Robotics Simplified

An Illustrative Guide to Learn Fundamentals of Robotics, Including Kinematics, Motion Control, and Trajectory Planning

DR. JISU ELSA JACOB
MANJUNATH N

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Dedicated to

To all my beloved ones. . .

Especially to my parents, husband
and my lovely daughter Joanna

Jisu

To all those who inspired it.

Manjunath

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Acknowledgement

In this book, we have made a humble attempt to present a simple, self-explanatory, and structured content for learning the basics of robotics. We urge all the readers to utilise this book to its full potential and feel free to send your comments and suggestions to us.

We acknowledge the authors of the leading books in this subject, some of which are mentioned in the references. They have helped us in understanding the concepts and have enabled us to expand our knowledge as well during the process of writing this book.

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Jisu Elsa Jacob

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Preface

Robotics is an interdisciplinary area of science which demands integration of mechanical engineering, electronics engineering, control theory and computer science for designing the system and managing and controlling its operation. The technology is so relevant to the present age that its applications include all areas including medical, defense and industrial automation. Most of the books available now in robotics provide only the basics or fundamentals without including the technical know-how about robotic technology which in turn leaves the reader clueless. This book attempts to bridge the gap between theoretical basis and application of robotics. Most of the available literature in this field are written either with a greater affinity towards Mechanical Engineering, or solely based on the instrumentation of robots.This book is written in such a way that any professionals, students and engineers of all disciplines can equally understand and follow since it provides all basics of robotics.

The book is divided into five sections. **Section 1-Introduction** introduces the readers to the major terms in robotics and explains the key concepts in this subject. **Section 2-Robot Components** covers the hardware of robot system which mainly includes end-effectors, sensors actuators and vision systems.Various hardware components and robot's physical systems have been discussed in chapters 2 to 5 coming under this section. **Section 3-Robotic Dynamics** covers the basic concepts and theoretical explanation related to robot kinematics. **Section 4-Robotic Control** explains the control systems, theoretical basis and various control systems that are employed in robotics. It covers various examples and numerical problems related to this topic. The book concludes with **Section 5-Applications** which explains the application of robotics in various areas.

Over the 11 chapters included in this book, you can learn and understand the following topics:

Chapter 1: Introduces the basic concepts of robots, definition and history of robotics and evolution of robots. This chapters gives an overview of the anatomy of robot and various areas of application.

Chapter 2: Discusses the significance of end-effector in robots and various types of end-effectors and grippers. The advantages and disadvantages of various end-effectors have been discussed in detail.

Chapter 3: Explains the various possible sensors that can be used for robotic vision. Their specifications and various types are explained in detail in this chapter.

Chapter 4: Describes the use of various actuators, which are the muscles of the robot. Various types of actuators are explained in detail in this chapter including the comparison of various actuators and their applications. This chapter also describes how to control electric motors using microprocessors.

Chapter 5: Gives a basic overview of robotic vision systems including the various image processing techniques. The various algorithms of image processing techniques have been explained in this chapter with simple examples.

Chapter 6: Aims to draw parallels to the basic Newtonian mechanics from elementary schooling to understand the relative motions of robots. Robots being an assemblage of rigid bodies having relative motion, a detailed discussion of freedom of movements, types of motions and their analytic representations.

Chapter 7: Discusses in detail of forward and inverse kinematics in robotics and D-H representation of robot kinematics of standard robotic configurations.

Chapter 8: Explains about the velocity, acceleration linked with the robotic motions. With an insight on velocity kinematics the trajectory or path planning methods and algorithm of robot links are provided in this chapter

Chapter 9: Describes the control systems and its basics. Various types of controllers like proportional-plus-integral controllers, proportional-plus-derivative controllers, and proportional-integral-derivative controllers are discussed and numerical problems are included in this chapter.

Chapter 10: Describes the basics of robot programming. It explains various types of robot programming and includes the basic commands in VAL programming. Some examples with VAL commands, MATLAB and PYTHON programming have been included in this chapter.

Chapter 11: Elucidates the numerous intelligent applications of robots invarious fields of human life. The chapter exclusively debates on a few important fields of robot applications, such as defense, space, medical, and industrial sectors.

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CHAPTER 1

Introduction to Robotics

Introduction

The word creates an image of a human look alike machine in a listener's mind. The inducement for this perception is the influence of fictional literature, motion pictures, and mythology. Mankind was obsessed with reducing the effort in doing things, which led to the invention of tools, and later, machines. It can be seen even from the mythologies that humans always fantasized of artificially creating their replicas for sharing efforts, stress, and sometimes for special purposes (like killing giants or monsters as in myths!). But, the word robot in the modern world means a lot more than just anthropomorphic machines. Now, the word robot represents a wide spectrum of automated machines that can do almost any job. Initially, industrial robots were employed to do repeated and unskilled jobs, whereas now they are capable of replacing people from hazardous, highly accurate, and too precise or boring and hectic jobs. Robots became the means to perform jobs with better accuracy and precision along with higher speeds, which resulted in higher productivity and better efficiency.

Extensive variety of robots have been devised till date, ranging from space robots in outer space exploration to nano-robots employed at the cellular level of organisms. This book aims at broadening the horizons of a reader's idea of robots or even robotics for that matter. Our book offers a simple yet structured knowledge foundation for this intriguing interdisciplinary field of science.

Structure

In this chapter, we will discuss the following topics:

History of robots

Definition of robots

Laws of robotics

Classification of robots

Anatomy of robot

Robot characteristics

Robot configurations

Areas of applications

Objective

The main objective of this chapter is to break all the fictional notions about a robot and robotics and to help readers build scientific foundations instead. The readers will be able to appreciate and differentiate the concepts of a robot and robotics. This chapter gives a very simple definition of a robot, how it evolved over years, and unraveling of robotics into diverse fields of application. The subsections in this chapter will be useful as a roadmap to all other chapters in this book. Explanations of the various types of robots and their areas of applications are incorporated in this chapter to give an understanding to the readers about the characteristics and specifications of robots.

History of robots

The term *robot* originated from the Czech word which means *forced* or *compulsory* The word robota was introduced by the Czech writer *Karel Capek* in 1922 in his play named **Rossum's Universal Robots** This story portrayed robots as machines that resemble people, and they work tirelessly. In 1927, there came a German film that was based on robots, named Metropolis, which includes Electro, a walking robot, and his dog, Sparko.

Even though the robots started evolving to its modern form from the second half of the 20th century, the idea existed and was crafted from the early 15th century. Those machines are not known as robots but as *"automatons"* (plural: automata). Automata (means self-acting; Greek) are self-powered self-acting machines or devices that can often carry out a sequence of predetermined operations. Then, the term automata were used for any device that could mimic human actions. Automata were robots theirs ages; however, they are not comparable to modern robot definitions.

Influence of myths and fictions: Imagination fuels both the artistic and scientific expressions of humans. Arts and science had always influenced and nourished each other. Things that were once branded as impossible or daydreams are now so real. This is true in the case of robots as well. Greek, Hebrew, Hindu, and many other mythologies mention the use of robots or automata in them. In Greek mythology, there is a giant metal robot made by Hephaestus for safeguarding against pirates, made of ivory by *Pygmallion* was brought to life by goddess Living statues made of bronze by etc. can be inferred as ancient fictional robots. *Tripodes Horses of the Khalkotauroi Golden celedones* all these can be counted as automata according to the Greek myths. The Golems made of clay and given life by magical chants are introduced in Hebrew mythology. *Sakatasur,* a shape shifting demon who can take the form a cart, can be reckoned as a robot, and clockwork mechanisms for creating illusions in the palace of *Indraprastha* made by *Viswakarma* can be considered as automata in Hindu mythology. Apart from mythologies, fictional stories, such as *Frankenstein* by *Mary The Sandman* by *E T A Wizard of Oz* by *Frank Baum,* etc., have some kind of robots or characters resembling robots in them.

The words of famous scientist and inventor, *Thomas A Edison is one percent inspiration and ninety-nine percent* Now, let us see some of the milestone events in the history of robots created by some real-world geniuses who made all those imaginations a reality:

Al-Jarzai published a book of comprehensive knowledge of all mechanical automations of that time. He is considered as the father of robotics by some.

Leonardo da Vinci created a metal-plated warrior that can move its head and open its visor.

Hans Bullmann made first androids in human form.

Jacques de Vaucanson invented 3 automatons, a metal duck, the flute player, and the tambourine player.

Friedrich Kaufmann invented a mechanical trumpet player.

Hisashige Tanaka invented the method making mechanical dolls in Japan.

Thomas Edison invented a talking doll.

Seward Babbit and *Henry Aiken* designed the first crane having a gripper.

Karl Capek introduced the term Robota for humanoid machines in his play RUR.

Fritz Lang gave publicity to the word robot through his film Metropolis.

Roy Wensley made *Herbert* the first ever humanoid robot for Westinghouse Company.

Makoto Nishimura created a humanoid robot that can move, write, and make facial expressions.

A smoking, talking, and walking robot named *Elektro* was displayed in New York world's fair.

Elektro's dog, *Sparko* that could move forward and back, sit down, turn its head, wag its tail, and bark was also added in world's fair show.

Isaac Asimov in his fictional story Runaround coined the word "robotics" and three golden rules for the robots.

George Devol developed the magnetic controller, a playback device.

MIT built first **Numerically Controlled** machine.

The first programmable robot was built by *George*

Denavit and *Hartenberg* developed a simple representation of homogeneous transformation matrices for forward kinematics.

George Devol received a patent for an arm-type industrial robot that was to be manufactured by Unimate for General Motors (GM).

The first robotics company Unimation was formed by *Joseph F Engelberger* (considered as the father of robotics) and *George Devol* in Danbury, Connecticut. The first industrial robot Unimate was operated on the GM assembly line. It was a robotic arm for transporting die castings from assembly line and for welding those parts on auto bodies.

Mark II robot was released by Unimate in Japan for spray painting applications.

Stanford Research Institute developed the first intelligent robot Shakey, provided with three rotation motions and a vision system. It can be considered as the early experiments of Artificial Intelligence (AI) in robotics.

Victor Scheinman developed Stanford Arm as a research protocol in 1969.

Cincinnati Milacron released the T3 (The Tomorrow Tool) robot arm, which was designed by *Richard Hohn,* which can be considered as the first commercially available industrial robot that can be controlled by a mini computer.

The company ASEA (now ABB) introduced the first microcomputer-controlled (using INTEL chipset) electric industrial robot named IRB-6, allowing continuous path motion with movements in 5 axes and with a lift capacity of 6 kg.

The first **Programmable Universal Machine for Assembly** robot was developed by *Victor Scheinman* for GM at Unimation.

Hiroshi Makino developed Selective Compliance Assembly Robot Arm (SCARA) in Yamanashi University, Japan. The ground-breaking 4-axis low-cost design was perfectly suited for small parts assembly as the kinematic configuration allows fast and compliant arm motions. Flexible assembly systems based on the SCARA robot can be utilized in conjunction with compatible product designs.

GM and FANUC of Japan signed an agreement to start jointly *GMFanuc Robotics*

Honda introduced its first humanoid robot called E0, the first two-legged robot that could walk. Here, represents model, the first bi-pedal (two-legged) robot was made to walk.

Rodney Brooks developed Genghis, which is a six-legged autonomous walking robot in the **Massachusetts Institute of Technology**

Waseda University Humanoid Robotics Institute developed Hadaly-2, a humanoid robot that can interact with humans.

Waseda University Humanoid Robotics Institute developed WABIAN series that incorporated humanoid walking.

First "affordable" personal robot called Cye robot, which was developed for applications in homes and offices without the need of any heavy programming techniques to operate it.

Da Vinci medical robotic system was developed for laparoscopic surgeries.

Honda creates a humanoid robot Advanced Step in Innovative Mobility (ASIMO).

Fujitsu developed HOAP-1, its first commercial humanoid robots. HOAP series are designed for applications of **research and development** in robotics.

Technical University of Munich developed JOHNNIE, which is an autonomous walking robot to realize anthropomorphic human-like walking model, which has a dynamically stable gait.

A robot with realistic silicone *"skin"* called **Actroid** was developed by Osaka University with Kokoro Company Limited.

Mitsubishi Heavy Industries developed a robot to provide assistance to elderly and disabled humans.

KUKA lightweight robot, a compact 7-DOF robot arm with advanced force-control capabilities. The reduction of the mass and inertia of robot structures was a primary research target, where the human arm with a weight-to-load ratio of 1:1 was considered the ultimate benchmark.

Robonaut a highly advanced humanoid robot was developed by NASA and GM for enabling space walks for NASA.

2012 : *Curiosity Rover* of NASA touched down in Mars.

first talking humanoid astronaut developed by Japan deployed in the **International Space Station**

Pepper developed by SoftBank Robotics can recognize faces and basic human emotions.

Sophia first ever humanoid robot to get citizenship was developed by Hong Kong-based Hanson Robotics.

Rossum's Universal Robots

In this play, a scientist named Rossum develops the idea of creating human-like machines to assist people in their work with more precision and with more reliability than human beings. Because of this, robots grew tremendously huge in number, and after some years, they started dominating the human race and threatened it to extinction, though it was saved at the last moment.

Definition of a robot

Encyclopedia Britannica defines a robot as *automatically operated machine that replaces human effort, though it may not resemble human beings in appearance or perform functions in a humanlike* Whereas the Oxford dictionary defines a robot as *machine that can perform a complicated series of tasks* The above given two definitions are generic ones that label robots only as automatic machines. However, the international organizations dealing with robots define it more in an industrial context rather than indicating its broader aspects. Let us check some definitions of robot by some national and international robot associations.

The **Robotics Industries Association** of the USA defines a robot as, *reprogrammable multifunctional machine designed to manipulate material, parts, tools, or specialized devices through variable programmed motion for the performance of a variety of* But, the earlier versions of robot definitions by RIA had the term "*manipulator,*" which literally indicates an arm in it, *robot is a reprogrammable multifunctional manipulator designed to move material, parts, tools, or specialized devices through variable programmed motions for the performance of a variety of* By defining so, they gave a notion of all robots are machines that must have arms, but the drastic changes in robotic technology forced them to streamline their narrative.

According to the **British Robotic Association** *industrial robot is a re-programmable device designed to both manipulate and transport parts, tools, or specialized manufacturing implements through variable programmed motions for the performance of specific manufacturing* The British added the transportation aspect in their definition and without specifying need of a manipulator. The BRA is now **British Automation and Robotic Association**

International Standard of Organization formally defined a robot as, *automatically controlled, reprogrammable, multipurpose manipulator programmable in three or more axes, which may be either fixed in place or mobile for use in industrial automation applications: ISO*

Similar definitions were given by various other societies like **Japan Industrial Robot Association** and **Swedish Industrial Robot Association** all of which emphasized the are and *"multifunctionality"* of robots. These two specialties of the robot make it unique and different from **Computer Numerical Controlled** machine tools.

Dr. Antal Bejczy of NASA's Jet Propulsion Laboratory enlightened the definition of robots as: *are three parts to the technical definition of robots. First, robots are general purpose mechanical machines. Second, they are programmable to perform a variety of work within their mechanical capabilities. Third, they operate* From his explanation, automation is the crucial element that is spearheading the state of the art in robotics. And, his account helps us to correlate between the bonding of mechanical engineering, electrical and electronic engineering, and computer science in the world of robotics.

Robotics is the field of engineering is *with the design, construction, and operation of robots in* And, by ISO, robotics is defined as the *and practice of designing, manufacturing, and applying* robots."

Laws of robotics

Isaac Asimov (1920–1992), apart from a professor of biochemistry, was one of the famous science fiction writers of his time. In 1940s, Isaac Asimov projected a robot as a helper of humankind in his science fiction stories to remove the concern among people that robots will take away people's jobs. He postulated three basic rules, which are known as **laws of** They are as follows:

A robot must not harm a human being, nor through inaction allow one to come to harm.

A robot must always obey human beings unless that conflicts with the first law.

A robot must protect itself from harm unless that conflicts with the first two laws.

All these laws were introduced in Asimov's science fictions, and later, he and many authors attempted to correct the ambiguity related with the laws. Even though these laws may sound conceivable, they were a work of fiction rather than based on any scientific rationale.

For instance, the state of the art of robotics has robots employed in military and medical fields. The robots designed for military or defense operations may find their commands in conflict with the fundamental laws. The same can happen for a robot employed in surgical applications when it is required to amputate a limb of human or carryout an abortion of a pregnancy. Advancement in **AI** are only increasing the difficulties in framing a comprehensive set of rules instead of easing them.

The major flaw in the Asimov's laws is that they are based on a cognitive bias or a faulty assumption that we humans know exactly the ethical boundaries. But do we? The never-ending and ever-worsening global tensions point the other way.

Hence, as there are numerous conflicts that arise from the inadequacy of the so-called "**laws of** we need a set of comprehensive laws with a solid scientific foundation, and they should be constantly improvised to adapt with advancement of robotics.

Classification of robots

The classification of robots is a simple yet confusing process as there are many disciplines and varieties involved. This section provides a generalized classification scheme for robots that can help the readers get acquainted with most of the existing robot varieties. Figure 1.1 gives a generalized classification of robots. Robots can be broadly classified as **fixed** and **mobile** robots. The requirements for a robot vary based on their working environment and tasks. Many industrial robotic manipulators that work in well-defined environments are fixed robots. Fixed industrial robots can perform specific repetitive tasks such painting or soldering, which do not demand the movement of robots. Such robotic manipulators are also being used in healthcare like for carrying out high-precision surgery to aid the surgeons.

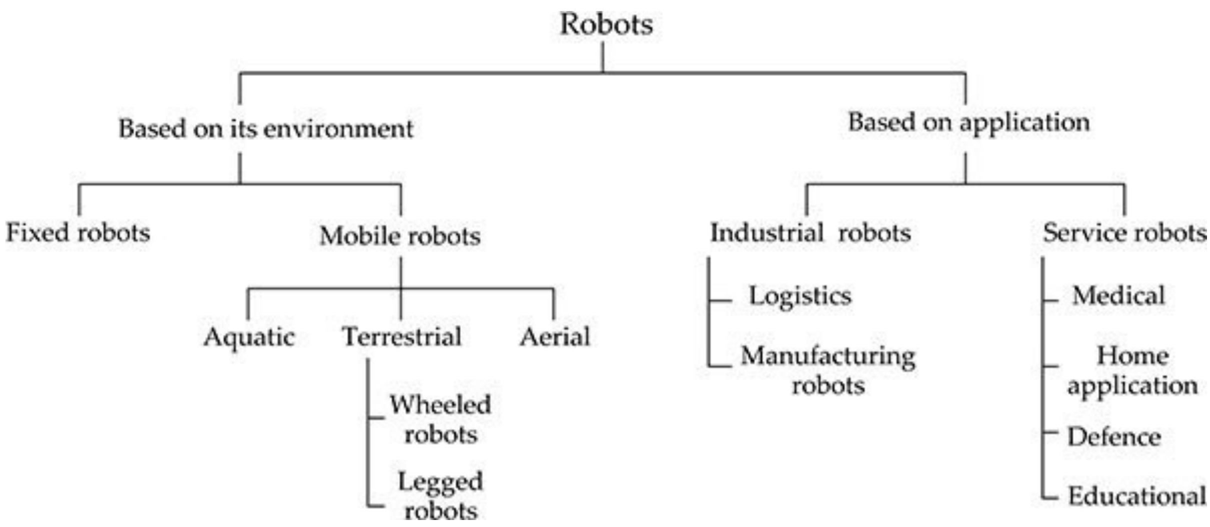

Figure 1.1: *Generalized classification of robots*

Whereas some robots have to move around and perform tasks in a large area that cannot be predefined or may not be repetitive and also to be performed in not so well-defined working environments. Such robots are mobile robots that are required to deal with uncertain situations and environments that are not predefined and that can change over time.

In particular, fixed robots are attached to a stable mount, called base, on the ground, and it operates with the arm by computing their position based on their internal state. But, in case of mobile robots, the location for their movement should be computed by perceiving the environment using various powerful sensors. Based on the environment of operation, they can be further classified as: and *aerial* robots. Also, for some applications, a robot needs to move on both ground and in water. Such robots are called amphibious robots. A terrestrial robot, which is meant to move on the ground, can be further classified as wheeled robots and legged robots. Aerial robots can be divided into fixed-wing and rotary-wing type.

Based on the criteria of application, robots are classified as industrial robots and service robots.

Industrial robots are comparatively less complex, because the well-defined environment simplifies their design. Industrial robots were first designed to do repetitive jobs with lesser accuracy and precision, but now, robots are designed to outperform humans in accuracy and precision. The most common applications of robots in industries include pick and place, material handling, assembly, welding, painting sorting, packaging, sealing, inspection, etc. Now, even small-scale manufacturers employ robots in their firms to make the processes cost-effective. Some of the reasons for wide acceptability of industrial robots can be listed as follows:

Nature of work: repetitive, dull, heavy, extreme, etc.

Maintenance cost of robots is less compared to ever-rising labor costs.

Better accuracy in process and good-quality products.

Unavailability of skilled labor.

Quick movement down the production line.

Less human interference.

Computerized inspection and quality checking provisions.

Safer work environments.

Robots can be easily reprogrammed to comply with change in products or process.

Robots can work around the clock and during all days of the year.

Service on the other hand, assist humans in their tasks. These include chores at home like vacuum cleaners, transportation like self-driving cars, and defense applications such as reconnaissance drones. Medicine, too, has seen an increasing use of robots in surgery, rehabilitation, and training. The **International Federation of Robotics** defines service robots as *robot which operates semi: or fully autonomously to perform services useful to the well-being of humans and equipment, excluding manufacturing* Service robots are a vast subfield of robotics and a promising future technology with abundance of amazing possibilities. Service robots that assist humans with their daily chores, education, and entertainment, help to socialize, serve as a support for elderly and physically challenged people, etc. are sometimes referred to as personal robots. Apart from personal robots, service robots are employed in different capacities, such as in logistics, security, defense, agriculture, surveillance, etc. Still, newer applications of service robots are being invented day-by-day.

Now, we shall look into the classification of robots defined by some robot organizations of the world. The **Japan Robot Association** previously JIRA, the Japan Industrial Robot Association) provides six type classifications for robots as follows:

Class 1 – manual manipulator: Operator-controlled or teleoperated robots having multiple degrees of freedom. Some robots belonging to this category are known as co-bots.

Class 2 – fixed-sequence robot: A robot that performs predetermined set of tasks following a sequence of commands from a specific program.

Class 3 – variable-sequence robot: This robot is similar to the second type but can be reprogrammed in order to modify the tasks performed or to add new ones.

Class 4 – playback robot: This type of robot requires an initial walkthrough by an operator; robot records the sequence of operations and can repeat those actions henceforth.

Class 5 – numerical control robot: This type of robots can be reprogrammed easily by changing the NC program or codes at the will of the operator. The NC program can be modified easily with numerical data.

Class 6 – intelligent robot: Robots that can understand, adapt, and respond to the changes in its environment to perform its assigned task.

Similar to JARA, the **Association Francaise de Robotique** classifies robots into four types:

Type A: Manually controlled or teleoperated robots similar to JARA Class 1.

Type B: Robots functioning on the basis of predetermined cycles. Comprises Classes 2 and 3 of JARA. Type B1 corresponds to JARA Class 2, whereas Type B2 corresponds to Class 3.

Type C: Servo-controlled programmable robots (termed as the first-generation robots) that covers Classes 4 and 5 of JARA. Type C1 are robots with less than 5 programmable joints, and Type C2 has more of such joints.

Type D: Intelligent and adaptable (second-generation) robots; equivalent to JARA Class 6.

Third-generation robots, according to the AFR, have the ability to understand natural languages, 3D vision, etc. However, the classifications of different robot organizations may vary according to the industries they represent. For instance, the RIA does not agree with the 1 and 2 classes of JARA.

Androids and cyborgs

Android and cyborgs are two terms that often get confused with robots, yet they are not the same. An android is an *resembling a human being in form and* Similar to a robot, the word android also has its roots in science fictions. The word android began to be used in the more modern sense after its usage in a fictional story named Tomorrow's Eve (1886) by its French author *Auguste Villiers de* In the story, androids are defined as robots with indistinguishable human appearance and physical abilities. But, nowadays, the word android is more popular by a mobile operating system used in most of the smartphones.

A cyborg is an integration of a machine and an organism, mostly human, to extend and enhance his/her physical abilities. "Cyborg" is a hybrid of "cybernetics" and "organism." The word cyborg was coined by Manfred Clynes in his article named *and* in the September 1960 issue of the journal Astronautics. Cybernetics was an emerging area of science then. It is the science of control systems in engineering and biology. The word cybernetics was first used by Norbert Wiener. The word cyborg got its popularity similar to the words androids and robots; from fictional stories, especially from DC comic series.

Anatomy of a robot

Robots are of different types and forms, making it puzzling for us to compare and equate between them. Still, the robots can be compared and contrasted by the functional analogy of their subsystems. Almost all robotic systems need some fundamental subsystems so as to fulfil their intended functions, whatever that may be. Any robotic system can be divided into three subsystems as follows:

Motion subsystem: The *motion subsystem* includes the physical structure of the robot that is responsible for carrying out the desired motion similar to human arms. This subsystem consists of all the elements of the robot that provide structural rigidity to the robot, all components of the actuation systems and the transmission system. The structural members of robots include different types of links and joints, including the base and tool. Actuation systems are of different types; their function is to power and execute the required movements of target link. A transmission or drive system helps in the propagation of motions, to vary the speed or power and the direction of movements.

Recognition subsystem: The *recognition subsystem* includes various sensors that are the input device to the robot, providing information about the robot itself and about its surroundings and about the object on which it has to act. Robot works on the basis of the information received from various sensors like vision sensors, touch sensors, etc. The recognition subsystem includes the sensors as well as the **Analog to Digital Converter** components.

Control subsystem: The *control subsystem* controls or impacts the motion of the robot and directs it to achieve a particular goal or perform a given task using the information provided by the recognition subsystem. The control subsystem consists of a digital controller (computer/processor, memory devices, input/output devices, software, etc.), **Digital to Analog Converter** components and amplification systems. *Figure 1.2* shows the major components of a robot.

Instead of requiring a mechanical engineer for working on motion subsystem, electronics engineer for sensors and recognition subsystem, and electrical engineers for control systems, the robotics field demands people with knowledge in all these areas to work together, thus making it a highly interdisciplinary area. In areas like robotics, we can see people working out of their specialization for developing highly efficient robotic systems.

As robotics is a very vast, diverse field and our book deals with deeper discussions about robotic manipulator or industrial robotic arm, let us understand the anatomy of a robotic arm. A robotic arm or manipulator is analogous to a human arm in function and structure. It resembles the human arm from shoulder to fingers, yet the parts are named accordingly. The major difference being the last portion of the manipulator is called an end-effector instead of a hand:

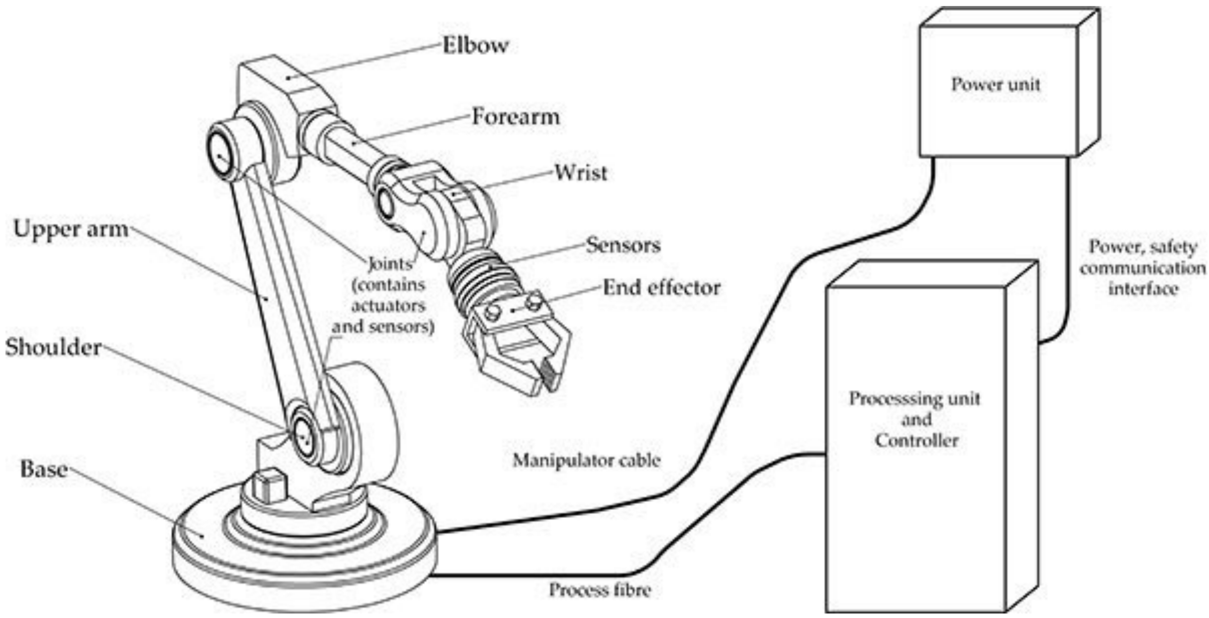

Figure 1.2: *Different components of a robot system*

The major physical parts of a manipulator consist of wrist, forearm, elbow, upper arm, and its base, as shown in [*figure*]. It contains many links and joints (also called **kinematic** that are normally connected in series. The joints are generally rotary or translational types. In the context of robotics and its mechanisms, the joints are classified as revolute and prismatic joints. The hinge of a door is a simple example for revolute joint, and a piston-cylinder arrangement is an example for prismatic joint.

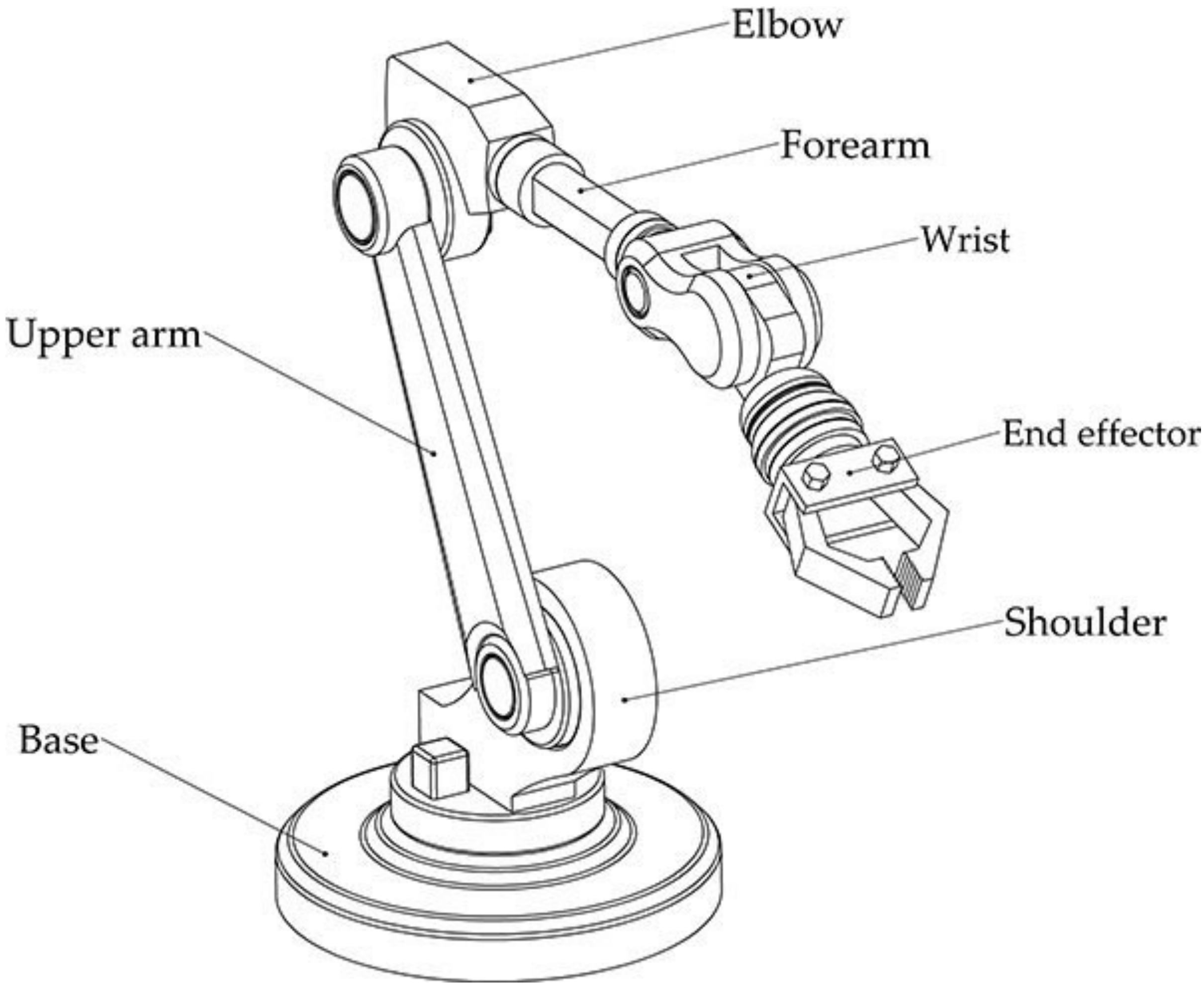

Figure 1.3: *Different components of a manipulator*

A manipulator consists of links, joints, and other major components of the robot, such as sensors, actuators, and end-effectors of the robot. In many literatures, the terms robots and manipulators are used interchangeably to refer to robots. But the word "manipulator" in the context of robots means a robot that has an arm-like structure.

End-effector

An end-effector is attached to the end of arm, that is, the last joint of the manipulator, and is designed to handle or grip various objects, perform certain tasks, and make connection with other machines. The positioning of the end-effector is primarily controlled by the arm and wrist assemblies. A robotic arm is provided with wrist, and an end-effector is attached to it, which performs certain task or gripping certain objects. End-effectors mainly are of two types: *grippers* and

Grippers are used to grip or hold various objects. They are selected on the basis of the object to be gripped. Different types of grippers include mechanical grippers, magnetic grippers, adhesive grippers, vacuum cups, etc. *Tools* are end-effectors that are specifically used for certain task or applications like welding or painting. Generally, the hand of a robot or manipulator is provided with arrangements for attaching various end-effectors that are specifically designed for a particular task. Various tools include a welding torch, a paint spray gun, spot welding gun, rotating spindles, etc. Several factors have to be considered for selecting a tool to connect to the robot for a particular task. It includes the weight of the tool, the positional and angular accuracy with which it must aligned with the work piece, the sensing technique to be utilized, the extent of rigidity with which the tool can be held, reliability, etc.

In most of the cases, an end-effector is controlled by the controller of the robot, and its motion is controlled by robot programming. The robot controller communicates with the controlling device of the end-effector. Thus, the end-effector forms the end or the last link of the robot or manipulator. As the end-effector is attached to the end of the robot manipulator, it is also called **end-of-arm** It directly operates with the environment, and in most of the cases, in direct contact with certain objects. *Chapter 2: End-Effectors* gives a detailed explanation of various types of end-effectors.

Sensors

Sensors, as the word suggests, sense or collect information about the internal state of the robot as well as its surroundings and outside environment. In the robot, the controller gets information about the internal state, that is, about each joint or link from various sensors integrated in it. Sensors also provide information about the surroundings using external sensory devices, such as force sensors, touch or tactile sensors, vision sensors, etc., thus enabling the robot to communicate with the outside world.

Thus, sensors are the components in the robot system used for detecting and gathering information about both internal and external states. They send information about each link and joint to the control unit, thereby enabling the control unit to determine the configuration of the robot. *Chapter 3: Sensors* explains about various types of sensors used in robotics and their working.

Actuators

Actuators of the robot are analogous to the "muscles" of a human body. As the muscles help in the movement and coordination of humans, actuators move or actuate the joints and links of the robot as per the signals given by the controller. The actuators help the robot to withstand the forces of gravity, inertia, and to work against the external forces while its operation. Simply saying, the working of actuators decides the spatial position, orientation, and function of robots. The actuators are of electric, hydraulic, or pneumatic types. Actuators transform the provided power into proposed motion

The common types are electric motors, including servomotors and stepper motors, hydraulic actuators, and pneumatic actuators. Many other novel actuators like piezoelectric, **Shape Memory Alloy** polymeric, etc. are also used in specific applications. The significance and different types of actuators are discussed in detail in *Chapter 4: Robotic Drive Systems and*

Controller

A robot controller functions similarly to the human brain; it controls and coordinates all the activities of the robot. A robot controller can either be incorporated within the robot or may be provided as an external control unit. A robot controller or control unit may require input, output, and processing hardware and software such as an operating system, programming languages, etc. for its proper functioning. Some robotic systems have a combined processing and controlling unit. The controlling units determine the motions to be executed to reach the specified destinations, calculate the speed and power required by the joints to perform them, and oversee the process by a feedback control loop. The program or codes are fed into the controller through the input devices; the output devices like monitors enable the viewing of the codes or errors messages. The processor is basically a computer that processes the input instructions and signals the actuators to carry out the required functions.

The controller or control unit has three roles as follows:

Collecting information: It collects the information from various sensors like vision sensors, touch sensors, etc. through input ports and processes the data required for its functioning.

Decision-making: Based on the data available and input data from sensors, it has to decide and plan the geometric motion of the robot.

Channel of communication: It gets data from the sensors (input), processes it, and sends it to the actuators (output), thus organizing the transfer of information between the robot and its surroundings.

The controller controls and coordinates the motions of the joints through the actuators with the help of feedback information provided by the sensors. Suppose the robot is required to lift a box from the ground and place it on a conveyor belt. First, the controller will seek information about the current position of the end-effector from the sensors. After finding the current position of the end-effector, if it is not positioned above the part to be picked, then the controller will determine the motion, calculate the speed and power required to reach the required position. It will send signals to the actuators, like current to the electric motors of the joints; making them to move the links and coincide with the destined position. The position sensors provide spatial information so that it stops sending a signal to change positions. Then, the controller will calculate the gripping force required to grab the part and the power to raise the load, then provide signals to the corresponding actuators to execute the function. The motion to the conveyor belt is carried out in a similar fashion as that of the approach motion.

According to the control method, the robots can be classified into two; servo or closed-loop control and non-servo or open-loop control robots. A servo robot functions using a feedback control system that will make it an easily reprogrammable and adaptable device. Open-loop robots are more like a fixed-sequence robot that can move between predestined positions and are mostly used in material handling operations.

Most commonly, there are three kinds of software required for the functioning of the robot controller. The first software is the operating system of the processor itself. The next kind includes the proprietary software custom-made to make calculations based on the geometry of that specific type of robot, often developed by the robot manufacturer and provided along the robot. The third kind of software is the one that interacts with the operator. Such software takes commands from the operator to modify the operations, displays any cautions or error messages, and functions similar to a graphical user interface.

Robotic wrist

A robot wrist is the most significant and indispensable part of a robotic arm; it bridges the end-effector to the rest of the manipulator body. It is a vital part in robot arm with 3 rotational degrees of freedom. In most of the manipulators, it will be the sole component with that many degrees of freedom. The main function of the wrists is to provide orientation to the end-effectors. Spherical joints are joints that can provide 3 rotational degrees of freedom, but it may not be a perfect candidate for many classes of robotic manipulators owing to its inferior load-carrying capabilities. But spherical joints make the wrists most dexterous and least complicated. Most manufacturers were keen on combinatorial revolute joints to create robotic wrists, but degeneracy becomes a major issue in such cases.

Degeneracy is condition in which the wrist may lose one or more rotational freedom due to the overlapping of rotational axes in 1 plane. A robotic wrist should be designed to have low levels of degeneracy; otherwise, there will be larger regions unapproachable by the end-effector. Degeneracy conditions require longer paths, extra speed and power to the actuators to achieve certain points in the workspace. *Figure 1.4* shows a robotic wrist with its 3 degrees of rotational freedom. The direction of the body axis of the end-effector is often named as an approach vector, and the rotation about it is termed as *roll* The upward or downward displacement results from the rotation called *pitch* and the sideways movement to the body axis is facilitated by *yaw* rotation.

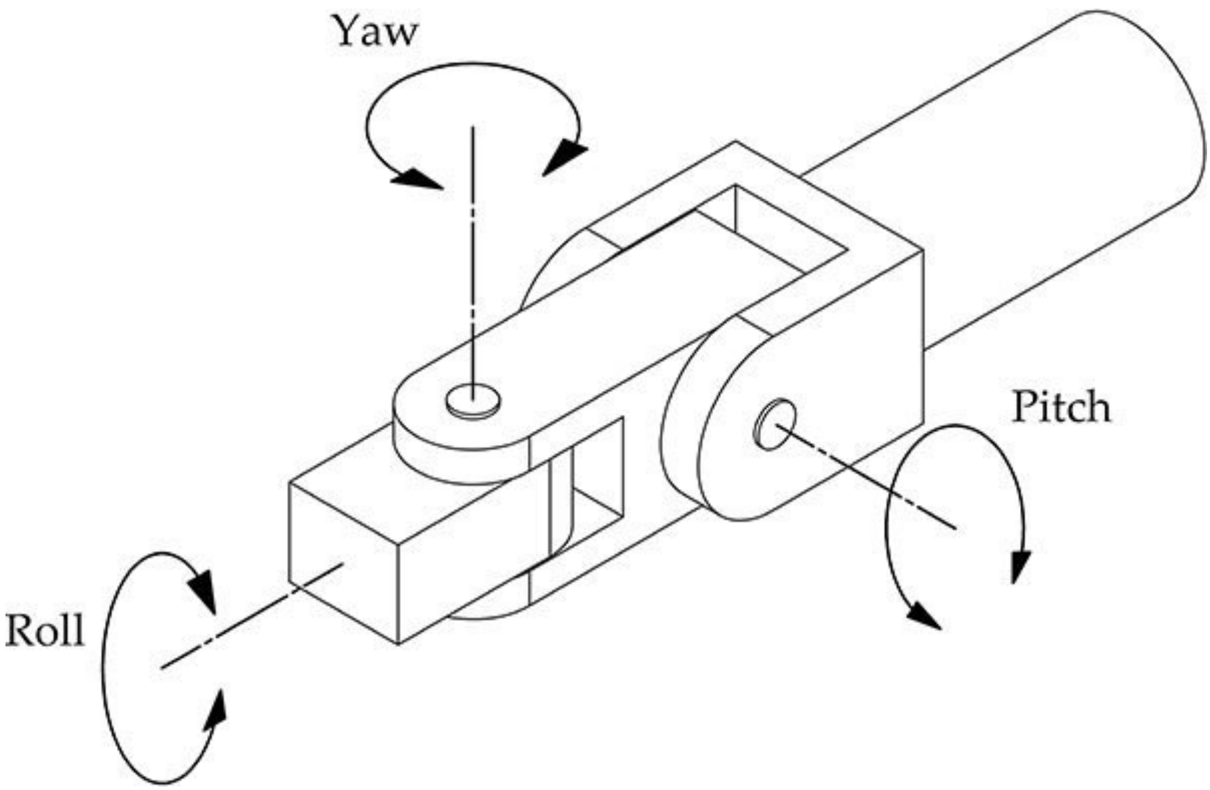

Figure 1.4: *Wrist movements*

Characteristics of a robot

The characteristics of a robot are the set of features and their values that make it easier for manufacturer as well as the consumer to understand the functionality of any given robot. When the characteristics of a robot are provided with a range of its values, then they are known as **specifications of that robot** The characteristics or specifications of the robots become the criteria to compare between different models of any particular robot. There can be many characteristic features for robots, but most important of them to easily distinguish a robotic manipulator are listed as follows:

Payload: Payload is the maximum weight that a robot can carry without any failure or deformations in its component parts. The speed of motion and amount of load carried are interrelated. The robots can operate at their maximum operating speeds with heavier payloads. So, there will be a safer range of speed for the corresponding weight of payload, which, if violated during the operation, the robot may not follow the defined trajectory. The unbalanced force created due to greater acceleration can overthrow the payload or cause detour from the path of operation. The maximum payload and data on the ranges of safe operating speeds will help the consumer in making better choice for their required application.

Number of axes: The number of axes of a robot gives the idea of the degrees of freedom related with that robot. If a robot is said to have n number of axes, then it is understood that a particular robot is free to move about *n* axes. The motions can either be translation or rotary. The axes can be classified into major and minor axes. The axes that are used to position the wrist of a manipulator are known as major axes, whereas the axes utilized to orient the end-effector are known as minor axes.

Reach and stroke: Reach is the extent that the wrist of the robot can reach, and stroke is the extent of reach of the end-effector or the wrist mounting. The reach and stroke are there in both horizontal and vertical directions. Horizontal reach is the maximum horizontal distance that a robot wrist can access inside its workspace. Horizontal stroke is the maximum horizontal reach of the wrist mounting. The vertical reach and vertical stroke can be defined similarly, but in the vertical direction. From the corresponding definitions, it is evident that the reach will be always greater than the stroke for a robot. The range of reach and stroke gives the rough estimate of the work envelope of a robot. The reach of a robot will be a function of type of joints and lengths of links of a robot, whereas the stroke will be a function of type and degrees of freedom of the wrist.

Accuracy and precision: Accuracy is the measure of how close the robot can reach to the intended value, whereas the precision is the closeness of the values the robot can reach when the action is repeated. The accuracy and precision values of a robot give the validity or trueness with which the assigned operation can be executed by the robot.

Repeatability: Repeatability is a significant characteristic of a robot; it is the ability of a robot to reach the same point again and again. Repeatability of a robot is the measure of variability of the functioning of the robot. Repeatability has higher importance than precision. The robot can be programmed or taught to reach a specific point during initial adjustments, but when the robot repeats it operations in its own, there should not be any variation.

Robot configurations

A better method of defining manipulators is to classify them by their workspace geometries. Even though there are numerous models of manipulators developed by different manufacturers around the world, they can be grouped into five major configurations according to the motions associated with their joints and the resultant volume of workspace generated. Two basic motions that may be associated with any joint are rotation and translation. The joints that facilitate translational movements are known as prismatic joints and are denoted by The joints that enable rotational motion are known as *revolute joints, represented by* The *figure 1.5* shows both prismatic and revolute joints.

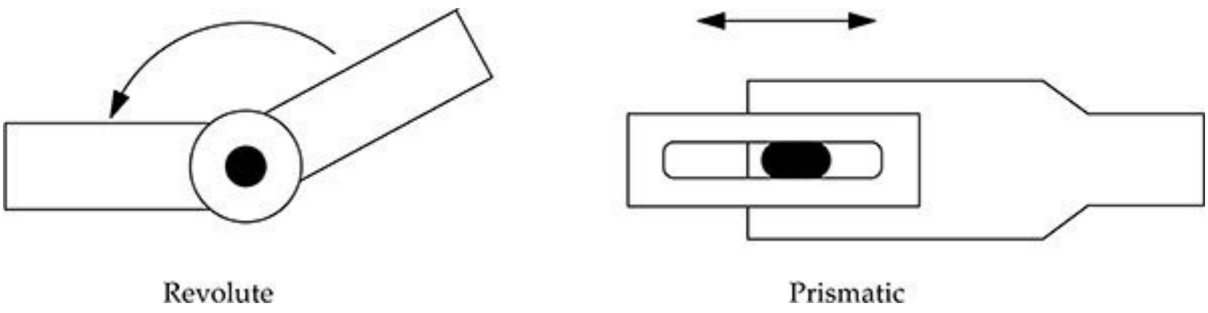

Figure 1.5: *Revolute and prismatic joints*

The different sequence of these two joints in a robotic arm helps to achieve different-shaped work envelopes in space. The five important configurations present in the mainstream commercially available manipulators are listed as follows:

Cartesian/gantry/rectangular/PPP: Cartesian robots are made of three prismatic joints, which may or may not follow a spherical wrist to orientate the end-effector. A simple version of Cartesian robot is shown in *figure* As the robot uses 3 mutually perpendicular translational movements, it is known as **Cartesian** or a rectangular coordinate robot, represented PPP (annotation of 3 sequential prismatic joints). Gantry robots are the larger versions Cartesian robots mounted over a rectangular frame:

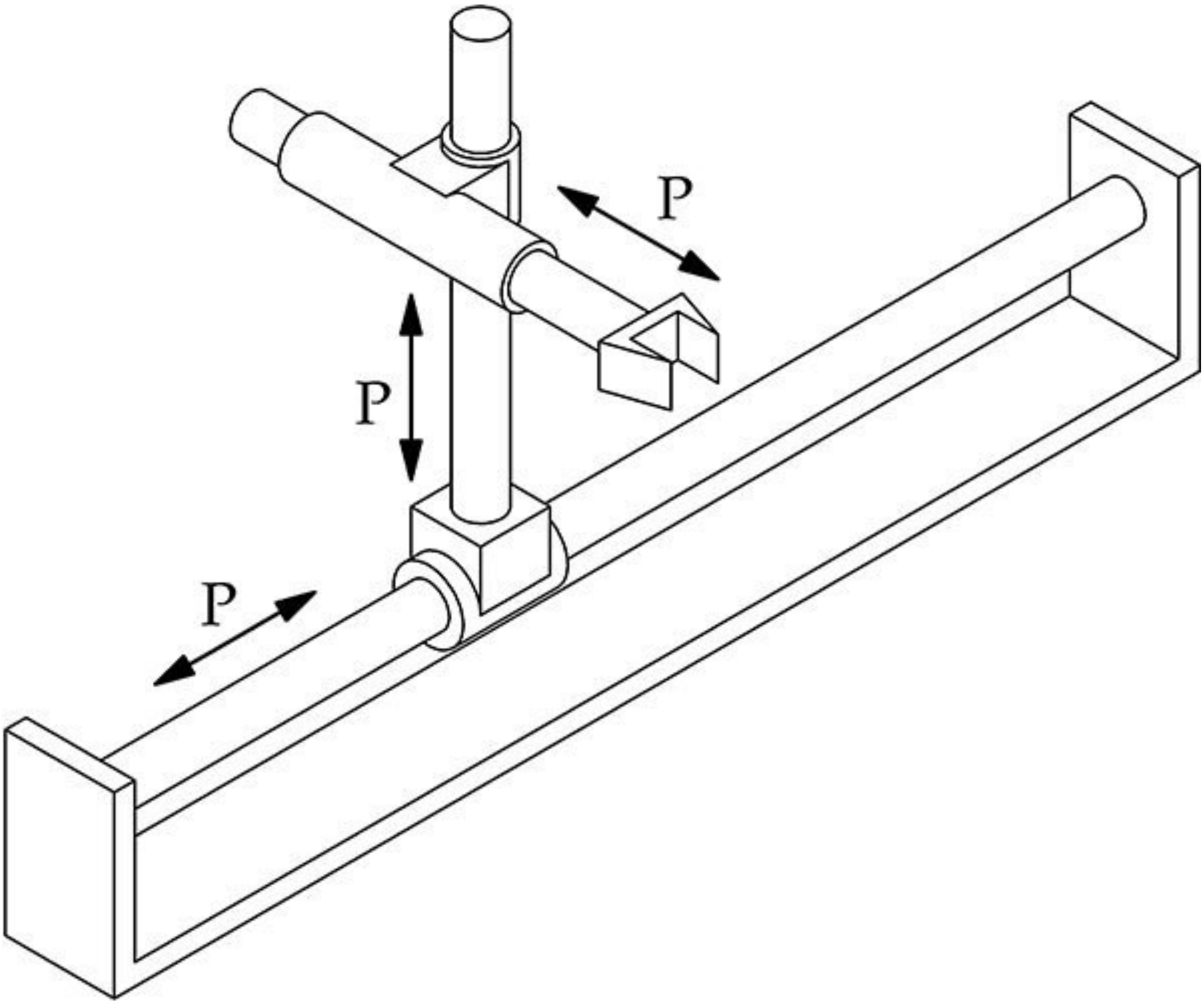

Figure 1.6: *Cartesian configuration*

The absence of rotational joints makes the Cartesian coordinate robot more rigid, which makes them capable of lifting comparatively heavier loads. The most common applications of these robots are material handling as in pick and place, loading, and unloading, etc. The higher positioning accuracy associated with them finds better functionality in 3D printing, and CNC machines. The advantages of Cartesian coordinate robots are high accuracy, greater load-carrying capability, higher operating speed, low cost, and versatile working with simple operations. And the requirement of larger areas for installations poses the major disadvantage.

Cylindrical/PRP: Cylindrical coordinate robots are composed of two prismatic joints and a one revolute joint in between them. Cylindrical coordinate robots may or may not have a spherical joint for orientating the end-effector. The *figure 1.7* shows a cylindrical coordinate robot. The revolute joint provides a rotational movement about the axis perpendicular to the robot base. This kind of robots have almost all the advantages of the Cartesian coordinate robots, with the ability to work inside comparatively lesser installation area. But the disadvantages is having lesser load-carrying capacity and lower work volume compared to the PPP type:

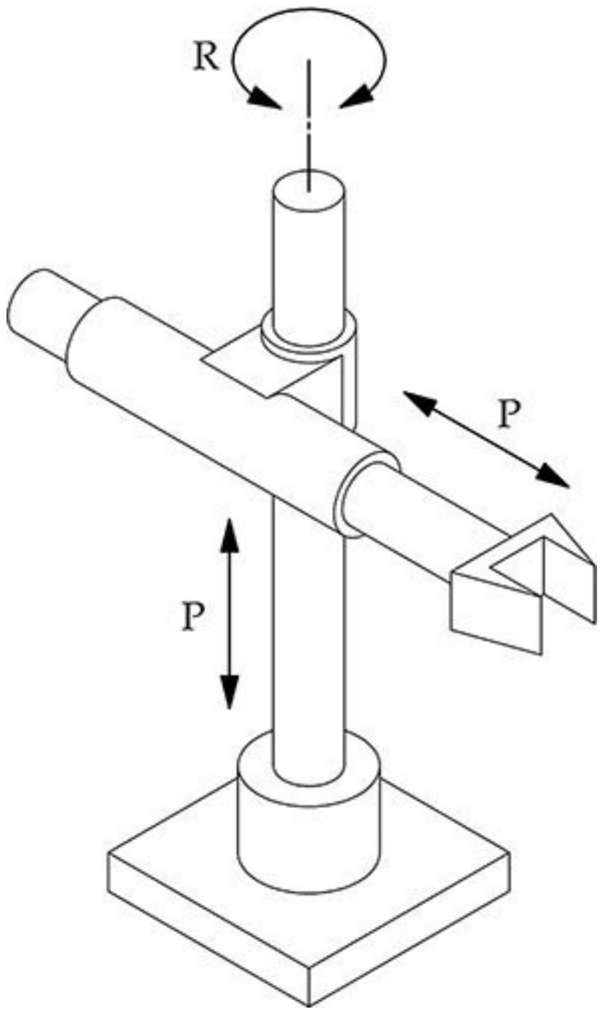

Figure 1.7: *Cylindrical configuration*

Spherical/polar/RRP: Spherical coordinate robots have 2 revolute joints and 1 prismatic joint and works in a spherical coordinate system (refer to *figure* This type of robots also can have a spherical wrist for orientating:

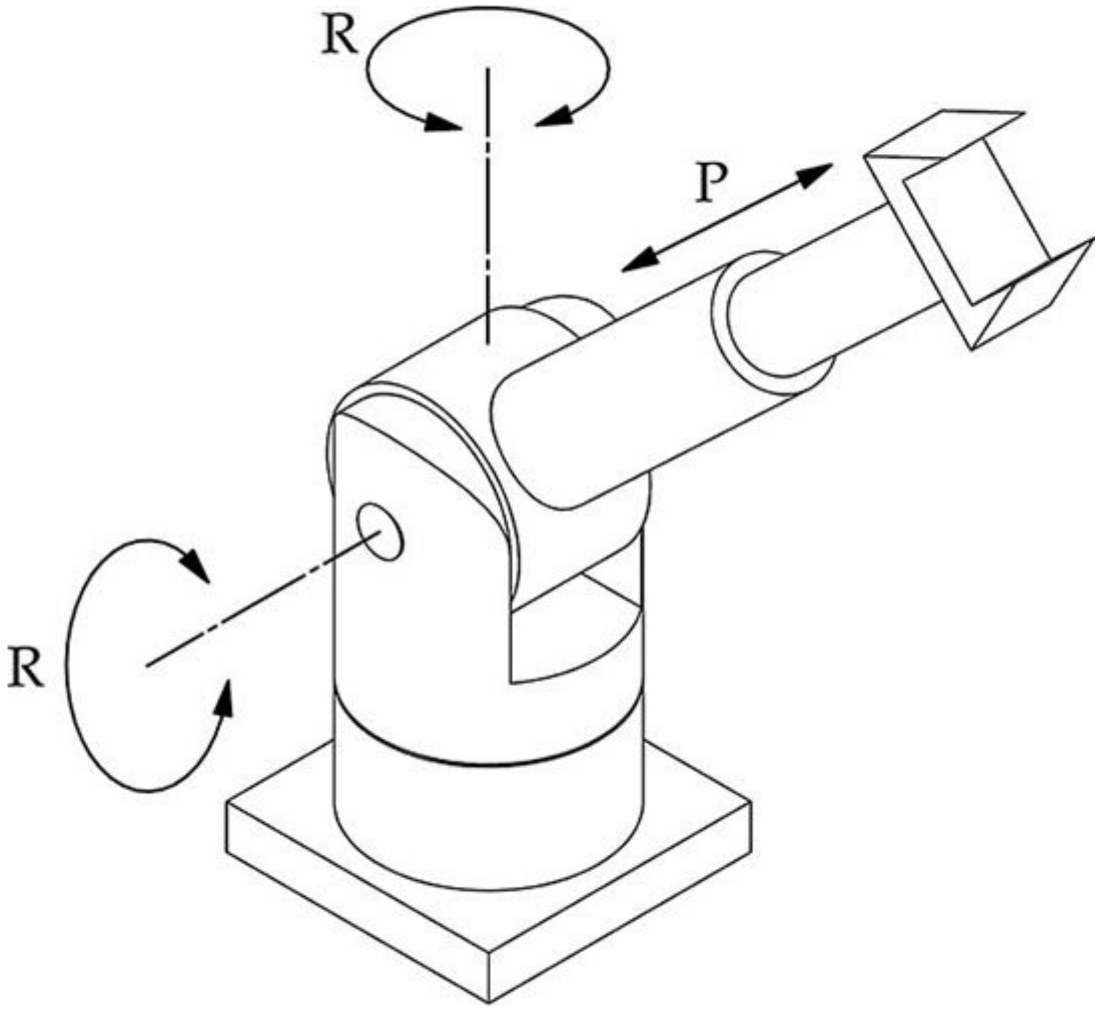

Figure 1.8: *Polar configuration*

SCARA: SCARA robots have 2 revolute joints with parallel axes and a prismatic joint, making it an RRP configuration. This robot differs from the cylindrical robot in concentrating on the horizontal movements at the expense of vertical rotational movement. The 2 revolute joints enable a greater horizontal sweep, and the prismatic joint provides the vertical translational motion. SCARA robots are developed particularly for assembly operations. The *figure 1.9* shows a SCARA robot. SCARA robots find application also in packaging, palletization, loading, and unloading. SCARA robots have the advantages of higher operation speeds with short strokes. The major disadvantage of a SCARA robot is that it requires a dedicated robot controller with PLC besides the master controller:

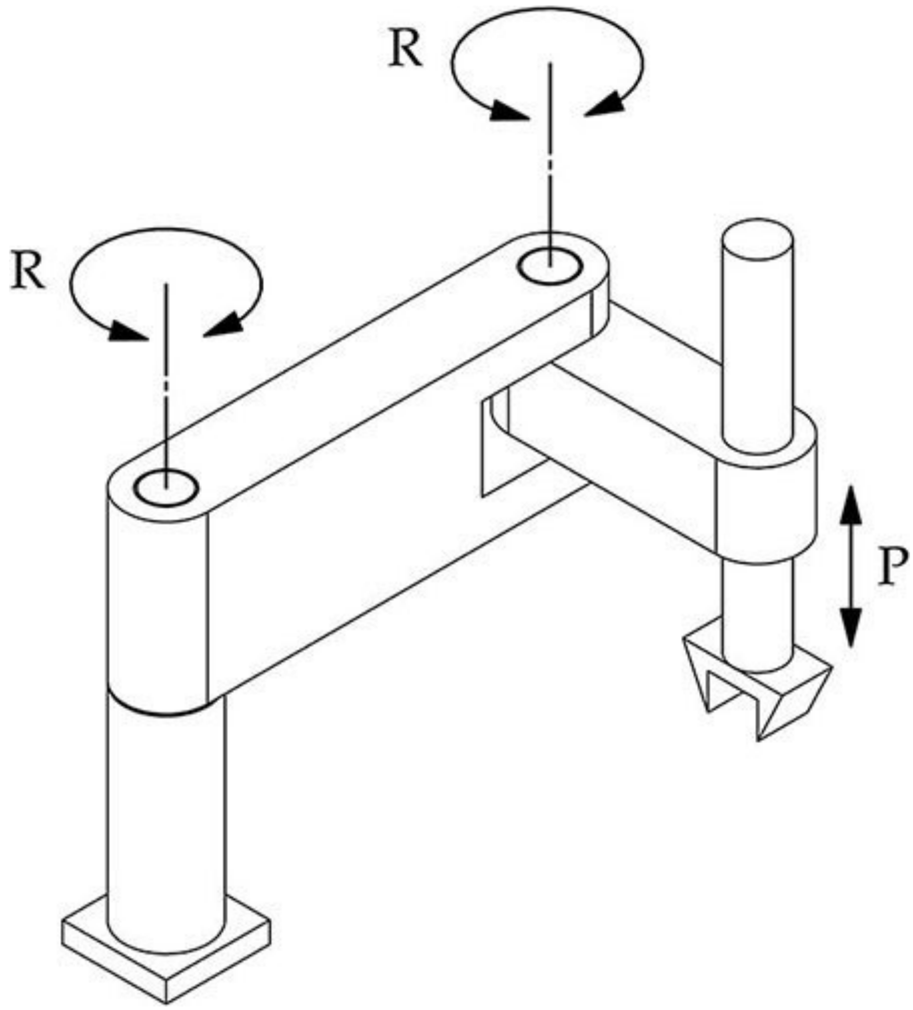

Figure 1.9: *SCARA configuration*

Articulated/anthropomorphic/RRR: An articulated robot resembles a human arm in having all the three joints of the revolute type. Its close resemblance to human arm gives it the name anthropomorphic. It is the most used configuration of industrial robots. As all joints are revolute, it is termed as an RRR robot or simply revolute robot. The *figure 1.10* shows the articulated configuration robot. Articulated arm robots are versatile with ability to reach maximum points in the 3-dimensional space they work. An articulated robot can have different variants by the relative positions of the joint axes; joint axes can be parallel or perpendicular to each other. Articulated robots have maximum number of applications, including material handling, palletizing, foundry applications, welding, painting, etc. The advantages of articulated robotic arms are high speeds, better and unique controllability, and maximum avenues of applications. The disadvantages are it may require larger working volumes and dedicated robot controller:

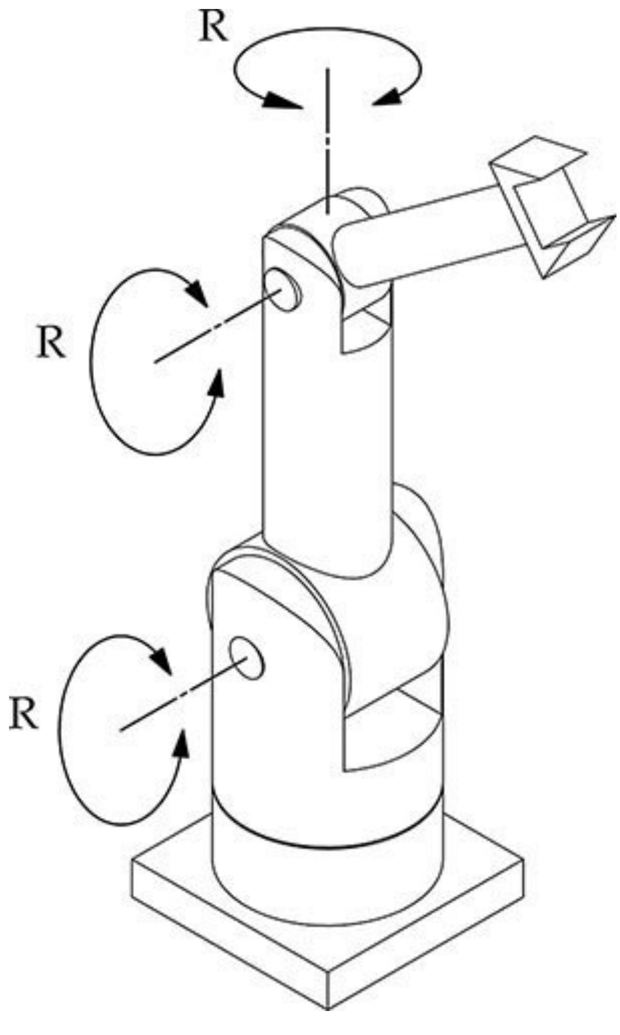

Figure 1.10: *Anthropomorphic configuration*

From the above discussion, it is easy to understand that all these configurations evolve from a particular combination of revolute and prismatic joints. The preceding given list is not exhaustive, as there exists many combinational possibilities. The preceding given five configurations represent a wider range of manufactured and available robots.

Workspace

The workspace of a manipulator is the total volume of space within which the end-effector can reach any given point. The imaginary blanket covering the 3-dimensional space of operation around a manipulator is known as the work envelope. It can be defined as the locus of all the extreme points that can be reached by the end-effector. The workspace will always be the result of combined action of all the joints in a particular robot.

The workspace is of two types: reachable workspace and dexterous workspace. Reachable workspaces are a set of all those points that can be reached by many possible orientations, whereas the dexterous workspace is the set of all those points that can be reached by at least one orientation. The work envelope of any robot is determined by the following characteristics:

Configuration of the robot

Geometrical dimensions of its components

Constraints on the joint movements

The shape of the workspace is unique to a specific robot and is an outcome of its design. The workspace can be mathematically modeled if the equations of motions of all the links and joints are known *to their* An important point to be noted is that the joints do not provide the full extent of motions as it may sound, due to the space constraints placed by the joints and mechanization. For example, the rotation provided by a revolute joint is far less than 360°. The workspace can be roughly approximated by combining the range of space that each joint can reach, and then deducting the space under joint constraints. Accurate workspace determination may require a thorough simulation or manufacturers' data. The workspace of the known configurations of manipulators are as follows:

For a Cartesian coordinate robot, 3 prismatic joints provide the vertical, horizontal, and lateral movements. So, it is easily predicted that the workspace will be rectangular box-shaped (refer to

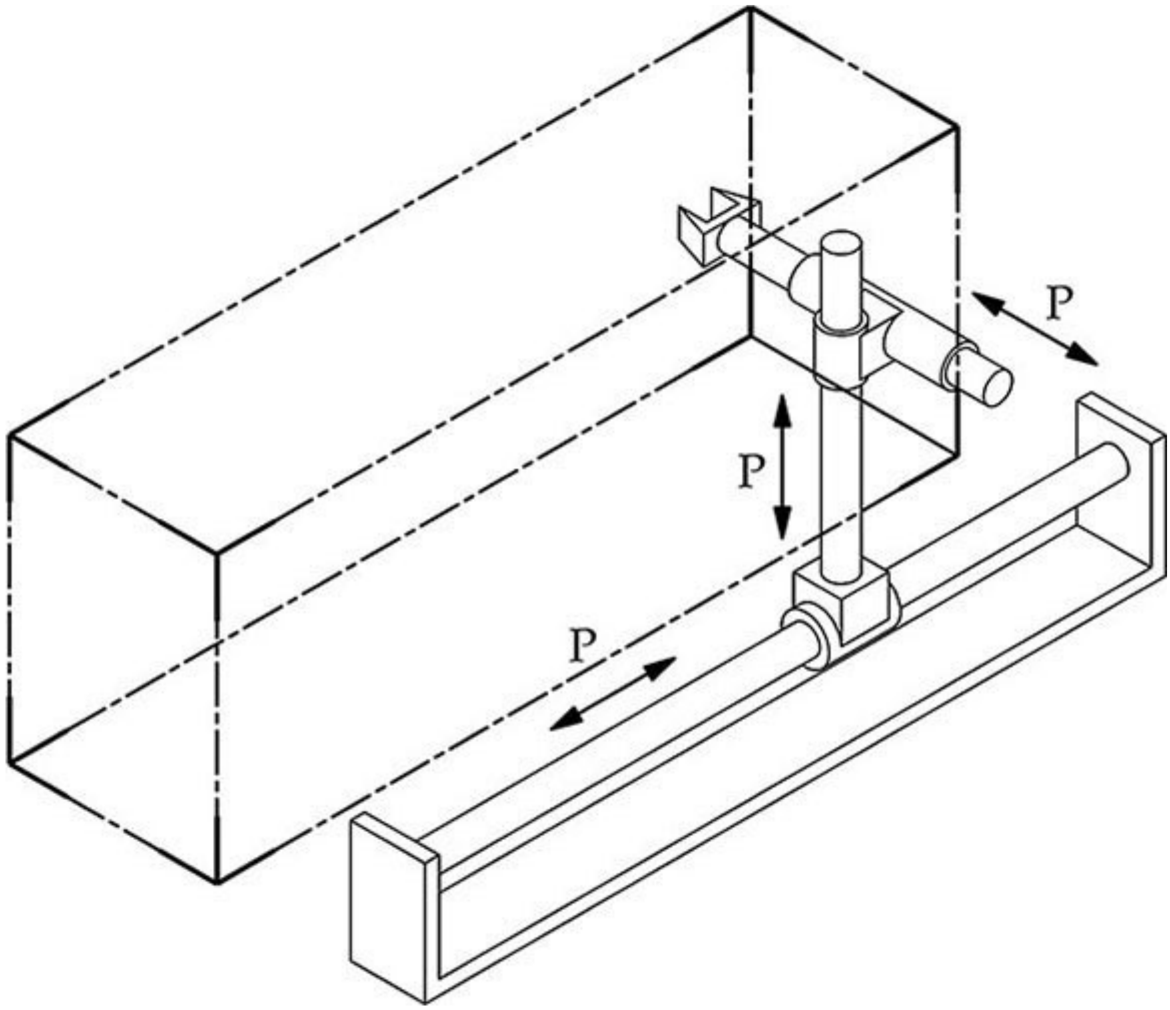

Figure 1.11: *Workspace of a Cartesian coordinate robot*

The cylindrical coordinate robot has a revolute joint that enables a rotational motion and the 2 prismatic joints provide horizontal and vertical movement. So, the work envelope developed will be the in the shape of a hollow cylinder, as shown in *figure* but the constraint in full rotation reduces some space:

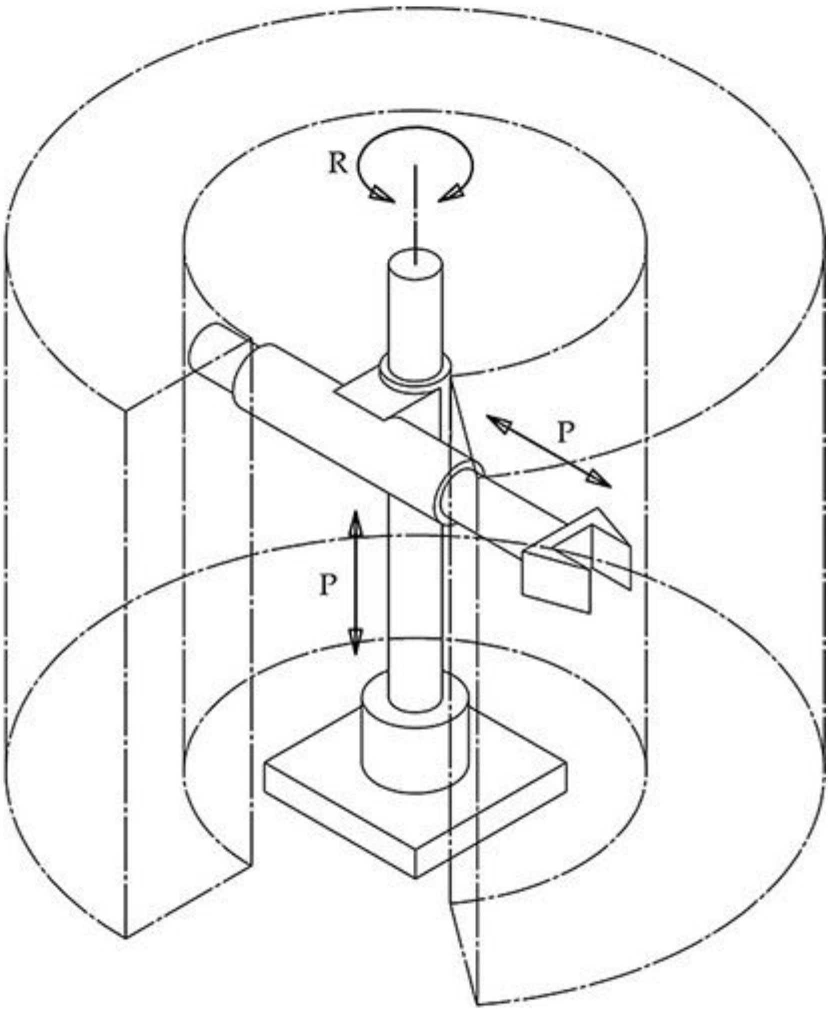

Figure 1.12: *Workspace of a cylindrical coordinate robot*

A cylindrical coordinate robot has two revolute joints with mutually perpendicular axes; such a combination of rotations will develop a spherical space where the prismatic joint helps in moving radially in and out. The work volume developed in this case will be somewhat similar to a hollow sphere that is truncated vertically above and follows the base with deductions of regions that cannot be reached due to joint limitations (refer to figure

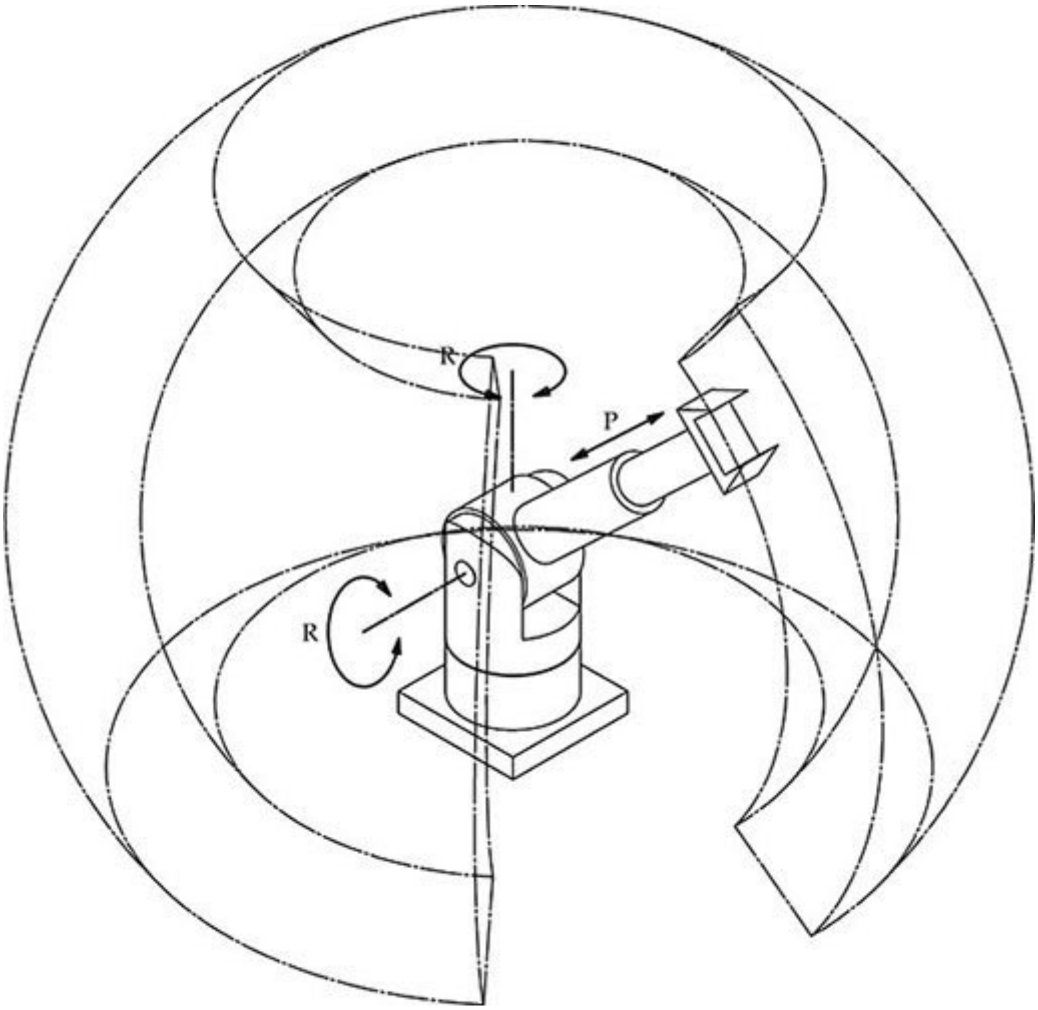

Figure 1.13: *Workspace of a spherical robot*

A SCARA robot has 2 revolute joints and 1 prismatic joint with all their axes placed vertical to the base. The first revolute joint will develop a cylindrical volume about the shoulder, whereas the second revolute joint creates another cylindrical volume at the elbow level, and the reach of prismatic joint decides the height of both those cylindrical volumes. As the workspace of the SCARA will be the combination of these volumes, it can be quite complicated to develop and will always depend on the ranges of reach of the joints. The articulated arm also has a complex workspace geometry. As all the joints are of revolute type, the workspace of an articulated arm robot will be a combination of spherical volumes stacked according to the location of the joints. The cross-section of the workspace of an RRR robot will remind you of a crescent. The complexity of the workspace of articulated robot can be easily understood by comparing it with that of a human arm.

Advantages and disadvantages of robots

The robot industry is an ever-growing industry now as robots find their applications in every aspect of human life. The application of robots has many advantages along with some disadvantages.

The advantages of using robots are as follows:

Use of robots minimize the errors

Higher efficiency

Productivity can be increased

Operating costs can be reduced

Product quality can be improved

Quality of working environment can be enhanced

Better accuracy can be obtained

Increased flexibility in product manufacturing

Repeatability

Reduces labor turnover

The disadvantages of using robots are as follows:

Safety concerns

Higher initial investment

Greater cost of maintenance

Slow returns on investment

Four Ds of robotics

Earlier, there was an idea of using 4Ds for checking the suitability of robots for performing certain tasks in industrial settings. The 4 jobs that may require the use of a robot were classified by 4Ds: and

The first D, dull, represents repetitive tasks that do not require much thinking or decision-making. Workers have to repeat the same task over and over again for months and years. Physical tasks involving continuous rigorous use of joints can affect their health, sometimes leading to injuries requiring complete joint replacement. In addition, such jobs create boredom, and workers may lose interest and lose attention called **running on** This carelessness or decrease in efficiency will not occur if robots are employed for such dull jobs. A robot is a perfect choice to perform a particular task a million number of times, with minimal maintenance and complete focus. This allows better utilization of human workers and their talents for better jobs.

The second D stands for dirty, which represents tasks that involve dust, grease, sludge, or other substances. Such tasks can cause irritation or allergy to the human workers. They may not be comfortable doing such jobs as at the end of the day, their body and clothes will be covered with such stuff. It can also affect the work satisfaction. Robots are perfect choice to work in a dirty environment, and the only concern is to keep its mechanical parts without damage.

The third D represents difficult jobs. Like tasks that require workers to bend, twist, or move in ways that are not easy for human workers, based on the requirement, the robot can be designed for any application. The fourth and final D represents dangerous jobs like those in excessively high temperature, near fire, environment with toxic fumes or radiation, etc. or working conditions that involve high risk of injury or accident for humans. This is indeed a perfect scenario to utilize robots as they can be repaired if damaged unlike in the case of human workers.

Presently, there are a lot more Ds within the sphere of modern robotic applications. Dear, domestic, delicate, etc. are some of the new Ds in the robotic application spectrum. The dear or expensive jobs are now being handled by the robots because of their better accuracy and cost-effectiveness. More and more domestic appliances are being automated, and robots are invading all areas of house and personal space. The convenience of use, comparatively cheaper prices, and unavailability of household helps makes it an attractive alternative for domestic applications. Delicate jobs such as surgery, gem cutting, precision assembly, etc. are now at the hands of robots because of their accuracy, precision, and dexterity.

Areas of application

Robots have a wide range of applications in almost all areas. The industrial applications of robots are broadly classified as manufacturing applications and material handling applications.

Manufacturing applications include welding, cutting, drilling, and fastening, part dipping and inspection. Highly skilled workers are needed for manual welding as perfection is needed in the work. Robotics perform metal inert/active gas welding in industries. In the automatic arc-welding process, a consumable wire electrode and a shielding gas are fed through a welding gun. Sensors can be employed to track the gaps in welding and measure weld seams during the welding process, thereby improving the perfection in the process.

Robots have a major role in assembling a car body. Jobs like handling and positioning the metal sheets, spot welding, spray painting, and transporting body frames, which are hazardous as well as physically demanding to the workers, can be done easily with robots. Robots are widely used in spray painting, mainly in automobile industries. Spray guns used in robots can deliver uniform quality with minimum quantity of paint and solvent possible and easy switching between different paint colors. Spray painting robots replicate the movements copied from human workers. Similar areas of application of robots include laser cutting, milling, and drilling, deburring, grinding, screwing, wiring and fastening, assembling various parts, etc.

Robots have been greatly employed in material handling operations. Robots can properly locate the parts required and can grasp them properly. They are well utilized for pick-and-place applications. They are also used for home applications like robot vacuum cleaners, which randomly move through the area available and sweep the dirt. ASIMO robots can walk or run like humans, climb stairs, and can interact with them. They are used for menial jobs like serving coffee and food, cleaning small areas, carrying heavy loads, etc.

Other than industrial applications, robots are used in medical fields for diagnosis and intervention of diseases, for surgeries and treatment, and in rehabilitation and therapy. Many robotic-assistive devices are developed for supporting people and disabled children with cognitive disabilities, autism, etc.

Robots have been also employed for defense and military applications for better awareness of the situation, reducing human intervention, facilitating quick movements, for ensuring the protection of soldiers. They are used extensively used in underwater, space and locations that are inaccessible. NASA developed a humanoid robot named which can function as an astronaut.

The robotic industry is an ever-growing one with newer and innovative additions every year. From the statistics of the IFR, it is seen that the production of robots has been increased by more than 250% in the last decade itself. The *figure 1.14* shows the rate of production of robots in the last decade:

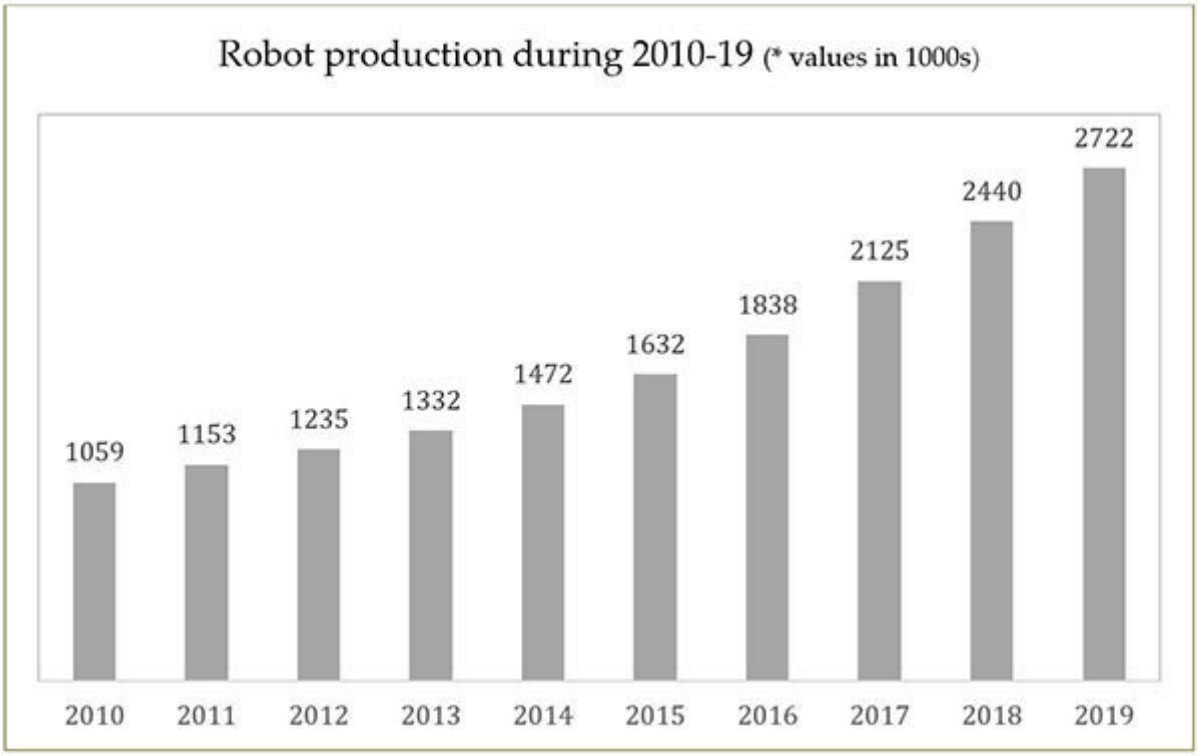

Figure 1.14: *Increase in robot production during 2010–2019*

The automobile sector dominates in the utilization of robots in their industries. Automobile industries have a lot of repetitive and cumbersome jobs that are well suited for robotic applications. The continuous production line of automobile manufacturing with heavier components creates difficulties for human workers to keep up their pace. The second most robotic-intense industry is the electronics or electrical manufacturing sector. The high-speed production with greater accuracy and precision mandates the usage of robots in such industries. The food processing industry still hesitates to make their firms robotic intensified due to the fear of gambling with customer satisfaction. The chart in *figure 1.15* shows the distribution of robots in the user industries and their variation during last 3 years according to the World Robotics 2020 Symposium by the IFR:

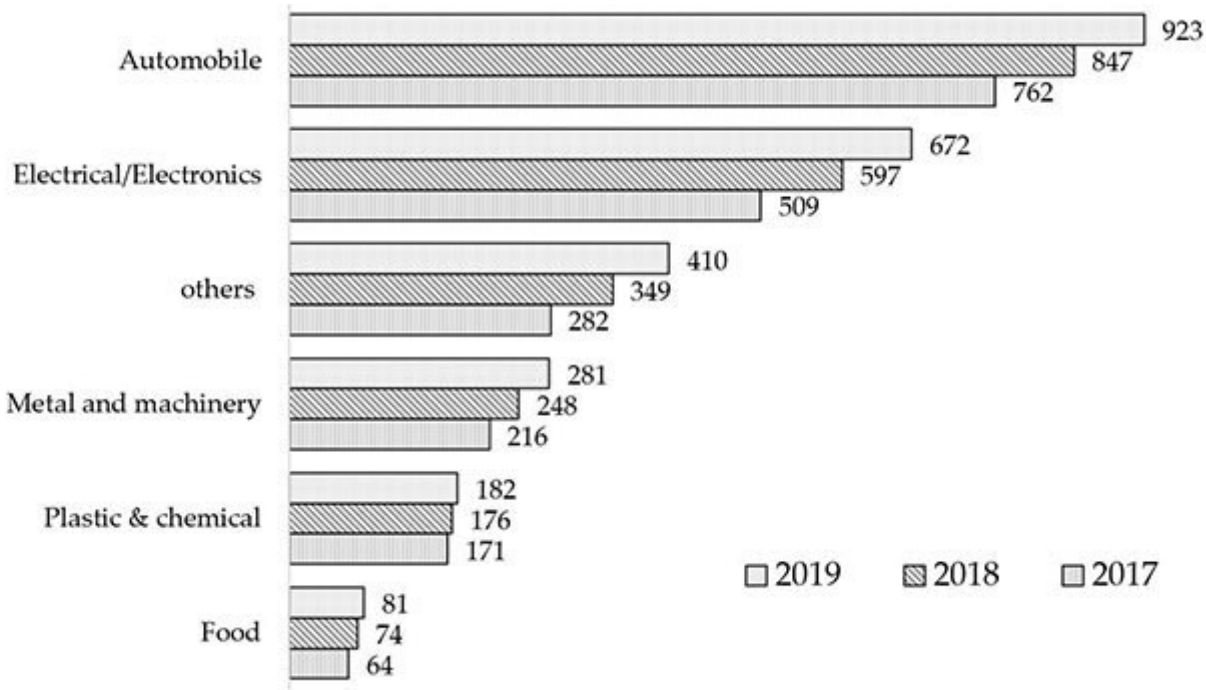

Figure 1.15: *Robot production for various consumer sectors during 2017–2019 (*values in thousands)*

The *figure 1.16* shows the distribution of robots employed in different applications across the industries by the end of 2019:

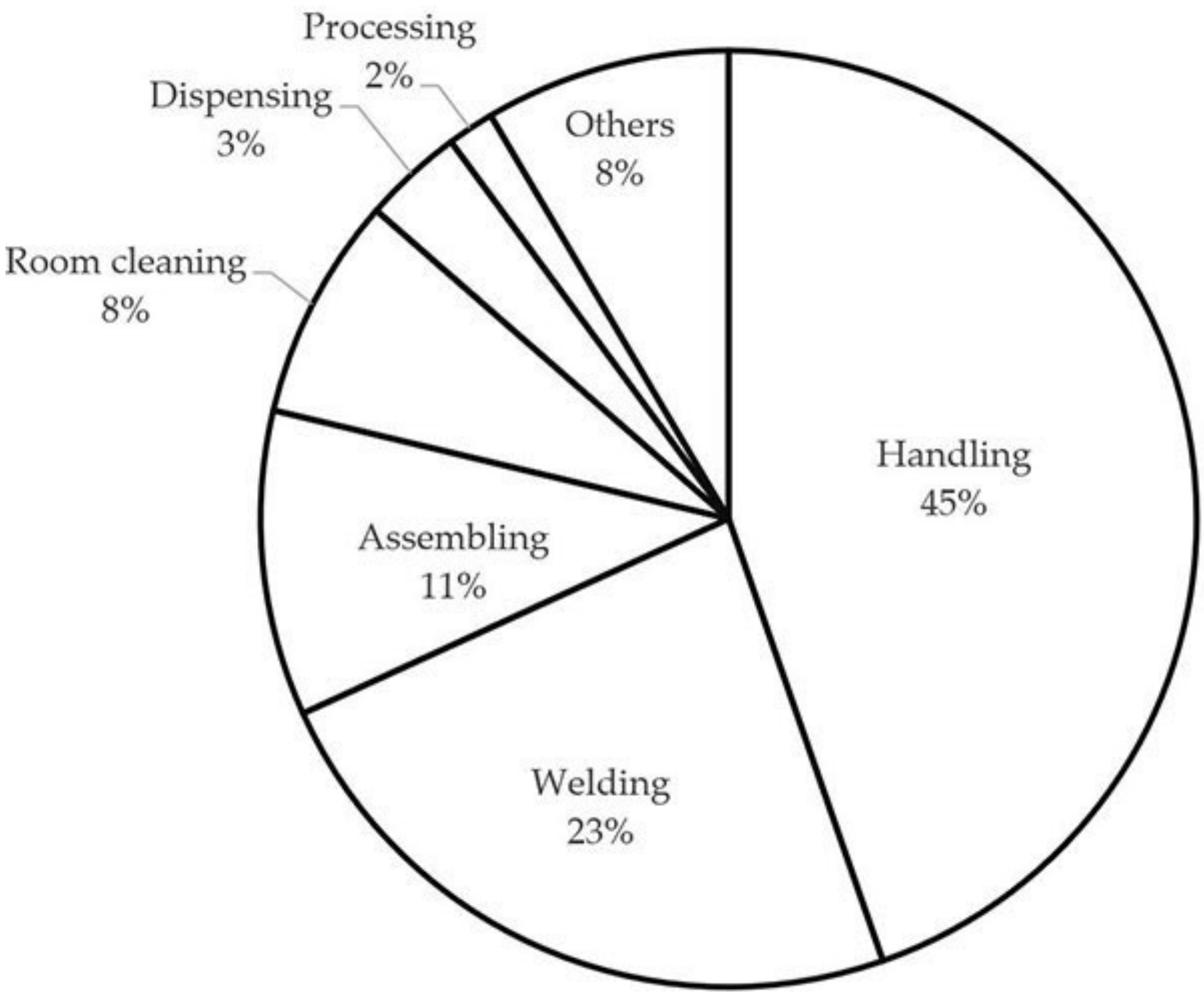

Figure 1.16: *Robot utilization across different applications*

The robotic applications dominate the material handling operations; almost half of all the robots in the industrial application are being engaged in the material handling operations like loading, unloading, palletizing, depalletization, packing, sealing, transferring, etc. Welding applications utilize one-fourth of the robots in industries. No human can perform like robots in the hot and heavy welding applications with intense flashes of light.

Conclusion

A robot is an automatically operated machine that may or may not resemble a human, but can function better than humans in most of the works. The idea of a robot has reached at the level of an artificial, super-intelligent, and versatile device from the levels of simple mechanization used to ease mechanical labor. This chapter discussed the history, evolution, and classification of robots with its underlying science. All robots are not humanoid but can have human-like functionalities.

This text mostly discusses about a robotic manipulator or arm-like robot as it is the most common and highly manufactured industrial robot. The next chapter deals in detail about the important and last link of a robotic arm, the end-effector.

Points to remember

Robots existed even in myths and ballads, showing that humans were always obsessed with creating automatic machines.

Automatons are primitive form of robots that could carry out a set of predetermined motions like a clockwork mechanism.

Robots got their name from a Czech play named RUR, and the word robotics is coined by Isaac Asimov in one of his science fictions.

A general robot is defined by Britannica as any automatically operated machine that replaces human effort, though it may not resemble human beings in appearance or perform functions in a human-like manner.

Different nations have national robot organizations for regulating the manufacturing and usage of robots in their country. And the IFR is an association of different regional robot organizations.

End-effectors are the hands for the robot. They are the devices attached to the wrist of the robotic arm.

Sensors are the sensory organs of a robot that help it to perceive and understand its surroundings.

Actuators are motion subsystems of a robot that help it in moving and load-carrying applications.

A robot wrist is the most significant part of a robot that has multiple degrees of freedom.

Workspace is the volume of space within which all points are accessible to the end-effector of a robot.

Robots can be classified according to their applications, shapes, working environments, etc.

Multiple-choice questions

What are self-powered self-acting machines or devices called?

Automata

Robots

Android

All of these

What term refers to a robot with resemblance to humans?

Robot

Manipulator

Anthropomorphic

Cyborgs

How many classes of industrial robots are there according to JARA?

Three

Four

Five

Six

The robots that can understand natural languages and their surroundings are known as

Androids

Programmable robots

Adaptive robots

Intelligent robots

The configuration of a SCARA robot is

PPP

RRP

PRP

None of the above

What are known often termed as the muscles of a robot?

Sensors

End-effector

Actuators

Links of robot

Answers

a

c

d

d

b

c

Questions

Robots are not the thought of the 19th century. Substantiate.

Define what is a robot and all the important functional keywords in it.

Explain the major three subsystems in robot anatomy.

Explain the most used industrial robot configurations.

Define and explain the workspace of a robot.

Discuss the term EOAT (end-of-arm tooling) concept.

What are the uses of end-effectors in robotics?

Compare the advantages and disadvantages of robots with different applications.

Describe the various applications of robotics.

Key terms

Automata: Self-powered, self-acting machines or devices that carry out a sequence of predetermined operations.

CNC machines: Computer numerical controlled machines.

PUMA: Programmable universal machine for assembly.

Robot: An automatically controlled, reprogrammable, multipurpose machine.

Law of robotics: A set of three laws developed by a science fiction writer Isaac Asimov.

IFR: It is an international organization developed by the association of various robot organizations of the world.

End-effector: The last link of a robotic manipulator that performs the intended function of that robot.

Actuators: Robotic subsystems that functions as the muscles of the robot, helps in the coordination of movements.

Controller: A robotic subsystem that helps in the controlling of robot.

Articulated arm: A robot arm with all revolute joints and functions similar to a human arm.

SCARA: It is a dedicated robot for part assembling application.

CHAPTER 2

End-Effectors

Introduction

An end-effector refers to the *"hand"* of the robot, which refers to the device mounted to the wrist or end of the robotic arm. It is designed for performing specific tasks. The end-effector acts as an interface between the robotic arm and the environment outside to be accessed. The end-effector enables the robot to access the environment around and to interact with it and operate on it. Some tasks demand greater accuracy of end-effectors to complete them in a smooth manner by avoiding errors like slipping off the objects or objects getting damaged during the process.

Structure

In this chapter, we will discuss the following topics:

Need for end-effectors in robotics

Various types of grippers

Various types of tools

Factors to be considered for selection of end-effectors

Various modes of gripping and power sources for grippers

Engelberger criteria for end-effector selection

Objectives

The main objective of this chapter is to familiarize the readers of the significance of end-effectors and their various modes of operation. This chapter explains in detail the working of various types of grippers like mechanical grippers, magnetic grippers, vacuum grippers, adhesive grippers, etc., as well as various types of tools used for various applications like welding, spray painting, etc. This chapter aims to give an understanding to the readers about the basics of gripping, comparing the advantages and disadvantages of various types of grippers. It also explains the various factors to be considered for the selection of grippers and Engelberger criteria for its selection.

End-effectors

Robots are designed for various purposes, and their size as well as payload capacities will vary for various operations. Therefore, they need some tools called which are the tools at the end of robotic arm. These robots use specific tools as end-effectors. The end-effector is decided based on the specific purpose, and its orientation and control are the major design considerations.

The end-effector has a major role in the robot system. In the initial design phase, a flow chart is prepared to describe the tasks to be performed in each step. For example, it describes the steps on how to move the end-effector to handle the object, how to grab it, hold it, where to place it, etc. All these details are required to design an end-effector. For designing an end-effector specific to a particular process, it is required to know the dimension of the object to be grasped, the surface texture of objects to be handled, their orientation, position, surrounding environment, etc. From all these data, the specifications needed for an end-effector for the particular purpose are prepared, and a suitable end-effector is designed.

Another important factor is the environment where it operates. For working in a clean environment like semiconductor manufacturing factories, end-effectors should be planned and designed such that they will not generate any particles during the operation. End-effectors should be made of selected materials like stainless steel or polymers or coated with materials like baked-on powder coating. End-effectors can make use of polymer washers and bearings to avoid the use of oil and surfaces that are not in direct contact with each other to avoid generating particles and wearing out of its parts. Air bearings are also employed in some applications where extreme clean environment is required.

In some cases, the end-effector needs to be protected when it is employed to work in a hazardous environment where the operation involves the presence of highly reactive chemicals, and a protective covering may be provided to avoid chemical reactions. The material of the end-effector can also be chosen such that it will not react with the chemicals present in the working environment. End-effectors made with aluminum and nickel alloys are preferred for working with chlorine, fluorine, or oxygen.

In robotic applications related to food processing, cleanliness is most important. Such an equipment would be manufactured using non-corrosive materials with well-insulated and sealed electrical connections. Sterilization of the equipment must be performed periodically to prevent contamination by bacteria, germs, and other pathogens. The end-effectors are mainly classified as grippers and tools.

End-effectors or tools connected at the end of robot wrist should have the following characteristics:

They must be capable of gripping, lifting, and releasing the part or work piece required for the process.

It should be possible to sense the presence of a part in the gripper by utilizing sensors placed either on the tooling or at a particular position in the work area.

The weight of the end-effector should be at a minimum possible value as it adds up to the weight of the part for calculating the maximum payload.

It should be ensured that the part to be operated is properly gripped under all possible conditions of acceleration.

End-of-arm tooling is defined as the subsystem included in an industrial robot that links the mechanical option of the robot to the art being handled or worked on. An industrial robot simply takes the form of a mechanical arm with a flat tool-mounting plate at its end, which can be moved to any location within its reach accurately. The robot is linked to the work piece or part through the tools or grippers attached to the tool-mounting plate. It is the end-effector that enables a robot for production by making its arm usable for operation.

Types of end-effectors

An industrial robot is essentially a mechanical arm with a flat tool-mounting plate at its end that can be moved to any spatial point within its reach. End-of-arm tooling in the form of specialized devices to pick up parts or hold tools to work on parts is physically attached to the robot's tool-mounting plate to link the robot to the work piece. A robot can become a production machine only if an end-effector has been attached to its mechanical arm by means of the tool-mounting plate. End-effectors are normally classified as grippers and tools. Grippers are specifically used to grip or hold the objects. They grab or grip the objects to be taken from one position to another. It is mainly used in loading and unloading processes, picking parts from a case or conveyor belt, arranging parts in a pallet, etc. Grippers are mechanical hands made of suction devices, magnets, or hooks.

All other functions like welding, spray painting, etc. are done using specific tools attached to the robot wrist called tools. Tools are designed for specific purposes and are available in various shapes and sizes based on the application.

Grippers

Grippers provide *"fingers"* to the robot, enabling it to properly grip or hold the objects. They grab or grip the objects and move it from one position to another. It is mainly used in loading and unloading processes, picking parts from a case or conveyor belt, arranging parts in a pallet, etc. Grippers are mechanical fingers made of suction devices, magnets, hooks, or with adhesive property. The most sensitive part in material handling is the gripping phase. The position of gripper should be precise, and any possible collision with nearby objects needs to be avoided. The *figure 2.1* shows a gripper attached to the end of a robotic arm:

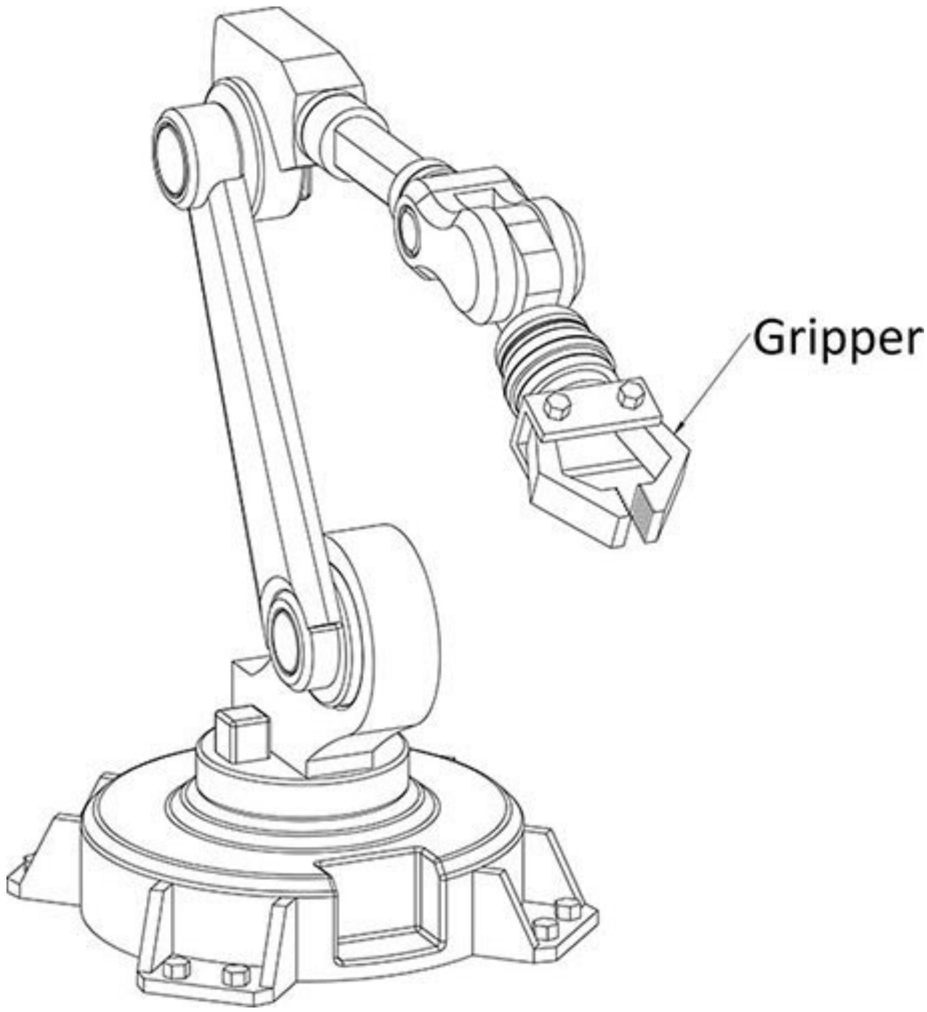

Figure 2.1: *Gripper*

Mechanical grippers

Grippers provided with mechanical fingers to grip or grasp an object are called mechanical grippers. It is like a robotic hand with fingers to grip the parts and is securely held by the gripper because of the friction between the gripper and the object it is holding. Friction depends on the type or material of the surface and the force with which the gripper grips the object. Grippers can be mechanical in nature using a combination of mechanisms driven by or *pneumatic* power.

Mechanical grippers are classified on the basis of the grasping mechanism. An object can be held by various forces using magnets, suction cups or vacuum cups, adhesives, etc. Thus, mechanical grippers can be pneumatic gripper, vacuum gripper, adhesive gripper, magnetic gripper, etc. The *figure 2.2* shows a simple model of a mechanical gripper. Mechanical grippers are also classified on the basis of how they grip an object. External grippers grip the object on its exterior surface, whereas internal grippers grip it on the internal surface:

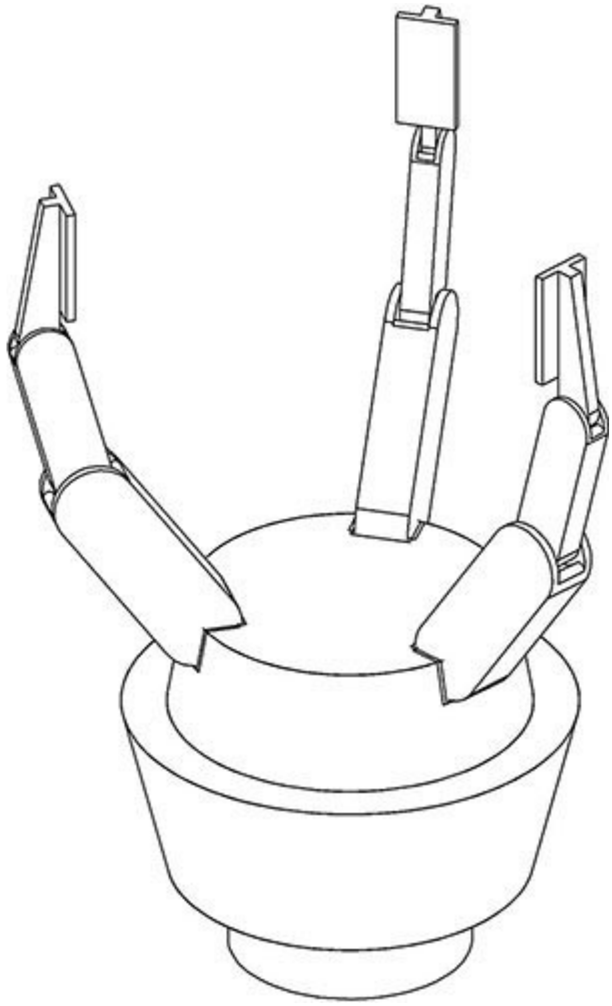

***Figure** Mechanical gripper*

A common form of gripper is made with two fingers, which can grasp the object properly. To overcome the gravity in order to grasp an object, two methods are commonly employed. One method is the physical constriction method by applying an opposite force that is to be lifted (refer to *figure* It is implemented by making the contact surfaces of the gripper fingers to match with the shape of the part:

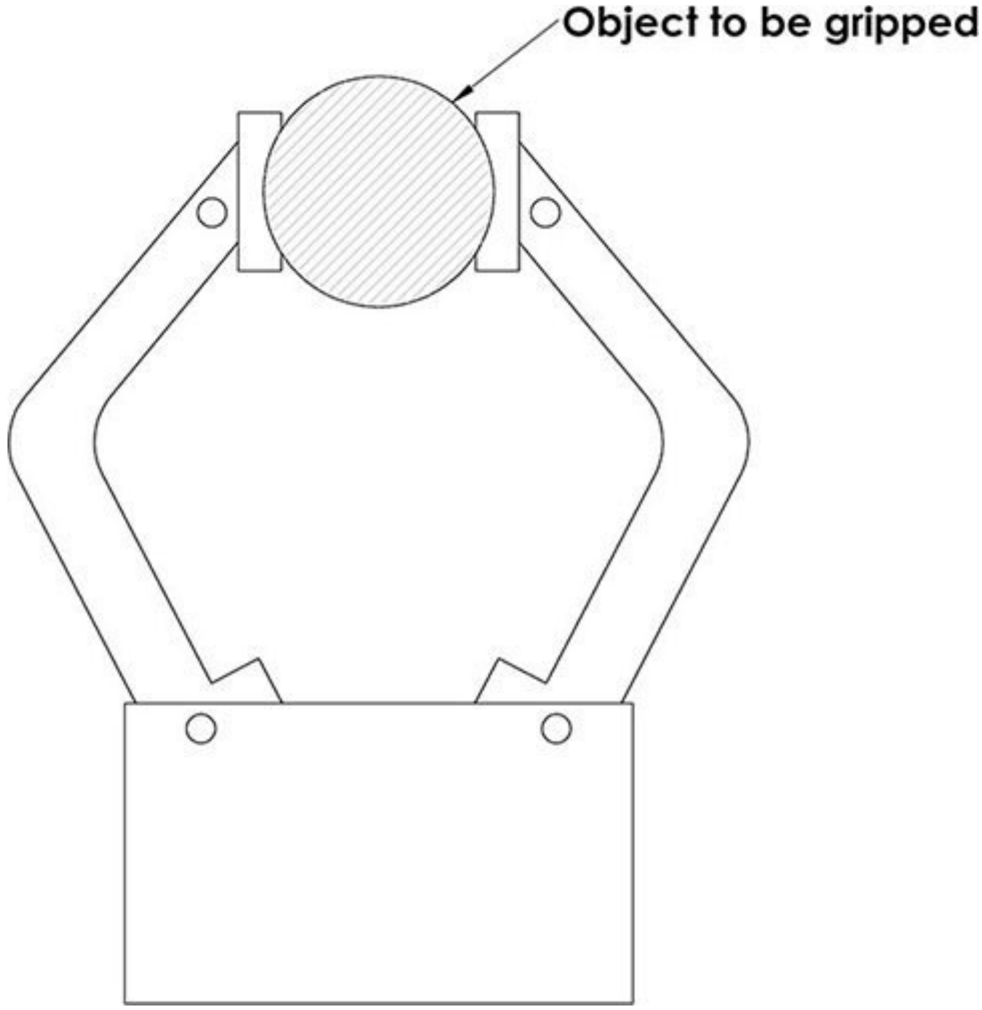

Figure 2.3: *Mechanical gripper (physical constriction method with pads)*

Another method is to utilize the friction, where the fingers apply a frictional force on the work piece that is strong enough to counter the gravitational force acting on it. If we consider a simple case when only gravity is acting on the object to be gripped:

$$= mg$$

where

μis the coefficient of friction

n is the number of fingers to grip the object

F is the gripping force

m is the mass of the object

g is acceleration due to gravity

Mechanical grippers are provided with a polyurethane pad for getting greater friction and thus better gripping. These pads are made of materials that are relatively soft. They have higher values of coefficient of friction and protect the object from scratch or damage. Pads will also protect the part from damage while gripping. This method is more economical because of the low complexity design of the fingers of the gripper. Mechanical grippers can be designed and developed on the basis of their specific application and based on the size of object to be grasped. Some robots are provided with dual grippers to increase productivity and in cases in which a robot needs to load two objects in a single task. Some grippers are provided with three fingers useful for handling cylindrical pieces.

Example 2.1: Find out the weight of an object that can be gripped by a parallel-fingered gripper if the coefficient of friction between the object and gripper fingers is 0.23 and the force on the gripper finger is 2,800 N.

When frictional force is utilized for gripping, where the fingers apply a frictional force that is strong enough to keep the part against gravitational force:

$$= mg$$

where μ is the coefficient of friction, *n* is the number of fingers to grip the object, *F* is the gripping force, *m* is the mass of the object, and *g* is acceleration due to gravity:

$$m = \frac{\mu n F}{g} = \frac{0.23 \times 2 \times 2800}{9.81} = 131.29 \text{ kg}$$

Magnetic grippers

Magnetic grippers are utilized in applications where the work piece to be handled is made up of ferromagnetic materials. Because of their magnetic character, these grippers can easily handle the parts with holes. The gripping effect will be maximized when the magnet has complete contact with the surface of the metal part. Flat metal parts are best suited for magnetic grippers as there will not be air gaps between the materials, which can reduce the strength of magnetic force. Stronger magnets are required to grip an irregular-shaped object. The *figure 2.4* shows the working of a magnetic gripper:

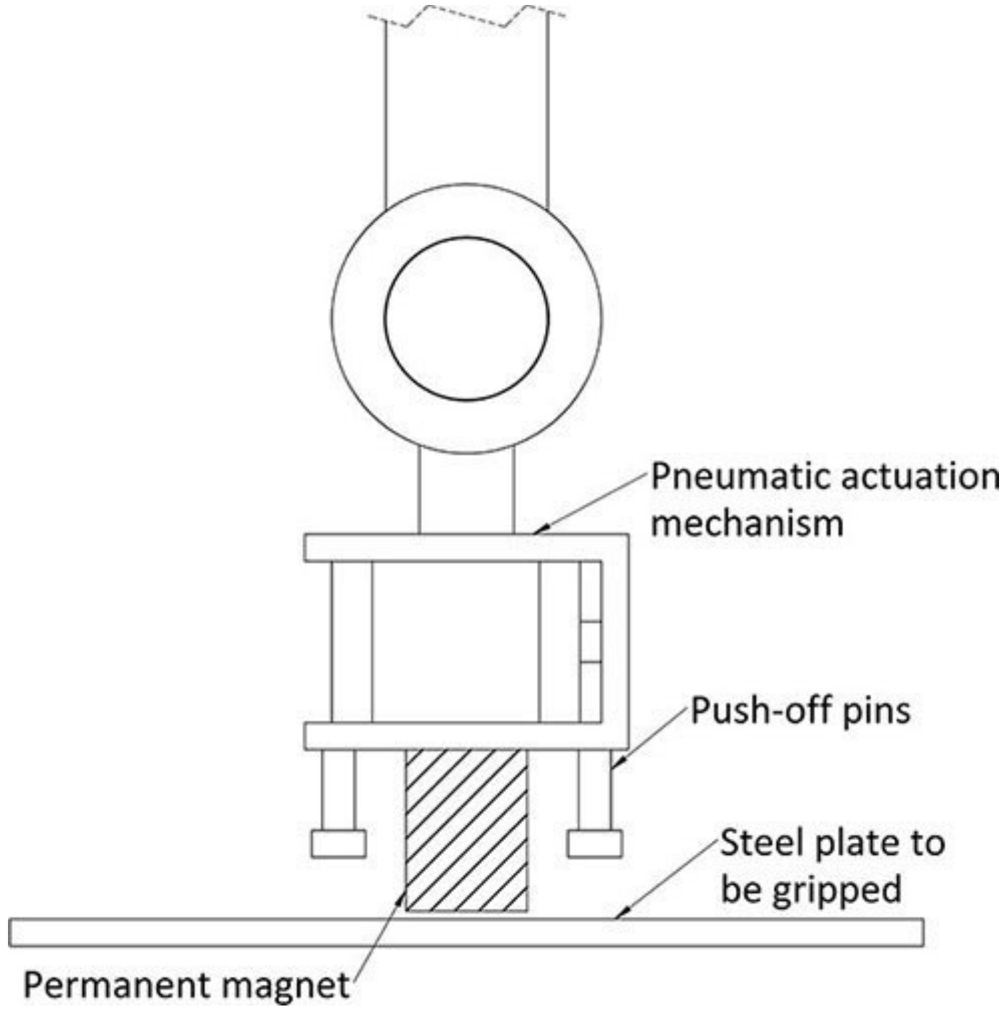

Figure 2.4: *Magnetic gripper*

The advantage of using magnetic grippers is that they leave very less or even no residual magnetic charge when turned off, thus allowing the part to be released from the gripper instantly. Another advantage is that they have enormous power for holding and gripping when compared to their compact size. Magnetic grippers need only one surface for gripping. They can grip parts with holes also, which is not possible with vacuum grippers. Gripping time is very fast with magnetic grippers.

In addition to permanent magnets, electromagnets can also be utilized for gripping. It is easier to control electromagnets when compared to permanent magnets but require DC power source and control circuitry for its action. As they are operated with electric current, the part that is gripped can be dropped due to power failure and result in an unsafe mode of operation. Therefore, permanent magnets can be utilized in such hazardous environments, while in some other areas of operation, electromagnets can be employed due to their easier control and faster picking and releasing of work parts. Permanent magnets are also employed in applications where the atmosphere has an explosive character and, in such atmosphere, electric equipment may create sparks, which can cause hazards.

The drawback with magnetic grippers is their dependence on temperature. At a very high temperature, permanent magnets tend to get demagnetized, thus making magnetic grippers less efficient in applications where prolonged contact with a hot work piece is needed. Most of the magnetic materials behave normally up to high temperature of around 100°C. The time duration when the hot work piece is in contact with the magnet determines the effect of heat in gripping with magnetic grippers.

Another issue with magnetic grippers is that while grasping a metal sheet from a stack of sheets, they can take multiple sheets because of the force of magnetic attraction. One method to solve this is to separate the sheets by giving provision for the same in the stacking device for proper picking by the magnetic gripper. For taking sheet at the top of the stack, a charge is induced in the iron sheets using a magnetic field, due to which the top sheet repels the rest of the sheets because those same charges repel each other. Such a stacking arrangement device is called Another method is to design the magnetic gripper such that the effective depth of penetration of the magnetic force corresponds to the thickness of the sheet so that the other sheets below it is not displaced by this magnetic force.

Vacuum cups

Vacuum cups are a simple form of grippers that can be used for gripping objects with smooth, flat, and clean surfaces (refer to *figure* But they cannot be used for gripping all types of objects and surfaces with holes. Their major advantage is that they do not require electric power, and thus, the issue of slipping of the object during power failure does not come in vacuum grippers. The gripper based on vacuum is light in weight and needs only one surface of the object to grip. Its drawback is that its application is limited to smooth, clean, and flat surfaces. They are manufactured from silicone, neoprene, etc. similar to rubber or soft plastic material. The number of suction cups is decided based on the dimensions of the object to be grasped:

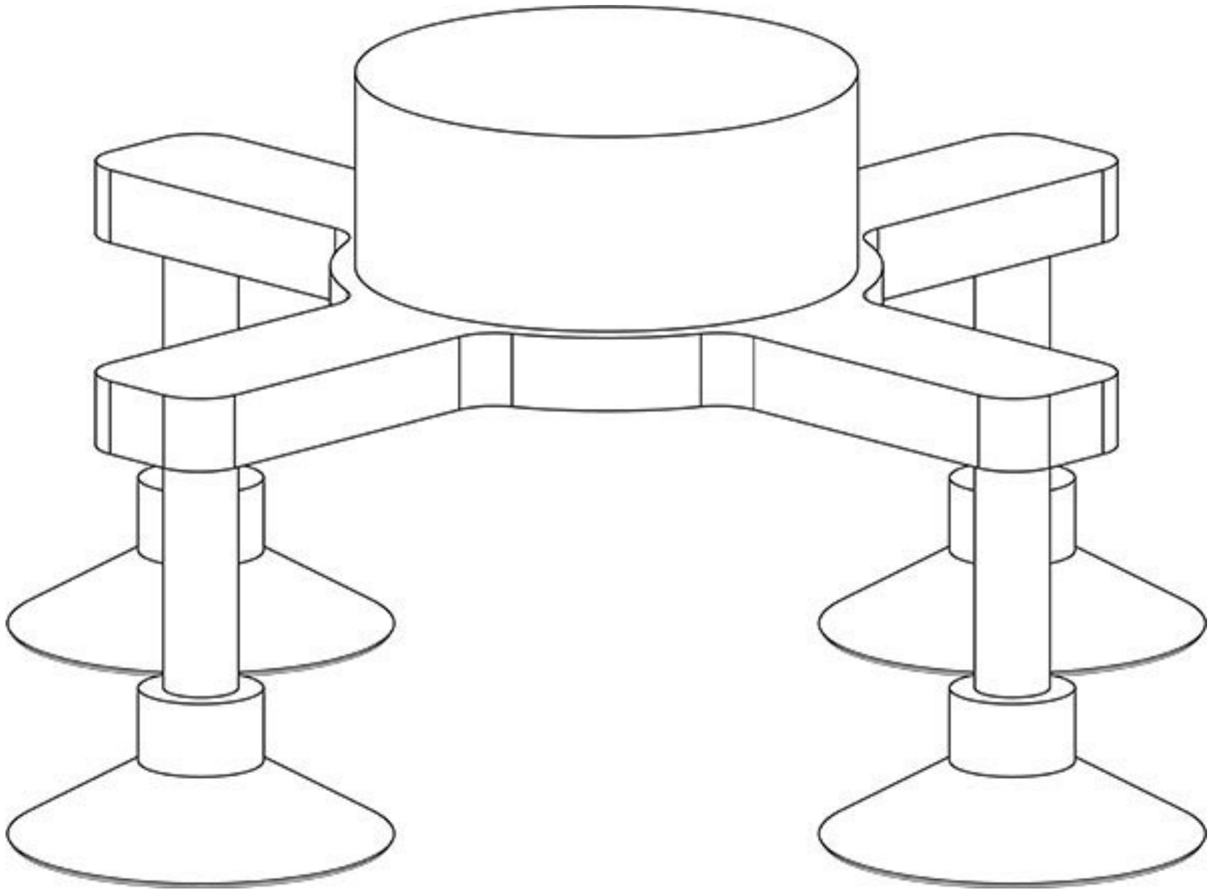

Figure 2.5: *Vacuum cups*

These types of grippers are provided with a vacuum pump or venturi to create vacuum by removing the air between the cup and the object to be gripped. The gripping capability of the vacuum cup is given by:

$$F = P \times A$$

Where P is negative air pressure between the vacuum cup and the object, and A is the area of vacuum cup with effective vacuum.

Adhesive grippers

Some grippers can utilize adhesive materials for gripping lightweight materials like fabrics. Such application does not require high power and force. This gripping technique is utilized when the object must grip on one surface and when vacuum or magnetic gripping is not possible. The drawback of this mechanism is that its efficiency is easily affected as the adhesive used for gripping will lose its adhesive property when used many times. After each use, its adhesiveness, and hence, the reliability of gripper, decreases. Therefore, provision should be made to load the adhesive continuously like the ribbon of a typewriter so that adhesion is ensured during the gripping process.

Tools

Robots require grippers in applications where they must grasp a work part or hold or pick and place an object. In many applications, robot needs to manipulate a tool instead of gripper for a particular operation. Robots require certain devices called tools for performing certain tasks like drilling, welding, spray painting, etc. Tools are designed for these specific tasks and are designed such that they can be held or fitted to the end of the robotic arm.

Programming can be done for changing, selecting, and operating them without human involvement. For an end-effector, the path control is of utmost importance; hence, it needs to be steadily and continuously controlled during every instant of its motion. For the effective operation of the tool, it should be able to move in continuous path for a careful and steady motion for its operation. When a spray gun is used as a tool by the robot, the paint will be too thin if it moves fast and will be too thick if it moves slowly.

Some of the tools used in robotics are as follows:

Tools for arc welding

Tools for spray painting

Tools for spot welding

Rotating spindles

Deburring tools

Tool for arc welding – welding torch

In arc welding, an electric current is passed through the electrode as an electric spark, or this spark produces sufficient heat to melt metals for welding as well as the filler material. The molten metals to be welded and filler in molten state will all mix and get hardened into a single piece as they cool. The use of robots has become very popular for arc welding applications. Welding torch is used for this purpose as a tool.

Jointed arm type has gained maximum popularity for this application as this configuration allows the welding torch to be manipulated in almost the same way as is handled by a human being. The torch angle and travel angle can be varied to ensure high quality in welding. Jointed arm robots make it possible to reach areas that are not easy to reach in the manual welding process. Jointed arm robots are very compact and have the largest work envelope compared to their size.

A *welding torch* directs the welding electrode into the arc and conducts welding power to the electrode, and provides shielding of the arc area. The type of welding torch is selected based on the welding process, the welding current needed, size of electrode, shielding medium, etc. Figure 2.6 shows the model of a welding torch:

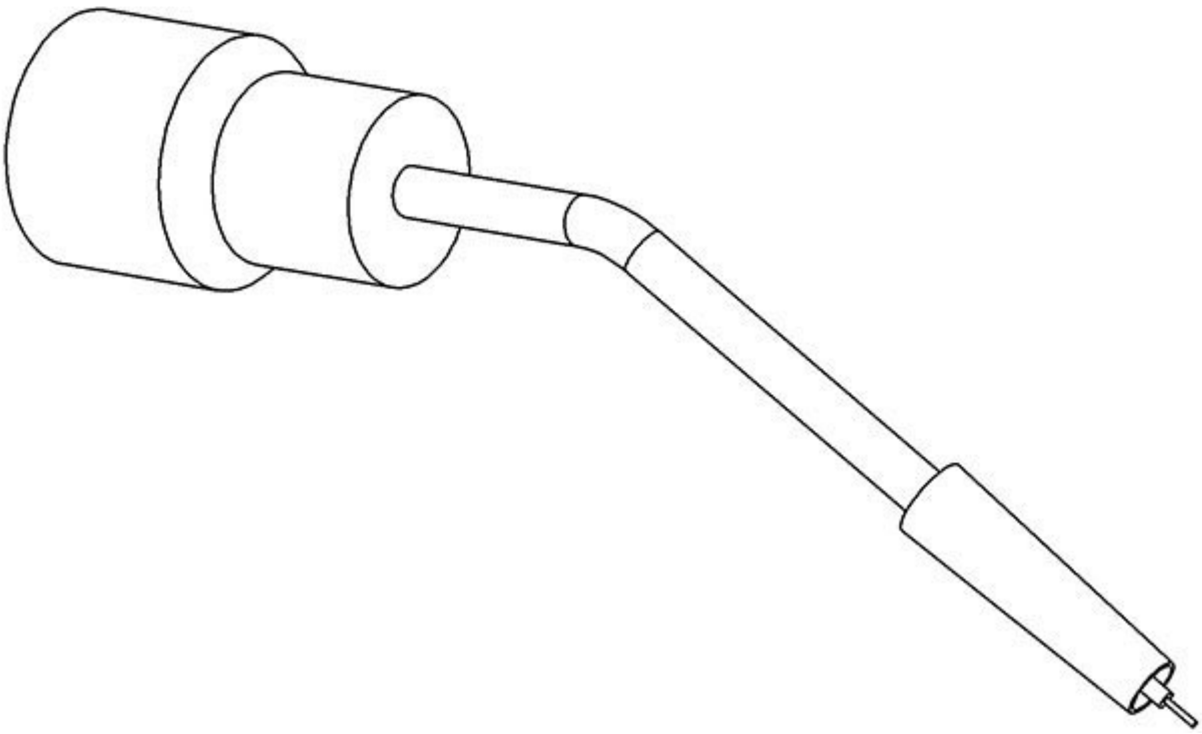

Figure 2.6: *Arc welding tool - welding torch*

Welding torches are classified on the basis in which they are cooled. Some are water-cooled by circulating cooling water, and some others are air-cooled by circulating ambient air. A torch can be used for a consumable electrode welding process such as gas metal arc or flux-cored arc welding. Some welding torches are straight in shape, and some others have a bend in their barrel.

A torch with a bend is more commonly employed in robotic arc welding applications to provide access for the weld. The welding torch delivers the welding current to the electrode. It also delivers the shielding gas, if needed, to the arc area. Gas metal arc welding uses a shielding gas that is active in nature like carbon dioxide or its mix with an inert gas like argon.

Tools for spray painting

Painting is done as the final step in production for finishing and protecting the metallic material from corrosion. Robots should be used for spray painting as the fumes may be carcinogenic and can affect the health of person performing the painting task if done manually. In robotic spray painting, a spray gun is used to coat the paints on a metal. It has a spray gun nozzle through which paint is disbursed to any surface. It should be done consistently with uniform spraying so that the whole area is painted with minimum wastage of paint. It is clearly shown in *figure* For this application, a robot with a continuous path control capacity is employed:

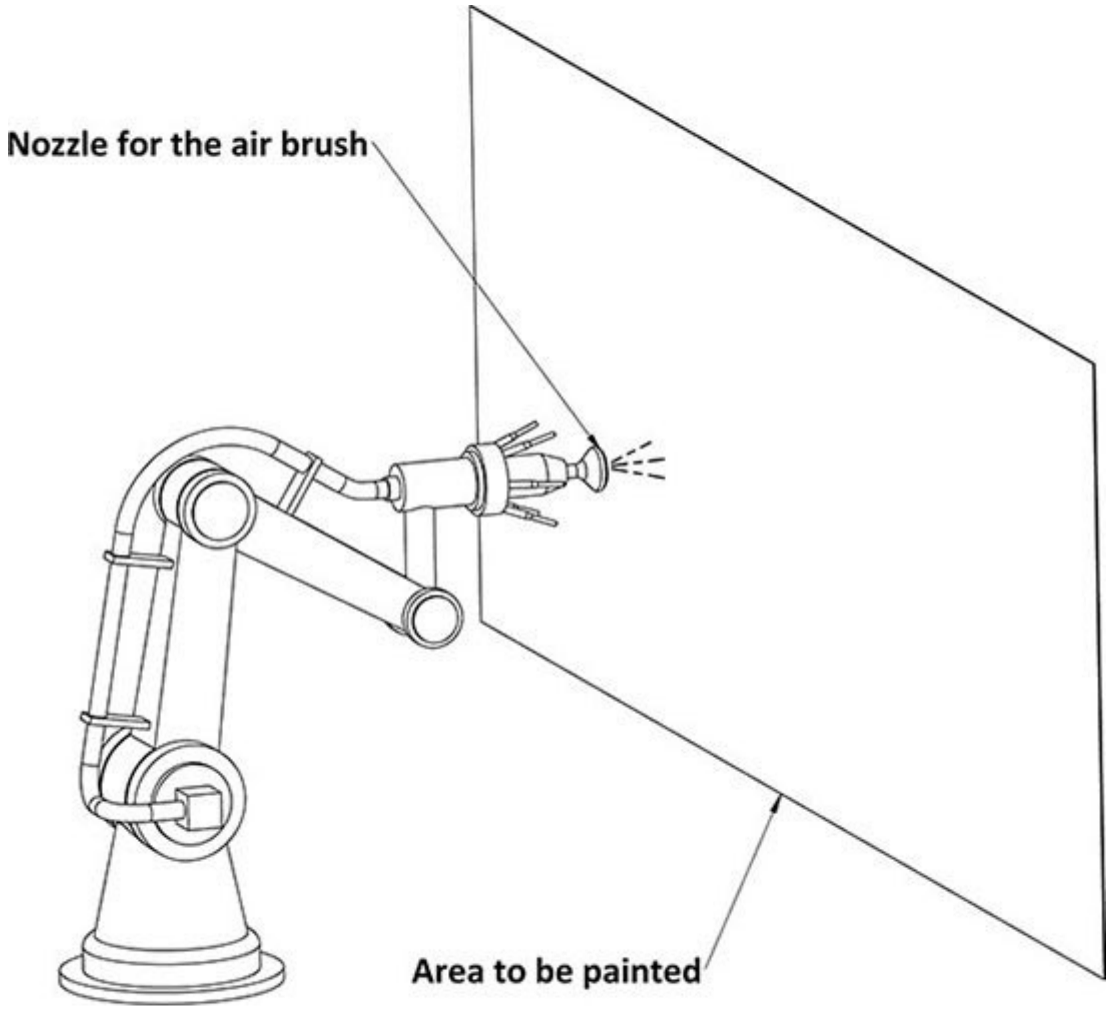

Figure 2.7: *Spray painting tool - spray gun*

The advantages of robotic spray painting are the ability to remove the operators from hazardous environment filled with fumes, carcinogenic components, and fire hazards. It also enables smooth movement of the spray-painting device for better finish.

A spray gun is controlled by the robot by proper program execution. During the spray-painting operation, the major factors like turning nozzle of spray gun ON and OFF, rate of paint flow, fluid pressure, etc. are controlled and maintained using interlock functions of the robot controller through programming.

The spray gun needs to be cleaned periodically, which is done effectively by including a cleaning cycle in the program at regular intervals, without much loss of production time. The spray nozzle is placed in cleaning jets, which spray the solvent on the nozzle for cleaning.

Tools for spot welding

Spot welding or resistance spot welding is the welding technique in which metal sheets are joined together by applying heat and pressure from the electric current to the area to be welded. In this process, copper alloy electrodes are kept in contact with the metal sheets to be welded at localized points to be welded.

In the spot-welding process, pressure and heat are applied to the weld area using shaped alloy copper electrodes, which allows an electrical current to pass through the weld pieces. The material melts with this heat, and this molten material solidifies and makes the joint for the two sheets. The current passed should be sufficient to reach its melting point by means of resistance heating. The end-effector commonly used in spot welding robots is a spot-welding gun at the end of a robot wrist.

The robot performs the spot-welding operation based on the program. The parts to be welded are held together, and the electrodes are positioned at the points to be welded. Then, these electrodes are squeezed together against the parts, and the current is passed through when it gets welded because of the heat. The electrodes are removed and allowed to cool before next welding. The electrode cooling process is speeded up using the water circulation system.

Specific spot-welding needs just a second, while more time is required for properly positioning the parts and electrodes. Also, wear and tear of the tip of electrodes of spot-welding guns occur quickly due to the heat used in welding. Therefore, the tops of electrodes are periodically dressed for removing the residues and deposits of previous welding operations, and the shape is restored for maintaining the quality of welding.

Thus, robotic spot welding improves the quality of the process, provides better safety for the operators, minimizes labor cost, and gives a better control for the operation. The welding gun consists of a frame to open and close the pair of electrodes (refer to *figure* The current is delivered to the electrodes by means of large electric cables. A powerful robot is needed to manage the spot-welding gun, causing it to be very heavy, weighing almost 100 kg, including the pair of electrodes and large cables attached.

The most common application is spot welding of car bodies in motor industries. Spot welding guns are available as pneumatic and hydraulic guns. As pneumatic guns are faster and apply a uniform force on the electrode, they are preferred more. Hydraulic guns are employed in welding applications where limited space is available or higher forces need to be applied on the electrodes. Based on the type of action, spot welding guns are classified as C-type and X-type guns. In a C-type gun, the operating cylinder is connected directly to the moving electrode, and in the X-type guns or scissors, the operating cylinder is remotely located with respect to the moving electrode, and the force is being applied with a lever arm. C guns are generally the cheapest and the most commonly used.

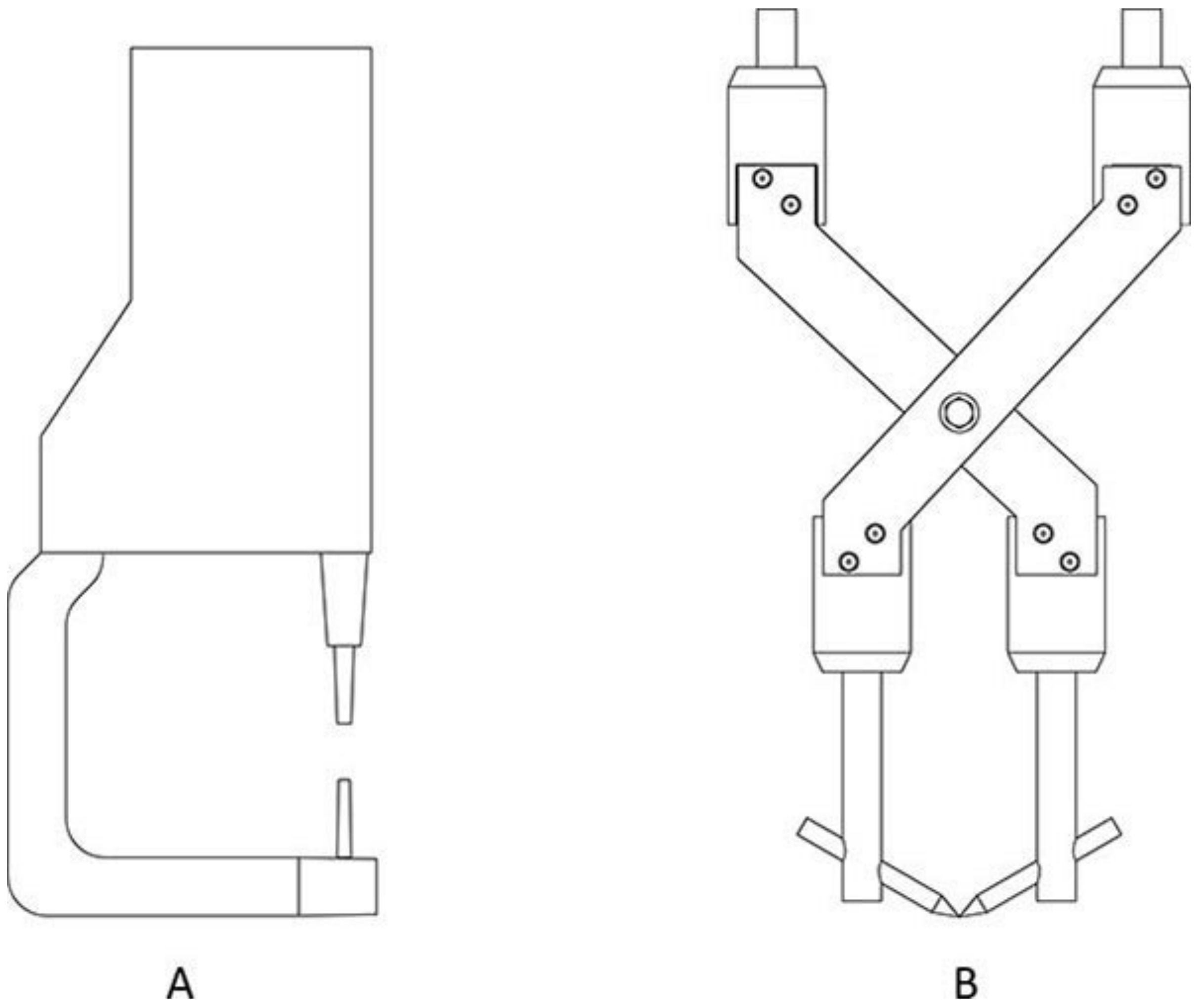

Figure 2.8: *Spot welding gun (A) C-type and (B) X-type*

Rotating spindles

For applications like drilling and grinding, a rotating spindle is used as an end-effector. Based on the application, a drill or cutting tool may be added to the spindle for the drilling or cutting operation.

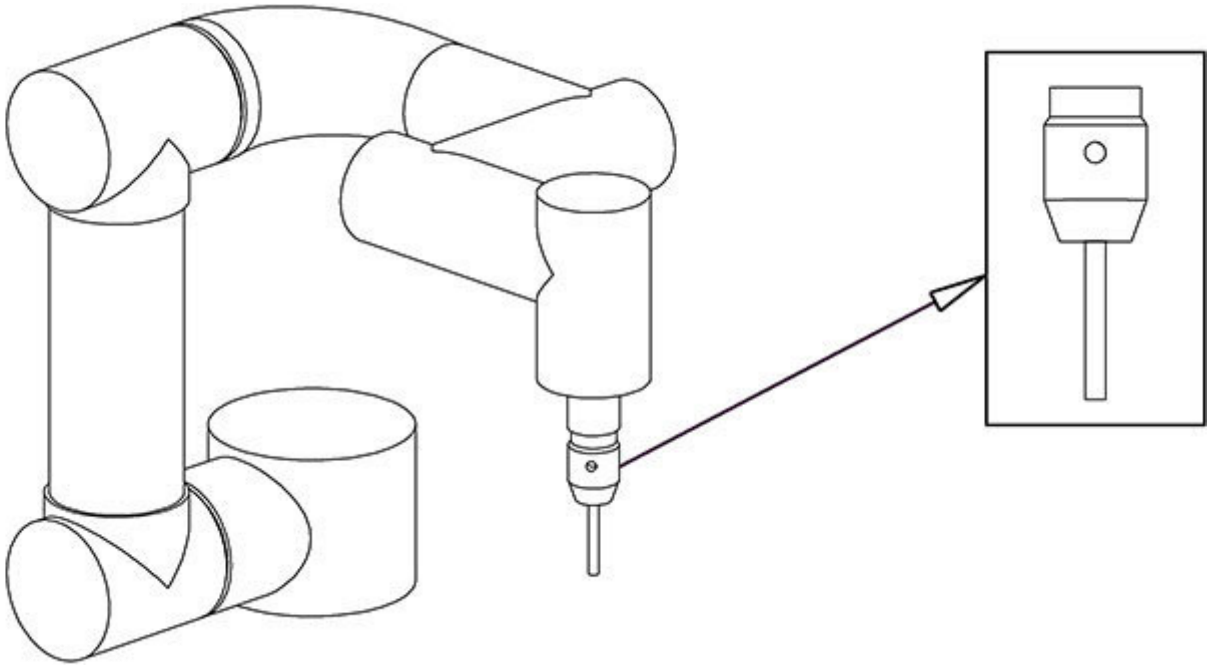

Figure 2.9: *Rotating spindle*

In most of the machining operations like drilling, grinding, polishing, and other processing operations, the robot utilizes a rotating spindle. The spindle rotates various tools like drill in drilling operation or grinding wheel for grinding.

Robotic spindles should match the manufacturer's needs. Rotating spindles are small pieces designed to fit into small spaces, as well as robust and powerful, making it suitable for harsh material removal operations. The *figure 2.9* shows a rotating spindle. Spindles are used for drilling operations by selecting spindle parameters based on the depth and diameter of hole and tolerance allowed. Spindles are also used for milling applications like engraving or routing, which involves material removing at high speeds and finishing surface materials with high precision.

Some spindles are used for grinding using a grinding wheel to grind away materials like metal, glass, ceramics, or other materials to the desired shape or finish. Spindles used for deburring should be operated with high speed and low torque. Spindles used for finishing and polishing should allow the tool to glide gently over the finished work piece with high RPMs and low horsepower. Thus, in all these applications, spindles and their performance are responsible for the proper execution of each operation.

Deburring tools

A burr is defined as an undesirable effect like a raised edge or small piece of the material that is protruded at the edge of a work piece after the machining or modification process. It can also occur during casting, forging, welding, cutting, plating, painting, etc. Deburring is a finishing process to remove these burrs from the work piece as they create hindrance in assembly work, and its sharp edges can injure a worker's hands. Also, it affects the finishing of the product. Deburring tools are used in robotics for this purpose. They have straight, angular, or multi-positioned head and are actuated by electric, pneumatic, or hydraulic power.

While spinning at high speeds, a rotary cutting deburring tool moves on an air cushion that provides a reliable field of compliance, as well as maintaining a constant force. It provides more stiffness for the tool in the path direction and a lower stiffness in the direction of contact. Robotic deburring tools are mostly radially compliant or axially compliant. Some tools offer resistance in a direction in line with the axis of the tool and are radially compliant. They can be utilized for removing parting lines or flash from work parts. Flash refers to the excess unwanted material attached to a final product, which must be removed. This normally occurs due to leakage of the material between the two surfaces of a mold. Some other tools are stiff in the radial direction, perpendicular to the axis of the tool, and are axially compliant. These axially compliant tools operate with a motor and floating rotary file for cutting.

A robot deburring system comprises of a spindle motor, a deburring tool, and a tool holder. The deburring tool is rotated and oscillated in the required direction by the spindle motor and rotates the work piece when required. This is possible only when the work piece is small and lightweight. Robot deburring tools include flexible tools, rotating files, oscillating files, and internal deburring tools.

Flexible tools include belts used for straight line edges and brushes utilized for the corners. Brushes are made of aluminum oxide, ceramic, or silicon carbide filaments on nylon or steel material with a rigid base (refer to *figure* Belts are manufactured with coated abrasives with cloth or paper backing. Solid deburring tools are rotary files that are widely used for various applications (refer to *figure* They are available in different shapes and geometry and made of different materials. Oscillating files are used for removing small and slender burrs.

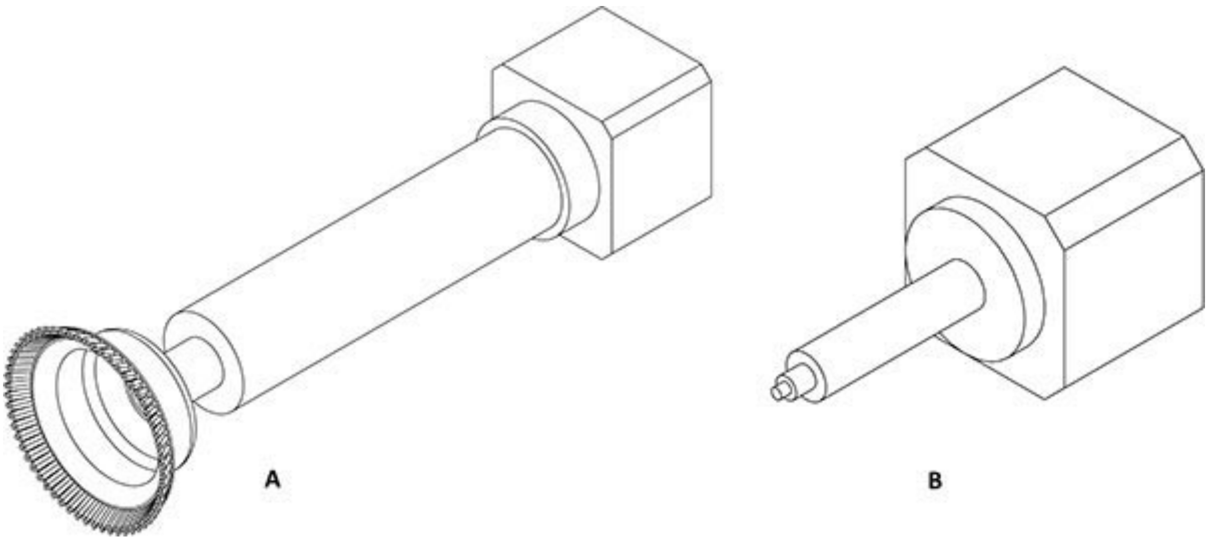

Figure 2.10: *Tools for deburring (A) Deburring brush (B) Deburring tool*

Design and selection criteria for grippers

The selection of a gripper is usually made by examining the geometry of the part, its orientation, the space available, and the manufacturing treatment to be performed. External gripping is the most widely used type, where the closing force is utilized to clench the part. An internal grip makes way for unobstructed access to the outside surface of the part, which is necessary for polishing/buffing, grinding, or painting applications. The opening force of the gripper is used to hold the part. There are numerous types of grippers both in style and power source. Determining which is the best type to use is an important issue that robotics users must face. Selection of the gripper is based upon several factors that may need consideration:

Source of power: Based on the source of power for its operation, they are classified as: pneumatic, hydraulic, and electric grippers:

Pneumatic grippers operate with the power obtained by introducing compressed air into a chamber of the device and powering a piston attached to a rod. The *figure 2.11* shows a simple diagram of a pneumatic gripper. This energy is utilized for the mechanical motion of the gripper. In pneumatic grippers, jaws operate either in parallel or angular manner. The force required for its actuation is managed by the air pressure by adjusting the valve. The drawback is that it cannot be controlled fully. Mostly the jaws would mostly be in either open or close state:

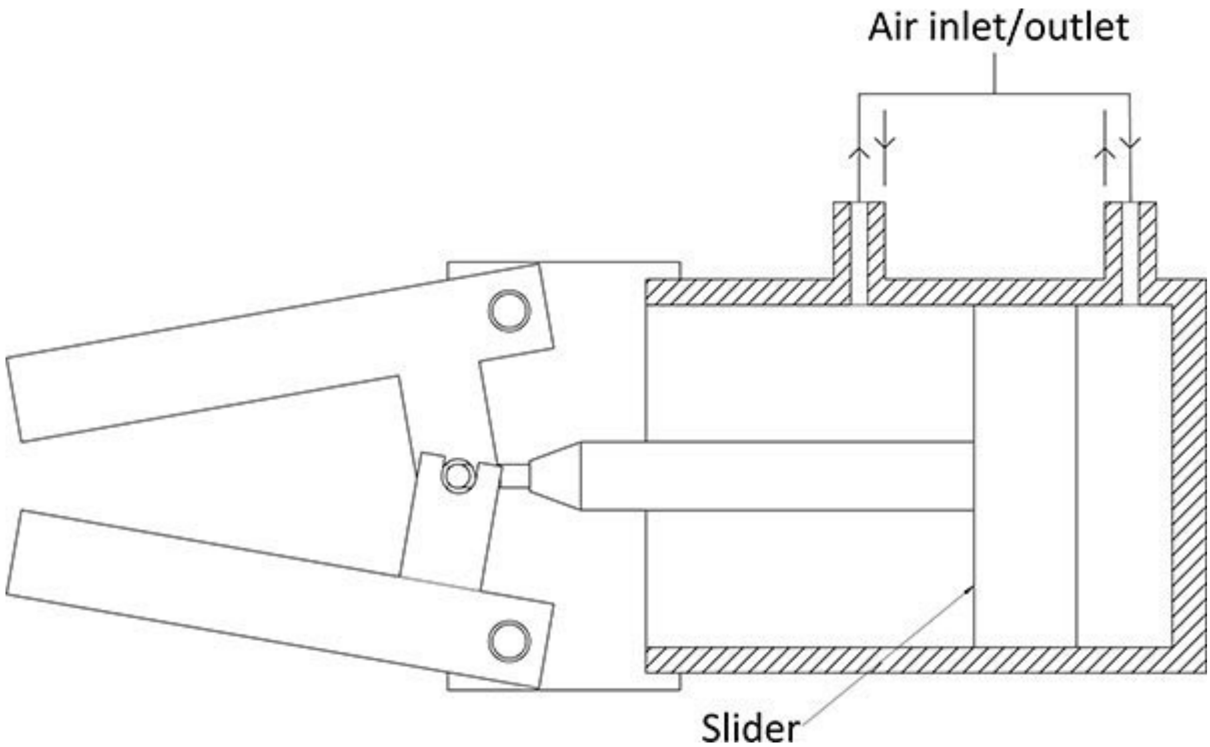

Figure 2.11: *Pneumatic gripper*

Electric grippers use electric power for actuation and allow greater control. They allow higher speed of operation and precise control of force, as well as movement. They do not generate dirt particles and can be used for applications where a clean environment is required. Unlike pneumatic grippers, their operation can be controlled and the extent to which gripper jaws can be opened or closed can be adjusted. It can be achieved by making use of stepper motors. They are more controllable than pneumatic grippers. Also, they do not generate dust or waste particles and are ideal for application in a clean environment. The drawback is that they tend to be larger in size than pneumatic grippers.

Hydraulic grippers use hydraulic fluid instead of air in pneumatic grippers. The *figure 2.12* shows a hydraulic gripper. Fluid ports are provided for the working fluid to get in and out of the cylinder. Their major advantage is that gripping power is very high as the hydraulic fluid is not as compressible as air used in pneumatic grippers.

They are not commonly used as their accuracy is less compared to pneumatic and electric grippers. They are more costly and generate dirt, making it unsuitable for clean room applications as there is a chance for leakage of hydraulic fluid like oil.

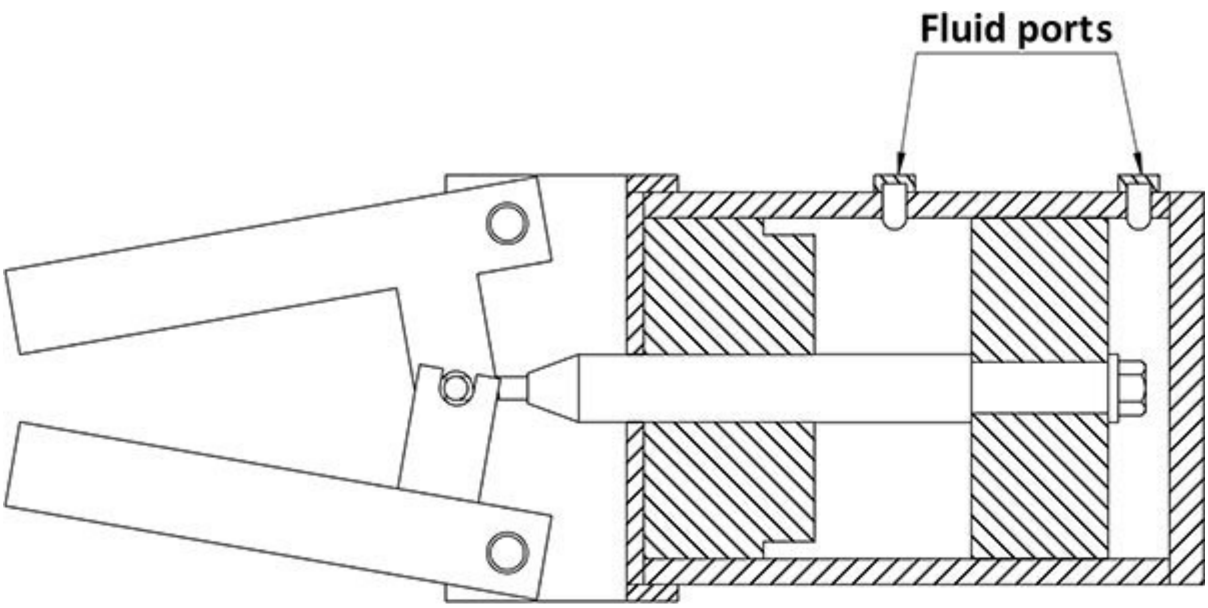

Figure 2.12: *Hydraulic gripper*

Gripping force: The force required for gripping an object depends on its mass and its acceleration due to robotic motion. Gripping force also depends on the coefficient of friction between the gripping part and the gripper. The required gripping force can be reduced by designing fingers exactly for the gripping part. Even though it increases the weight-carrying capacity, it reduces the flexibility of handling.

Style of gripping: Gripping can be done in an angular or parallel manner. In parallel grippers, the jaws move parallel to the body of the gripper, and in angular grippers, the jaws of the gripper move in the form of an arc by opening and closing around a central pivot point. This is implemented based on some linkage mechanisms. Parallel grippers (refer to *figure* are made with guide rails along which the base of fingers move parallel to each other.

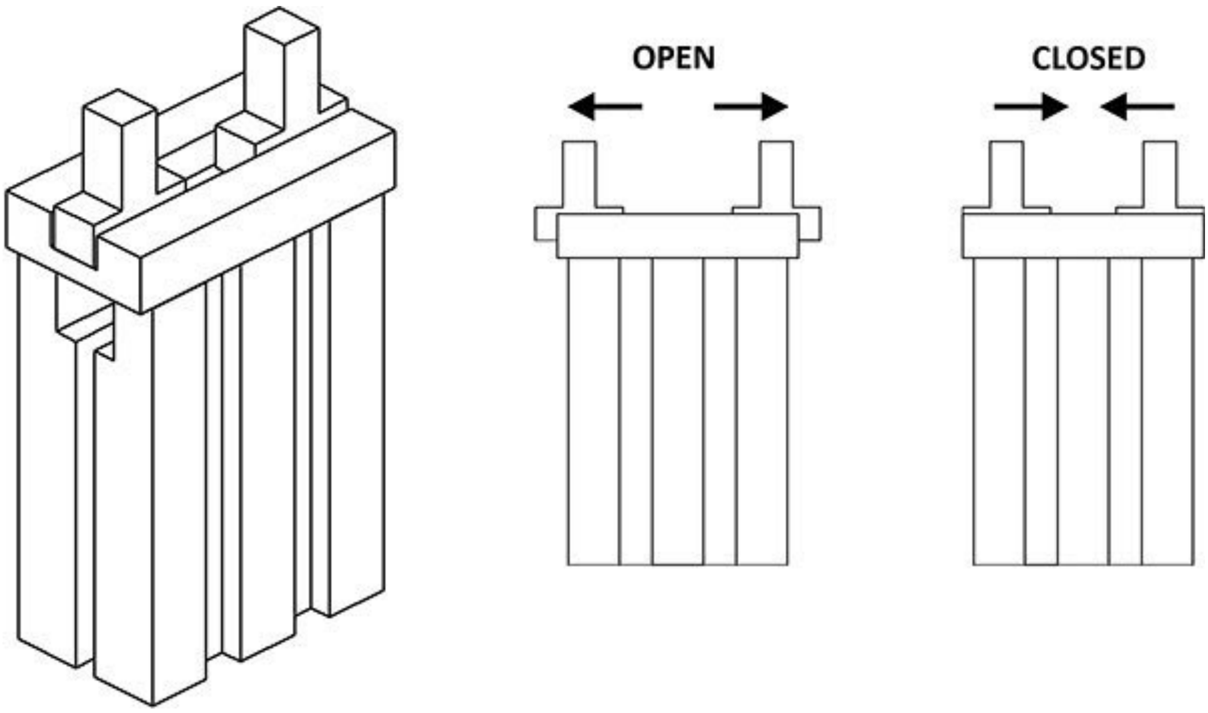

Figure 2.13: *Parallel gripper*

The type of gripping is determined based on the specific needs of an application. Though angular grippers are more economical, they cannot be used for all applications due to their sweeping action.

The figure 2.14 shows a simple diagram of angular grippers. Parallel grippers are employed more in applications with space constraints. Their fingers fit into small areas in a better way and are commonly employed for pulling a part out of a machine laying deep inside. The most popular configuration is two-jaw parallel grippers as they are easy to design and program as it works only in one axis of motion:

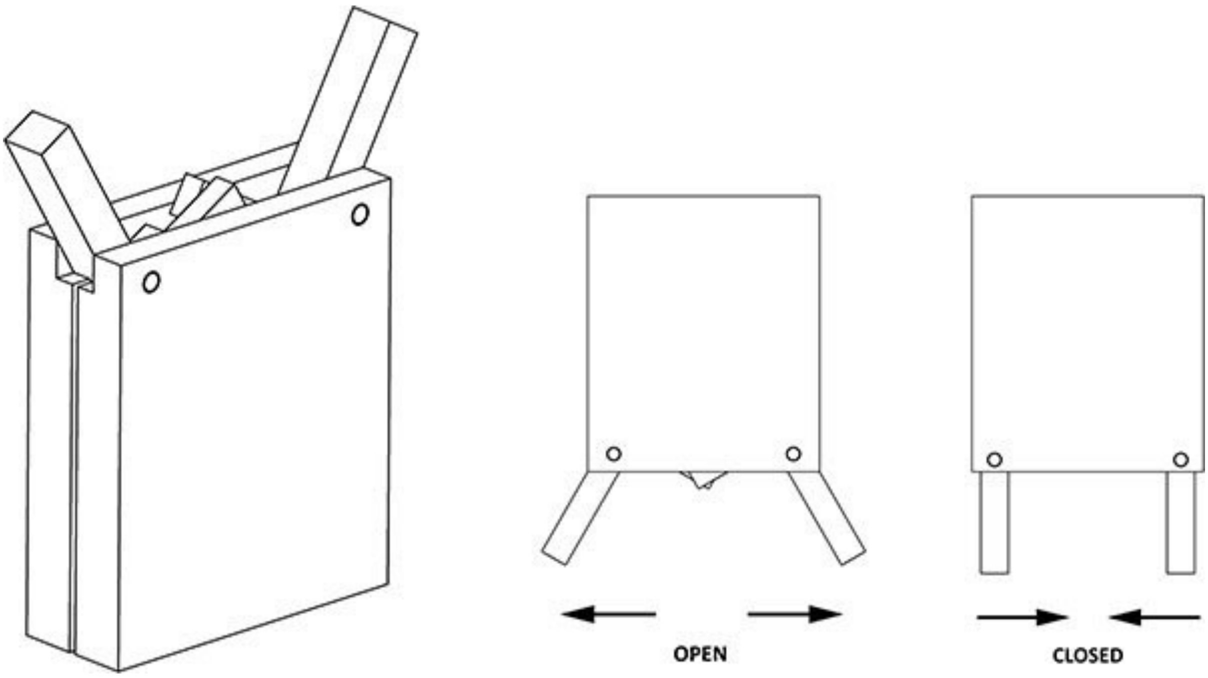

Figure 2.14: *Angular gripper*

A gripper can also be classified as external or internal gripper. External grippers grasp the exterior surface of the handling part with their closed fingers, whereas internal grippers grip the internal surface of the handling part with their open fingers. Internal grippers are used in cases in which some objects need to be held from inside like a coil of wire or when the external part of the object must be accessed and must be kept free. The figure 2.15 shows an internal gripper where the object is gripped internally like holding a bottle by gripping on the internal surface or through the opening of the bottle. Thus, the object is gripped by the opening force of the gripper:

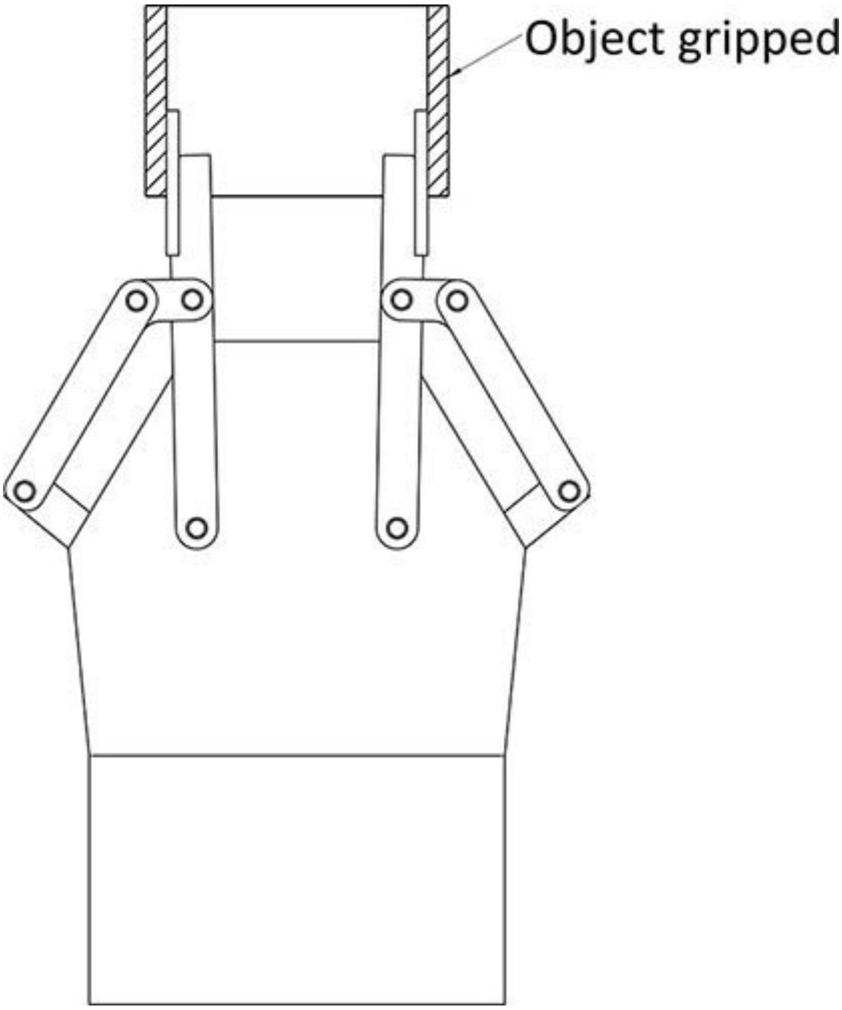

Figure 2.15: *Internal gripper*

External gripping is a simple technique, and shortest stroke length is required for this method. The *figure 2.16* shows an external gripper where the object is held externally. The object is gripped by the closing force of the external gripper:

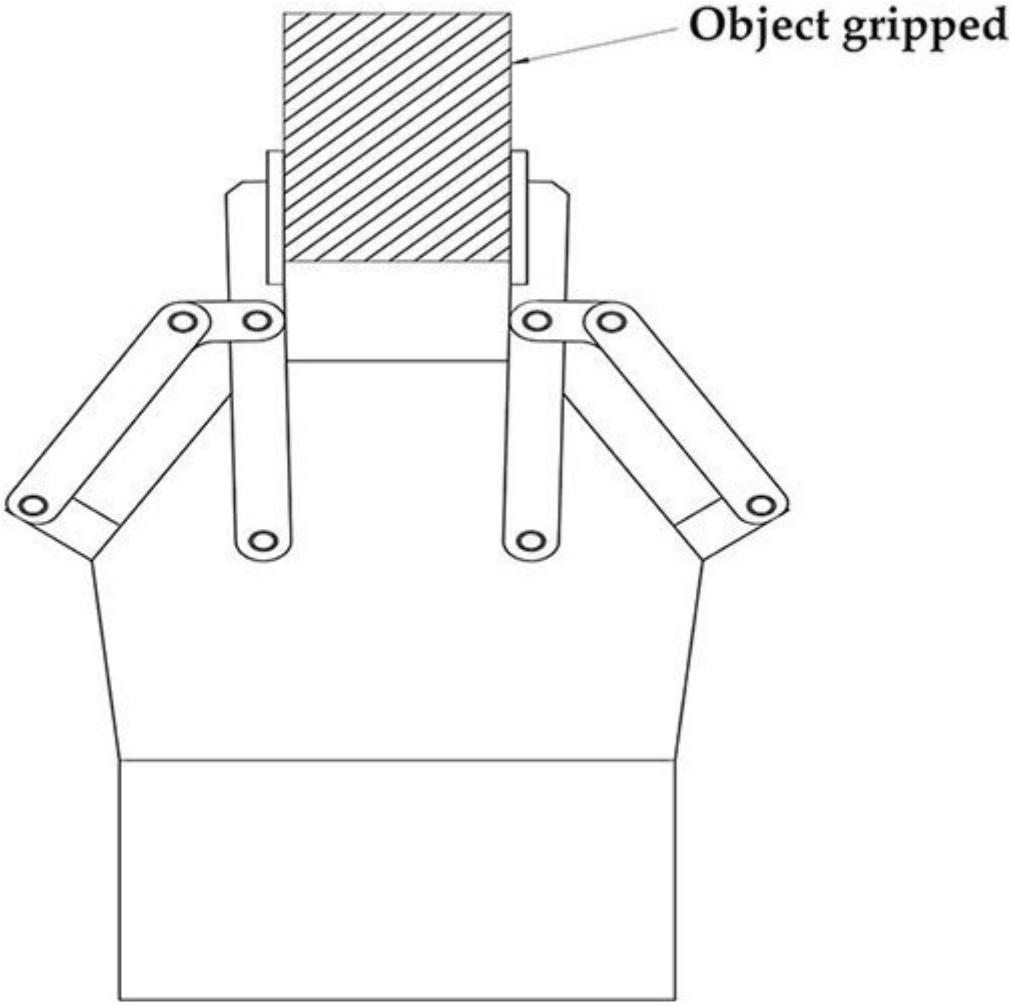

Figure 2.16: *External gripper*

Weight: The maximum weight that it can handle.

Environment of operation: Based on the environment where it is working, specifications and design considerations should be made for its operation. For example, if they are to work in a hostile environment, end-effectors should be made of material to handle high temperature or in presence of highly reactive chemicals.

Sensor capabilities: Some applications require an input from the gripper such as conveying information if an object is between the jaws of gripper or to give information about the distance from an object, etc. This can be done by combining sensors like proximity sensors or force sensors to calculate the force experienced on it.

Many other factors have to be considered like the speed of movement of gripper jaws, the possible range of size of components that it can grip or handle, number of jaws of the gripper, level of maintenance required, etc.

In 1988, Engelberger discussed in detail the various factors to be considered for the selection of a gripper in his paper *knowledge-based system for robot gripper selection: criteria for choosing grippers and surfaces for* in *International Journal of Machine Tools and*

The following are the major points pointed out by Engelberger:

It should be possible for the gripper to reach the part to be gripped.

The variation in the size of the part to be worked has to be accounted for positioning the part with maximum accuracy.

Design of a gripper should be done by considering the part size variation during the loading and unloading of part.

The gripper should not create any problem like scratching or distortion of the part to be gripped.

If possible, grasping of part with larger dimension should be selected for better stability.

Self-aligning fingers called resilient pads can be designed such that each finger makes multiple contacts with the part in different positions.

Thus, the following factors should be considered while selecting the gripper to be employed for a specific task:

Part to be gripped or handled: The dimension and weight, shape of the part, shape modifications during handling, condition of the surface, etc. should be considered.

Method of actuation: It should be taken into consideration which method of actuation to be implemented in this system. It can be mechanical grasping, using magnet, adhesive gripping, vacuum cups, etc. (Refer last sections for detailed explanation of each.)

Source of power and control signals: End-effectors require power to operate and control signals to control its operation. The main types that can be opted are pneumatic, hydraulic, electric, or mechanical. These have been explained in the last section of this chapter.

Conclusion

A robot is provided with hands by end-effectors. These tools and grippers enable the robot to perform various actions and complete certain tasks. This chapter discussed the various types of grippers, including mechanical grippers, vacuum grippers, magnetic grippers, adhesive grippers, and explained in detail the advantages and disadvantages of each type. Various tools used in robotic applications like welding, spray painting, etc. are explained.

Points to remember

End-effectors are the hands for the robot. They are the devices attached to the wrist of the robotic arm.

End-effectors are of two types: grippers and tools. Grippers are used to grasp or hold objects, and tools are used for specific tasks like welding, spray painting, deburring, etc.

Mechanical grippers physically hold the object using fingers or jaws either using the physical constriction method or making proper use of friction between the gripper and surface of object.

An internal gripper holds through the interior surface of the object to be grasped, while an external gripper holds through the external surface of the object.

Magnetic grippers handle ferrous materials using magnetic force. It can grip the part through one surface and can handle parts with holes, which is not possible with vacuum grippers.

Vacuum grippers hold flat objects with smooth, clean surfaces by creating vacuum between the surface of the object and the vacuum cup.

Adhesive grippers hold lightweight objects like fabric using adhesive substances.

Engelberger has suggested few major factors to be considered for the selection of grippers.

Multiple-choice questions

Which part is referred to as the hands of the robot?

End-effectors

Sensors

Actuators

None of these

Which of the following are not grippers?

Vacuum cups

Magnetic grippers

Deburring tools

Mechanical grippers

Based on the mode of power transmitted, grippers are classified as:

Hydraulic

Pneumatic

Electric

All of the above

Based on the mode of gripping, they are classified as:

Mechanical grippers

Magnetic grippers

Vacuum grippers

All the above

The gripper used for holding a lightweight material like fabrics is:

Magnetic gripper

Adhesive gripper

Vacuum gripper

Mechanical gripper

The gripper used to grip objects with a flat, smooth, and clean surface is:

Magnetic gripper

Adhesive gripper

Vacuum gripper

Mechanical gripper

Answers

a

c

d

d

b

c

Questions

Discuss the uses of end-effectors in robotics.

Explain the difference between grippers and tools.

Discuss the advantages and drawbacks of magnetic grippers.

Explain vacuum grippers. Which fields of application can make use of vacuum grippers?

Describe the various types of grippers used in robotics and their fields of application.

Describe the various tools used in robotics for various applications.

Differentiate between internal and external grippers.

Compare the advantages and disadvantages of mechanical grippers, magnetic grippers, and adhesive grippers.

With neat sketches, distinguish between internal and external grippers and their working.

With neat diagrams, differentiate between parallel and angular grippers.

Discuss the differences between hydraulic, pneumatic, and electric grippers.

Illustrate the various considerations for gripper selection given by Engelberger.

Key terms

End-effector: A device attached to the wrist of the robotic arm.

Gripper: A type of an end-effector used to grip or hold a work part or object.

Magnetic gripper: A gripper used to handle ferrous materials using magnetic force. It can grip the part through one surface and can handle parts with holes, which is not possible with vacuum grippers.

Vacuum cups: Grippers that hold flat objects with smooth, clean surfaces by creating vacuum between the surface of the object and the vacuum cup.

Adhesive gripper: A gripper that holds light weight objects like fabric using adhesive substances.

Internal gripper: A mechanical gripper that holds an object from the interior surface of the object.

External gripper: A mechanical gripper that holds an object from the exterior surface of the object.

CHAPTER 3

Sensors

Introduction

Just like our sense organs, sensors provide sensory inputs to robots. Just like humans, robots also need inputs to take actions and perform a task properly. Robots, like humans, must acquire the information from the surrounding areas and should learn about the environment around them, for proper functioning. In some cases, they need to know the location, how close an object is, or if there is any obstacle in their path. And, in some other cases, they require data input of variables, like temperature. All this information can be obtained through sensors.

A robot arm should know if there are any obstacles nearby for its motion in a three-dimensional space, and it must decide on its speed based on this. It should also be able to know the nature of the material, whether it is heavy, high temperature, or fragile. These requirements are met by employing sensors to provide all the necessary inputs for the robot to perform a task.

Structure

In this chapter, we will discuss the following topics:

Need for sensors in robotics

Various classifications of sensors

Contact and non-contact sensors

Characteristics of sensors

Applications of sensors

Objectives

The main objective of this chapter is to give a brief introduction on robot sensors and the significance of sensing the surroundings and objects of interest by the robot. This chapter gives a detailed explanation on position sensors, velocity sensors, as well as non-contact sensors like force sensor, proximity sensor, etc. This chapter also describes the various characteristics of sensors and their applications.

Introduction to sensors

The very idea of developing a robotic system arose from the need to replace human intervention or involvement in various operations, favoring increased efficiency, productivity, and reduced likelihood of accidents that result from working in unsafe and hazardous environments. So, ideally, every robot that is designed would be programmed to carry out the tasks it was built for, in the form of a set of instructions.

We humans are capable of making intelligent decisions every day because of our understanding of ourselves and our surroundings. For this purpose, we use our sense of taste, touch, smell, hearing, and sight. These senses essentially provide our brain with all the data required to carry out the tasks that we do in our daily lives, mostly intuitively. These include visually tracking objects around us and using that data to identify them and understand their characteristics or to estimate the distance from them, ability to estimate temperatures, texture, rigidity, etc. by touch, understanding words when spoken, or ability to estimate sound levels, so on and so forth.

Similarly, for a robot to carry out the set of instructions it was assigned, it requires some or all these features depending on what it was built for. It is for these purposes that sensors were built. It allows a robot to gather data about itself and its surroundings to execute its tasks flawlessly. As mentioned before, the sensors required by a machine would depend on the task it is supposed to perform.

Sensors, therefore, provide feedback signals to the control system, which allows them to behave according to the environment, thus offering more flexibility to the robots. This function is of primary importance as robots are expected to function in hazardous areas and industrial applications. The control of a manipulator or industrial robot is based on the correct interpretation of sensory information. Thus, it needs detailed information of the surroundings, objects to be handled, and obstacles, if any, in its trajectory to perform a task with higher efficiency.

There are several types of sensors that are presently being used for different purposes. Some of these include image processing sensors, range sensors, proximity sensors, temperature sensors, force sensors, weight sensors, direction sensors, etc. Most of you, who are savvy with smartphones, will be aware of at least a few of these. However, based on the data required, sensors are generally classified as either internal or external sensors. Internal sensors are those that gather the internal data of the robot, which may include parameters like, force, torque, velocity, direction, orientation, etc. External sensors are those that gather the environmental parameters or data pertaining to conditions or objects external to the robot itself.

Types of sensors

Based on the nature of the output signal, sensors can be classified as analog and digital sensors. They are analog sensors if they receive or generate analog or continuous signals. In analog sensors, output is continuous in nature. Analog sensors like a potentiometer gives an analog output with the variation in input. In case of digital sensors, the output is discrete in nature. Digital sensors include encoders, which generate digital output in 1s and 0s based on their input.

Sensors or transducers are broadly classified as internal and external sensors based on what they sense and from where the sensors require the data with respect to the robot's structure. Internal sensors include position, velocity, and acceleration sensors. Internal sensors sense the internal working of the robot. External sensors include vision sensors, force sensors, torque, touch, proximity sensors, etc. They give information regarding its interaction with the environment like to detect the presence of a work piece in a conveyor belt, identifying the pressure or force on a part or gripper, etc.

Sensors provide information to the controller regarding both internal and external factors. Thus, they enable the controller to control the movement of joints, adjusting force and pressure and controlling the actuation mechanism. A general classification of various types of sensors is given in *figure*

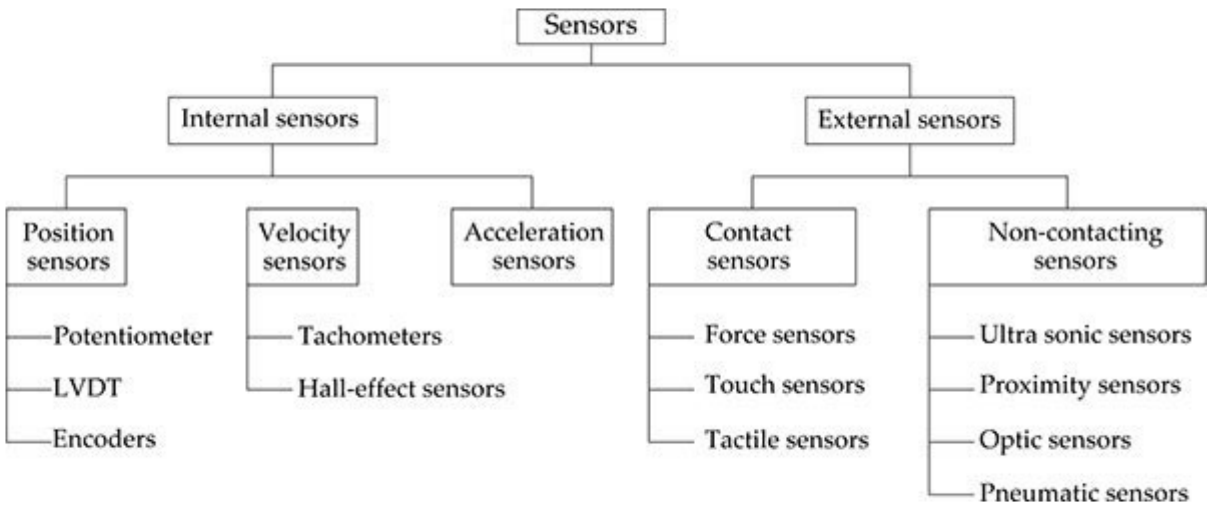

Figure 3.1: *Classification of sensors*

Internal sensors

Internal sensors sense the internal states of the robot, like position, velocity, acceleration, etc. These parameters of the robot are important to control the operation and further movements of the robot for completing the task. These input sensors collect this data and route it to the controller for further processing.

Position sensors

A robot needs to find the position of an object in order to grasp it properly. Sensors that measure both linear and angular displacements are called position sensors. Servocontrol is possible only with position sensors. Position sensors are the primary source of feedback to the robots.

Potentiometer

A potentiometer generates a voltage across the resistor corresponding to the position information. A potentiometer has a wiper or a sliding contact on the variable resistor. As position varies, the location of the wiper on the potentiometer also varies, depending on which effective resistance also varies:

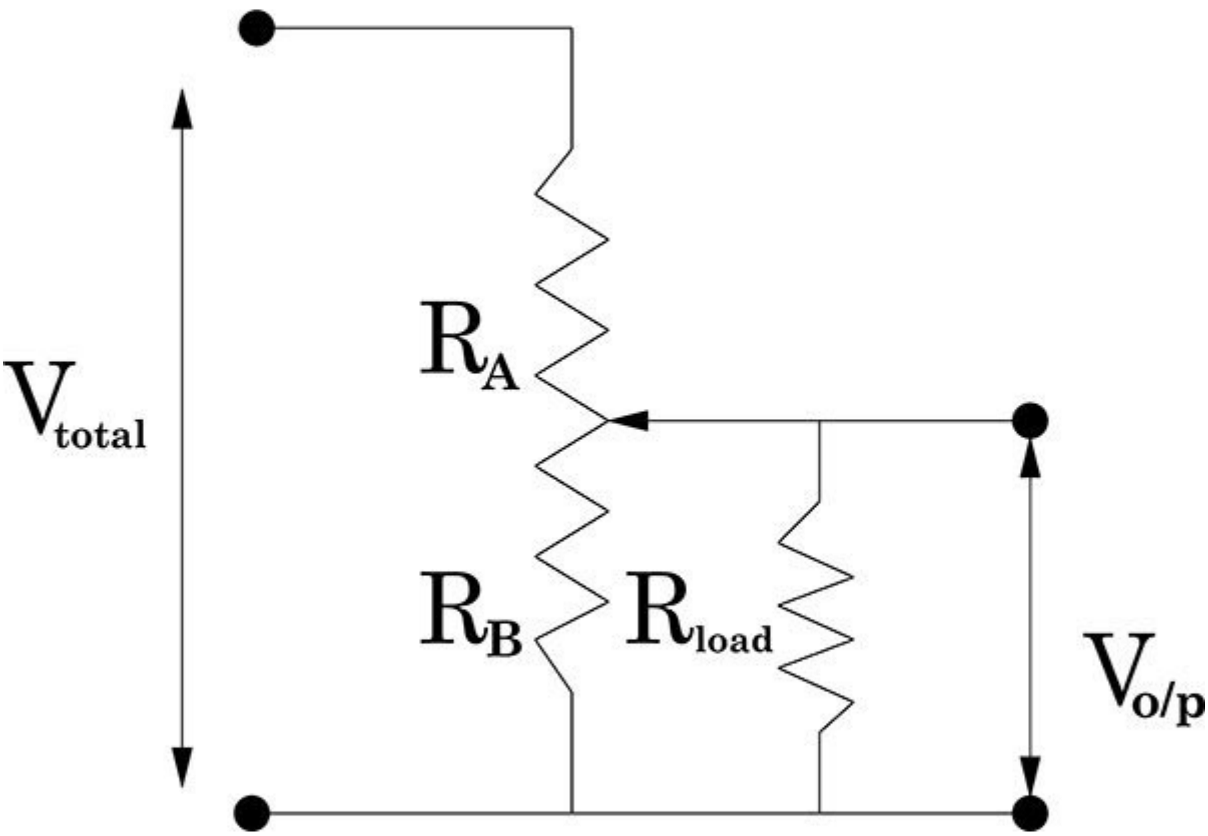

Figure 3.2: *Potentiometer as a position senor*

In *figure* a potentiometer is shown as a position sensor where the output voltage is taken across load resistance which is in parallel with and both are in series with Thus, the potentiometer, which acts as a voltage divider, will generate an output proportional to the resistance:

$$\text{Let } Rx = R_B \| R_{load} = \frac{R_B \cdot R_{load}}{R_B + R_{load}}$$

Then, is output across , which is in series with

$$V_{0/p} = V_{\text{total}} \times \left(\frac{R_x}{R_A + R_x} \right)$$

$$V_{o/p} = V_{\text{total}} \times \left(\frac{R_x}{R_A + R_x} \right)$$

$$V_{o/p} = V_{\text{total}} \times \left(\frac{\frac{R_B \cdot R_{load}}{R_B + R_{load}}}{R_A + \frac{R_B \cdot R_{load}}{R_B + R_{load}}} \right)$$

$$V_{o/p} = V_{\text{total}} \times \left(\frac{R_B \cdot R_{load}}{R_A \left(R_B + R_{load} \right) + R_B \cdot R_{load}} \right)$$

$$V_{o/p} = V_{\text{total}} \times \left(\frac{R_B \cdot R_{load}}{R_A R_B + \left(R_A + R_B \right) \cdot R_{load}} \right)$$

If load resistance is very high, product can be neglected:

$$V_{o/p} = V_{\text{total}} \times \left(\frac{R_B}{R_A + R_B} \right)$$

Encoders

The encoder is an optical device that encodes or generates a digital code corresponding to a small motion. By counting a single bit or by decoding a set of bits, the pulses can be converted to relative or absolute measurements. Thus, encoders are of incremental or absolute type. These types are further classified as linear and rotary.

An encoder can be described as a simple device in the form of a strip or disk divided into smaller sections. These smaller sections are completely made with transparent and completely opaque strips arranged alternatively. *Figure 3.3* shows an incremental encoder. Each section can be either opaque or transparent, and a light source like an LED is placed on one side of the strip.

In an **incremental** a beam of light is made to fall on one side of the encoder and a light detector on the other side. The light passing through this encoder film or disc passes through each section to its other side and is received by a light-sensitive sensor or photo detector, like phototransistor. If the position of the disc is such that the light is allowed to pass through the transparent section, then the sensor on the opposite side receives this light and turns ON and will give a high signal. But, if the position of the disk is such that the light is occluded by the opaque section, preventing it from reaching the light sensor, then the sensor will remain OFF, and its output will be a low signal.

In a **linear** a strip is used, and its linear position is noted before it is operated. In rotary encoders, a disk is used, and its angular starting position is noted. As the disk rotates (in rotary encoders) or strip moves (in linear encoders), it can continuously send signals. If the signals are counted, the approximate total displacement of the disk can be measured at any time. It will be a pulse train (ON and OFF signals alternatively), and its frequency indicates the speed of rotation of the disk. This principle of working is termed as incremental encoding.

The most common type is a quadrature encoder, which has two sets of lines, which are slightly offset to each other. They both generate pulse output, corresponding to each set of light source and LED. This allows the encoder to detect the position relative to the starting position (not absolute value). Thus, it determines only the positional change by counting the number of pulses from the start point to the stop point:

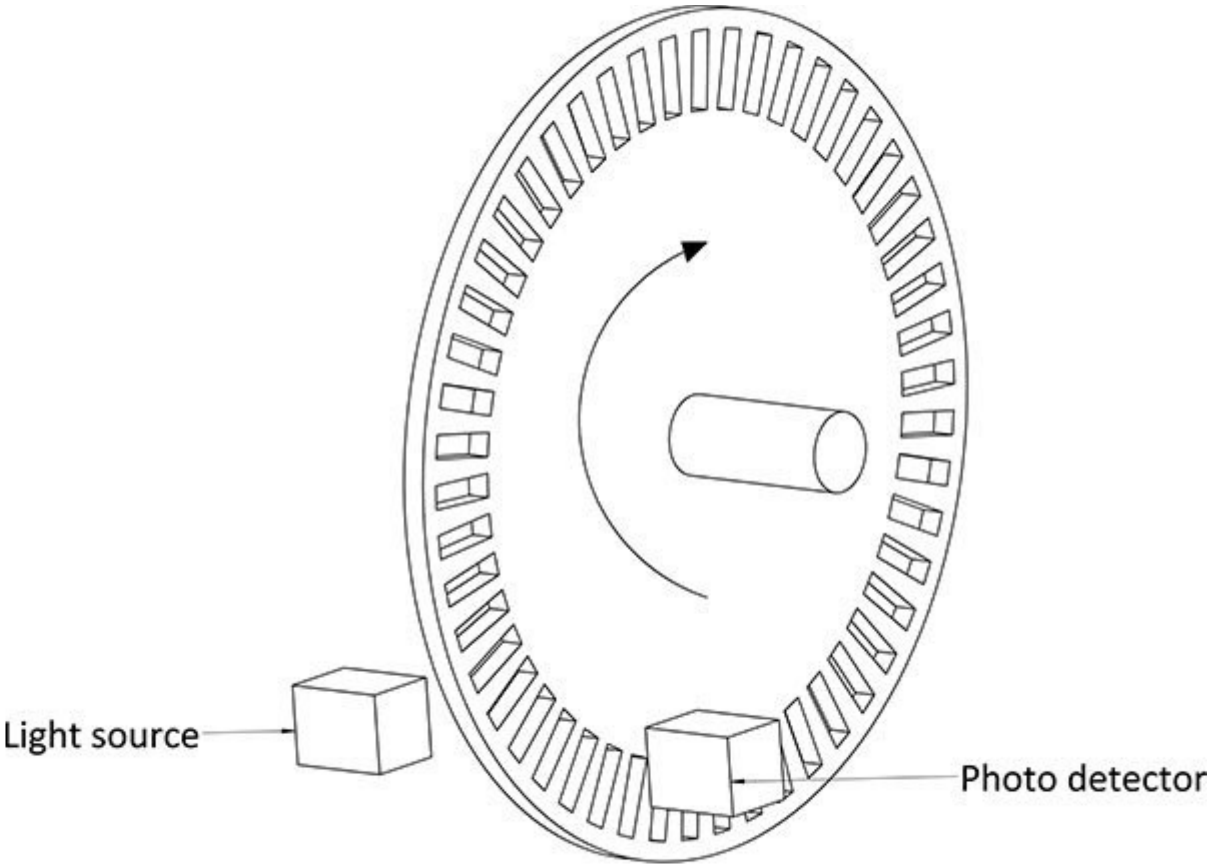

Figure 3.3: *Incremental encoder*

In an **absolute** each portion or location of the encoder disk's angular displacement has a unique combination of clear/opaque sections that give it a unique digital code. Through this unique code, the exact position of the disk can be determined at any time. Thus, it eliminates the need for a starting position. At any point of time, the exact position can be identified with the unique code of that point in the disk (in case of rotary encoder) or the corresponding point in the strip (in case of linear rotor). The *figure 3.4* shows a linear absolute encoder where each position corresponds to a unique digital code. As it gives a unique code corresponding to a position, it is absolute encoding:

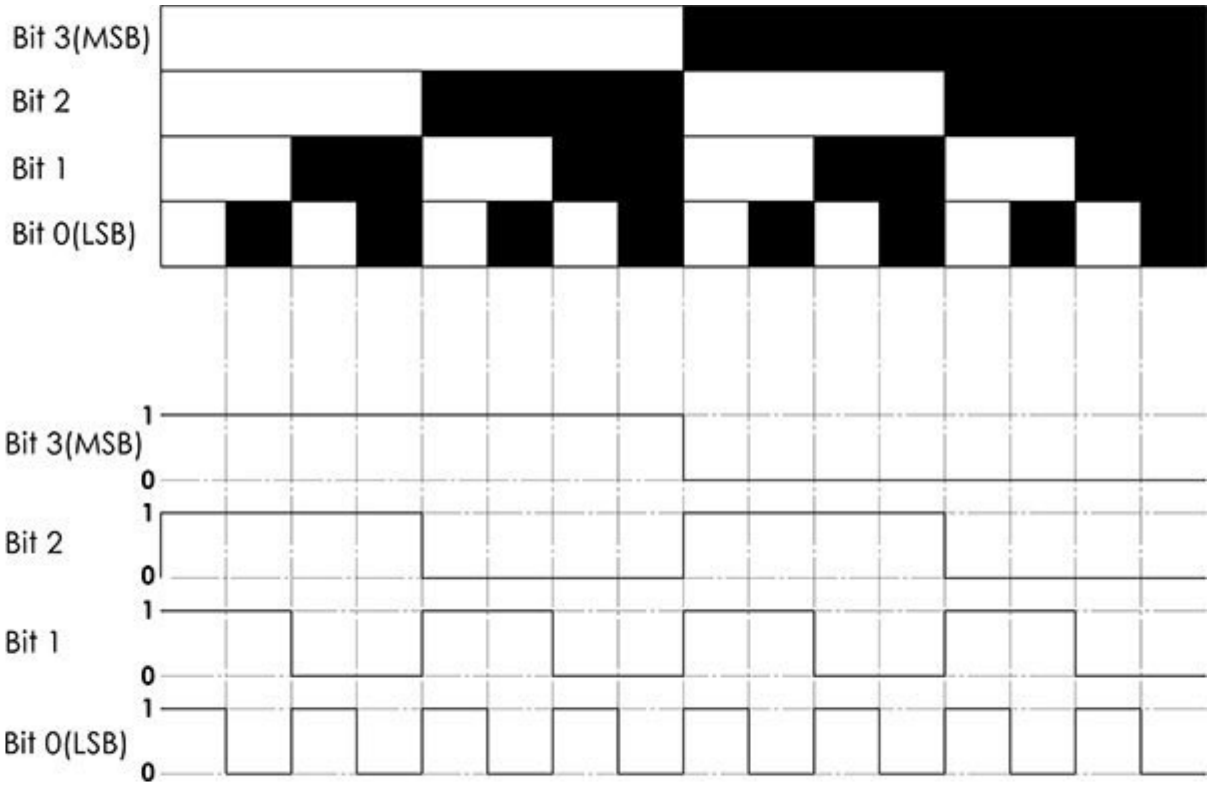

Figure 3.4: *Absolute encoder (linear)*

The *figure 3.5* shows a rotary absolute encoder where each angular position corresponds to a digital code. Here also, a unique code is generated corresponding to the angular position, and hence called absolute encoding:

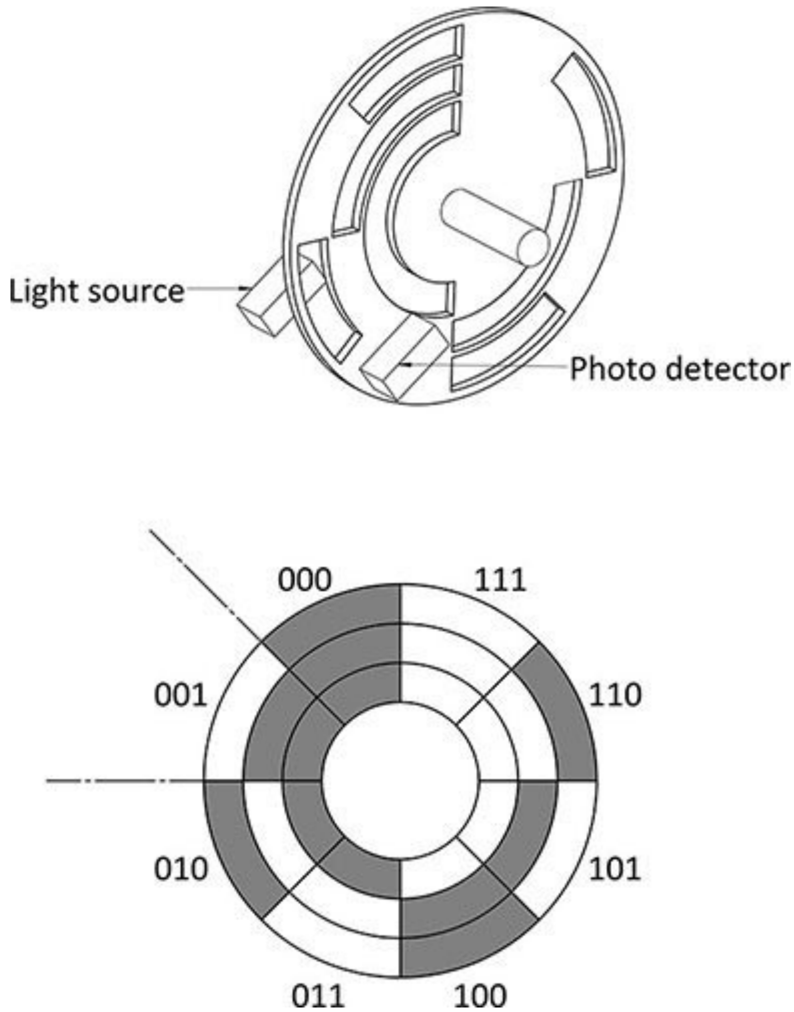

Figure 3.5: *Absolute encoder (rotary)*

The resolution of an encoder can be calculated as where *n* is the number of tracks. In *figure* there are 3 tracks. Therefore, resolution is = 8, and the angle covered in each increment is given by 3600/8 = 450. In a rotary encoder, with 4 tracks, resolution is = 16, and the angle covered in each increment is given by 3600/16 = 22.50.

LVDT

A **linear variable differential transformer** (or is a transformer that generates an analog output voltage proportional to the displacement, which occurs due to the proportional movement of the core. In general, a transformer is an electric-to-electric energy converter that changes the voltage/current ratio. The total energy input to the device is the same as the total energy output from the device. Based on the number of turns, a transformer increases or decreases the voltage in proportion. The corresponding current changes inversely with the number of turns in a transformer.

The flux created in one coil due to electric current induces a voltage in the other coil proportional to the ratio of the number of turns in the windings. As the number of turns in the secondary coil increases, the output voltage also increases proportionally, whereas the current decreases proportionally. Subsequently, the current decreases proportionally. Thus, **an LVDT** gives an accurate measure of the displacement.

To describe this, an iron core moving in a magnetic field will generate AC signals with an amplitude proportional to the displacement of the iron core. The core is surrounded by two identical secondary coils and a primary coil, as shown in *figure* As the core changes position with respect to the coils, the magnetic field changes, resulting in a change in the voltage amplitude in the secondary coil as a linear function of the core displacement over a considerable segment. The output voltage of an LVDT varies linearly and proportional to the input position of the core:

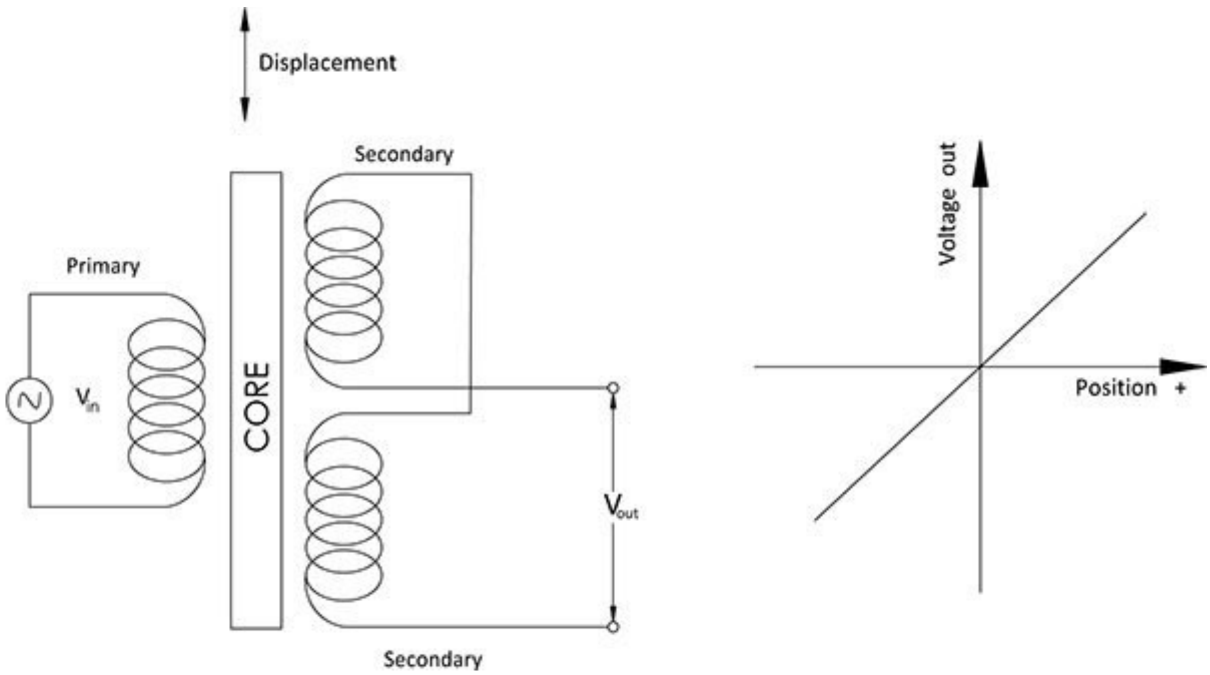

Figure 3.6: *LVDT*

Synchros and resolvers

Both synchros and resolvers are like transformer with a primary coil connected to a rotating shaft (rotor) and stationary secondary coils (stator). The outputs for both synchros and resolvers are analog in nature and need to be converted to a digital form using an analog to digital controller before feeding to the controller.

Synchros are more costly and difficult to manufacture as they have 3 windings with 120° orientation. The primary winding of this transformer resides on the stator, and the secondary on the rotor. The *figure 3.7* shows a simple configuration of synchros. The voltage across stator windings is proportional to the angle between the axis of stator winding and rotor winding (refer *figure 3.7* for equations):

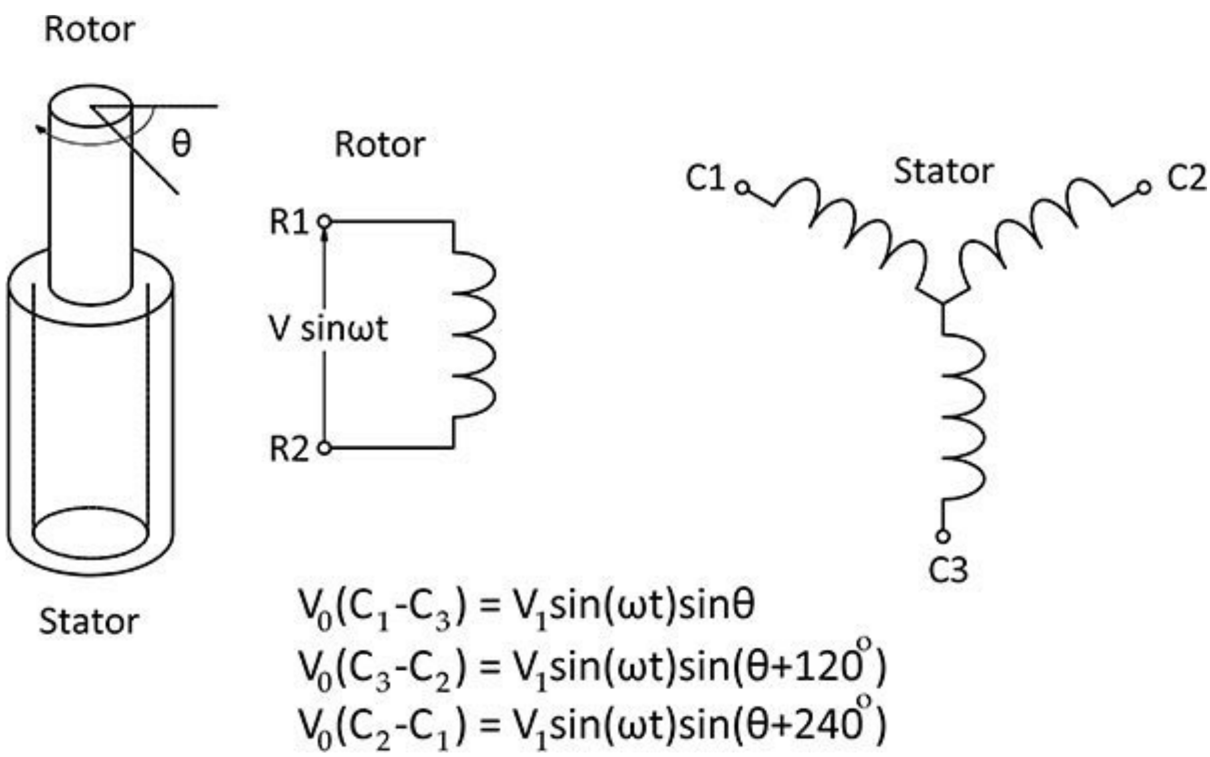

Figure 3.7: *Synchros*

In a resolver, the primary coil is connected to the rotating shaft, which carries AC (alternating current), either through slip rings or from a brushless transformer. There are two secondary coils, placed 90° apart from each other (refer *figure* As the rotor rotates, the flux developed in the coil is varied, resulting in an induced EMF. The voltage induced in the coil is maximum when the primary coil is parallel to either of the two secondary coils. As the rotor rotates, the voltage in one secondary coil decreases and gradually becomes zero, while the second coil develops its maximum voltage. In between these two values, both secondary coils develop a voltage proportional to the sine and cosine of the angle θ between the primary and the two secondary coils, respectively (equations given in *figure* The advantages of resolvers are that they are more reliable, robust, and give accurate results:

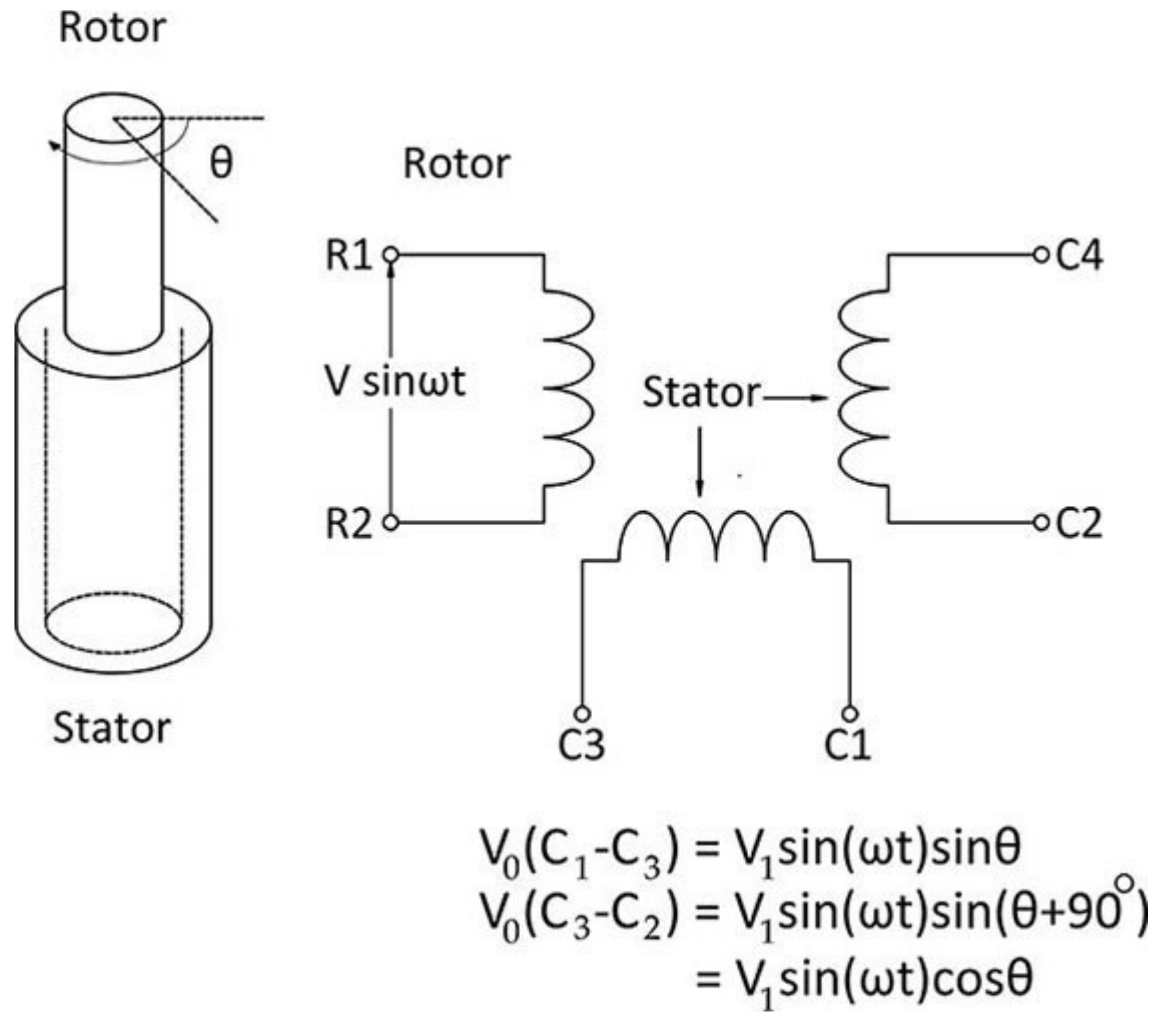

Figure 3.8: *Resolvers*

Velocity sensors

Velocity can be calculated by monitoring the position changes in a fixed time interval. Hence, all position sensors can be utilized for calculating velocity also. While using encoders, the number of pulses, which gives the measure of displacement when divided by the time taken, will give the velocity measure. This will depend on the controller for its computation and increase the computation load.

Tachometer

It directly measures the velocity or rotations of an element in unit time. It works based on Fleming's rule, which states that the voltage produced is directly proportional to the magnetic flux linkage. In *figure* the conducting coil develops a voltage as the shaft rotates in a magnetic field produced by the permanent magnet (stator), and the voltage developed in the coil is proportional to the speed of rotation of the shaft. The arrangement can also be reversed by keeping a magnet on the rotating shaft and making the magnet as the rotor and coil on the stator. In both cases, the speed of rotation of shaft can be measured using the voltage developed in the coil as they are proportional to each other:

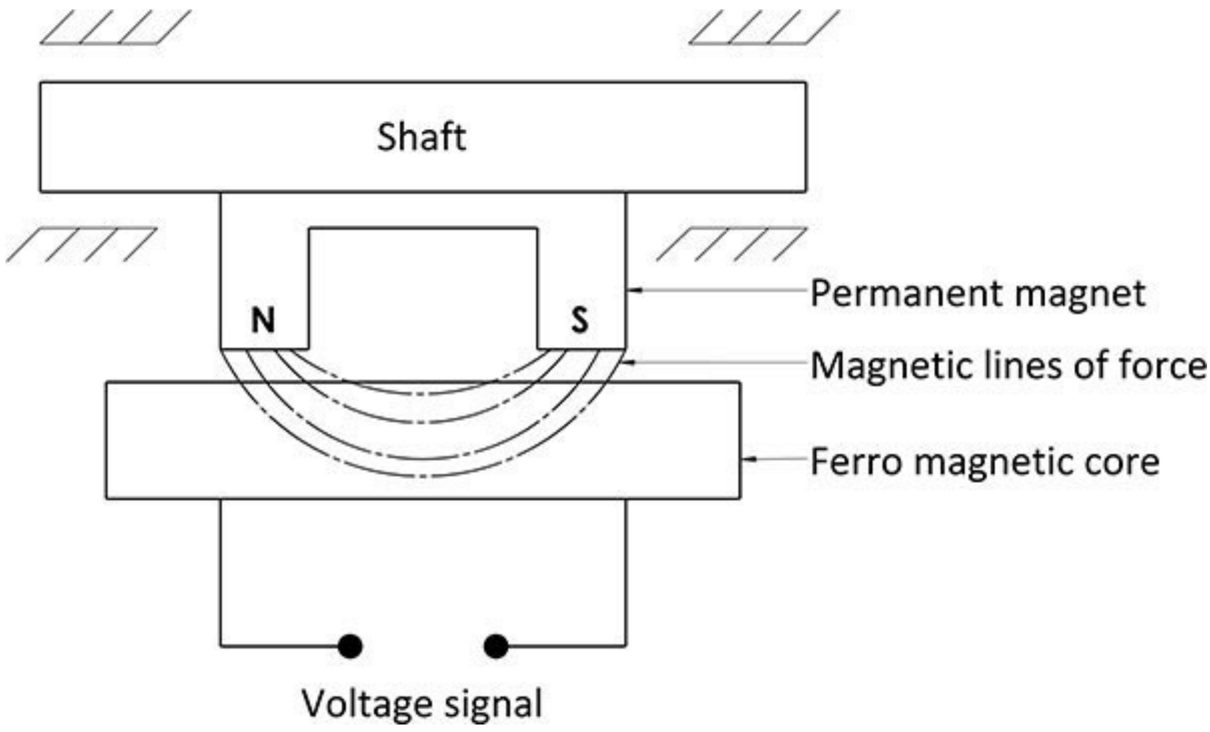

Figure 3.9: *Tachometer*

Hall effect sensors

In 1879, *Edward H Hall* described the Hall effect, which is seen in conductors and semiconductors where a voltage is developed in the hall element proportional to the magnetic field. In a Hall effect sensor, the voltage across the current-carrying conductor varies on the basis of the magnetic field. The voltage of the sensor varies as the magnet approaches it. Thus, it gives a measure of proximity or speed of rotation. As the output voltage is analog, it needs to be converted to digital for applications that require digital processing.

The *figure 3.10* shows a Hall chip where a voltage is applied on the opposite sides of the chip. If the magnetic field in a direction perpendicular to its surface is zero, no voltage is developed. Otherwise, a voltage is developed proportional to the magnetic field strength. Hall sensors can be used to sense the rotation and measure the rotations per minute. Here, when the shaft is rotated, the magnet also rotates, and the presence of the magnet generates voltage in the hall sensor, thus detecting the approach of the magnet and thus sense its rotation. Thus, a Hall effect sensor can be used to find the velocity of a device using the voltage developed in the Hall element proportional to the magnetic field and is commonly employed in electric drives and motors. It is also used for positioning, proximity sensing, torque measurement, current sensing, etc.

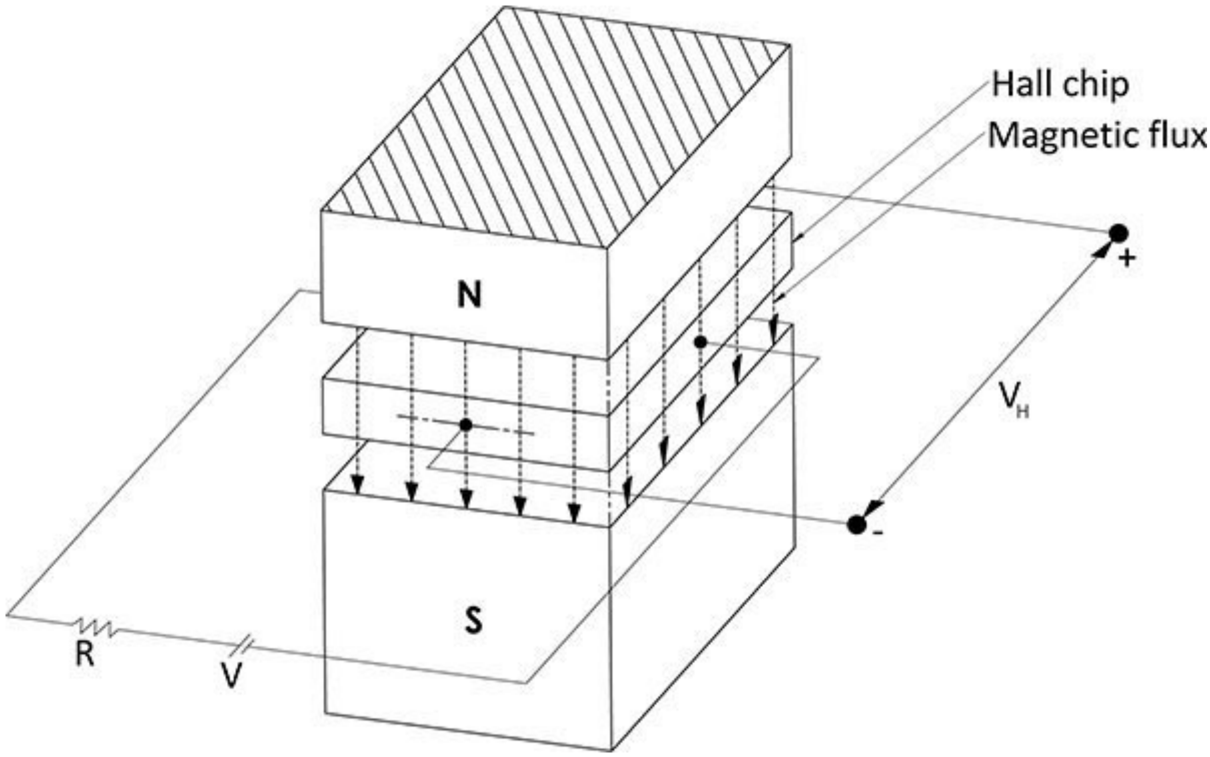

Figure 3.10: *Hall effect sensor*

Acceleration sensors

Accelerometers or acceleration sensors are not much used in robots for industrial purposes. Just as velocities can be computed from the data given by position sensors, acceleration can also be computed from them. Velocity sensors can also be used for computing acceleration as it is the time rate of change of velocity. Acceleration can also be calculated from force as:

$$\text{Acceleration, } a = \frac{F}{m}$$

F can be obtained from force sensors like strain gauge. But, in all these cases, computation needs to be done, and it imposes a load on the processor and can affect the speed of the operation. So, it cannot be taken as an efficient method.

External sensors

External sensors interact with the environment and surroundings of the robot and provide external information, especially about the objects and parts to be handled and other information needed for proper functioning. They include touch sensors, proximity sensors, force and torque sensors, vision sensors, etc.

Contact sensors

Sensors that operate by being in contact with the robot's environment or objects nearby for sensing data from them are termed as contact sensors. Some of these types of sensors come in contact with objects nearby for sensing like touch or tactile sensors, while some other contact sensors are activated as a result of contact, like force/torque sensors.

Force sensors

Sensors used for calculating the force applied or experienced are termed as force sensors:

Strain gauge: Strain gauges are popularly used in robotics for calculating the force applied at the end-effector and the wrist of a robot. In a few applications, they are also employed for measuring the loads on the joints and links of the robot. A strain gauge consists of a conducting material of fine wire or foil that is cemented on an insulating support like a wafer unit as the base (refer to *figure* It is in this base where strains are to be measured.

The resistance changes due to the change in length of conducting wire due to the strain. The resistance of a conductor is directly proportional to its length and inversely proportional to the cross-sectional area. When a conducting wire is stretched or compressed, its resistance varies depending on the amount of stress/force applied on it. The typical value of resistance for a strain gauge varies in the order of 100 to 500 Ω:

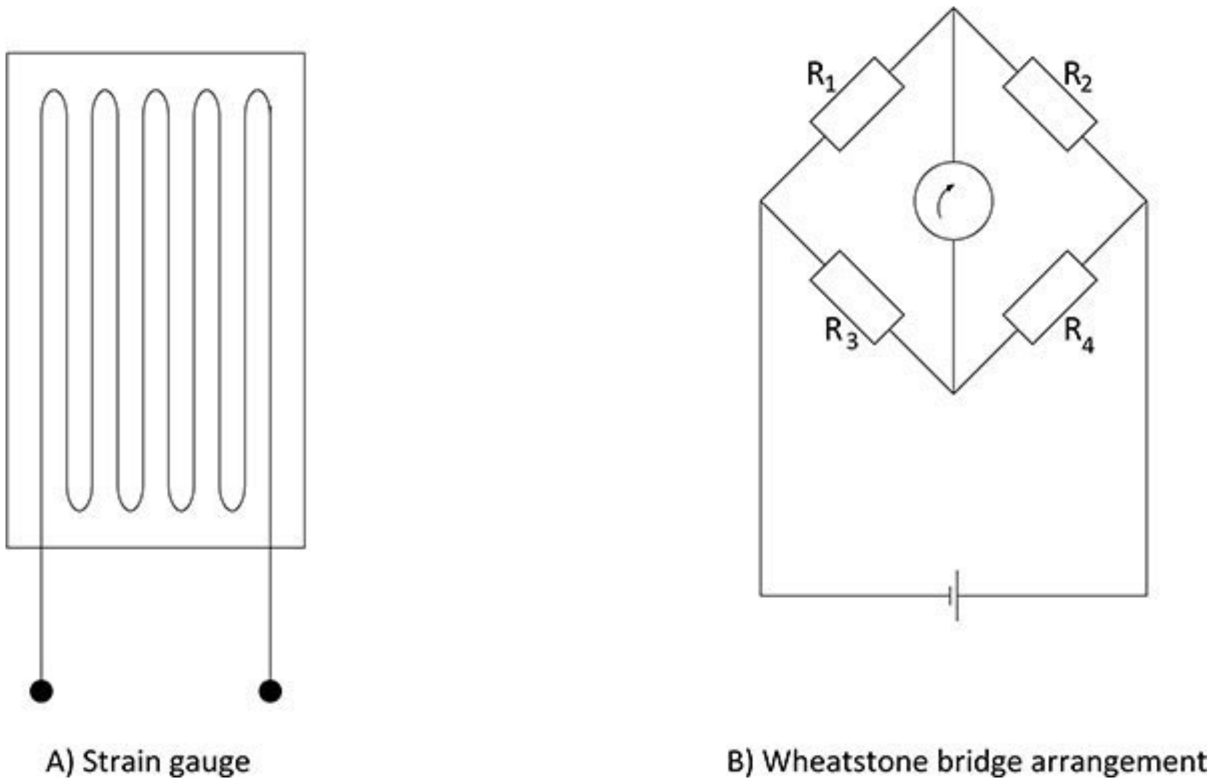

Figure 3.11: *Strain gauge-based sensor*

A Wheatstone bridge arrangement can be used for employing the strain gauge for the calculation of force. The strain gauge can be connected as one of the arms (variable resistor) in a wheatstone bridge say in *figure* If the bridge is balanced, the points across would develop same potential, and there will not be any current flow. If the resistance in any of the four arms changes, the bridge is no longer balanced and there will be a current flow. Thus, when the strain gauge is connected in one of the arms of the Wheatstone bridge, its change in resistance can be calculated, and from this resistance change, the corresponding force or pressure applied can be calculated.

The change in resistance is calculated by:

$$\frac{R_1}{R_2} = \frac{R_3}{R_4}$$

Sensors from piezoelectric materials: Materials that exhibit piezoelectric effect are called piezoelectric materials. Such materials develop a potential difference on its surface when force is applied on it. They are made of asymmetrical, elastic crystals, which develop an electric potential when deformed by a force. This piezoelectric effect is reversible. Sensors made of piezoelectric material can measure instantaneous changes in force by monitoring the potential difference developed on its surface. Piezoelectric materials can be used for calculating force and pressure from the voltage developed in it due to the force or pressure applied on it.

Touch sensors

The simplest form of a touch sensor can just identify if an object is present or not and is in the form of a gripper with a set of microswitches. A microswitch simply turns ON or OFF based on the presence of an object. It is simple, robust, and inexpensive and is also used for turning off the current and for sending signals. Though a very simple system, microswitches are widely utilized in robotics. Another form of a tactile sensor is made from a pressure-sensitive piezoelectric material, which generates electric current when it is stressed by applying force. Thus, both force and pressure can be calculated by measuring the electric current produced in it.

A tactile sensor is arranged in the form of an array of touch sensors, which enables it to provide extra information on the shape, size, and type of material of the object:

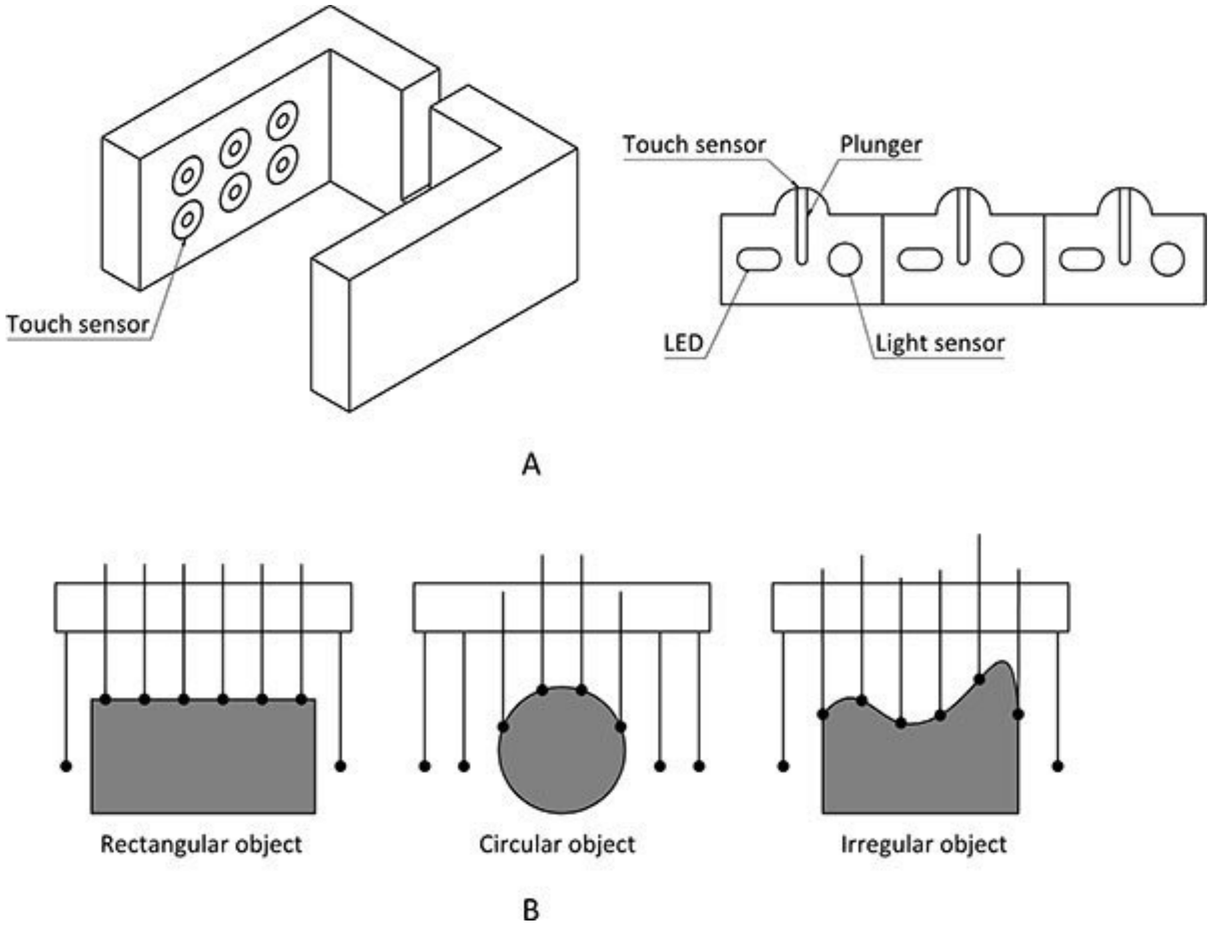

Figure 3.12: *Tactile sensor made as an array of various touch sensors*

A touch sensor is shown in *figure* which consists of an **light-emitting diode** source, a detector, and a plunger. Based on the movement of the plunger, light from the LED gets altered and is detected by the detector or light sensor. The light sensor generates an output based on the plunger displacement, thus sensing the displacement of an object.

As the tactile sensor contains various touch sensors, all sensors in the tactile sensor respond differently in different levels, based on the shape and size of the object. This information can be fed to the microcontroller for identifying the shape and size of the object. *Figure 3.12B* demonstrates how the shape of a cube, cylinder, and a random-shaped object is identified with tactile sensor.

Non-contact sensors

Sensors that do not come in contact with the robot's environment are called non-contact sensors. Sensors used to calculate range or distance of an object from the robotic arm are all examples of non-contact sensors. The distance of an object can be measured without having direct contact with the object. Such sensors like pneumatic sensors, optical sensors, and ultrasonic sensors are all examples of non-contact sensors.

Ultrasonic sensors

Sensors that can measure the distance of an object by transmitting ultrasonic sound waves and then analyzing the reflected signals are called ultrasonic sensors. They are commonly used for proximity sensing and in obstacle detection systems. They are simple, inexpensive sensors with low power consumption.

Ultrasonic sensors work on the basis of measuring the distance using time-of-flight technique, where a transducer emits a pulse of high-frequency ultrasound through the medium. When there is an object present in its path, the ultrasound waves get reflected and is received by the receiver. The wave, thus, travels twice the distance between the transducer and the object. This can be equated to the product of time elapsed and speed of sound.

In this method, the accuracy of the result depends on the wavelength of the signal as well as accuracy in measuring the time interval between ultrasound wave emission and reception after striking the object as well as the speed of sound. The speed of sound in a medium depends on the frequency of wave as well as the density and temperature of the medium. Background noise is a major issue with these types of sensors. As many industrial operations and technique result in sound waves with ultrasonic waves up to a frequency of 100 kHz, it is recommended to operate ultrasonic sensors above 100 kHz.

Proximity sensors

A sensor used to determine how close or near an object is with respect to another object or gripper is called proximity sensor. It includes various types like magnetic, eddy current, and Hall effect, inductive, and capacitive, optical, ultrasonic, etc. In most of the applications, it is required to identify how close the gripper is to the work piece or if a particular object is present or not. All these can be sensed by proximity sensors. Distance can vary from few centimeters to few meters depending on the sensors:

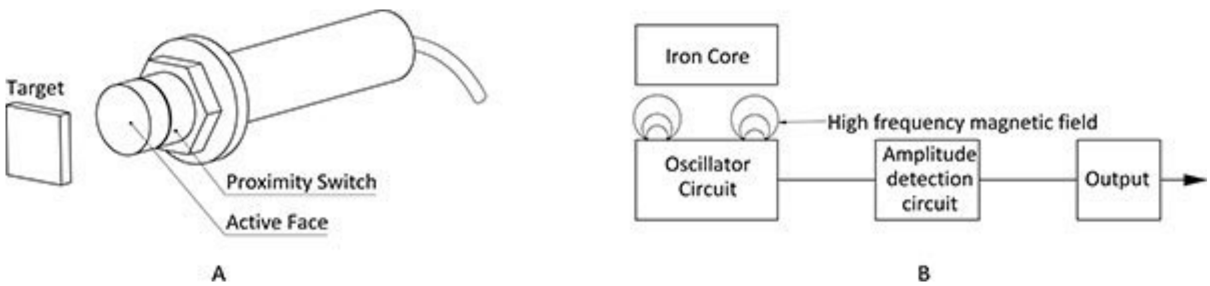

Figure 3.13: *Inductive proximity sensor*

Metal surfaces are detected using inductive proximity sensors (refer to *figure* It consists of a coil with a ferrite core, an oscillator, and an amplitude detector (refer to *figure* The amplitude of oscillation diminishes when there is a metal object present near to the sensor. The output is obtained from a solid-state switch, which is connected to the output of the amplitude detection circuit. The detector senses the change in the amplitude and turns the solid-state switch off. When the object leaves the range of the sensor, it turns on again.