherical outer surface and the inner surface having scallops due to the constraints of the joints.

Figure 1.15 Revolute coordinates



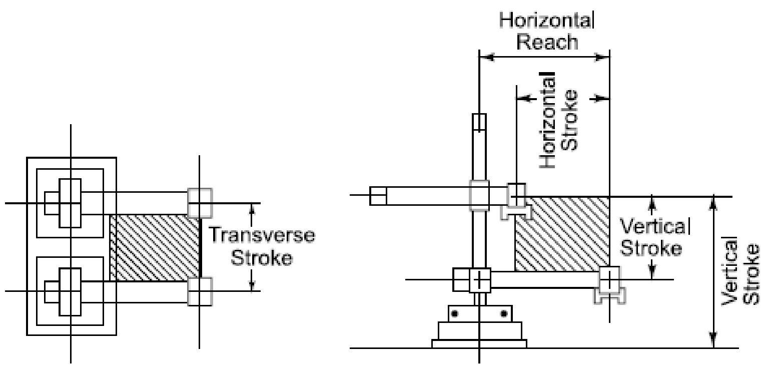
A simple way to define the manipulator body or arm in terms of lower pair connectors is to represent the robots in a rectangular coordinate system as P-P-P robot, in a cylindrical coordinate system as P-R-P robot, in a spherical coordinate system as R-R-P robot and in a revolute coordinate system as R-R-R robot.

1.6.1.3. Work Envelopes

The volume of the space surrounding the robot manipulator is called the work envelope. Accordingly, the work envelope for the rectangular coordinate robot, the cylindrical coordinate robot, the spherical coordinate robot and the jointed arm (revolute) coordinate robot are different due to the different movement of the arm.

The work envelope of a rectangular cartesian coordinate robot is shown inFig. 1.16. The elevation view indicates the vertical and horizontal reach obtained due to the rise and fall of the arm on the vertical column and in and out positions of the robot's arm. The plan view also shows a rectangle due to the combined action of the sliding of the arm on the horizontal axis and the transverse stroke. The work envelope of a rectangular coordinate robot is a parallelopiped.

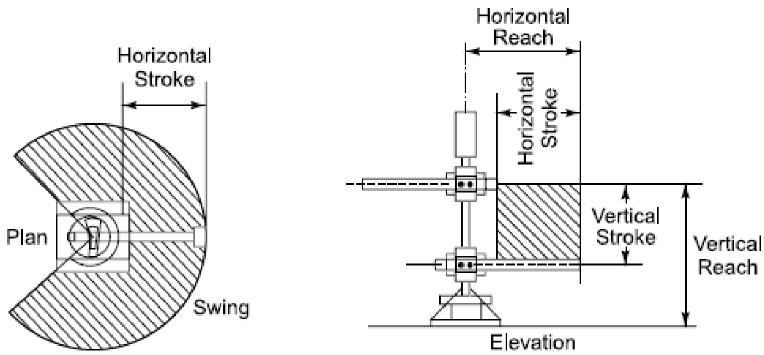
Figure 1.16 Work envelope of a cartesian coordinate robot



Rectangular coordinate robot is very rigid and suitable for pick and place operations in hot environment as in a furnace. It is also a suitable manipulator for overhead operations as it covers a large work area.

The work envelope of the cylindrical coordinate robot is indicated in Fig. 1.17. The elevation view indicates the vertical and horizontal reach. The vertical and horizontal strokes combine to form a rectangle-section. The plan view indicates the robot arm pivoted at the centre of the base which can form a portion of a circle by the action of swing. The plan view also shows the horizontal reach. Thus, the work envelope of a cylindrical coordinate robot is a portion of a cylinder.

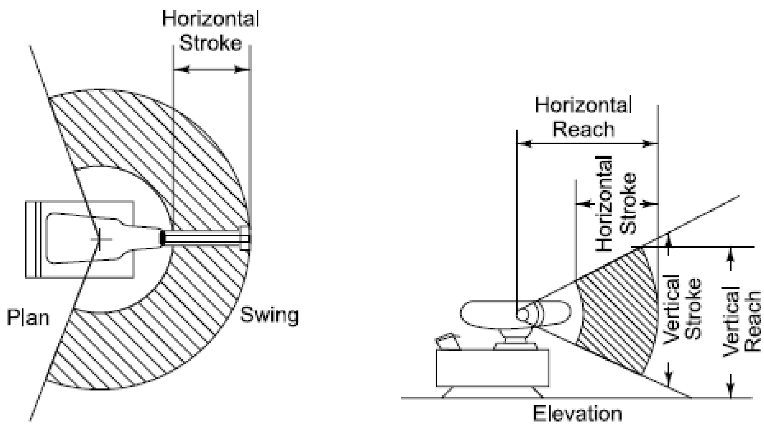
Figure 1.17 Work envelope of a cylindrical coordinate robot



Cylindrical coordinate robot is suitable for handling parts in the machine tools or other manufacturing equipment. It cannot pick up objects from the floor on which the robot is mounted.

Spherical (or polar) coordinate robot encompasses an envelope shown in Fig. 1.18. The elevation view indicates the vertical reach and the horizontal reach. Unlike the cylindrical coordinate robot that makes up and down motions on the vertical axis, the polar coordinate robot is pivoted and forms an arc while the horizontal stroke extends from the inner circle to the outer circle in the elevation view. The plan view indicates a swing of the robot's arm as it is rotated around its base. The work envelope of the extension arm of a spherical coordinate robot is the volume swept between two partial spheres.

Figure 1.18 Work envelope of a spherical coordinate robot



Spherical coordinate robots are most suitable for transferring parts on machine tools. They are suitable for picking components from the floor. They are extensively used in flexible manufacturing systems.

The work envelope of a revolute or jointed arm coordinate robot is shown in Fig. 1.19. The elevation view indicates a complex work envelope that is swept by the combined motion of the waist, elbow and wrist of the manipulator. The vertical and horizontal reach are also shown in the elevation view. The plan view indicates the same swing as shown in the plan view of the cylindrical coordinate robot.

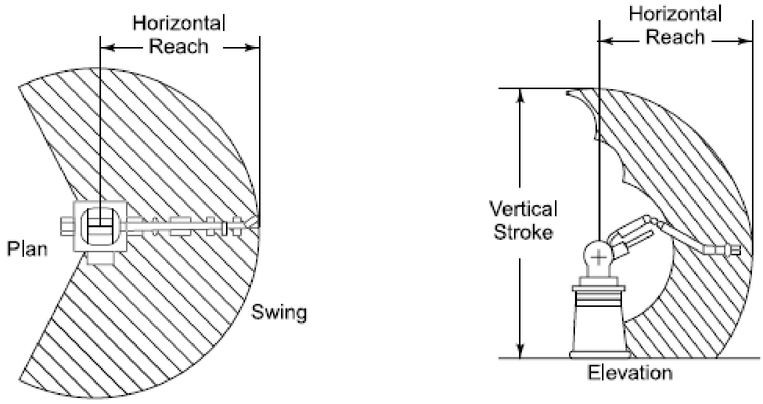


Figure 1.19 Work envelope of a jointed-arm coordinate robot

Jointed arm robot is flexible and versatile as it can easily reach up and down and can also swing back. The joints are all rotary. This type of anthropomorphic robot is suitable for loading and unloading components or tools in CNC machines and machining centres, and finds wide applications in forging and metal working industry.

1.6.1.4. Robot Wrists

It has been mentioned that the 3-DOFs of the robot arm permit it to locate or position an end-effector at any point in 3-dimensional space in its working envelope, but to orient the end-effector properly with respect to the task to be performed, it is required to have three additional DOFs in general. A wrist may have three to five degrees of freedom to solve the problem of orientation.

Three rotational freedoms of the wrist are usually designated as *pitch, yaw* and *roll* as they are very popular terms used in aviation. A pitch is defined as rotation about a horizontal axis and it is with this pitch motion, an aircraft is able to move its nose up or down. Yaw is a rotational movement about the vertical axis and this motion moves the nose of the aircraft to the left or right. A roll is a rotational freedom about the aircraft's own axis. With the roll motion, a craft can turn about its own axis. This concept has been extended to the design of the robot end-effector attached to the wrist.

Figure 1.20 shows the pitch, yaw and roll motions of a robot wrist. Figure 1.21 shows the pitch, yaw and roll motions of a wrist used commonly in a Unimate 4000 robot. Figure 1.22 illustrates the wrist of a Unimate spherical robot and its wrist bend, wrist yaw and wrist swivel. However, to define the wrist orientation, the robot end-effectors are broadly classified into three different groups as follows.

				Wrist Orientation	Wrist Axes
1.	(i)	Group	1A	Roll	Roll
	(ii)	Group	1B	Pitch	Bend
2.	(i)	Group	$2A_1$	Pitch–Yaw	Roll–Roll
	(ii)	Group	$2A_2$	Pitch–Roll	
3.		Group	2B	Pitch–Roll	Bend–Roll
4.	(i)	Group	$3A_1$	Pitch–Yaw–Roll	Bend–Bend–Roll
	(ii)	Group	$3A_2$	Pitch–Yaw–Roll	
5.		Group	3B	Pitch–Yaw–Roll	Bend–Roll–Roll
6.		Group	3C	Pitch–Yaw–Roll	Roll–Bend–Roll
7.		Group	3D	Pitch–Yaw–Roll	Roll–Roll–Roll
Note: Pitch and Yaw axes may be indexed by 90°.					

Figure 1.20 A robot wrist indicating pitch, yaw and roll motions

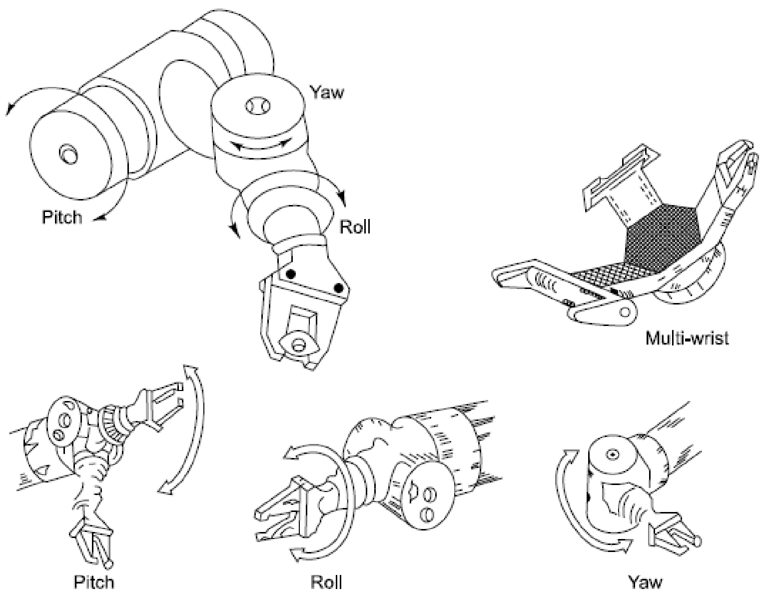


Figure 1.21 Unimate 4000 robot wrist with pitch, yaw and roll motions

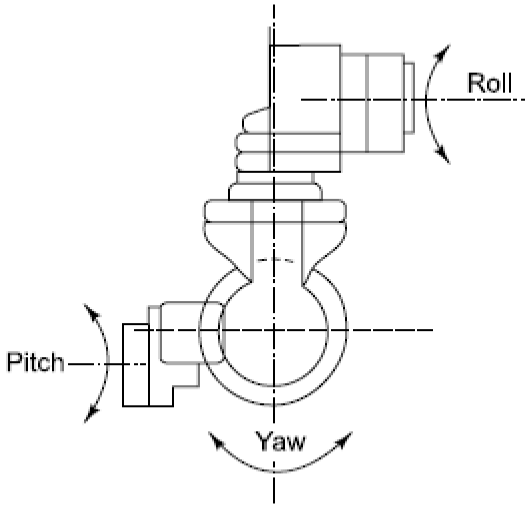


Figure 1.22 Unimate 2000 robot indicating wrist yaw and swivel motions

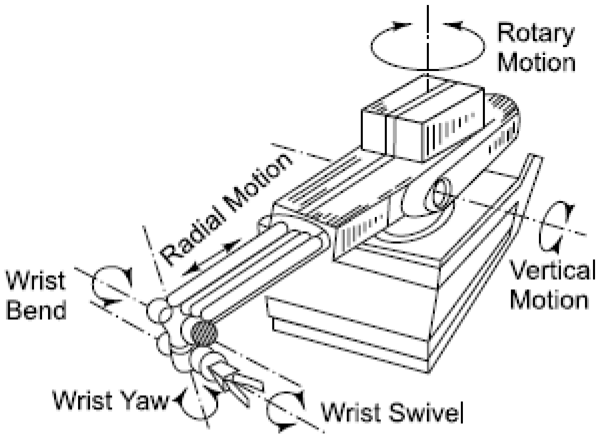
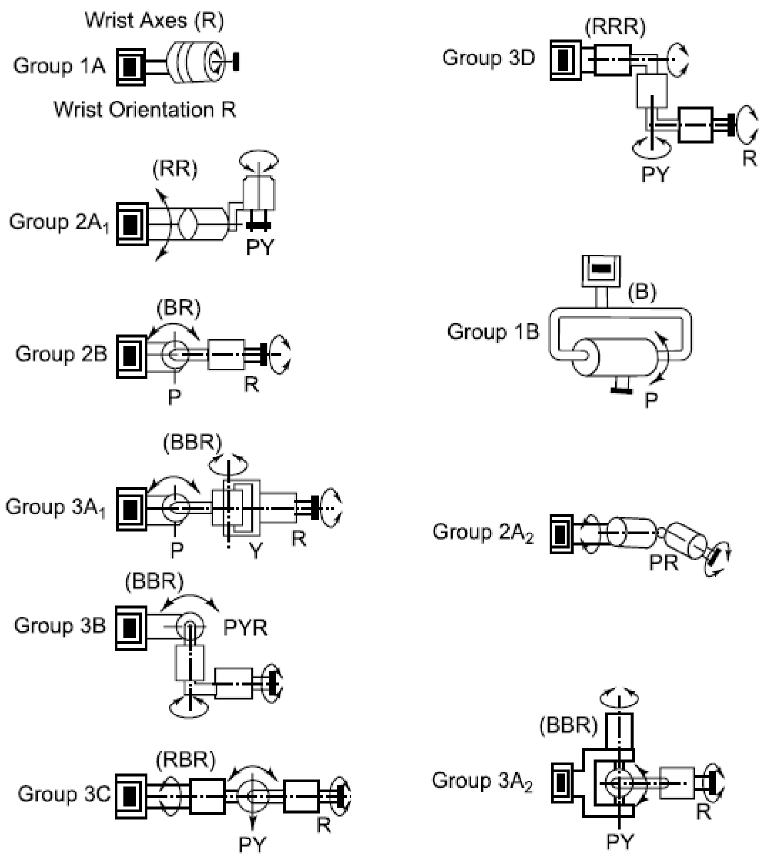


Figure 1.23 illustrates different designs of wrists orientations of 1-DOF, 2-DOFs and 3-DOFs end-effectors respectively.

Figure 1.23 Different schemes of robot wrist orientations



1.6.2. Robot End-Effectors

Robot end-effector is the gripper or end-of-arm tooling mounted on the wrist of the robot manipulator arm. A robot performs a variety of tasks for which various tooling and special grippers are required to be designed. A robot manipulator is flexible and adaptable, but its end-effector is task- specific. A gripper designed for picking up a tool to be fitted to a CNC machine tool is not suitable for welding a railway wagon.

The wide range of gripping methods include

- Mechanical clamping
- Magnetic gripping
- Vacuum (suction) gripping

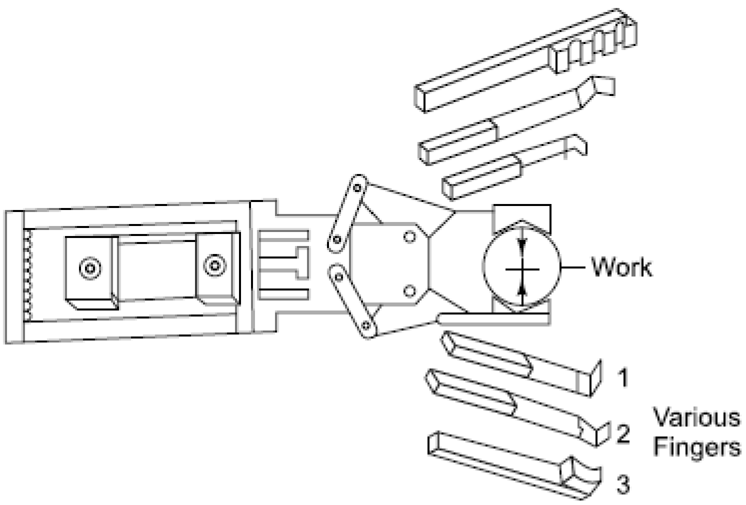
Mechanical type of grippers may simply use mechanical clamping with vice-type mechanism; it may use hooking or lifting mechanisms and mechanisms for scooping or ladling powders, molten metal or plastics. Mechanical type of grippers find wide applications in forging and metal working industry.

Magnetic grippers may be employed for transfer of steel sheets or chips.

Vacuum cups may be used for transfer of sheets of glass, plastic or thin sheets of papers.

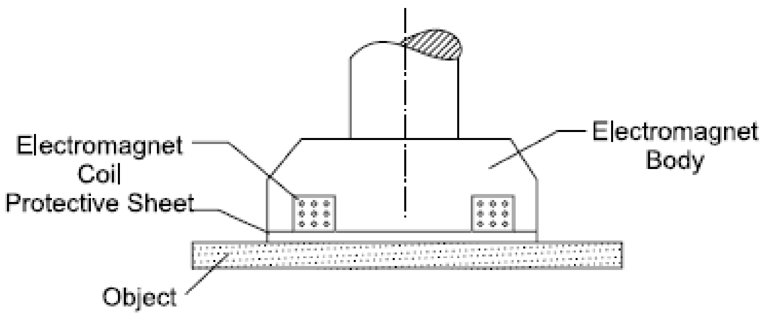
A typical end-effector is shown in Fig. 1.24 in which various designs of interchangeable finger tips can be adopted. This is a two linkage gripper and it is actuated by a linear drive system—a pneumatic or hydraulic piston that pulls or pushes the linkage causing rotation of the gripper linkages to close on or open free an object. Electrical motors may also be used to open or close the gripper with suitable linkage systems. However, suitable Vee-locations can be arranged for gripping, say, rotational components.

Figure 1.24 Two fingered end-effector with changeable finger-tips



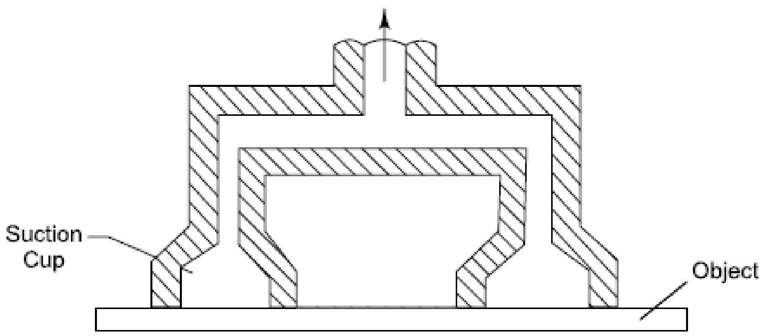
A typical electromagnetic end-effector or gripper is illustrated in Fig. 1.25 in which ferrous components can be easily gripped by the principle of electromagnetism.

Figure 1.25 Electromagnetic end-effector



A vacuum end-effector or gripper as illustrated in Fig. 1.26 indicates the suction cups to hold and transfer lighter objects. Small vacuum pumps create the pressure differential for necessary vacuum. Figure 1.27 indicates the MIG welding torch or gun held in a robot end-effector. The torch is joining two pipes following a weaving pattern. A robot end-effector, in a similar way, can also hold a spray gun for spray painting.

Figure 1.26 Vacuum end-effector with suction cups



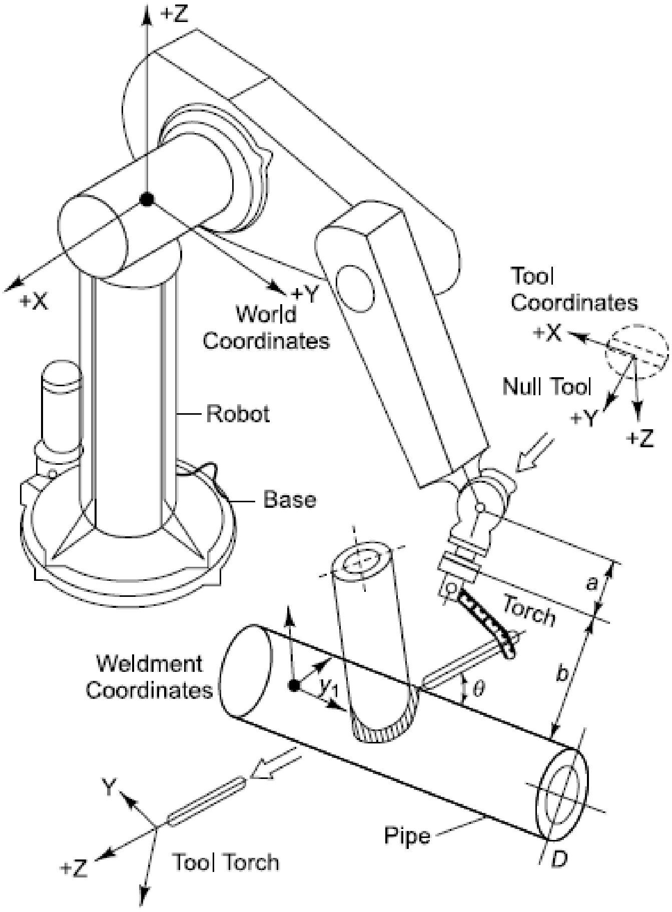
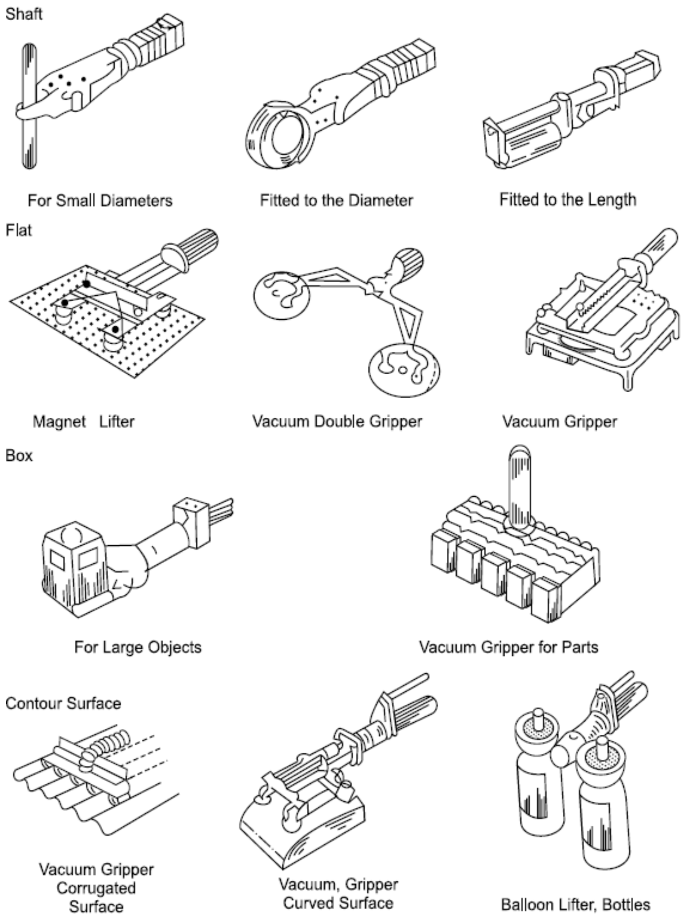


Figure 1.27 The welding gun (torch) weaving a weld pattern

Figure 1.28 indicates some typical examples of robot end-effectors suitable for manufacturing applications.

Figure 1.28 Robot end-effectors for different manufacturing applications

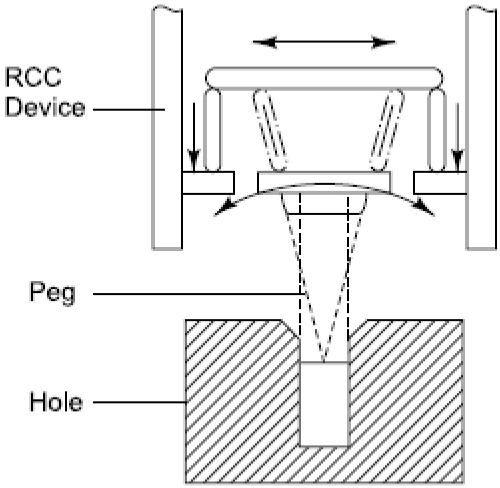


However, three or multifingered grippers provide greater flexibility and more dexterity. Dexterity of the fingers demands higher degrees of freedom. The fingers having more dexterity are suitable for gripping a variety of materials both soft and hard, thick and thin. But greater numbers of DOFs make the control-system more complex.

For assembly operations, compliant end-effectors are the most suitable types of grippers. Remote centre compliant (RCC) devices developed at the Charles Stark Drapper Laboratory, Massachusetts facilitate the rotational and translational alignment in response to the contact frictional forces when the part matches into its mating hole. Thus RCC reduces the positional and orientational errors.

Figure 1.29 indicates the principle of an RCC device. The gripper with compound compliance can have both lateral as well as angular movement to compensate for locational error or orientational error while a peg is inserted into a hole for the purpose of small assembly.

Figure 1.29 *The RCC end-effector*



1.6.3. Robot Actuators

The robot arm can be put to a desired motion with its payload if actuator modules are fitted in to provide power drives to the system. Actuators are classified into:

1. Electromechanical actuators that include

a. pneumatic actuators using compressed air

b. hydraulic actuators using fluid power

c. electric motors with

   i. d.c. motors

   ii. a.c. motors

   iii. stepper motors using electromagnetics

d. electrostatic actuators using electrical field that includes piezoelectric actuators

e. Micro-electro-mechanical systems (MEMS) actuators using combined micromachining and IC fabrication technology.

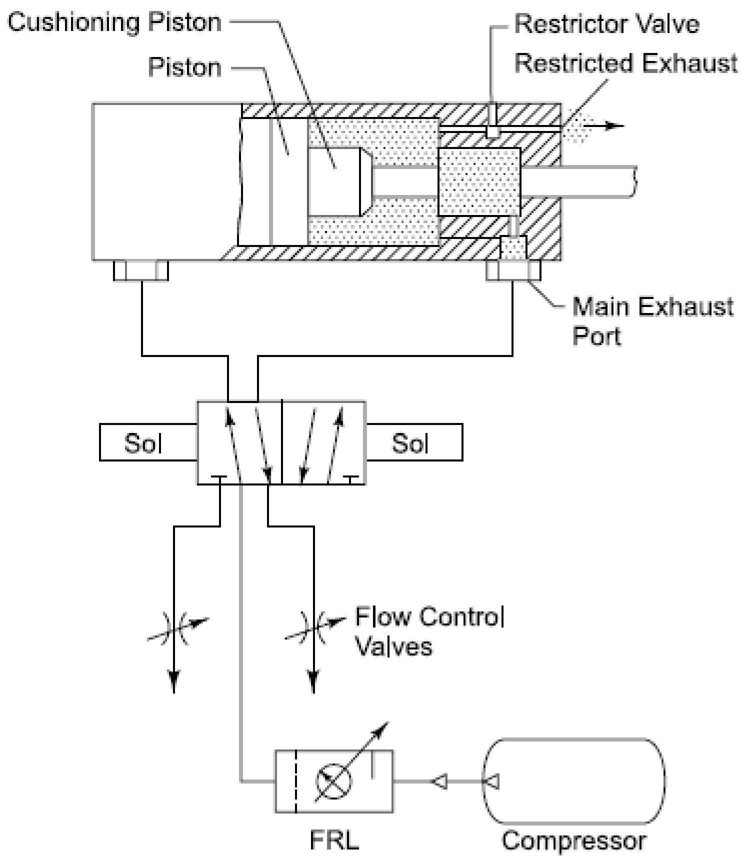
1.6.3.1. Pneumatic Power Drives

Pneumatic systems may employ a linear actuator, i.e. double acting cushioned cylinders or it may employ rotary actuators like vane motors. However, linear actuators are more popular.

Pneumatic power drive systems use compressed air to move the robot arm. Air is compressed by an air compressor and the compressed air is directed through filter, regulator and lubricator (FRL) units to the hose pipes and then to the pneumatic cylinders through the directional control valve. For stable supply, an air compressor usually pumps air into a storage tank and from there, it passes through FRL units to the pneumatic cylinder.

A scheme of a pneumatic power supply in a bang-bang (non-servo) robot is illustrated in Fig. 1.30. As air enters into the cylinder via the directional control valve, the piston moves on its outward stroke and when air is diverted to enter into the other end of the cylinder, the piston makes the return stroke. The return air is exhausted into the atmosphere. Pneumatic direction control valve can be operated by either levers, rollers or solenoids and this can also be pilot operated.

Figure 1.30 *Scheme of the pneumatic power supply*



Solenoid controlled valves are most common and they can be operated by micro switches which energize the solenoids.

The advantage of using pneumatic actuators is their simple construction. Non-servo robots can be built up with pneumatically powered actuators. The main disadvantage of a pneumatic system is the mass inertia and delayed response of the robot arm due to the sponginess and reduced repeatability. It may be mentioned that repeatability refers to the robot's ability to return to the actual programmed point or a point in space that had previously been taught to the robot. Usually, the robot will not always return to the same programmed point, but will reach the point with some error known as repeatability error. Repeatability should not be confused with robot accuracy. The accuracy refers to the robot's ability to achieve a given target position. A robot due to its limitations of control resolution may not be able to move to the target point, but is capable of moving to a programmed point very close to the target point. The difference between the positions of the target point and the programmed point is the accuracy error. The repeatability error is a normal random variable and may be plus or minus a particular value centering around the programmed point. However, to have a good precision covering both the aspects of accuracy and repeatability for a pneumatically actuated robot, the control system becomes expensive and the main advantage of simplicity in construction is lost. Servo controlled pneumatic systems are quite expensive.

1.6.3.2. Hydraulic Systems

In a hydraulic system, the electric motor pumps fluid (oil) from a reserve tank to the hydraulic actuators which are, in general, double acting piston–cylinder assemblies. Fluid at a higher pressure passes through control valves before its entry into the linear actuators. On the other hand, rotary actuators comprising some motors or hydraulic motors which rotate continuously may also be employed. Thus in a hydraulic system, both linear and rotational motions are possible.

Figure 1.31 indicates a schematic layout of a hydraulic power supply.

Figure 1.31 Scheme of the hydraulic power supply

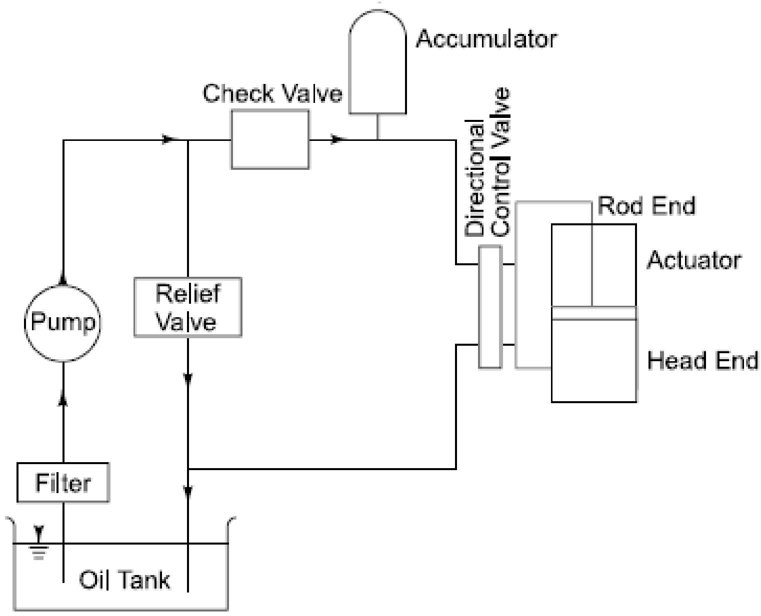


Figure 1.32 indicates the hydraulic circuit used in arm extension or shoulder swivelling arrangement of a bang–bang robot. Figure 1.33 illustrates the hydraulic circuit for waist movement achieved through a hydraulic motor.

Figure 1.32 Hydraulic circuit diagram for arm-extension of a non-servo robot

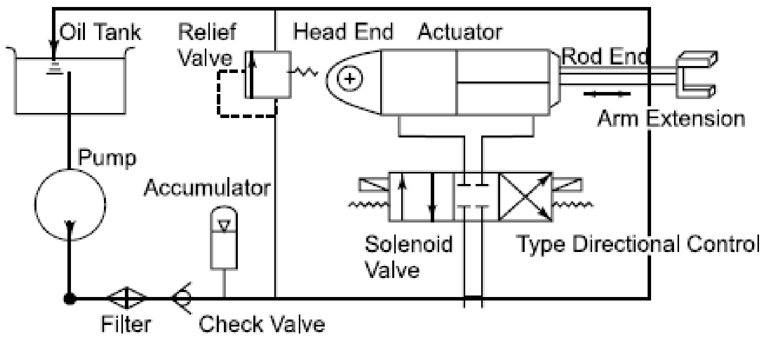
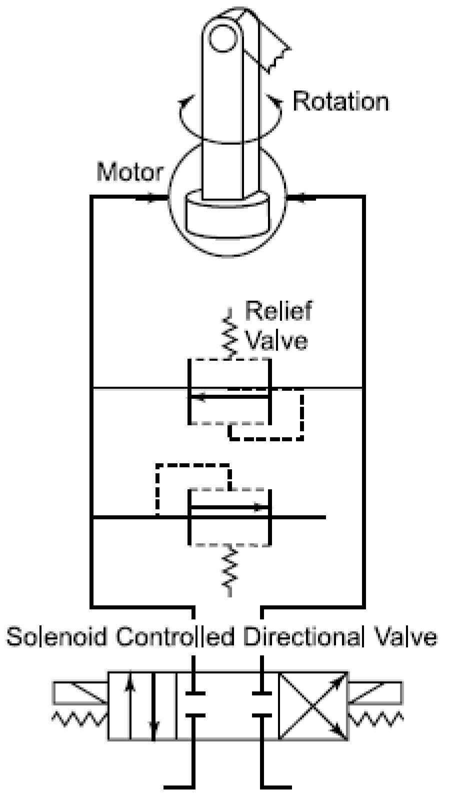


Figure 1.33 *Non-servo circuit for rotational movement*



Fluid is pumped from the tank and filtered. It then passes through a check valve, accumulator, solenoid controlled-spring centered-direction control valve to the cylinders used for extension of the arm, swing of the shoulder, or rotation of the waist. The circuit contains a pilot operated relief valve so that the fluid is returned to the tank. The filter separates out any foreign particles that may wear off the hydraulic system elements. It also filters the dirt that may be present. The accumulator helps the systems to send additional fluid to the cylinder if there is a sudden demand for the fluid and it also acts as a shock absorber.

The pilot operated relief valve maintains the system pressure constant. When the system pressure increases, it allows the fluid to pass through the central bore of the spool to open a pilot spool and facilitates the fluid to return to the tank. It eliminates noise and vibration by streamlining the pulsations of the system pressure and holding the system pressure at the preset value.

The check valve allows the hydraulic fluid to flow in only one direction and restricts the fluid to flow in the reverse direction. The check valve also helps to maintain system pressure.

The direction control valve allows the fluid to enter into the valve from the pump and then to either the rod end or the blind (head) end of the cylinder by moving the spool to the right or to the left. The spool is pulled by a solenoid and is held in the centre (neutral position) by a spring. By energizing the solenoid, the spool can be shifted. Solenoid-operated direction control valve is used in non-servo or bang-bang type of robot. However, servo-controlled valves use jet pipes (discussed in Chapter 3).

A hydraulic power source is generally used for increased payload. It may be used in hazardous, volatile and explosive environments like a spray painting booth. However, maintenance of hydraulic systems to prevent leakage of oil is very important. The hydraulic fluid can be recycled. It can take heavy loads yet provide smooth operation.

Many robots use electrical drives. Electrically driven robots are reliable, inexpensive and can be used in applications such as welding, material handling and assembly operations. DC servo motors are generally used to meet the wide range of power required for various operations. Electrically powered robots have relatively low payload.

Besides the actuators, there are other power-driven elements like gears, recirculating ball screws, harmonic drives and linkages that transmit motion. Harmonic drives provide large reductions of the order of 100 : 1 with high accuracy and negligible backlash in gearing systems. Another important trend in power drive systems of the robots is to use brushless dc motors and reversible ac servo motors.

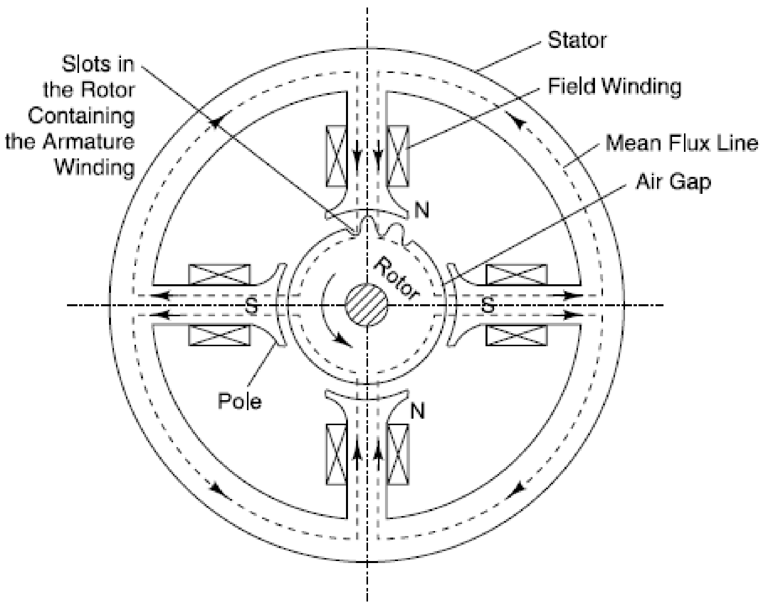
Electrical stepper motors are also used in robots whenever power and torques are small.

Considering the different power drive systems, it may be observed that hydraulic drives provide greater power and higher torque when compared with low power and torque of electrical motor drives. In servo controlled hydraulic systems, electrohydraulic valves which are quite expensive are used while in electrical drive system, electrical amplifiers and other electronic control circuits are used and they are less expensive. However, stepper motors are used for open loop systems and are not popular. The lowest cost of operation is in the use of pneumatic drive system. Pneumatic power drive is also reliable.

1.6.3.3. Electrical Motors

d.c. Motor An electrical actuator (motor) has a stationary part called a stator, and a rotating part called the rotor with an air gap as shown in Fig. 1.34. In a d.c. machine, the field windings are on the stator and armature winding on the rotor. In an induction motor, the stator carries a 3-phase winding which draws a current and sets up a rotating flux pattern with alternate north–south in the air gap rotating at synchronous speed corresponding to the frequency of the supply and the number of poles of the motor. The motor runs at speeds below the synchronous speed. The rotating field induces current in the short-circuited rotor windings or short-circuited conducting bars located at the slots. The stator and rotor fields interact to produce a torque. The rotor is mounted on a shaft. In d.c. motor, brushes and commutator are used.

Figure 1.34 Four-Poles d.c. motor



The force on a current carrying conductor is given as

$$F = B\,L\,I$$

The torque on one armature conductor is

$$T = F.r = (B\,L\,I)\,r$$

Total torque on the armature for Z_a armature conductors connected in series is

$$T_{\text{total}} = \frac{\Phi p I_a Z_a}{\pi}$$

where *F* = Force on the conductor

B = magnetic flux density under a pole

I = current in the conductor

L = axial length of the conductor

r = radius of armature conductor about the centre of rotation

I_a = current in the armature conductor

φ = flux per pole

2*p* = magnetic poles

and $T\ \alpha\ I_a\varphi$ and $N\ \alpha\ \frac{V}{\Phi}$

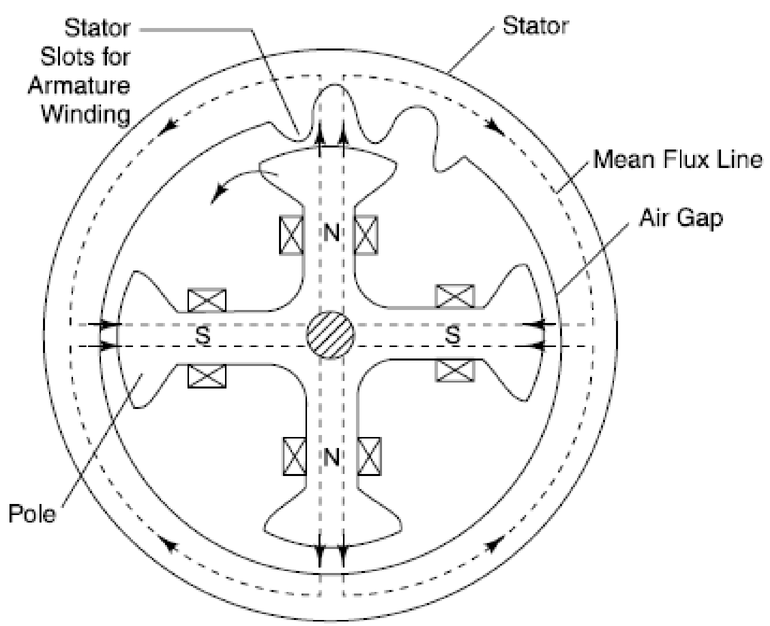
Torque, *T*, is proportional to armature current and the magnetic flux.

The speed of the motor, *N*, is directly proportional to the applied voltage, *V*, and inversely proportional to the magnetic flux, φ.

a.c. Motor a.c. motors are mainly of two types.

Single phase a.c. motor and polyphase a.c. motor. The motors may be induction or synchronous type. Induction motors are widely used. In robotics, a.c. motors are not preferred due to the complexity of speed control. However, Fig. 1.35 indicates a salient pole synchronous motor with 4 poles. The field windings are placed on the rotor and armature windings are on the stator. The field poles are salient type (cylindrical, non-salient type poles may also be used). The field windings are excited through slip rings from a d.c. source. The machine runs at fixed speed called synchronous speed corresponding to the frequency and number of poles.

Figure 1.35 Salient poles synchronous motor



The rotational speed of the field is given by

$$N_s = \frac{60f}{\text{No. of poles pairs}}$$

where N_s = rotational speed of field

$$f = \text{frequency of supply current}$$

The torque is sinusoidal in nature and is given by

$$T = T_{max} \sin \delta$$

where T_{max} = the maximum rated torque

δ = load angle (the angle of misalignment between the rotor and the stator).

The Stepper Motor The stepper motor converts d.c. voltage pulse train into a proportional rotation of a shaft. The rotation takes place in a discrete way, and hence it is suitable for digitally controlled system. The speed of the stepper motor can be varied by changing the rate of pulse train input. There are three different types of stepper motor, viz:

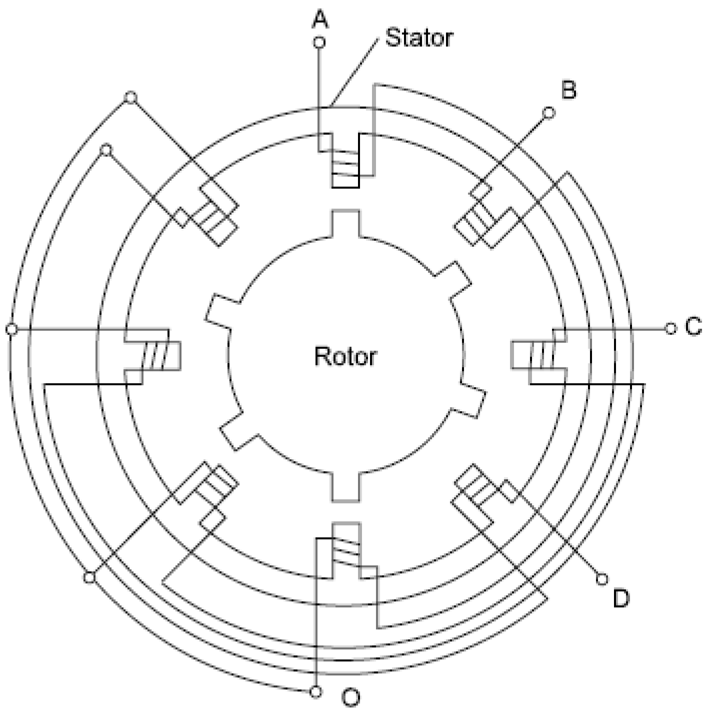
a. Variable reluctance stepper motor

b. Permanent magnet stepper motor

c. Hybrid stepper motor

Variable Reluctance Stepper Motor This is a stepper motor having a soft iron multi-toothed rotor with wound stator. The step angle depends on the number of teeth on the rotor, stator and the winding configuration and the excitation. The rotor may have (say) 6 teeth, and stator may have 8 teeth as illustrated in a typical variable reluctance four-phase motor as shown in Fig. 1.36.

Figure 1.36 Variable reluctance stepper motor



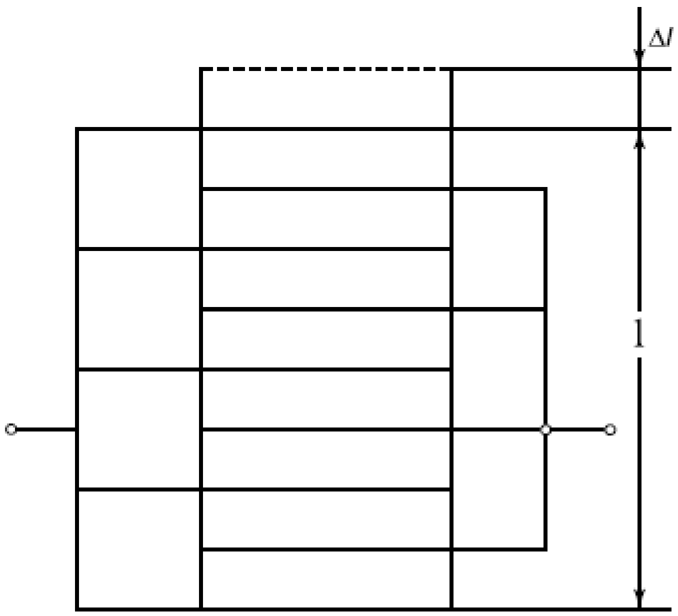
If phase A of stator is activated alone, two diametrically opposite rotor teeth align themselves with phase A teeth of stator. The next adjacent set of rotor teeth is 15° out of step in the clockwise direction with respect to stator teeth. Activation of phase B winding would cause the rotor to rotate a further angle of 15° (60° rotor teeth angle – 45° stator teeth angle) in counter-clockwise direction for alignment of the adjacent pair of diametrically opposite rotor teeth. If stator windings are excited in sequence of A, B, C, D, then the rotor will move in consecutive 15° steps in counter-clockwise direction. Clockwise rotation of motor will take place if excitation sequences are reversed. When the stator and rotor teeth are aligned, the reluctance is minimized and the rotor is at rest at this position.

Permanent Magnet Stepper Motor The rotor is a permanent magnet stepper motor and it comprises of a circular permanent magnet mounted onto the shaft. PM stepper motors give a larger step angle say 45°–120°.

Hybrid Stepper Motor Hybrid stepper motor is a combination of variable reluctance type and permanent magnet type. The stator may have 8 salient poles energized by a two-phase winding. The rotor is a cylindrical magnet axially magnetized. The step angle varies from 0.9° to 5°. The popular step angle is 1.8°. The motor speed depends on the rate at which pulses are applied. The direction of rotation depends on the order of energizing the coils in the first instance; the angular displacement depends on the total number of pulses.

Piezoelectric Actuators Piezoelectric effect is to generate electric charge in proportion to externally applied force. There are certain piezomaterials like ferroelectric ceramics and lead zirconate titanate. There are piezopolymers (PVDF) that can be used as a thin film and PVDF can be laminated on the structural materials. A piezoactuator is able to generate a force in a stroke range of hundred micrometers. The basic types of piezoactuators are stacked on and are of laminar design. A typical stacked actuator contains thin layers of piezoelectric materials between metallic electrodes in parallel connection as illustrated in Fig. 1.37.

Figure 1.37 Stacked piezoactuator



Microrobots, microgrippers and micromanipulators use piezoactuators that may give smaller strokes and control upto several KN forces with resonant frequencies.

Microelectromechanical system (MEMS) technology gives microscale devices like actuators (say, slotless permanent magnet brushless micromotor) and sensors by using the fabrication technologies like bulk micromachining, surface micromachining and technology of IC/CMOS manufacturing. By the method of etching deeply into the silicon wafer, 3-D structures can be fabricated. Surface micromachining processes use lithography and etching. Lithography–Galvanoforming–Molding (LIGA) technology is also used to produce MEMS actuators.

1.6.4. Robot Controllers

1.6.4.1. Control Systems

The manipulator of a robot moves its arm, wrist and end-effector after it receives signals from the controller in the same way a man moves his arm or his body according to the signals sent by his brain. So, the controller acts as a brain of the robot. Control systems in a robot may be of two types (i) open loop and (ii) closed loop systems. Control may again be grouped as (i) non-servo and (ii) servo systems.

In the open loop control, drive signals are sent to the actuators and there is no feedback. However in non-servo control systems, drive signals are sent to the actuator via the solenoid valve, and as soon as the actuator drives the wrist or end-effector to the desired position, a signal through some limit switch is sent back indicating that the arm has reached the position.

On the other hand, in the servo control drive, reference signals are sent to the actuator via the servo valve and the actuator moves its arm, wrist or finger to a current position and continuous measurement is taken to estimate the error between the desired position and the actual or current position. This error signal is fed back continuously to monitor the position and as soon as the error becomes zero, the desired location is achieved and the actuator stops moving.

A non-servo system, also called bang–bang controlled system is illustrated inFig. 1.38. When the manipulator arm reaches the ends of some intermediate stops, it touches a microswitch which sends signals to the controller informing it that the arm has reached the desired position.

Figure 1.38 The non-servo system

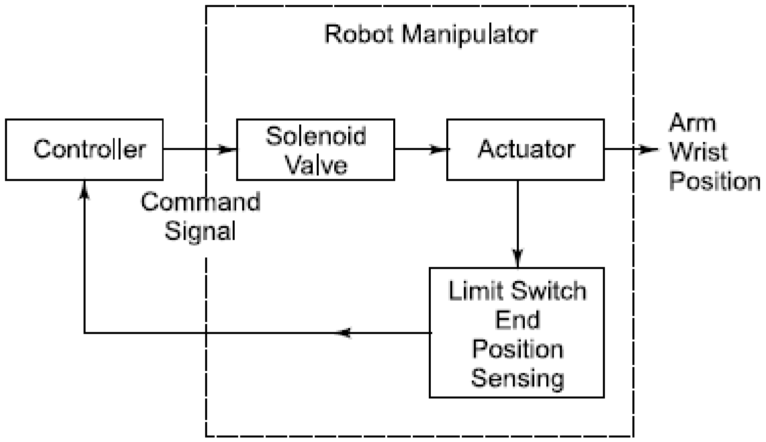


Figure 1.39 indicates a simple scheme of a positional servo. Position sensors are employed at the joints, wrist or suitable locations to feedback the positional information to the comparator. However, for precision and stable positional reach, velocity feedback is provided by a tachogenerator in addition to positional feedback as shown in Fig. 1.40. Thus servo system with position and velocity feedback ensures controlled arm position.

Figure 1.39 Simple positional servo system

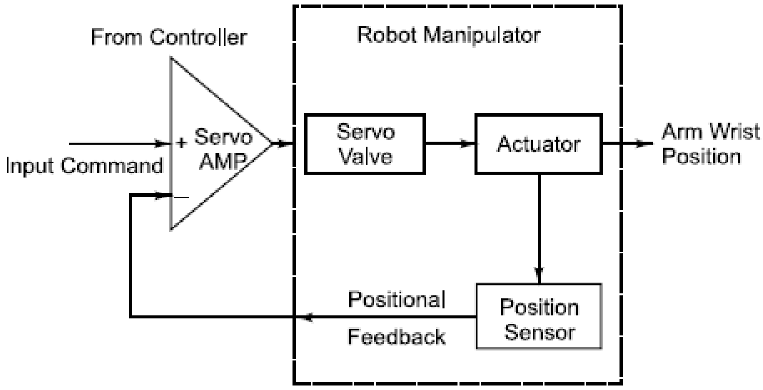
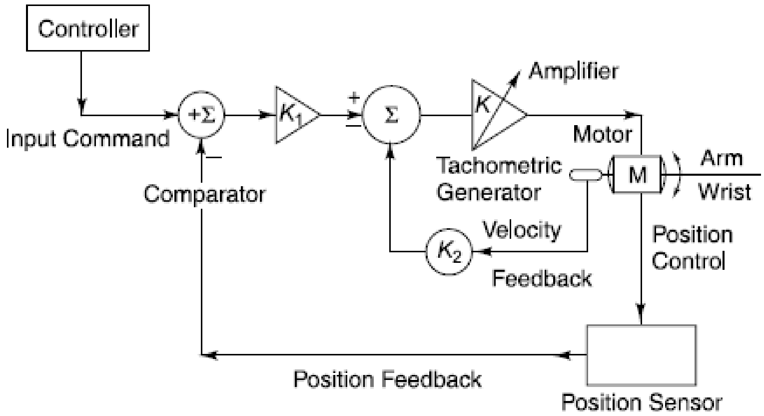


Figure 1.40 The servo control loop with positional and velocity feedback



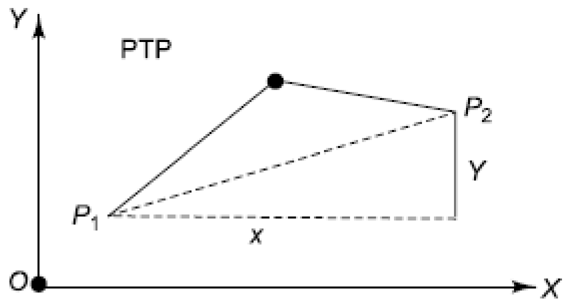
1.6.4.2. Motion Control of Robots

The robot manipulator can move its arm, wrist or gripper to the desired position describing a definite path. Programming for path generation can be accomplished in various ways and this path is controlled by the robot controller by the following methods:

1. Point-to-point control
2. Continuous path control

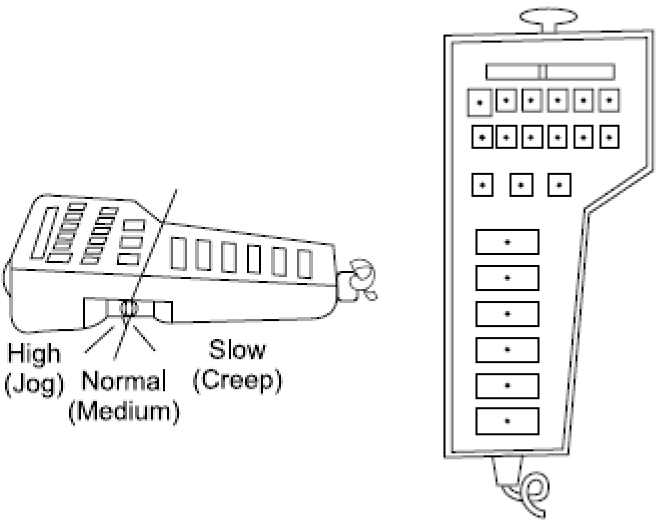
Point-to-Point Robot In the point-to-point programming method, the robot arm can be taught to move from a point to another in its work envelope. The robot can be programmed through some joysticks or man–machine interface as done in the teleoperated robot, or through push buttons in the teach pendant box. In this way, an individual axis can be moved independently or more than one of its axes can also be moved at a time. Once the robot arm has been brought to a particular point, the locational point is recorded into the robot's memory in the controller by the programmer who pushes a button. Next the robot arm is moved and brought to a second point and this new point or position is recorded by pushing a 'record' button. This method is known as teaching. Thus the point-to-point path generation in steps is done in the teach mode. In 'auto' mode, all the points so recorded are played back and the robot arm starting from the first point moves through the programmed points till it reaches the end point. The controller moves the manipulator back to the position of the first point and the entire path is repeated. However, in point-to-point control, the path generated between points P_1 and P_2 (Fig. 1.41) cannot be predicted during programming as two sequential moves from the first point to the end point may describe different paths. Figure 1.41 indicates a P-T-P controlled path. All the axes of the robot manipulators move at the maximum rate. In order to move from point P_1 to P_2, movement along the *x*-direction is greater than the movement along the *y*-direction. So the manipulator will complete the required vertical movement (*y*) long before the horizontal movement (*x*). All the the axes move in an uncoordinated manner. However, the individual joint motions may be controlled and the velocity may be adjusted so that all the axes motions reach the end point simultaneously.

Figure 1.41 Point-to-point motion control



A typical teach pendant is illustrated in Fig. 1.42.

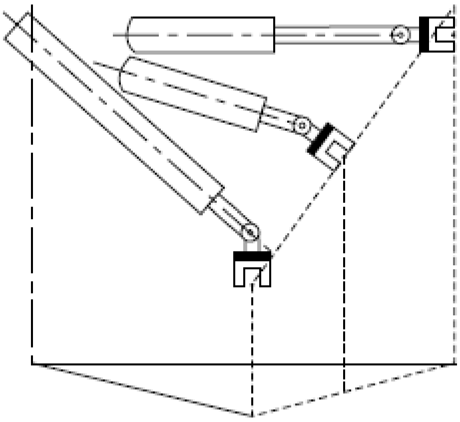
Figure 1.42 The teach pendant of a robot



Robot with Joint-Interpolated Motion In the joint-interpolated motion, different axes move at different velocities to reach the final position following a point-to-point generated path. In this method, the movement along the horizontal axis takes place at a higher velocity than the movement along the vertical axis as in case of Fig. 1.41 and both the axes reach the final position at the same instant. However, for a robot with multiple degrees of freedom, it is difficult to predict the path; nevertheless the joint-interpolated motion provides a smoother action compared to the simple P-T-P action. In the joint-interpolated motion, the axes move in a coordinated manner.

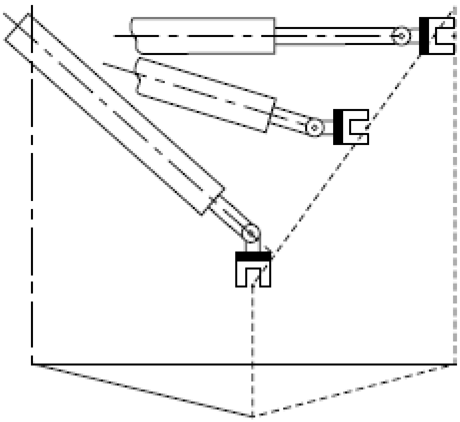
Robot with Controlled Path Motion In the point-to-point control, an exact path between the taught points cannot be predicted. In controlled path motion, the discrete points programmed earlier describe a straight line between the taught points as illustrated in Fig. 1.43. The robot arm therefore moves in a straight line. However, the linearity of the straight line can be strictly maintained if larger number of points are programmed. The path generation involves computations for coordinate transformations between joint angles and the Global coordinates.

Figure 1.43 Linearly interpolated controlled path motion



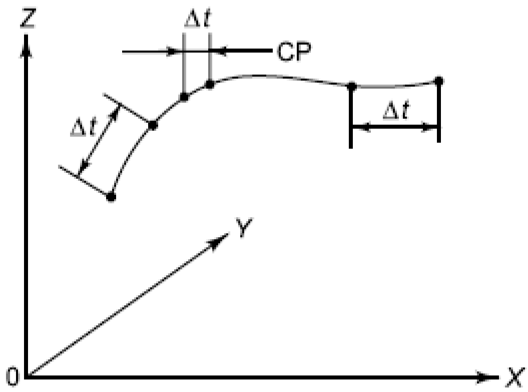
The intermediate points between two end points can be interpolated by computation in the global coordinates and the controller sends the command signals in joint coordinates. The solution for generating the straight line path is of course not unique as shown in Fig. 1.44.

Figure 1.44 Linearly interpolated move by a robot



Continuous Path Robot Continuous path motion is a coordinated motion. The robot arm, wrist or end-effector follow a specified path in a 3-D space. Continuous path motion is a coordinated point-to-point motion described very closely or continuously on a time base. In this programming method, the robot arm is led through the path describing several points at a fixed time or in discrete time intervals. The arm may be traversed very slowly following a point-to-point path at small intervals, or else the arm can be moved fast following wide apart points. Thus, several hundreds of individual points can be recorded in the controller's memory. The path of the robot may be any curve, or an arc of a circle. In specific cases, it may be a straight line. The recorded points along the curve may be stored in cassette tapes or floppy disks. When the programme is on playback mode, the robot moves continuously through the stored points as illustrated in Fig. 1.45.

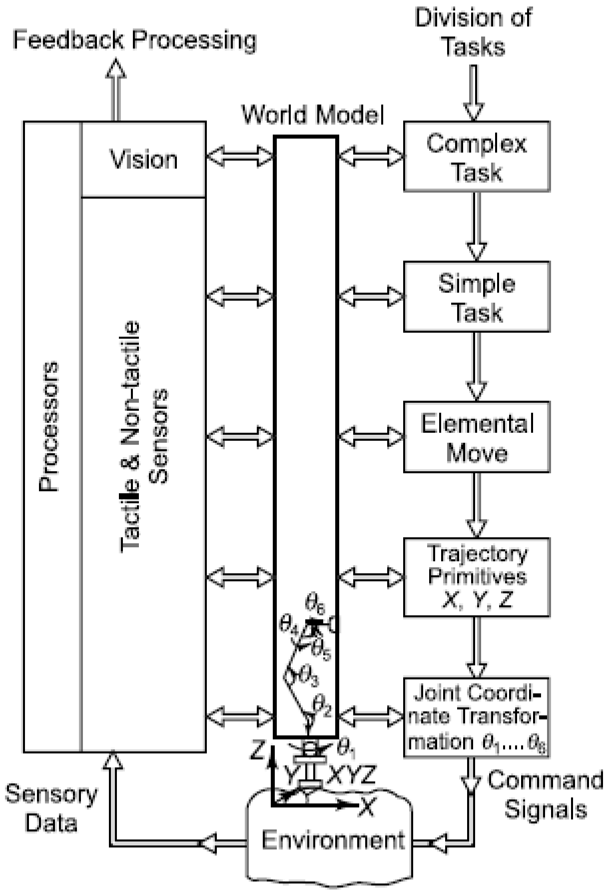
Figure 1.45 *The continuous path motion*



1.6.4.3. The Hierarchy of Servo Robots

The controller may employ a processor which accomplishes the tasks by breaking them down into several subtasks for which, a hierarchical level of control may be organized. For example, a vision robot may use a high-level vision processor that provides a knowledge of position as a component identity including its position, and orientation and avoidance of obstacles; the robot controller through its other sensory devices feeds back the data to accomplish the tasks at various levels including the movement of joints or axes of the robot. Thus a complex task may be divided into simple tasks. A simple task, say 'load', may be broken down to elemental moves, say 'move' and 'grasp', and the elemental moves may further be decomposed into action commands in *X*, *Y*, *Z* primitives of trajectory in the world coordinates. The world coordinate commands are then transformed into joint actuator commands, θ_1, θ_2, θ_3, ... through transformation coordinates and finally the drive signals are sent through positional and velocity servo of various joint axes of the robot. A scheme of control hierarchy is illustrated in Fig. 1.46.

Figure 1.46 The control hierarchy of a robot



1.6.4.4. Types of Robot Controls

There are different types of controllers used in robotics. They are:

1. Drum controller
2. Air logic controller
3. Programmable controller
4. Microprocessor-based controller
5. Minicomputer-based controller

Drum Controller In drum controller, as the drum rotates, it actuates those switches which are wired to hydraulic or pneumatic valves. Thus, the manipulator movements are controlled by the rotational advancement of the drum. It is now obsolete.

Air Logic Controller Air logic controller employs a number of pneumatic valves which in turn control the opening and closing of the main valves of the robot manipulator in close synchronization with the timers.

Programmable Controller In a programmable controller, the sequential order in which the switches are to be operated is kept in the memory. It can be entered into the controller with the help of a keyboard. The programme can also be displayed on the CRT screen. A programmable controller may be used to control and coordinate various tasks to be done by the peripheral equipment including robots.

Microprocessor-Based Controller The microprocessor-based control is the most popular robot control system.

Microcomputers of various types may be employed to program the sequential tasks or motions and store them in its memory. It contains special circuitry to interpret the programs kept in its memory and at the same time it sends drive signals to various actuators of the robot manipulator. It can also count the number of sequential events or tasks accomplished. It is versatile, programmable and has good memory. Point-to-point, continuous path and controlled path motions can be easily programmed in microprocessor-based robotic systems.

Minicomputer-Based Controller Robots having higher payload are manipulated through a minicomputer-based controller.

1.6.4.5. Programming Methods

Programming of a robot can be done by several methods.

- Lead through programming
- Teach pendant programming
- Textual programming using computer terminal

Lead through Programming In this method a robot is switched to 'program' mode when the operator holds the robot manipulator or its wrist and moves it through a desired path. The robot controller memorizes all the points so generated. During playback, the robot manipulator describes the same path as taught during learning. Moreover, editing facility can be provided to compensate for error.

Some of the robots with continuous path control system use 'teach arm' or joystick. As the joystick is moved in different axes, the robot manipulator axes follow the motions exactly. Speed commands are provided to increase or decrease the speed of the manipulator.

Teach Pendant Programming Teach pendant is the most popular method of programming industrial robots. It has earlier been described in Section 1.6.4 (Fig. 1.42).

Textual Programming Microcomputers or minicomputers are used for programming industrial robots and different languages have been developed for both on-line and off-line monitoring. Robot software languages include facilities such as subroutines, program branching, interruptions and signalling to peripheral equipment, etc. Different languages for robot software system include VAL used in Unimation robots, SIGLA used in Sigma robots, HELP used in Pragma assembly robots, AUTOPASS in IBM robots and so on. At present, there are many different robot programming languages with various important features like flexibility in editing, interpreting, compiling, simulating and debugging facilities.

1.6.5. Robot Sensors

In order to function effectively, a robot has to receive information from the environment for necessary manipulation, send signals to various joints for necessary movement and interact with the peripheral equipment. For example, when a robot picks up an object and places it in a definite location, it has to initially to get information about the presence of the object. As soon as it understands that the object is present, the arm approaches it with a controlled speed and acceleration. While approaching, it must avoid collision with any other obstacle. It may also attempt to find the shape and orientation of the object to be grasped. When the robot grips the object, it must identify the points where it should grip the object with specified force. The object should not be pressed hard or deformed, or slip. Sometimes it is necessary to have prior knowledge about the shape of the object before it is gripped. Therefore, it is required to sense and measure all the important geometrical parameters of the object lying in an environment. Sensory feedback is, of course, more important for unstructured environment.

Searching, recognizing, grasping and placing the object are, therefore, some of the important steps to be done by a robot in a pick and place operation for which various sensors—both internal and external—are incorporated. However, the signals or sensory data obtained through the sensors must be processed, interpreted and integrated properly in a robot controller so that the robot can effectively and reliably perform the task.

Usually there are two basic types of sensors. They are tactile and non-tactile. Tactile sensors are contact sensors that must be brought in contact with the object to obtain signals to measure the necessary quantities while non-tactile sensors are contactless sensors which sense the signals remotely, but only within the specified range of distance from the object. When the tactile sensors make physical contact with the object, an electrical analog or digital signal is generated and sent to the robot controller. Electrical signals may be obtained through the contacts of microswitches. Signal may also be obtained through mechanical pressures which change resistances of electrical strain gauges or generate electrical potentials in piezoelectric crystals.

Typical contact type robotic sensors include

- Force sensors
- Torque sensors
- Touch sensors
- Position sensors

Non-tactile sensors detect and measure magnetic fields, infrared and ultraviolet light, x-rays, electrical fields, ultrasonic sound waves or electromagnetic waves. Typical non-contact sensors include

- Electro-optical imaging sensors
- Proximity sensors
- Range imaging sensors

Imaging sensors may use a laser scanner. Computer-vision uses artificial intelligence (AI) to determine cause and effect phenomena to detect the fault or minimize their effects. Vision-robots acquire knowledge about the environment by the interpreting, generating and reasoning components. Various sensors collect and produce information and the direct actions are effected by the articulations of the robot arm or end-effector. A simplified AI model in connection with robotics is depicted in Fig 1.47.

Figure 1.47 Simplified model of AI and robotics

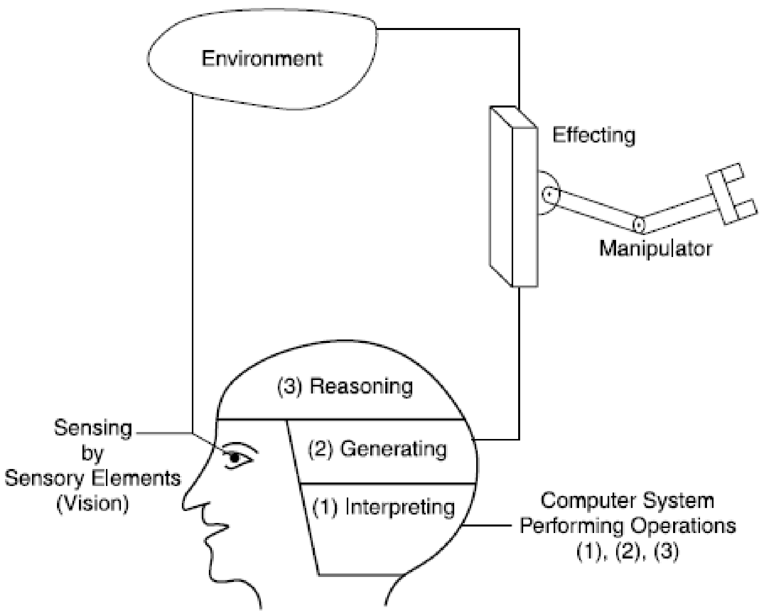


Figure 1.48 indicates a scheme of robot sensors. External sensors include CCD camera, force or torque transducers, proximity sensors and various tactile sensors to acquire knowledge or get information from the environment. Internal sensors may include encoders, technometers, force or torque transducers, electrical and optical devices that transfer information about the position, speed and articulations of the manipulator to interact with the environment.

Figure 1.48 Scheme of robot sensors

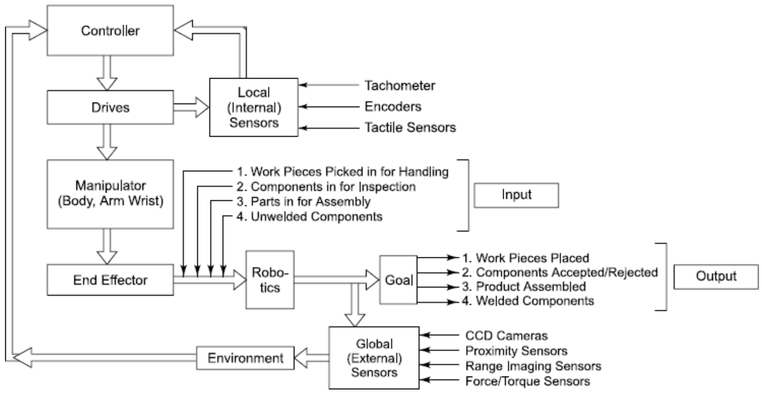
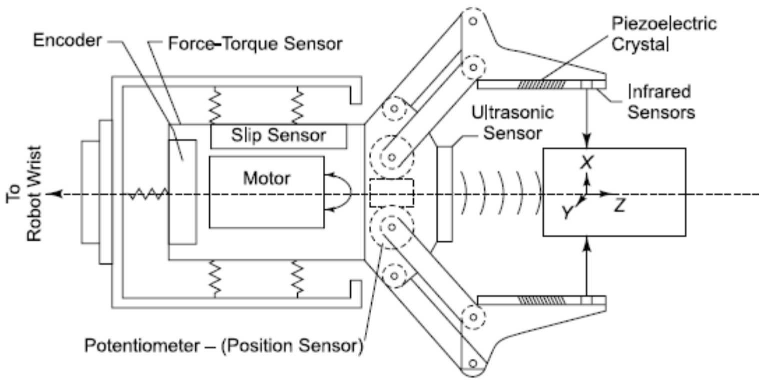


Figure 1.49 illustrates the use of force/torque sensors at the wrist and touch, infrared and ultrasonic sensors in the robot hand.

Figure 1.49 The sensor-based end-effector



An ultrasonic sensor transmits and receives acoustic signals for range-sensing and searches for an object for identification, position and orientation. Piezoelectric crystals and infrared sensors located in the fingers of the end-effector are useful in getting information about the object before it is picked up from a narticular location. Potentiometers are employed for position sensing.

Figure 1.50 illustrates the basic vision system components of a vision robot. An image sensor (CCD camera) takes the photograph and the image is processed and shown on a TV monitor. The output signals are sent to the robot controller to control the movement of the manipulating arm and gripper.

Figure 1.50 The vision system components

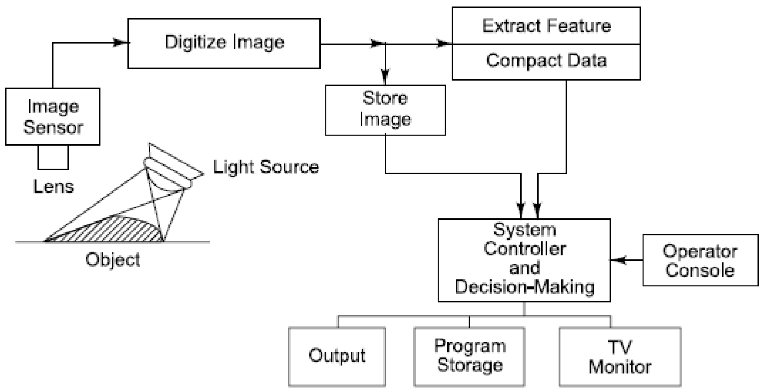
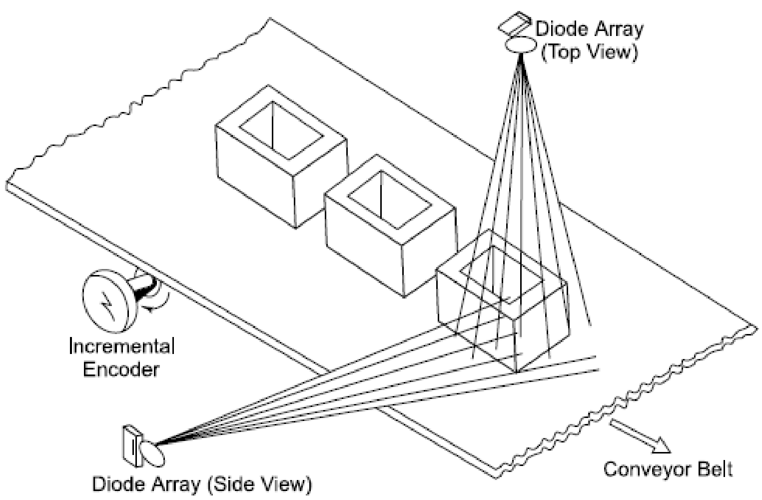


Figure 1.51 indicates the typical view of a box type object on a moving conveyor as seen by two diode arrays that have been triggered by position sensing encoders to initiate the scanning action.

Figure 1.51 Typical view of box-type object outlined by two linear diode



Typical tactile and non-tactile sensors are indicated in Table 1.3 and Table 1.4 respectively.

Table 1.3

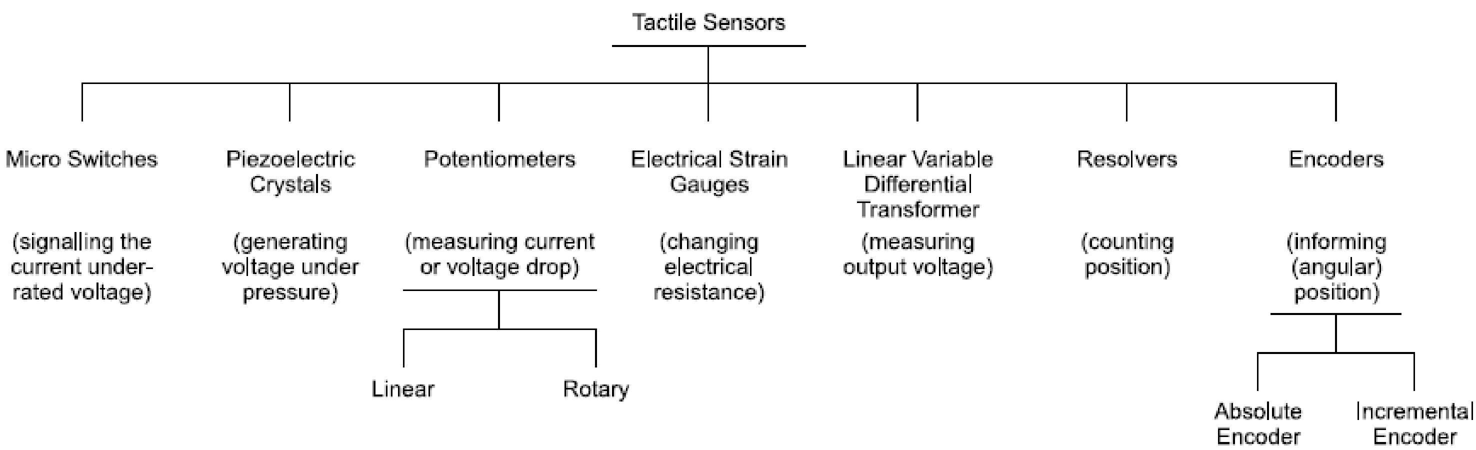
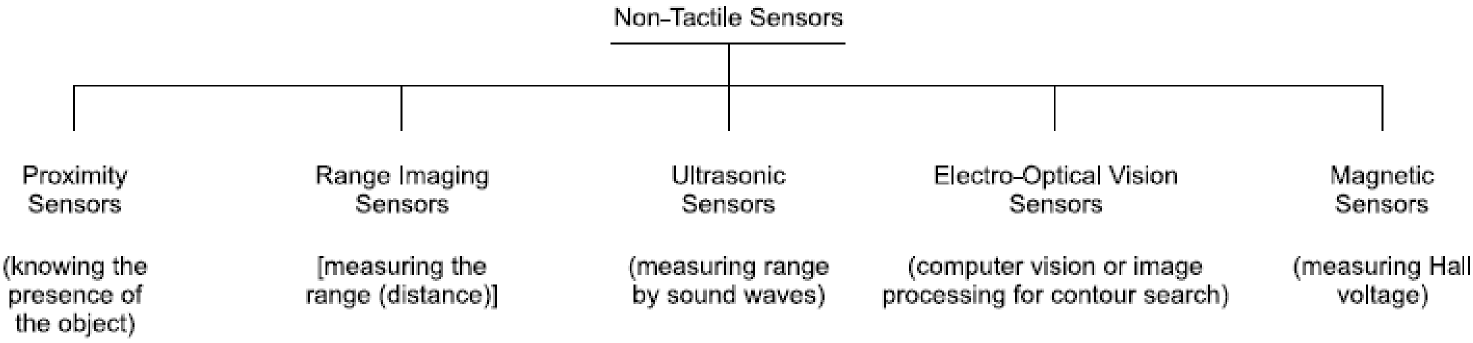


Table 1.4



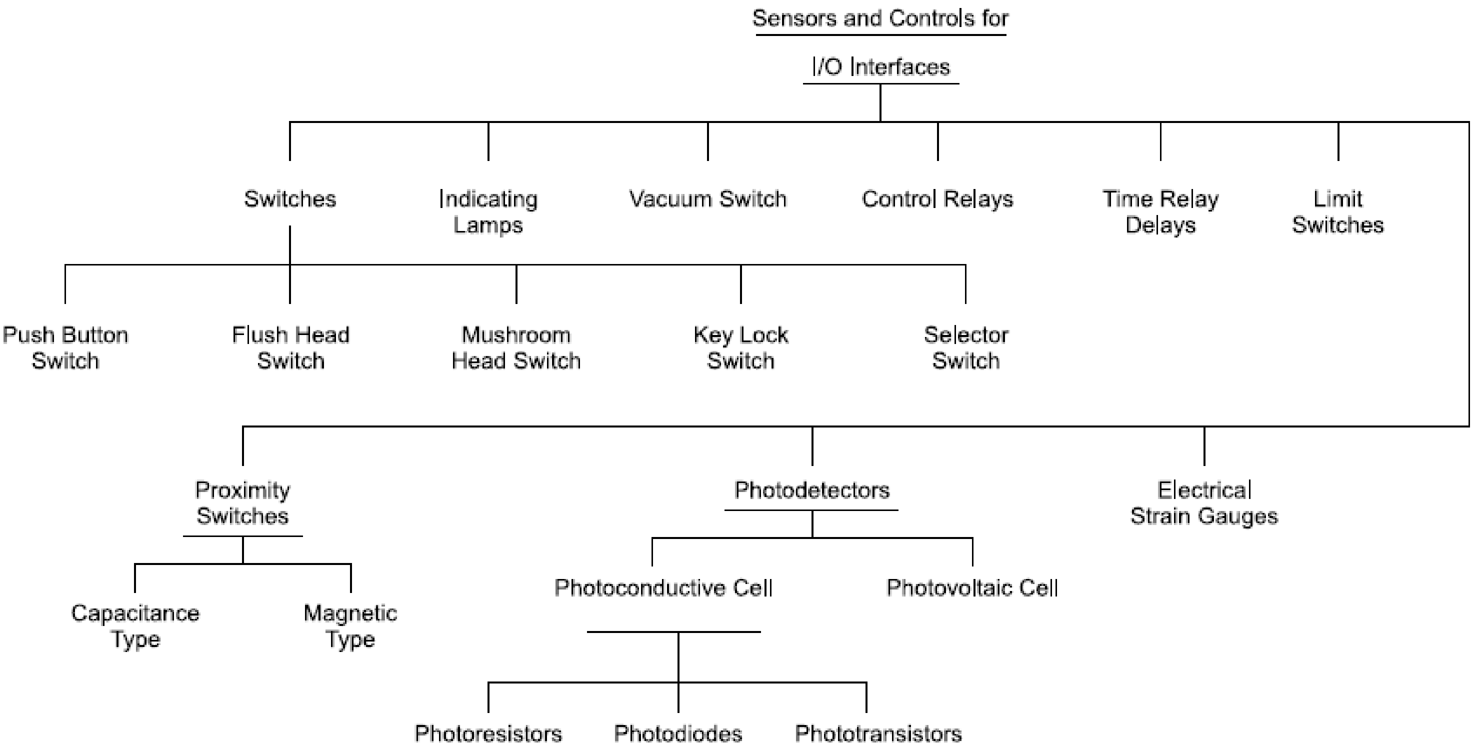
1.6.6. Robot Environment and Robot Input/Output Interfaces

A robot when employed as a stand-alone machine works with the help of information from internal sensors; when the same robot operates in an environment where a group of other machines work, it acquires information from the surrounding environment by means of external sensors and takes decisions with the knowledge so acquired and sends the necessary signals to the machine for user friendly work.

The inputs and outputs of a robot are similar to those of a programmable controller (PC) where the inputs and outputs are either a.c. or d.c. signals. However, all the inputs and outputs are controlled by the robot software running on its controller.

Various sensory elements or transducers are used to receive information and send signals through input-output ports. The controls and sensors used in I/O interfaces are indicated in Table 1.5.

Table 1.5

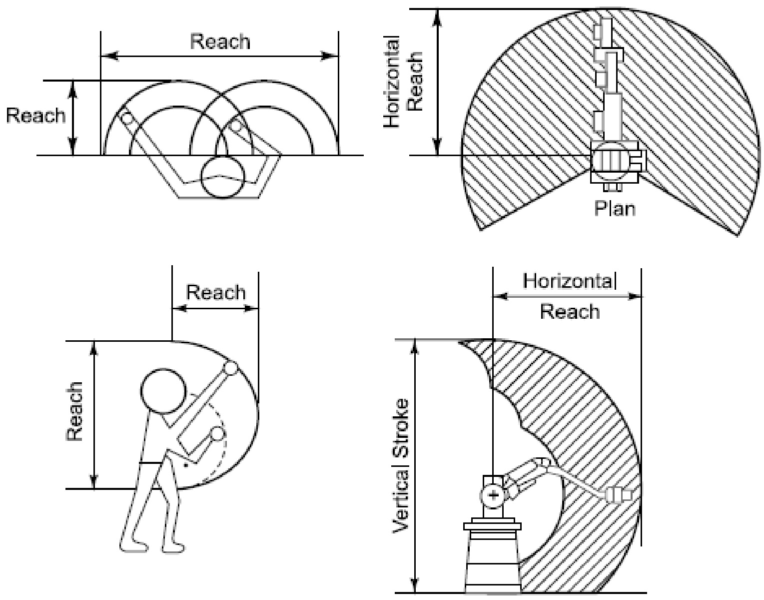


1.7. HUMAN SYSTEMS AND ROBOTICS

To decide whether a task should be accomplished by a human operator or a robot, a number of items need consideration. But the most important among them is the knowledge and estimation of the level of skill involved in the job. Once the skill level is determined, other comparable ergonomic specifications of the robots should be established. For example, certain tasks need intelligence, reasoning and interpretation, while some others do not need such consideration. Certain tasks require sensory capabilities, certain tasks do not need any such sensing. In the former case, say in assembly work, probably man is superior to the robot. Hence, artificial intelligence is another important branch that is being coupled with robotics so that human skill and decision-making capability through reasoning and interpretation can be simulated through computer programming and development of sensor technology. In a similar way, when the physical skill and consistency of a human operator is compared to those of a robot, probably, the robot may score more points. For example, man has more dexterity, but the human hand is not at all suitable from the viewpoint of strength, power, payload, physical dimensions and safety when compared to the robot wrist and end-effector.

Figure 1.52 indicates work envelope of a human operative and an anthro-pomorphic robot.

Figure 1.52 Human and anthropomorphic robot reach



The different work envelopes for cylindrical, spherical, revolute robots and human operative are plotted inFig. 1.53 to indicate their relative location and an area common to all of them can be found.

Figure 1.53 Work envelopes of the robots and the human operative

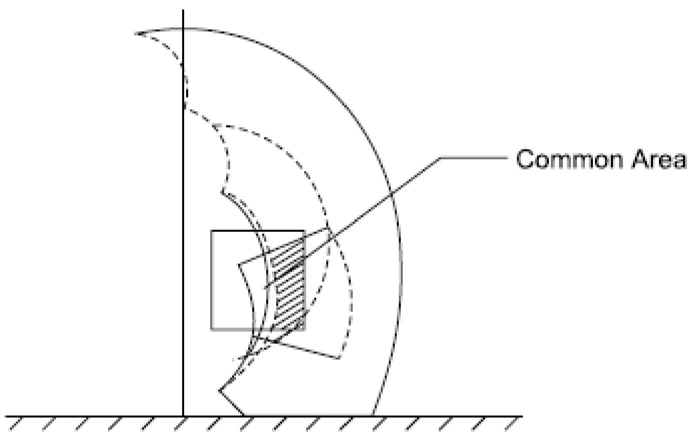


Figure 1.54 indicates the various arm configurations of a robot as compared to the human arm.

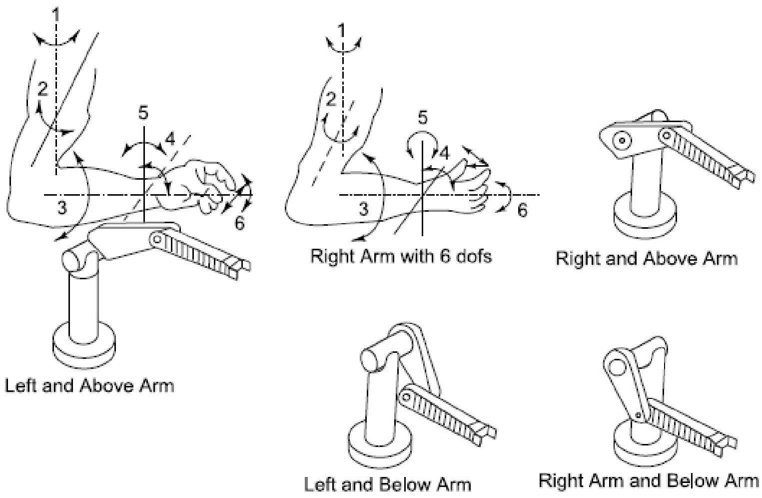


Figure 1.54 Various arm configurations of the robot (right and left arm)

Figure 1.55 illustrates the robot end-effector as compared to human hand with fingers.

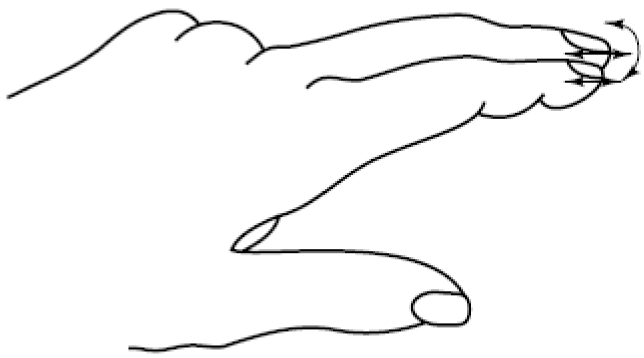
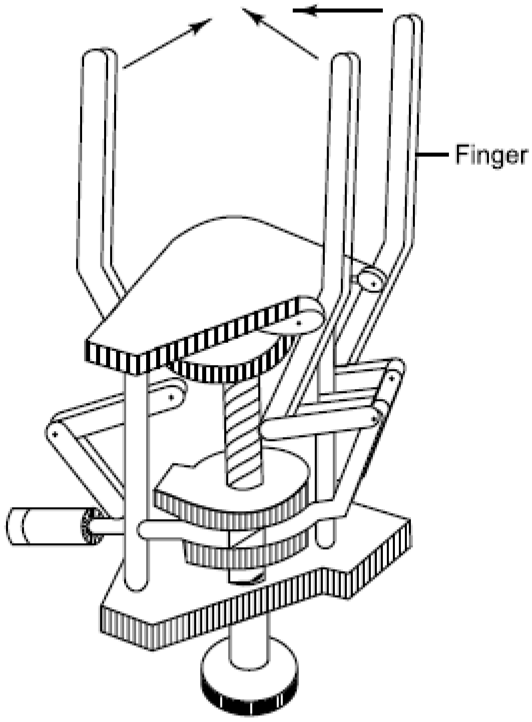


Figure 1.55(a) The human three-fingered grip (after Cutkosky)

Figure 1.55(b) The three-fingered gripper of a robot (after Cutkosky)



1.8. SPECIFICATIONS OF ROBOTS

Robots may be classified according to their characteristics, namely:

- Multiple task capability
- Level of machine intelligence
- Kinematic structure
- Geometric dexterity
- Mobility
- Actuator modules
- Payload capacity
- Precision, accuracy, repeatability
- Sensory capability
- Operational envelope
- Application groups

An industrial robot is classified mainly on the basis of its manipulating arm and the joint configurations to position the end-effector. Accordingly, robots have the following coordinate systems:

- Cartesian coordinate
- Cylindrical coordinate

- Spherical or polar coordinate
- Anthropomorphic or articulated or jointed arm coordinate

Sometimes robots may be classified according to the pair of joints which provide degrees of freedom. They are: R-R-P (revolute-revolute-prismatic), R-R-R, R-P-P, P-R-R, P-P-P, or a combination of all these.

A wrist of a robot may be specified by the type of motion it performs, viz., pitch, yaw and roll.

Accordingly the wrist (Fig. 1.23) may be broadly classified as

- Wrist type 1A (having single degree of freedom)
- Wrist type IB
- Wrist type $2A_1$
- Wrist type $2A_2$ (having 2 degrees of freedom)
- Wrist type 2B
- Wrist type $3A_1$
- Wrist type $3A_2$
- Wrist type 3B (having 3 degrees of freedom)
- Wrist type 3C
- Wrist type 3D

A robot may have different end-effectors. They are mechanical type, magnetic pick up and, vacuum or suction pick up.

Sometimes, a robot may have a two-fingered, three-fingered or multifingered end-effector.

Robots may be identified as fixed, mobile and walking or legged robot. There are various methods of specifying robot movement. They are:

- Fixed sequence robot
- Variable sequence robot
- Playback robot
- NC robot
- Intelligent robot

A robot may be non-servo (bang-bang type) or servo (proportional feedback type).

A robot may be classified according to the type of control. They are point-to-point robot, continuous path robot, and controlled path robot.

Robots may use various offline programming systems via different robot languages, viz, VAL, SIGLA, AL, PLACE, RAPT, AML, PAL, MCL, RAIL, HELP, RPL, JARS, ADA, etc.

A robot is further specified by its speed or maximum velocity at the end-effector. (Velocity,*V*, mm/s or rad/s.)

A robot is found to be efficient in repeating its movement under the same precisely defined conditions. Hence, repeatability may be defined as

$$\pm x, \text{ mm}$$

Robots may have different load carrying or lifting capacity. The playload, is thus defined as W, kg or N.

Robots may be grouped according to the sensory systems they are provided with. They are:

- Simple and blind robot (with internal sensors)
- Vision robot
- Moderately intelligent robot (with external tactile and non-tactile sensors)

Robots may also be specified according to the type of industrial applications, viz.

- Part handling robot
- Tool operating robot
- Assembly robot

Robots are sometimes classified in accordance with the specific task they perform, viz. die casting, investment casting, forging, pick-and-place operations, machine tool loading and unloading, welding, spray painting, inspection, assembly and education and training.

A typical classification system of robots is based on the skill of operation required in various manufacturing applications. They are:

1. Low accuracy contouring (for spray painting, spot welding, etc.)
2. Low accuracy point-to-point (loading/unloading from heat treatment furnaces, die casting machine, etc.)
3. Moderate accuracy contouring (arc welding, deburring etc.)
4. Moderate accuracy point-to-point (forging, loading/unloading machine tools, part orientation, etc.)
5. Close tolerance and assembly applications

Some of the typical broad robot specifications are given below:

1. Cincinnati Milacron

Model	—	T3 586
Manipulator end-effector	—	6 DOF, RRR-3A
Speed	—	900 mm/s
Actuator	—	hydraulic
Payload	—	100 kg
Repeatability	—	± 1.25 mm
Applications	—	Forging, investment, casting, machine tool loading, welding, machining, inspection, etc.

2. Puma (Unimation)

Model	—	550
Manipulator end-effector	—	6 DOF, RRR-3A
Speed	—	1000 mm/s
Actuator	—	Electrical
Payload	—	3 kg
Repeatability	—	± 0.10
Applications	—	Machine tool loading, part transfer, assembly, welding, inspection, education

3. Seiko Instruments

Model	—	M 700
Robot manipulator end-effector	—	3 DOF RP-1A
Speed	—	312 mm/s
Actuator	—	Pneumatic
Payload	—	1 kg
Repeatability	—	± 0.03 mm
Applications	—	Machine tool loading/ unloading, material handling, assembly, inspection.

1.9. PRESENT APPLICATION STATUS

In the initial stages, major applications of robots have been in unpleasant and hazardous tasks. Robots have found wide applications in doing repetitive and monotonous jobs where consistency and product quality are of primary importance. Usually robots are most suitable for automated tasks which require little sensing capability. However, intelligent robots are now in demand for running automated unmanned systems or factories.

Flexible manufacturing system (FMS) is an emerging field where flexibility of the cell and consistency of the products are combined. FMS works at various levels and replaces hard automation technology comprising transfer machines as well as dedicated and automatic machines. FMS is very much congenial for batch manufacturing. The broad subsystems of FMS as shown in Fig. 1.56 are:

- Flexible Manufacturing Module (FMM) (Fig. 1.57)

- Flexible Manufacturing Cell (FMC) (Fig. 1.58)
- Flexible Manufacturing Group (FMG) (Fig. 1.59)
- Flexible Fabrication–Machining–Assembly Systems (FFMAS) (Fig. 1.60)

Figure 1.56 Relation between number of different parts and yearly production of parts in FMS system

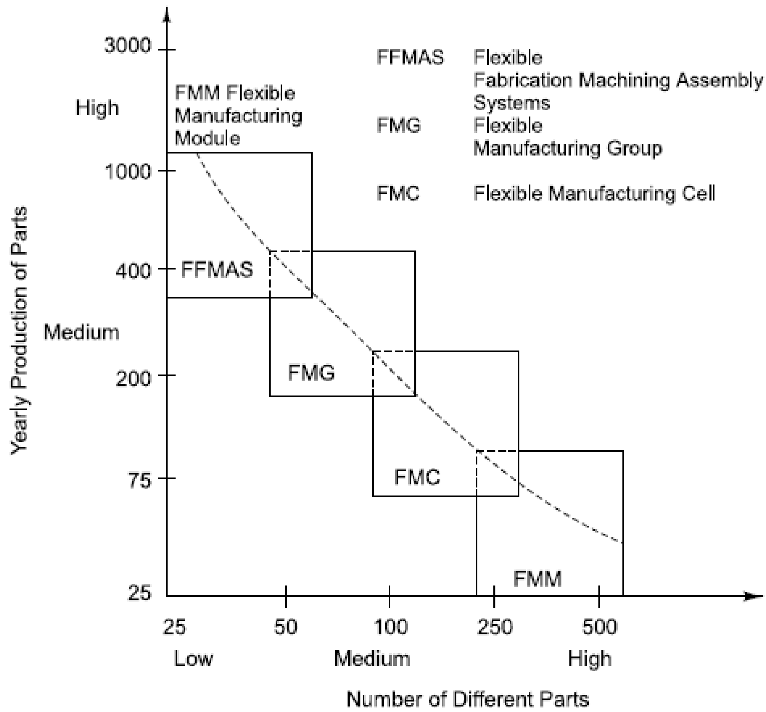


Figure 1.57 The flexible manufacturing module (FMM)

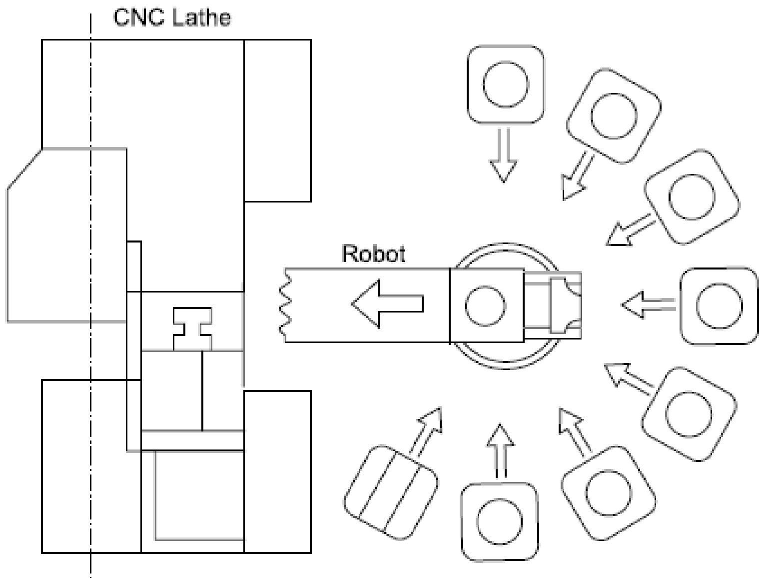


Figure 1.58 ***The flexible manufacturing cell (FMC)***

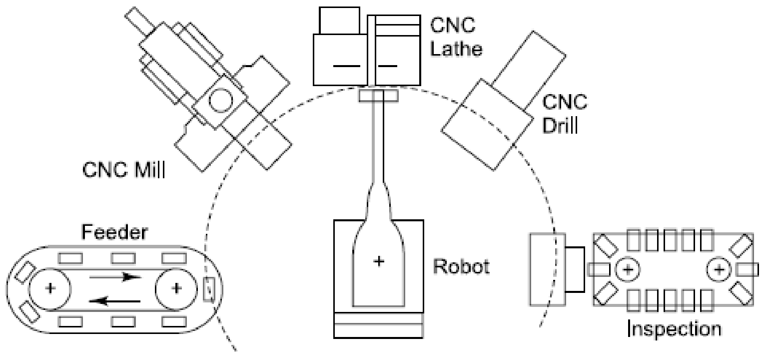


Figure 1.59 ***The flexible manufacturing group (FMG)***

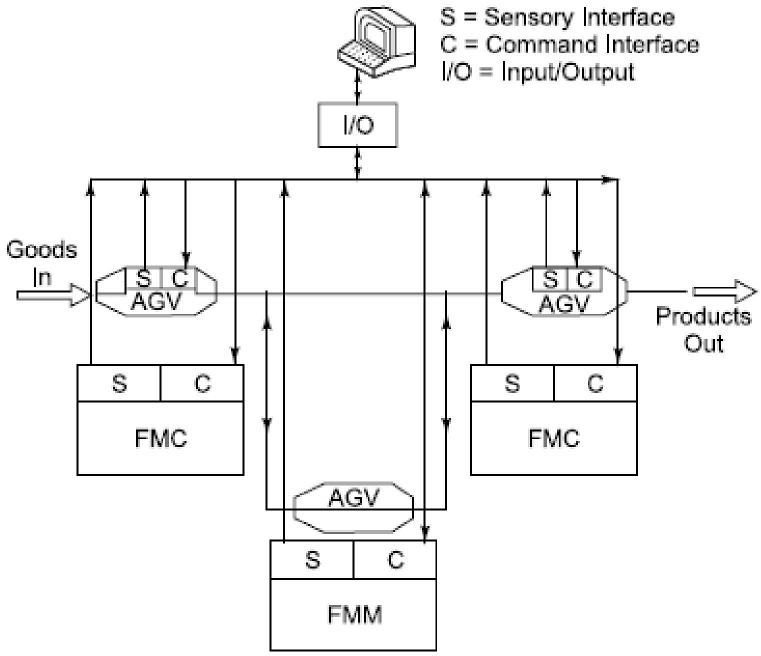
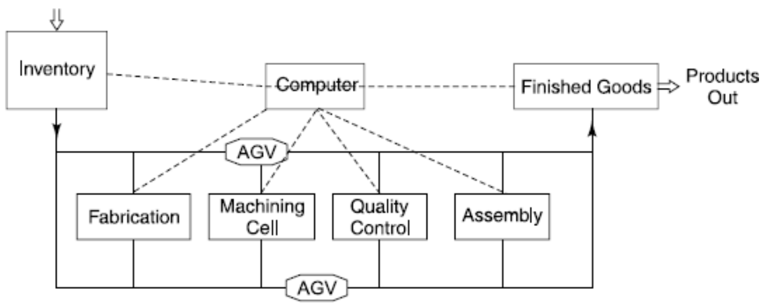


Figure 1.60 ***The flexible fabrication–machining–assembly system (FFMAS)***



In all these classes of FMS, robots and automated guided vehicle systems (AGVS) are extensively employed.

In flexible manufacturing module, a robot may be employed to load and unload parts or tools to a single computer numerically controlled (CNC) machine.

In flexible manufacturing cell, a single robot may be busy loading several CNC machine units.

Flexible manufacturing group comprises the combination of flexible manufacturing module (FMM) and flexible manufacturing cell (FMC) of the same kind to do all jobs of fabrication or machining or assembly operations.

In flexible fabrication-machining-assembly systems (FFMAS), the basic module may include different kinds of FMS subsystems.

The potential manufacturing applications of industrial robots are:

1.	Material handling	Depalletizing/palletizing Transporting components Transfer of components/tools Bottle loading Parts handling
2.	Machine loading/unloading components	Loading parts to CNC machine tool Loading a punch press Loading a die casting machine Loading electron beam welding and laser beam welding machines Loading/orientating parts to transfer machines Loading parts on the test machine
3.	Spray painting	Painting of trucks/automobiles Painting of agricultural equipment Painting of appliance components
4.	Welding	Spot welding Arc welding Seam welding of variable width
5.	Machining	Drilling Deburring Sanding Grinding Cutting Forming
6.	Assembly	Mating components Riveting small assemblies
7.	Inspection	In-process measuring and quality control, searching the missing parts
8.	Others	Heat-treatment, applications of adhesives, etc.

The non-manufacturing areas of robotic applications are:

1. Hazardous environments

(i) Mining	Exploration Search and rescue Tunnelling for main roadways Operations in short passages
(ii) Municipal services	Fire fighting Underground (dangerous gas-filled) sewer clearing
(iii) Nuclear	Maintenance of atomic reactors
(iv) Space	Space vehicles
(v) Underseas	Oil/mineral exploration Salvage operations

2. Medical
   (i) Rehabilitation engineering for handicapped
   (ii) Non-invasive/invasive diagnostics
   (iii) Surgery
3. Distribution
   (i) Warehousing
   (ii) Retailing (for food industry or for retail industry)
4. Agriculture
5. Hobby/household purposes

Military applications of robots may be in both manufacturing and non-manufacturing areas.

1.10. MACHINE INTELLIGENCE, COMPUTER AND ROBOTICS—FUTURE TRENDS

Intelligence is the intellectual faculty of a human being. Many intelligent functions are involved right from the planning stage to marketing of the products. The brain work of a man can be simulated to a considerable extent by a computer system. But all computer systems are not intelligent. The digital computers that process information, manage data bases, provide design solution through modelling are not intelligent systems. Even the computers that provide graphics are not intelligent. However, pattern recognition techniques are some of the attempts made in simulating some preliminary intelligent functions. When a machine is said to have some intelligent functions, it is referred to as *machine intelligence*. Machine intelligence in other words is called *artificial intelligence* (AI). Artificial intelligence draws heavily on the knowledge about the world or environment. These are sometimes referred to as *expert systems*. Artificial intelligence helps to acquire knowledge through various sensors and attempts to make inferences by the faculty of perception and interpretation. Artificial intelligence also makes an attempt to influence its environment by generating ideas either through language or through graphical displays and conveying information to another system in an intelligent way. Image processing is a low-level intelligent function done by an intelligent computer vision system.

Robots are important tools in the family of programmable or flexible automation technology. The first generation robots are deaf, dumb and blind and these robots can be taught by teach box to perform simple repetitive functions. Second generation robots contain inexpensive computers which improve some programming capabilities. These robots of the second generation are also not intelligent. Simple types of sensors are fitted and signal data can be integrated into the robotic system to follow the predetermined path.

The robots of the third generation include separate low-level processors for individual degrees of freedom and a central computer to supervise and coordinate a number of processors depending on the degrees of freedom. The basic idea of using multiple processors is to provide a hierarchical control system to bring flexibility to an automated system comprising a variety of machines, robots and other computer systems.

An intelligent robotic system consisting of many external sensors including vision, acquires knowledge, attempts to understand the environment from the sensory information by its reasoning and interpreting capabilities. High-level computer vision interprets images or natural scenes. Intelligent robotic systems use different robot computer languages like VAL, AL, WAVE, RAIL, MAL, AUTOPASS, RAPT, etc. mentioned earlier in Sec. 1.8. The softwares developed for robot languages are very much dependent on the computer hardware of the robots. However, present-day emphasis is to develop robot independent programs. The robot independent programming is sometimes known as task-level programming. For example, if a nut is to be fitted on a bolt, the task planner would specify the robot actions, like 'a nut is to be fitted to the bolt' instead of specifying the sequence of manipulating actions to be done by the robot in accomplishing the task, through robot programming languages. Task-level programming is suitable for assembly automation. Robotic systems using object-oriented languages would be able to communicate between robots and machines or between robots and humans more intelligently than the present man-machine-robot communication systems.

Future trends in the manufacturing industries point towards the use of intelligent work stations in the computer-integrated manufacturing (CIM) systems. Intelligent tele-robots have a great potential to be used in unstructured and hazardous environments as in mining, deep-sea, Arctic and Antarctic explorations. Smart robots will play an important role in homes and they can be user-friendly with handicapped persons. It is believed that the twentyfirst century would combine the full advantages of the solid-state revolution and information technology to make mechanized intelligent slaves or intelligent robots for relieving men from the burden of inhuman tasks. (The future trends discussed further in Sec. 10.8.)

1.11. FLEXIBLE AUTOMATION VERSUS ROBOTICS TECHNOLOGY

1.11.1.1. Flexible Automation

Flexibility refers to quick response to market changes and automation refers to the performance without aids of human efforts. In manufacturing sector, demand for variety is presently increasing faster than the demand for quantity owing to customer's competitive choice. In the capital goods sector, manufacturing of aircrafts, large diesel engines, military goods, rockets, locomotives, gas turbines, large motors, large pumps, mining equipment and mainframe computers, etc. produced on a smaller scale with wide varieties require modular reprogrammable, flexible and computer-controlled machine tools and equipments. The design and engineering costs also can be reduced by wider use of technologies like CAD/CAE, etc. Production planning, control and scheduling can be effected by means of CIM.

In the consumer sectors viz. watches, cameras, bicycles, PCs, domestic appliances, etc. produced on larger scale are manufactured usually on a dedicated plant. But, in case of wide variety of product design and product mix of shorter life cycle, flexible automation become useful.

In flexible automation, a wide variety of sensors including vision systems are used to get necessary feedback with hierarchical computer control or adaptive control.

Software is getting prime importance in place of hardware. In flexible automation, the machines are made to think and make decisions like human beings by using intelligence known as Artificial Intelligence (AI). In flexible automation, CAD, CAM, CNC/DNC Machines, Robots, Flexible Manufacturing Cell (FMC), Flexible Manufacturing Systems (FMS), different types of sensors using semiconductor technology to have a feel about the position, velocity, force/torque, acceleration, pressure, touch, etc. are extensively employed to manufacture variety of complex product-mix. The future plan lies in establishing an intelligent factory using adaptive controls of machines and pattern recognition devices. At present, AI is difficult to be applied due to cost constraints, though few expert systems have been attempted. The most important aspects in case of flexible automation are flexibility, adaptability, integration, computer control, intelligence and quality at a reduced cost.

1.11.1.2. Robotic Technology

Robots were introduced commercially around in 1960 when the actuators were either pneumatic or hydraulic. Early industrial robots were produced mostly for pick and place operations with point-to-point control. Robots with multiple degrees of freedom were difficult to control in the earlier period due to coordinational problems, constraints of high-power processors and lack of knowledge in digital control. They were mostly using analog control. With the advent of microprocessors, micro-electronic-based sensors and actuators like electrical drives with servo control, the robots became more flexible and versatile. In manufacturing of 60s and 70s, a number of machine tools used became numerically operated systems. The NC technology has been adopted with p-t-p and cp controls in robots. These NC robots can be interfaced with CNC machine tools and Machining Centres enhancing the ease of productivity of a wide variety of complex jobs. Robots using adaptable grippers and specially multiple degrees of freedom grippers are most suitable for manufacturing a wide variety of product-mix. Initially most of the robot programming and their software are proprietary controlled. Present day robots working on the principle of Mechatronics can be interfaced with CNC and other machines using NC technology. Simulation, particularly graphical simulation, assists in setting and programming large manufacturing cells and systems using CNC machines and robots. Even transfer lines are flexible. Today, multidimensional sensors including vision can be attached to the robots. Software programmability and information processing capabilities are added advantages of the electronically controlled present day robots, which can be adapted with other NC machines or standardized equipments used in manufacturing. This integration is an added strength of the robots. Infact, flexible automation technology is generic in nature. There are two classes of technology: Motive technology viz. mechanical, electrical, communication and computer technologies; and carrier technology viz. microprocessors, PLCs, mechatronics, MEMS technology, etc.

Robotic technology uses most of the motive (fundamental) technologies that can be integrated in flexible automation. Robots with suitable drives, sensors, programming ability, path control, obstacle avoidance algorithm, low artificial intelligence are most appropriate for use in flexible automation using 'the Carrier Technologies' like microprocessors, programmable logic controllers, computer-aided design (CAD) and computer-aided manufacturing (CAM).

1.12. SAFETY MEASURES IN ROBOTICS

The use of robots is to humanize the workplace. Human operators working in hazardous environment can be protected by proper use of robots. In industry, operations like spray painting, welding, forging, die casting, fettling and deburring justify the use of robots.

The robots may pose dangers to the human operators during (i) programming (ii) operating and (iii) maintenance of the robots. The operators engaged in robot programming must take precautions in testing the programs at the lowest speed and should use panic (stop) buttons in case of emergency.

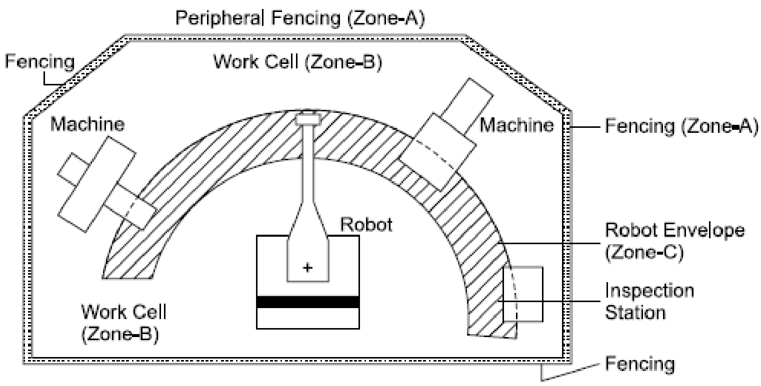
The important safety features remain in the design layouts of work cells. While laying out the cells, care should be taken to properly ground the electrical cables and arrange hydraulic or pneumatic lines in the proper way. During maintenance, the power mains should be switched off. During operations, proper guards and helmets should be used by the operators to avoid physical injury.

The following safety rules and measures, if followed, would protect the human operatives from accidents:

1. A fencing around the work cell in which the robot is interacting with the peripheral machine should be arranged. There should be gates to have an access or an exit from the work-cell. The gates may be provided with an interlocking device so that if the gate is opened, the action of the robot is interrupted. However, safety sensors may be used to make the safety foolproof.

Figure 1.61 illustrates the locations where the safety sensors have to be used in a robotic work cell. There are three distinct zones. The first is the periphery or area of fencing (Zone-A). The second is the area in the work cell (Zone-B) other than the robot envelope. The third is the area of robot envelope (hatched section, Zone-C).

Figure 1.61 Safety sensors to be located at different zones



Pressure mats on the floor are excellent sensing devices to provide safety in areas A and B. Anyone standing on the mat will activate the sensors to interrupt the robotic action. Pressure mats sometimes give warning alarms also. The robot arm and wrist may be provided with a proximity sensor to sense and detect the range in case of intrusion by anyone within the robotic work envelope. Speed monitoring to a reduced and safer level and principles of obstacle avoidance may follow the detection of intrusion by the sensors so that the robot motion may be diverted to avoid direct collision. Light sensors with photosensitive devices may also be used to detect the presence of a human operative interrupting the light beam if he enters into the zones of the work cell.

Safety is an important issue and should not be overlooked. Proper training and education in the safety rules should be undertaken to increase awareness and avoid accidents. Governments of different nations have framed safety rules for robotics devices.

1.13. EXERCISES

1.1 What do you understand by degree of freedom (DOF)? How many DOFs are required to position an end-effector at any point in 3-D space?

1.2 What are the different configurations of robots? Which of these configurations would be the most suitable for the following:

a. placing a component in a CNC machine tool
b. picking a part from a moving conveyor
c. placing an object in an oven for heat-treatment
d. painting a motor car body
e. welding a steel almirah frame
f. inserting a peg into a hole

Explain your choice.

1.3 What is the work envelope of a robot?

1.4 Sketch two views to indicate the work envelope of a

a. cartesian robot
b. cylindrical robot
c. polar robot
d. anthropomorphic robot

1.5 Distinguish between servo and non-servo robots. What is the hierarchy of control for servo robots?

1.6 What is a robot? Is Robotics an automation? What is flexible automation? Distinguish between hard automation and flexible automation.

1.7 What is point-to-point control in a robot? What is continuous path motion? Distinguish between joint interpolated motion and controlled path motion. Which method of motion control would be the best for spray painting by the robot?

1.8 What are the basic components of a robotic system? State the main function of each of the components.

1.9 What are the different types of actuators used for robots? What are the advantages and disadvantages of each? What are piezoelectric actuators? Mention some application areas of MEMS technology.

1.10 What are the common methods of teaching a robot? State the merits and demerits of each.

1.11 With the aid of a schematic diagram, describe briefly the working principle of a bang–bang robot.

1.12 Name at least three different types of grippers or end-effectors for robots. What is the advantage of each?

1.13 How do you specify a robot? Distinguish between the accuracy and repeatability of a robot.

1.14 What are the different classification systems of robots? To which category do Unimate Puma and Cincinnati T^3 robot belong?

1.15 How do you classify a robot end-effector? Mention some of the commercially available robots using these robot wrists.

1.16 What is a programmable controller?

1.17 What are the advantages of hydraulic actuator systems over electrical motors? What are different types stepper motors? State their principle of working. Briefly describe the advantages of using d.c., a.c. and stepper motors as robot drives.

1.18 State the advantages and disadvantages of a pneumatic drive, hydraulic drive and electrical drive in tabular form.

1.19 Briefly enumerate a chronology of historical events in the development of robotics.

1.20 What is the status of robots in the family of flexible automation technologies?

1.21 What are the common sensors used in the robots? State at least five different types of sensors mentioning the specific attribute to be measured by each.

1.22 Distinguish between tactile and non-tactile group of sensors used in robots. State three types of sensors for each group.

1.23 What is meant by machine intelligence? What is AI? Illustrate a unified model of AI and Robotics.

1.24 What are the different robot applications in industries?

1.25 What are the important items to be considered in deciding the use of robots in

a. manufacturing operation

b. hazardous operation

1.26 With the aid of sketches, describe briefly pitch, yaw and roll motions of a robot wrist.

1.27 Write short notes on the following:

adaptive control, AI, programmable automation, bang–bang control, proportional control, batch manufacturing, CAD/CAM/CIM, CPU, CCD camera, CNC, PTP/CP robot control, cartesian/cylindrical robot, encoder, end-effector, robot feedback, flexible manufacturing, group technology, hierarchical control of robot, high-level robot languages, I/O interface, master-slave manipulator, open loop/closed loop systems, programmable controller, RCC, teach pendant, transfer line, vision robot.

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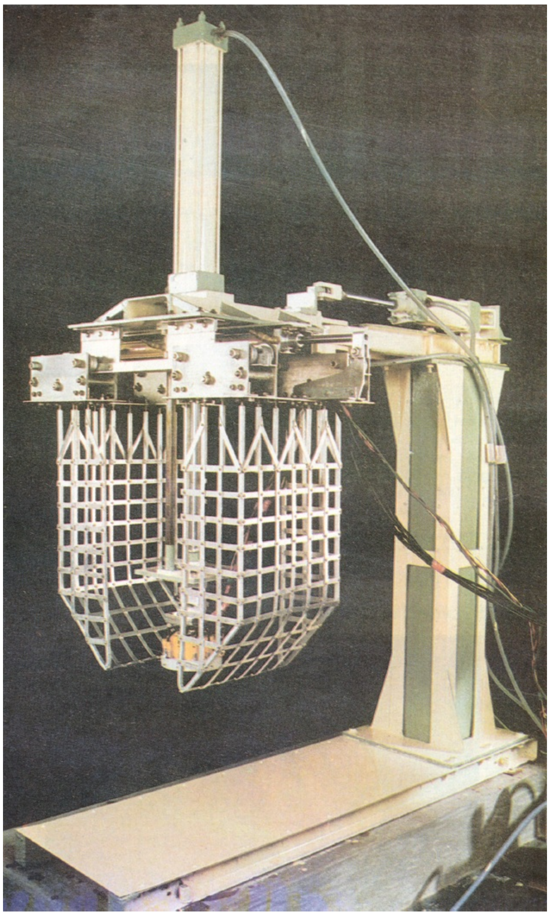
Photographs courtesy:

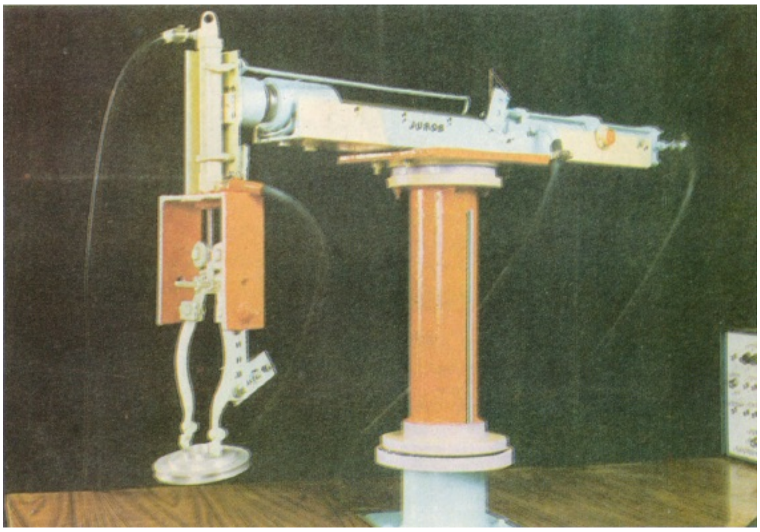
Robotics Laboratory, Jadavpur University

1. *A 4-axes electrically driven SCARA 'ADEPT-1' Robot*

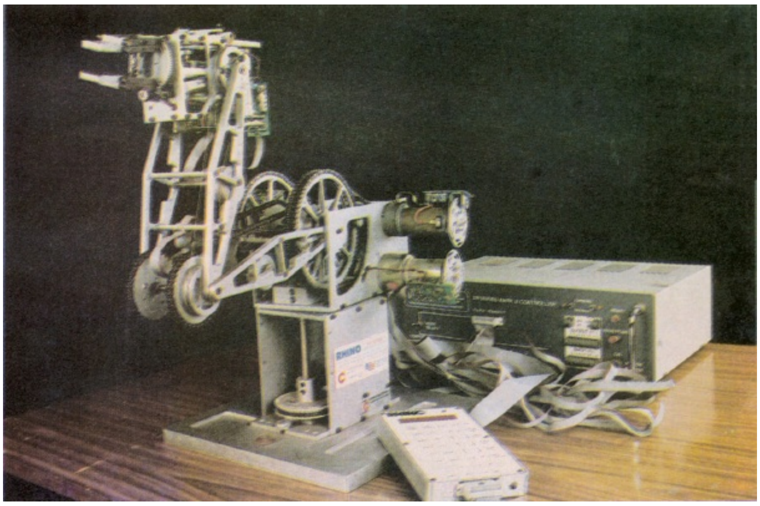
2. *A 6-axes electrically driven revolute 'PUMA' Robot*



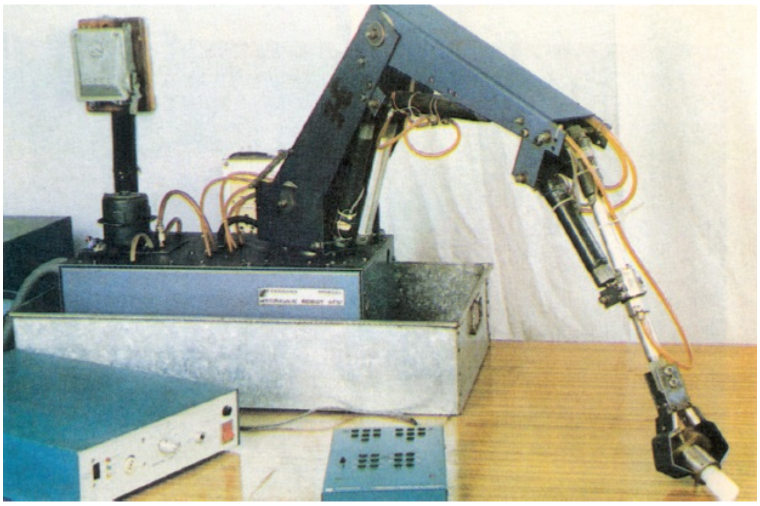
3. *A 'JU' manipulator fitted with a magnetic gripper and gripping fingers*



4. *A pneumatically actuated 'JUROB' manipulator*



5. *A 5-axes electrically driven revolute 'RHINO' Robot (teaching type)*



6. *A 6-axes hydraulically driven revolute 'FEEDBACK' Robot (teaching type)*

7. *A stepper motor controlled 6-axes revolute 'ARMOROID' Robot (teaching type)*