Subject: Principles of Robotics
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Theoretical: 3 hrs/wk
Practical: ---
Tutorial: 1 hrs/wk
Units: 3

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Syllabus

1. INTRODUCTION AND TERMINOLOGIES:

Definition-Classification- History - Robots components-Degrees of freedom-Robot joints coordinates- Reference frames-workspace-Robot languages-actuators-sensors Position, velocity and acceleration sensors-Torque sensors-tactile and touch sensors proximity and range sensors-social issues.

2. KINEMATICS:

Mechanism-matrix representation-homogenous transformation-DH representation Inverse kinematics-solution and programming-degeneracy and dexterity.

3. DIFFERENTIAL MOTION & VELOCITIES:

Jacobian-differential motion of frames-Interpretation-calculation of Jacobian-Inverse Jacobian-Design-Lagrangian mechanics-dynamic equations-static force analysis.

4. ROBOT CONTROL SYSTEM:

Sensor characteristics- Hydraulic, Pneumatic and electric actuators-trajectory planning decentralized PID control- non-linear decoupling control.

5. IMAGE PROCESSING & VISION SYSTEMS:

Two and three dimensional images-spatial and frequency domain representation-noise and edges-convolution masks-Processing techniques-thresholding-noise reduction edge detection-segmentation-Image analysis and object recognition

Chapter One: Introduction and Terminologies

1.1 Definition:

At the present time, most automated manufacturing tasks are carried out by special-purpose machines designed to perform predetermined functions in a manufacturing process. The inflexibility and generally high cost of these machines, often called ***hard automation systems***, have led to a broad-based interest in the use of robots capable of performing a variety of manufacturing functions in a more flexible working environment and at lower production costs.

The word ***robot*** originated from the Czech word ***robota***, meaning work. Webster's dictionary defines robot as "*an automatic device that performs functions ordinarily ascribed to human beings*." With this definition, washing machines may be considered robots. A definition used by the **Robot Institute of America** gives a more precise description of industrial robots: "*A robot is a reprogrammable multifunctional manipulator designed to move materials, parts, tools, or specialized devices, through variable programmed motions for the performance of a variety of tasks*."

A robot is a reprogrammable general-purpose manipulator with external sensors that can perform various assembly tasks. In addition, a robot must possess intelligence, which is normally due to computer algorithms associated with its control and sensing systems.

1.2 Classification:

Robots can be classified according to robot types as shown in Fig. 1.1:

Manipulator.

Legged Robot.

Wheeled Robot.

Underwater Vehicle.

Unmanned Aerial Vehicle.

Humanoid

Prosthesis

Fig. 1.1: Robots classification.

1.3 History:

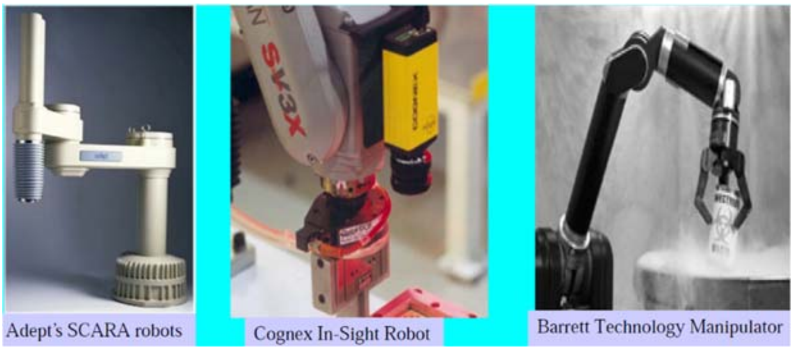
The first industrial robot: UNIMATE

1954: The first programmable robot is designed by George Devol, who coins the term Universal Automation. He later shortens this to Unimation, which becomes the name of the first robot company (1962).

1978: The Puma (Programmable Universal Machine for Assembly) robot is developed by Unimation with a General Motors design support

PUMA 560 Manipulator

1980s: The robot industry enters a phase of rapid growth. Many institutions introduce programs and courses in robotics. Robotics courses are spread across mechanical engineering, electrical engineering, and computer science departments.



1995-present: Emerging applications in small robotics and mobile robots drive a second growth of start-up companies and research.

2003: NASA's Mars Exploration Rovers will launch toward Mars in search of answers about the history of water on Mars

1.4 Robots components:

Some of the important components of Robot are as follows:

1. **Manipulator:**

Just like the human arm, the robot consists of what is called a manipulator having several ***joints*** and ***links***.

2. **Endeffector:**

The ***Endeffector*** is expected to perform tasks normally performed by the ***palm*** and ***finger*** arrangements of the human arm.

3. The Locomotion Device:

In the case of Human Beings the power for the movement of the arm, the palm and fingers is provided by muscles. For the robot the power for the movement (locomotion) is provided by the ***motors***. The ***motors*** used for providing locomotion in robots are of three types depending on the source of energy: Electric, Hydraulic or Pneumatic.

4. Controller:

The digital computer (both the hardware and the software) acts as a controller to the robot. The controller functions in a manner analogous to the human brain. With the help of this controller, the robot is able to carry out the assigned tasks. The controller directs and controls the movement of the Manipulator and the Endeffector. In other words, the controller controls the robot.

5. The Sensors:

Without the data supplied by the sense organs, the brain would be incapable of intelligence. In other words, the controller (the computer) of the robot cannot do any meaningful task, if the robot is not with a component analogous to the sense organs of the human body. Thus, the fifth and the most important component of the robot is the set of sensors. Sensors are nothing but measuring instruments, which measures quantities such as position, velocity, force, torque, proximity, temperature, etc.

1.5 Degrees of freedom (DOF):

The number of independent ways by which a dynamic system can move, without violating any constraint imposed on it, is called the number of degrees of freedom. In other words, the number of degrees of freedom can be defined as the minimum number of independent coordinates that can specify the position of the system completely.

Figure 1.2 illustrates the basic joints found in typical robots. Every joint connects exactly two links; a joint that simultaneously connects three or more links are not allowed.

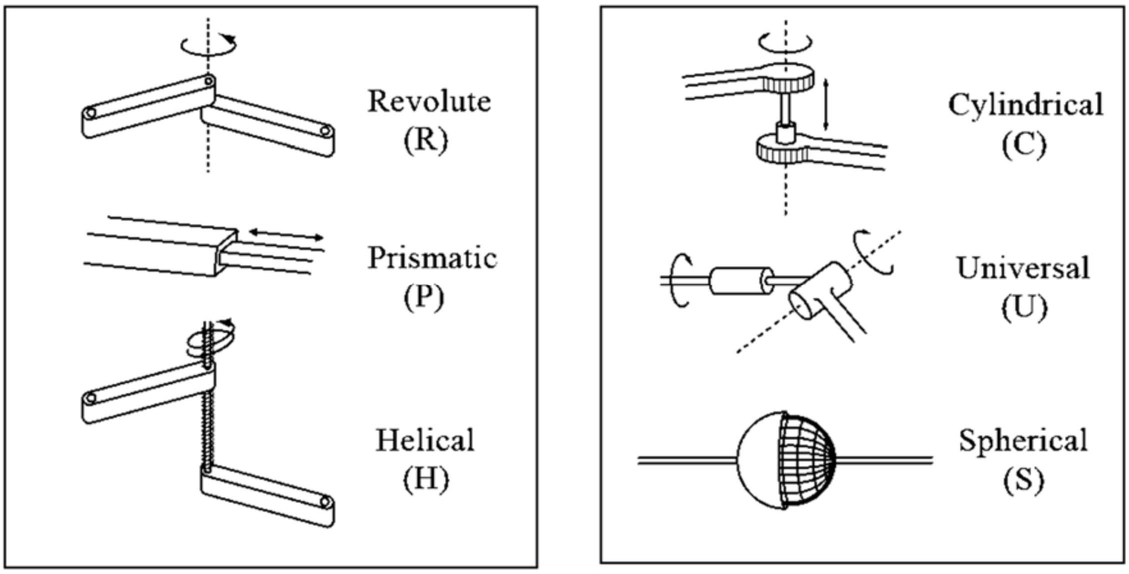


Fig. 1.2: Typical robot joints.

1. ***The revolute joint (R)***, also called a hinge joint, allows for rotational motion about the joint axis.
2. ***The prismatic joint (P)***, also called a sliding or linear joint, allows for translational (or rectilinear) motion along the direction of the joint axis.
3. ***The screw joint (H)***, also called a helical joint, allows simultaneous rotation and translation about a screw axis. Revolute, prismatic, and screw joints all have one degree of freedom. Joints can also have multiple degrees of freedom.
4. ***The cylindrical joint (C)*** is a two-dof joint that allows for independent translations and rotations about a single fixed joint axis.
5. ***The universal joint (U)*** is another two-dof joint that consists of a pair of revolute joints arranged so that their joint axes are orthogonal.
6. ***The spherical joint (S)***, also called a ball-and-socket joint, has three degrees of freedom and functions much like our shoulder joint.

A joint can be viewed as providing freedoms to allow one rigid body to move relative to another. It can also be viewed as providing constraints on the possible motions of the two rigid bodies it connects. For example, a revolute joint can be viewed as allowing one freedom of motion between two rigid bodies in space, or it can be viewed as providing five constraints on the motion of one rigid body relative to the other. Generalizing, the number of degrees of freedom of a rigid body (three for planar bodies and six for spatial bodies) minus the number of constraints provided by a joint must equal the number of freedoms provided by the joint.

The freedoms and constraints provided by the various joint types are summarized in Table 1.1.

Table 1.1: The number of degrees of freedom provided by common joints.

Joint Type	**N-DOF**	**Constraints c between two planar rigid bodies**	**Constraints c between two spatial rigid bodies**
Revolute joint (R)	1	2	5
Prismatic joint (P)	1	2	5
Screw joint (H)	1	N/A	5
Cylindrical joint (C)	2	N/A	4
Universal joint (U)	2	N/A	4
Spherical joint (S)	3	N/A	3

1.6 Robot joints coordinates and Reference frames-workspace:

There two references coordinate used to specifying joints and links in a three-dimensional euclidean space and map its coordinates expressed in a coordinate system OUVW (body-attached frame) and a reference coordinate system OXYZ.

In Fig. 1.3, we are given two right-hand rectangular coordinate systems, namely, the OXYZ coordinate system with OX, OY, and OZ as its coordinate axes and the OUVW coordinate system with OU, OV, and OW as its coordinate axes. Both coordinate systems have their origins coincident at point O.

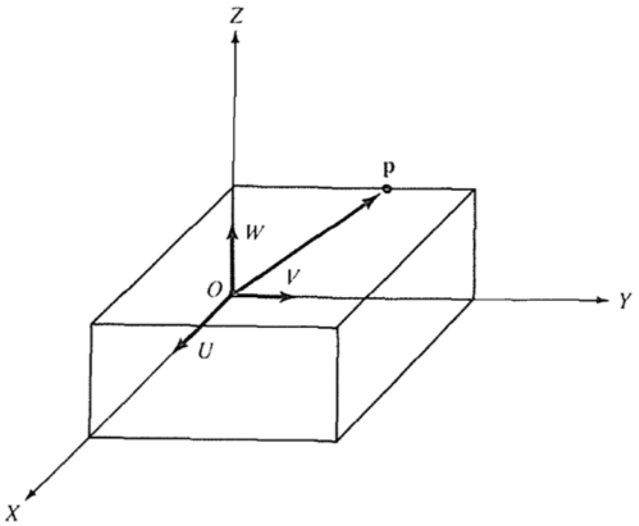


Fig. 1.3 Reference and body-attached coordinate systems.

The OXYZ coordinate system is fixed in the three-dimensional space and is considered to be the reference frame.

The OUVW coordinate frame is rotating with respect to the reference frame OXYZ.

Physically, one can consider the OUVW coordinate system to be a body-attached coordinate frame. That is, it is permanently and conveniently attached to the rigid body (e.g., an aircraft or a link of a robot arm) and moves together with it. Let (i_x, j_y, k_z) and (i_u, j_v, k_w) be the unit vectors along the coordinate axes of the OXYZ and OUVW systems, respectively. A point p in the space can be represented by its coordinates with respect to both coordinate systems. For ease of discussion, we shall assume that p is at rest and fixed with respect to the OUVW coordinate frame. Then the point p can be represented by its coordinates with respect to the OUVW and OXYZ coordinate systems, respectively, as

$P_{uvw} = (P_u,P_v,P_w)$ and $P_{xyz} = (P_x,P_y,P_z)$

where P_{xyz} and P_{uvw} the space with reference to different coordinate systems, and the superscript T on vectors and matrices denotes the transpose operation.

1.7 Robot languages:

A general approach to solve the human-robot communication problem is the use of high-level programming. Robots are commonly used in areas such as arc welding, spot welding, and paint spraying. These tasks require no interaction between the robot and the environment and can be easily programmed by guiding. However, the use of robots to perform assembly tasks generally requires high-level programming techniques. This effort is warranted because the manipulator is usually controlled by a computer, and the most effective way for humans to communicate with computers is through a high-level programing language. Furthermore, using programs to describe assembly tasks allows a robot to perform different jobs by simply executing the appropriate program. This increases the flexibility and versatility of the robot.

1.8 Actuators:

Actuators are used in order to produce mechanical movement in robots, which are the muscles of robots. There are many types of actuators available depending on the load involved. The term load is associated with many factors including force, torque, speed of operation, accuracy, precision and power consumption.

Types of actuators

1. Servomotor
2. Stepper Motor
3. DC Motor
4. Brushless Motor
5. Hydraulic Actuators
6. Pneumatic Actuators
7. Magnetostrictive Actuators
8. Piezoelectric Actuators

- ***Electromechanical actuators*** *convert electrical energy into mechanical energy. Magnetism is the basis of their principle of operation. They are DC, AC and stepper motors.*
- ***DC motors*** *require a direct current or voltage source as the input signals.*
- ***AC motors*** *require an alternating current or voltage source*
- ***Stepper motors*** *have capability of achieving precision angular rotation in both directions and are commonly employed to accommodate digital control technology.*
- ***Hydraulic and pneumatic actuators*** *are under fluid power actuators. Fluid power refers to energy that is transmitted via a fluid under pressure. When a pressure is applied to a confined chamber containing a piston, the piston will exert a force causing a motion.*
- ***Materials*** *which undergo some sort of transformations through physical interaction, are referred to as active materials. Piezoelectric (voltage-load), shape-memory alloys (react to heat), magnetostrictive are examples of these materials.*

Characteristics of actuating systems

A)Weight, Power-to-weight Ratio, Operating pressure

1. Stepper motors are generally heavier than servomotors for the same power.
2. The electric motors of high voltage are the better power-to-weight ratio.
3. Pneumatic systems deliver the lowest power-to-weight ratio.
4. Hydraulic systems have the highest power-to-weight ratio. In these systems, the weight is actually composed of two portions. One is the hydraulic actuators, and the other is the hydraulic power unit (pump, cylinders, rams, reservoirs, filter, and electric motor). If the power unit must also move with the robot, the total power-to-weight ratio will be much less.

B) Stiffness versus compliance

1. Stiffness is the resistance of a material against deformation. The stiffer the system, the larger the load that is needed to deform it. Conversely, the more compliant the system the easier it deforms under the load.

2. Stiffness is directly related to the modulus of elasticity of the material. Hydraulic systems are very stiff and non-compliant while pneumatic systems are easily compressed and thus are compliant.
3. Stiff systems have a more rapid response to changing loads and pressures and are more accurate.
4. Although stiffness causes a more responsive and more accurate system, it also creates a danger if all things are not always perfect.

1.9 Sensors:

The use of external sensing mechanisms allows a robot to interact with its environment in a flexible manner. A robot that can "see" and "feel" is easier to train in the performance of complex tasks while, at the same time, requires less stringent control mechanisms than preprogrammed machines. A sensory, trainable system is also adaptable to a much larger variety of tasks, thus achieving a degree of universality that ultimately translates into lower production and maintenance costs.

The function of robot sensors may be divided into two principal categories: internal state and external state.

- *Internal state sensors deal with the detection of variables such as arm joint position, which are used for robot control such as position sensor, velocity sensor, acceleration sensor, and torque sensor.*
- *External state sensors, on the other hand, deal with the detection of variables such as range, proximity, touch... etc.*

External state sensors may be further classified as contact or non-contact sensors.

- *The former class of sensors responds to physical contacts, such as touch, slip, and torque.*
- *Noncontact sensors rely on the response of a detector to variations in acoustic or electromagnetic radiation. The most prominent examples of non-contact sensors measure range, proximity, and visual properties of an object.*

1.10 Position, Velocity and Acceleration Sensors:

As their name implies, Position Sensors detect the position of something, which means that they are referenced either to or from some fixed point or position. These types of sensors provide a “positional” feedback.

One method of determining a position is to use either “distance”, which could be the distance between two points such as the distance travelled or moved away from some fixed point, or by “rotation” (angular movement). For example, the rotation of a robots wheel to determine its distance travelled along the ground. Either way, Position Sensors can detect the movement of an object in a straight line using Linear Sensors or by its angular movement using Rotational Sensors.

1.10.1 The Potentiometer

The most commonly used of all the “Position Sensors”, is the potentiometer because it is an inexpensive and easy to use position sensor. The principle of work is the resistance is proportional to position.

Potentiometers come in a wide range of designs and sizes such as the commonly available round rotational type or the longer and flat linear slider types. When used as a position sensor the moveable object is connected directly to the rotational shaft or slider of the potentiometer.

A DC reference voltage is applied across the two outer fixed connections forming the resistive element. The output voltage signal is taken from the wiper terminal of the sliding contact as shown below.

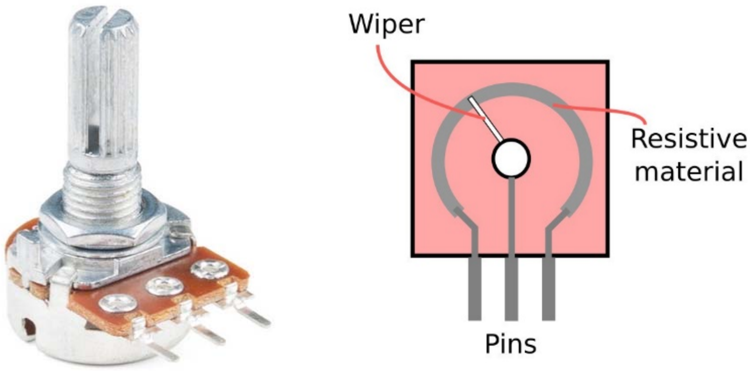


Fig. 1.4: Potentiometer Construction.

The output signal (V_{out}) from the potentiometer is taken from the centre wiper connection as it moves along the resistive track, and is proportional to the angular position of the shaft.

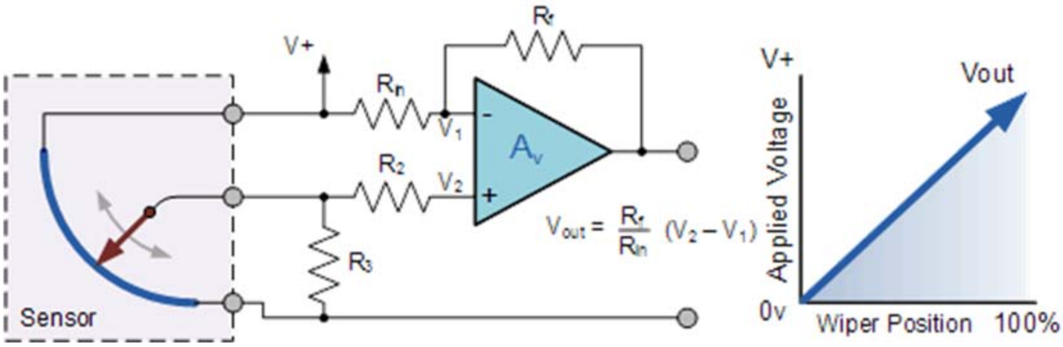


Fig. 1.5: Example of a simple Positional Sensing Circuit.

While resistive potentiometer position sensors have many advantages: low cost, low tech, easy to use etc, as a position sensor they also have many disadvantages: wear due to moving parts, low accuracy, low repeatability, and limited frequency response.

But there is one main disadvantage of using the potentiometer as a positional sensor. The range of movement of its wiper or slider (and hence the output signal obtained) is limited to the physical size of the potentiometer being used.

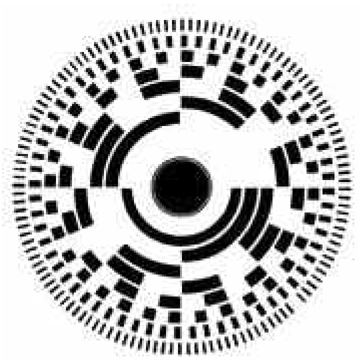
1.10.2 Rotary Encoders

Rotary Encoders are another type of position sensor, which resemble potentiometers mentioned earlier but are non-contact optical devices used for converting the angular position of a rotating shaft into an analogue or digital data code. In other words, they convert mechanical movement into an electrical signal (preferably digital).

All optical encoders work on the same basic principle. Light from an LED or infra-red light source is passed through a rotating high-resolution encoded disk that contains the required code patterns, either binary, grey code or BCD. Photo detectors scan the disk as it rotates and an electronic circuit processes the information into a digital form as a stream of binary output pulses that are fed to counters or controllers, which determine the actual angular position of the shaft.

There are two basic types of rotary optical encoders, Incremental Encoders and Absolute Position Encoders.

A. Incremental Encoder



Incremental Encoders, also known as quadrature encoders or relative rotary encoder, are the simplest of the two position sensors. Their output is a series of square wave pulses generated by a photocell arrangement as the coded disk, with evenly spaced transparent and dark lines called segments on its surface, moves or rotates past the light source. The encoder produces a stream of square wave pulses which, when counted, indicates the angular position of the rotating shaft.

Incremental encoders have two separate outputs called "quadrature outputs". These two outputs are displaced at 90º out of phase from each other with the direction of rotation of the shaft being determined from the output sequence.

The number of transparent and dark segments or slots on the disk determines the resolution of the device and increasing the number of lines in the pattern increases the resolution per degree of rotation. Typical encoded discs have a resolution of up to 256 pulses or 8-bits per rotation.

The simplest incremental encoder is called a tachometer. It has one single square wave output and is often used in unidirectional applications where basic position or speed information only is required. The "Quadrature" or "Sine wave" encoder is the more common and has two output square waves commonly called channel A and channel B. This device uses two photo detectors, slightly offset from each other by 90º thereby producing two separate sine and cosine output signals.

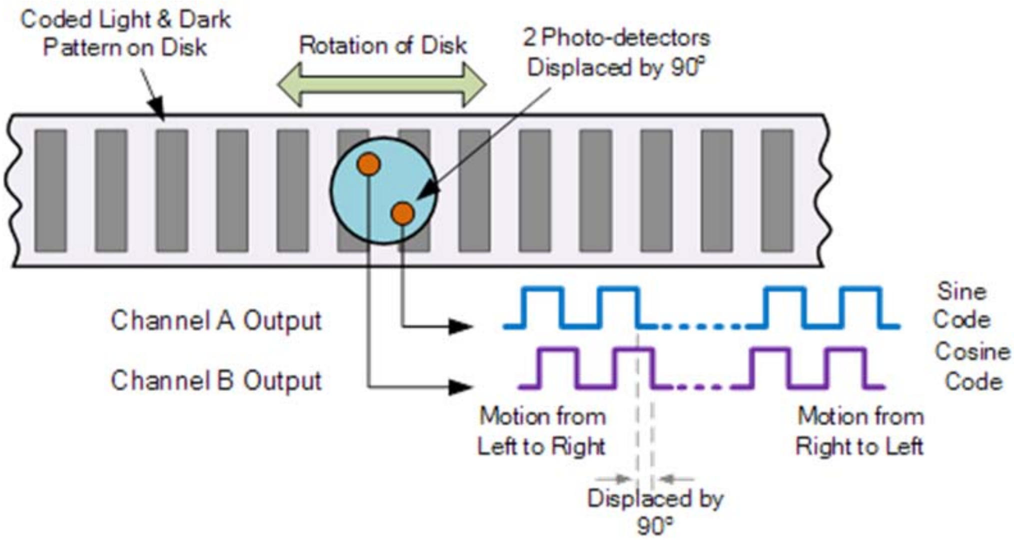


Fig. 1.6: Incremental Encoder.

Generally, the optical disk used in rotary position encoders is circular, then the resolution of the output will be given as: θ = 360/n, where n equals the number of segments on coded disk.

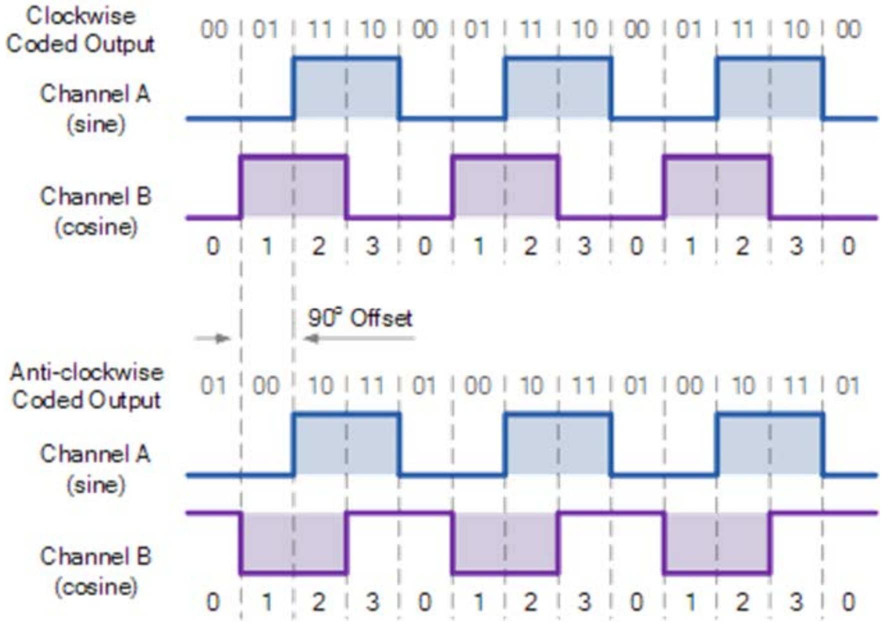


Fig. 1.7: Incremental Encoder output.

One main disadvantage of incremental encoders when used as a position sensor, is that they require external counters to determine the absolute angle of the shaft within a given rotation. If the power is momentarily shut off, or if the encoder misses a pulse due to noise or a dirty disc, the resulting angular information will produce an error. One way of overcoming this disadvantage is to use absolute position encoders.

B. Absolute Position Encoder

Absolute Position Encoders are more complex than quadrature encoders. They provide a unique output code for every single position of rotation indicating both position and direction. Their coded disk consists of multiple concentric "tracks" of light and dark segments. Each track is independent with its own photo detector to simultaneously read a unique coded position value for each angle of movement. The number of tracks on the disk corresponds to the binary "bit"-resolution of the encoder so a 12-bit absolute encoder would have 12 tracks and the same coded value only appears once per revolution.

One main advantage of an absolute encoder is its non-volatile memory which retains the exact position of the encoder without the need to return to a "home" position if the power fails. Most rotary encoders are defined as "single-turn" devices, but absolute multi-turn devices are available, which obtain feedback over several revolutions by adding extra code disks.

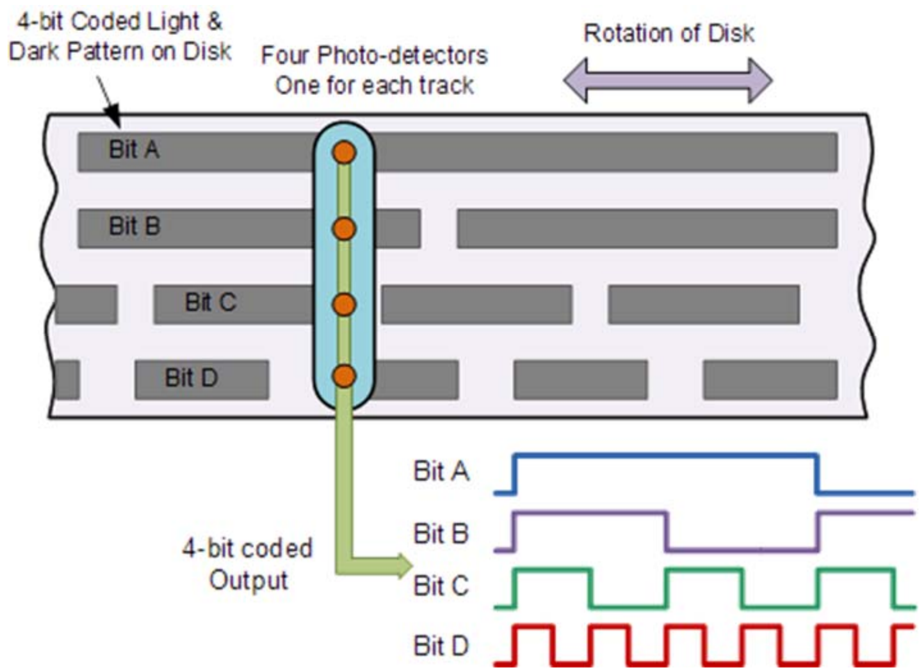


Fig. 1.8: 4-bit Binary Coded Disc.

The pulse rate will be directly proportional to the rotational speed; measuring the time between consecutive rising (or falling) edges and dividing that into the angle of rotation represented by a pulse will yield the rate of rotation.

$$\omega(t) \approx \frac{\frac{2\pi}{n}}{(t_1 - t_0)} = \frac{2\pi}{n\,(t_1 - t_0)}$$, where n = pulses per revolution

Linear velocity can be evaluated based on number of rotation, which is

$$v(t) \approx \frac{2\pi r N_r}{(t_1 - t_0)}$$, where N_r = number of rotation

$$N_r = \frac{n}{N_s}$$, where N_s = number of slots in shift encoder.

Acceleration represented the change of velocity in the duration of motion so

$$a(t) = v(t_1) - v(t_0)$$

1.11 Torque sensors:

Force and torque sensors are used primarily for measuring the reaction forces developed at the interface between mechanical assemblies. The principal approaches for doing this are joint and wrist sensing. A joint sensor measures the cartesian components of force and torque acting on a robot joint and adds them vectorially. For a joint driven by a dc motor, sensing is done simply by measuring the armature current. Wrist sensors, the principal topic of discussion in this section, are mounted between the tip of a robot arm and the end-effector. They consist of strain gauges that measure the deflection of the mechanical structure due to external forces.

Elements of a Wrist Sensor

Wrist sensors are small, sensitive, light in weight (about 12 oz) and relatively compact in design-on the order of 10 cm in total diameter and 3 cm in thickness, with a dynamic range of up to 200 lb.

In order to reduce hysteresis and increase the accuracy in measurement, the hardware is generally constructed from one solid piece of metal, typically aluminum. As an example, the sensor shown in Fig. 1.9 uses eight pairs of semiconductor strain gauges mounted on four deflections bars one gauge on each side of a deflection bar. The gauges on the opposite open ends of the deflection bars are wired differentially to a potentiometer circuit whose output voltage is proportional to the force component normal to the plane of the strain gauge.

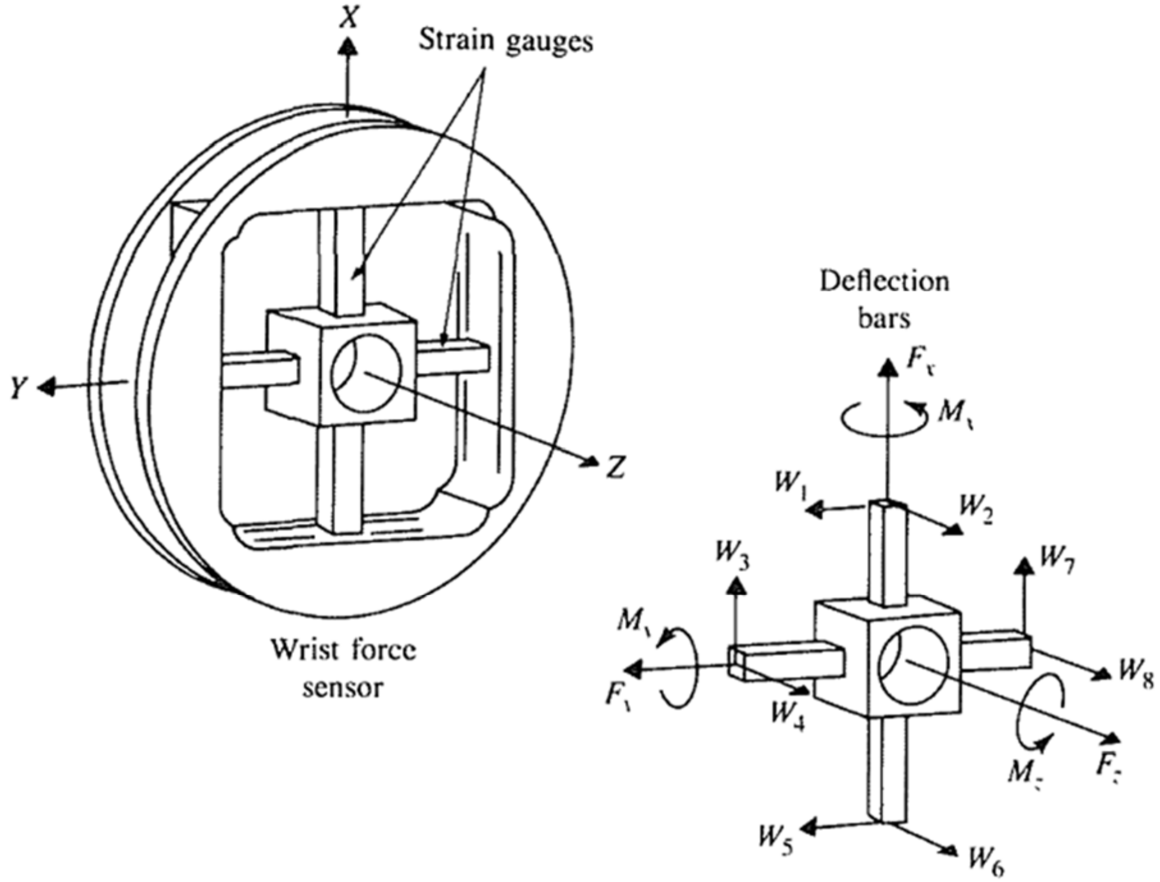


Fig. 1.9: Wrist force sensor.

Since the eight pairs of strain gauges are oriented normal to the x, y, and z axes of the force coordinate frame, the three components of force F and three components of moment M can be determined by properly adding and subtracting the output voltages, respectively. This can be done by pre-multiplying the sensor reading by a sensor calibration matrix.

It is important that the wrist motions generated by the force sensor do not affect the positioning accuracy of the manipulator. Thus, the required performance specifications can be summarized as follows:

1. ***High stiffness.*** The natural frequency of a mechanical device is related to its stiffness; thus, high stiffness ensures that disturbing forces will be quickly damped out to permit accurate readings during short time intervals. Furthermore, it reduces the magnitude of the deflections of an applied force/moment, which may add to the positioning error of the hand.
2. ***Compact design.*** This ensures that the device will not restrict the movement of the manipulator in a crowded workspace. It also minimizes collisions between the sensor and the

other objects present in the workspace. With the compact force sensor, it is important to place the sensor as close to the tool as possible to reduce positioning error as a result of the hand rotating through small angles. In addition, it is desirable to measure as large a hand force/moment as possible; thus, minimizing the distance between the hand and the sensor reduces the lever arm for forces applied at the hand.

3. ***Linearity.*** Good linearity between the response of force sensing elements and the applied forces/moments permits resolving the forces and moments by simple matrix operations.
4. ***Low hysteresis and internal friction.*** Internal friction reduces the sensitivity of the force sensing elements because forces have to overcome this friction before a measurable deflection can be produced. It also produces hysteresis effects that do not restore the position measuring devices back to their original readings.

1.12 Tactile and touch sensors:

Touch sensors are used in robotics to obtain information associated with the contact between a manipulator hand and objects in the workspace. Touch information can be used, for example, for object location and recognition, as well as to control the force exerted by a manipulator on a given object. Touch sensors can be subdivided into two principal categories: binary and analog. Binary sensors are basically switches which respond to the presence or absence of an object. Analog sensors, on the other hand, output a signal proportional to a local force.

1.12.1 Binary Sensors

As indicated above, binary touch sensors are contact devices, such as micro switches. In the simplest arrangement, a switch is placed on the inner surface of each finger of a manipulator hand, as illustrated in Fig. 1.10. This type of sensing is useful for determining if a part is present between the fingers. By moving the hand over an object and sequentially making contact with its surface, it is also possible to center the hand over the object for grasping and manipulation.

Multiple binary touch sensors can be used on the inside surface of each finger to provide further tactile information. In addition, they are often mounted on the external surfaces of a manipulator hand to provide control signals useful for guiding the hand throughout the work space. This latter use of touch sensing is analogous to what humans do in feeling their way in a totally dark room.

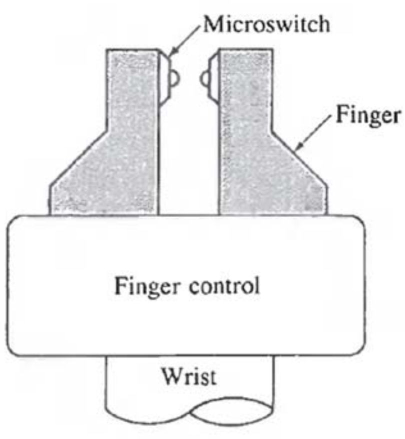


Fig. 1.10: A simple robot hand equipped with binary touch sensors.

1.12.2 Analog Sensors

An analog touch sensor is a compliant device whose output is proportional to a local force. The simplest of these devices consists of a spring-loaded rod (Fig. 1.11) which is mechanically linked to a rotating shaft in such a way that the displacement of the rod due to a lateral force results in a proportional rotation of the shaft. The rotation is then measured continuously using a potentiometer or digitally using a code wheel. Knowledge of the spring constant yields the force corresponding to a given displacement.

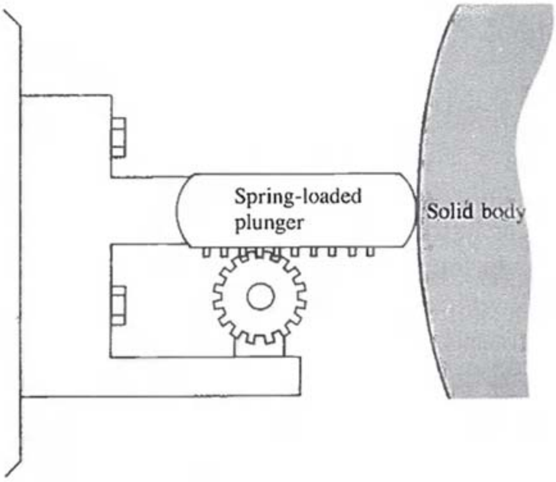


Fig. 1.11: A basic analog touch sensor.

During the past few years, considerable effort has been devoted to the development of tactile sensing arrays capable of yielding touch information over a wider area than that afforded by a single sensor. The use of these devices is illustrated in Fig. 1.12, which shows a robot hand in which the inner surface of each finger has been covered with a tactile sensing array.

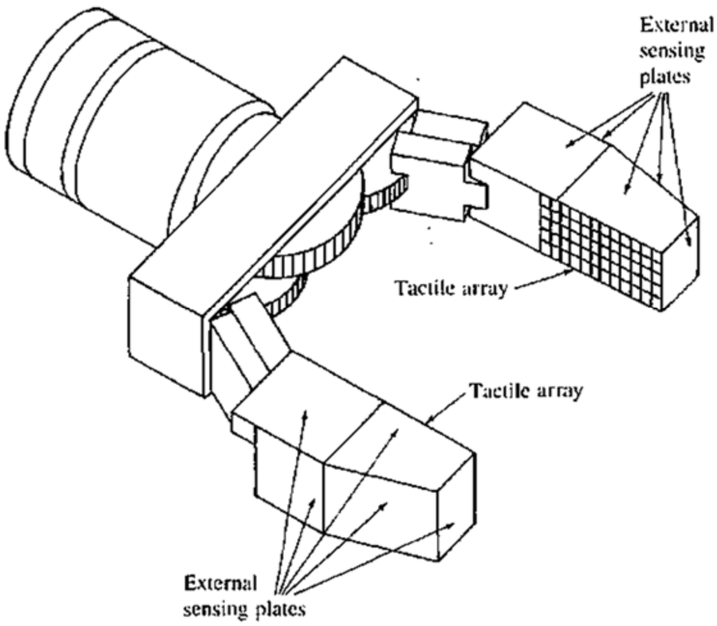


Fig. 1.12: A robot hand equipped with tactile sensing arrays.

Although sensing arrays can be formed by using multiple individual sensors, one of the most promising approaches to this problem consists of utilizing an array of electrodes in electrical contact with a compliant conductive material (e.g., graphite-based substances) whose resistance varies as a function of compression. In these devices, often called ***artificial skins***, an object pressing against the surface causes local deformations which are measured as continuous resistance variations.

The scheme shown in Fig. 1.13a is based on a "window" concept, characterized by a conductive material sandwiched between a common ground and an array of electrodes etched on a fiberglass printed-circuit board. Each electrode consists of a rectangular area (and hence the name window) which defines one touch point. Current flows from the common ground to the individual electrodes as a function of compression of the conductive material.

In the method shown in Fig. 1.13b long, narrow electrode pairs are placed in the same substrate plane with active electronic circuits using LSI technology. The conductive material is placed above this plane and insulated from the substrate plane, except at the electrodes. Resistance changes resulting from material compression are measured and interpreted by the active circuits located between the electrode pairs.

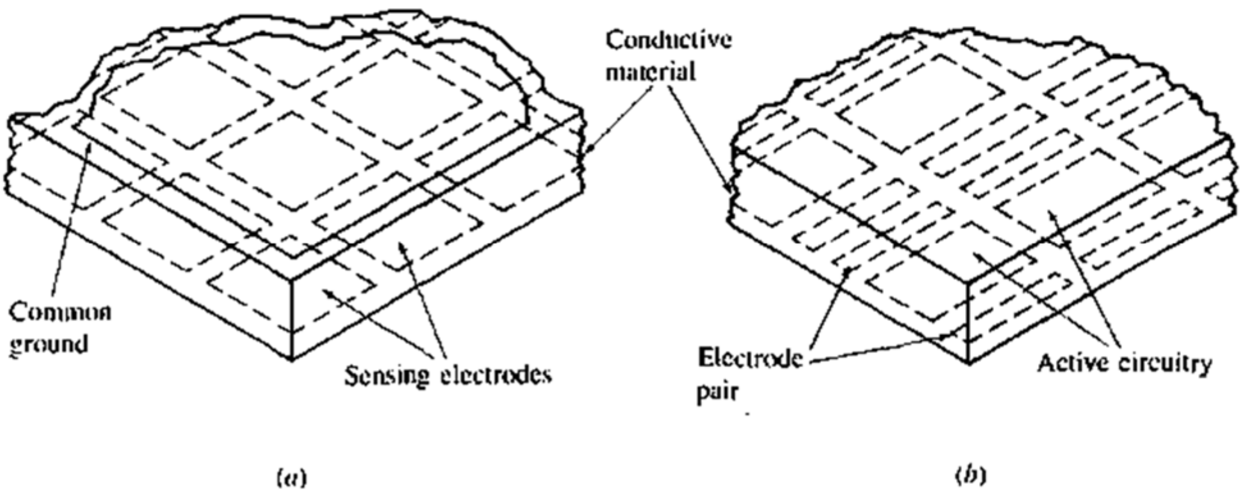
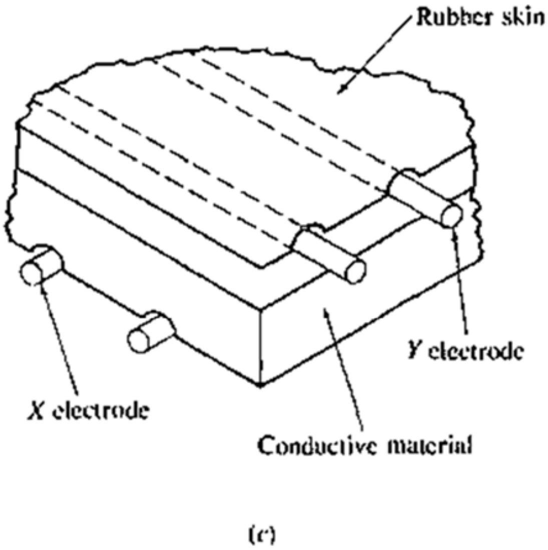
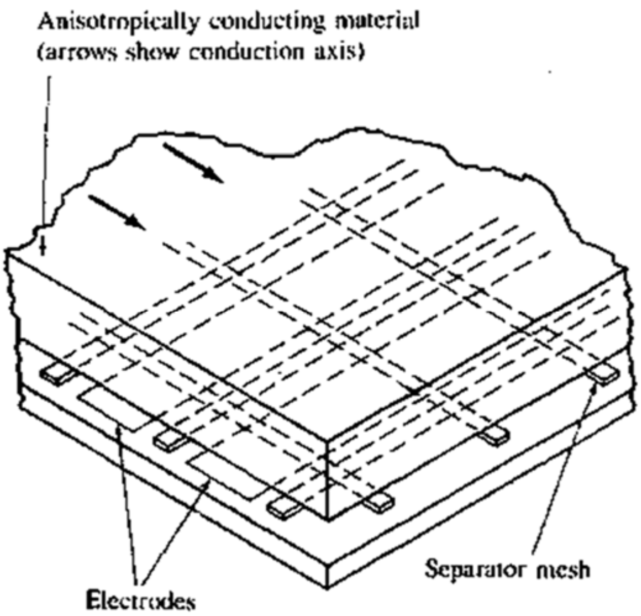


Fig. 13

Another possible technique is shown in Fig. 1.14a. In this approach the conductive material is located between two arrays of thin, flat, flexible electrodes that intersect perpendicularly. Each intersection, and the conductive material in between, constitutes one sensing point. Changes in resistance as a function of material compression are measured by electrically driving the electrodes of one array (one at a time) and measuring the current flowing in the elements of the other array. The magnitude of the current in each of these elements is proportional to the compression of the material between that element and the element being driven externally.

Finally, the arrangement shown in Fig. 1.14b requires the use of an anisotropically conductive material. Such materials have the property of being electrically conductive in only one direction. The sensor is constructed by using a linear array of thin, flat electrodes in the base. The conductive material is placed on top of this, with the conduction axis perpendicular to the electrodes and separated from them by a mesh so that there is no contact between the material and electrodes in the absence of a force. Application of sufficient force results in contact between the material and electrodes. As the force increases so does the contact area, resulting in lower resistance. As with the method in Fig. 1.14a, one array is externally driven and the resulting current is measured in the other. It is noted that touch sensitivity depends on the thickness of the separator.





(a) (b)

Fig. 1.14

1.13 Proximity and range sensors:

1.13.1 RANGE SENSING

A range sensor measures the distance from a reference point (usually on the sensor itself) to objects in the field of operation of the sensor. Range sensors are used for robot navigation and obstacle avoidance, where interest lies in estimating the distance to the closest objects, to more detailed applications in which the location and general shape characteristics of objects in the work space of a robot are desired.

A) Triangulation

One of the simplest methods for measuring range is through triangulation techniques. This approach can be easily explained with the aid of Fig. 1.15. An object is illuminated by a narrow beam of light which is swept over the surface. The sweeping motion is in the plane defined by the line from the object to the detector and the line from the detector to the source. If the detector is focused on a small portion of the surface then, when the detector sees the light spot, its distance D to the illuminated portion of the surface can be calculated from the geometry of Fig.1.15 since the angle of the source with the baseline and the distance B between the source and detector are known.

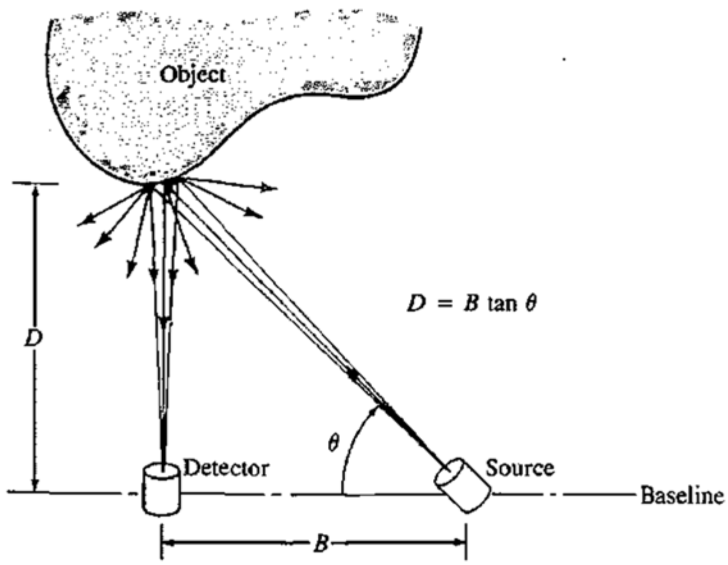


Fig. 1.15: Range sensing by triangulation.

B) Time-of-Flight Range Finders

Pulsed light

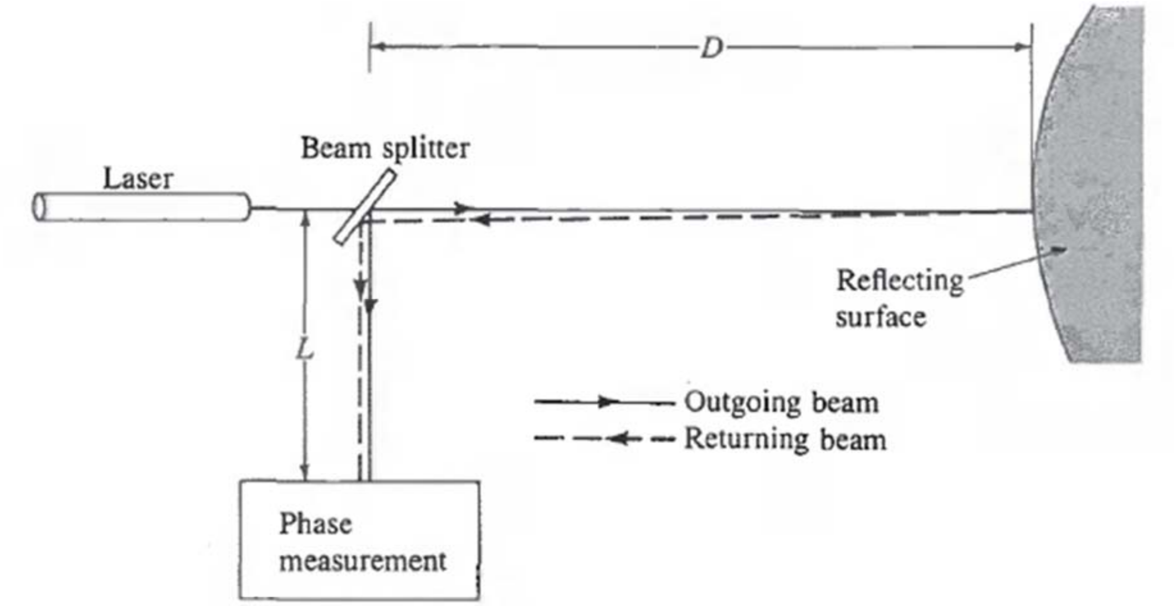
A pulsed light is to use a continuous-beam laser and measure the delay (i.e., phase shift) between the outgoing and returning beams. We illustrate this concept with the aid of Fig. 1.15. Suppose that a beam of laser light of wavelength X is split into two beams. One of these (called the reference beam) travels a distance L to a phase measuring device, and the other travels a distance D out to a reflecting surface. The total distance travelled by the reflected beam is D' = L + 2D. Suppose that D = 0. Under this condition D' = L and both t the reference and reflected beams arrive simultaneously at the phase measuring device. If we let D increase, the reflected beam travels a longer path and, therefore, a phase shift is introduced between the two beams at the point of measurement, as illustrated in Fig. 1.15b. In this case we have that

$$D' = L + \frac{\theta}{360}\lambda \qquad (1)$$

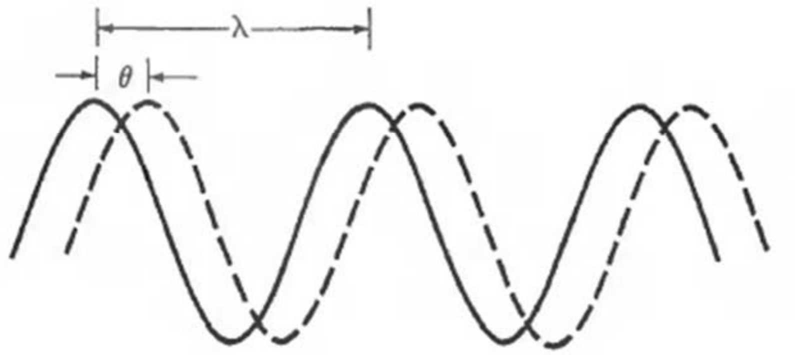
It is noted that if θ = 360° the two waveforms are again aligned and we cannot differentiate between D' = L and D' = L + nλ, n = 1, 2, …, based on measurements of phase shift alone. Thus, a unique solution can be obtained only if we require that θ < 360 ° or, equivalently, that 2D < λ. Since D' = L + 2D, we have by substitution into Eq. (1) that

$$D = \frac{\theta}{360}\left(\frac{\lambda}{2}\right) \qquad (2)$$

which gives distance in terms of phase shift if the wavelength is known.



(a)



(b)

Fig 1.15 (a) Principles of range measurement by phase shift. (b) Shift between outgoing and returning light waveforms.

Since the wavelength of laser light is small (e.g., 632.8 nm for a helium-neon laser), the method sketched in Fig. 1.15 is impractical for robotic applications. A simple solution to this problem is to modulate the amplitude of the laser light by using a waveform of much higher wavelength. (For example, recalling that $c = f\lambda$, a modulating sine wave of frequency f = 10 MHz has a wavelength of 30m.) The approach is illustrated in Fig. 1.16. The basic technique is as before, but the reference signal is now the modulating function. The modulated laser signal is sent out to the target and the returning beam is stripped of the modulating signal, which is then compared against the reference to determine phase shift. Equation (2) still holds, but we are now working in a more practical range of wavelengths.

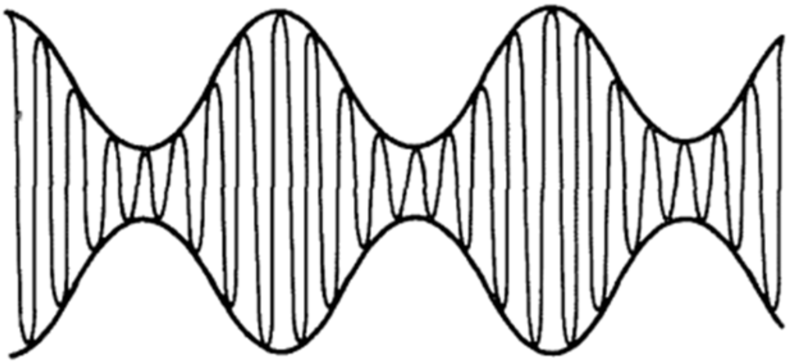


Fig. 1.16: Amplitude-modulated waveform. Note the much larger wavelength of the modulating function.

Ultrasonic

An ultrasonic range finder is another major exponent of the time-of-flight concept. The basic idea is the same as that used with a pulsed laser. An ultrasonic chirp is transmitted over a short time period and, since the speed of sound is known for a specified medium, a simple calculation involving the time interval between the outgoing pulse and the return echo yields an estimate of the distance to the reflecting surface.

In an ultrasonic ranging system manufactured by Polaroid, for example, a 1- ms chirp, consisting of 56 pulses at four frequencies, 50, 53, 57, and 60 KHz, is transmitted by a transducer 11/z inches in diameter. The signal reflected by an object is detected by the same transducer and processed by an amplifier and other circuitry capable of measuring range from approximately 0.9 to 35 ft, with an accuracy of about 1 inch. The mixed frequencies in the chirp are used to reduce signal cancellation. The beam pattern of this device is around 30°, which introduces severe limitations in resolution if one wishes to use this device to obtain a range image similar to those discussed earlier in this section. This is a common problem with ultrasonic sensors and, for this reason; they are used primarily for navigation and obstacle avoidance.

1.13.2 PROXIMITY SENSING

Proximity sensors have a binary output, which indicates the presence of an object within a specified distance interval. Typically, proximity sensors are used in robotics for near-field work in connection with object grasping or avoidance.

A) Inductive Sensors

Sensors based on a change of inductance due to the presence of a metallic object are among the most widely used industrial proximity sensors. The principle of operation of these sensors can be explained with the aid of Fig. 1.17. Figure 1.17a shows a schematic diagram of an inductive sensor, which consists of a wound coil, located next to a permanent magnet packaged in a simple, rugged housing. The effect of bringing the sensor in close proximity to a ferromagnetic material causes a change in the position of the flux lines of the permanent magnet, as shown in Fig. 1.17b and c. Under static conditions, there is no movement of the flux lines and, therefore, no current is induced in the coil. However, as a ferromagnetic object enters or leaves the field of the magnet, the resulting change in the flux lines induces a current pulse whose amplitude and shape are proportional to the rate of change in the flux.

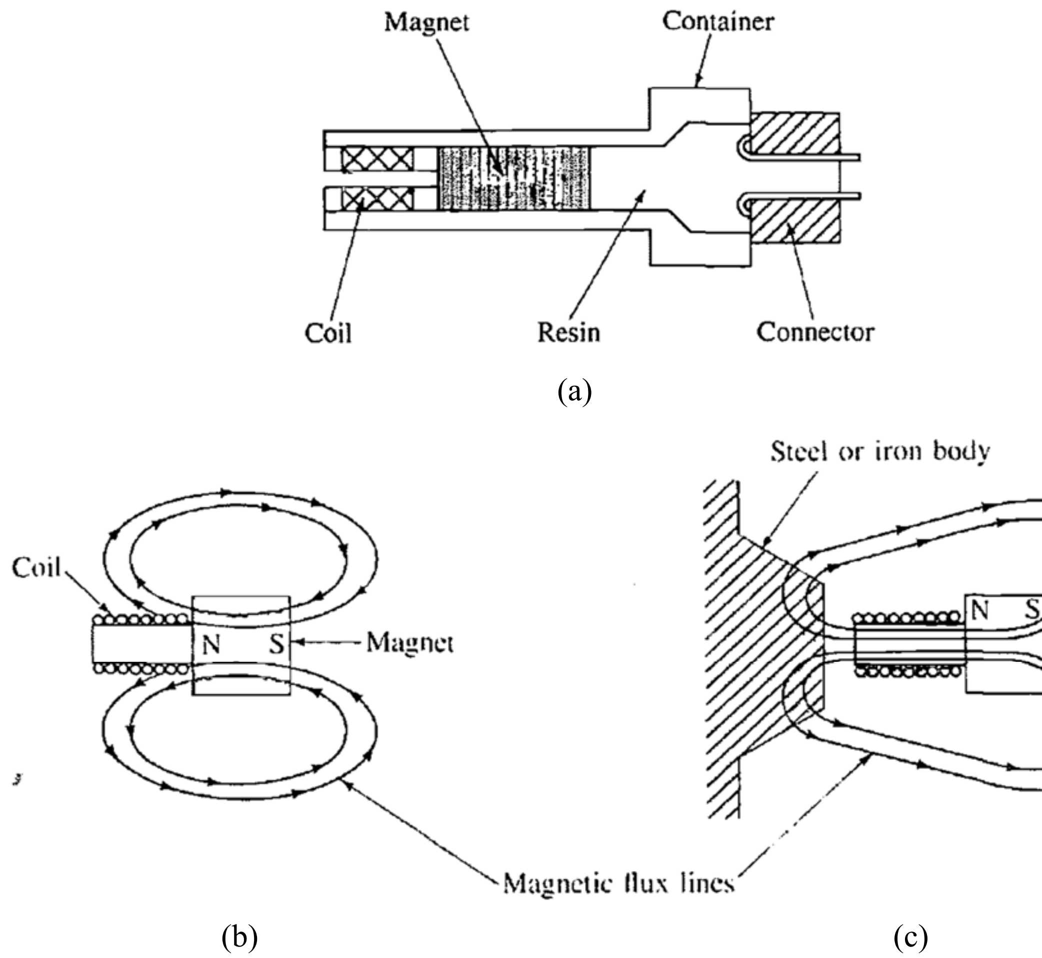


Fig. 1.17 (a) An inductive sensor. (b) Shape of flux lines in the absence of a ferromagnetic body. (c) Shape of flux lines when a ferromagnetic body is brought close to the sensor.

B) Capacitive Sensors

Unlike inductive sensor which detect only ferromagnetic materials, capacitive sensors are potentially capable (with various degrees of sensitivity) of detecting all solid and liquid materials. As their name implies, these sensors are based on detecting a change in capacitance induced by a surface that is brought near the sensing element.

The basic components of a capacitive sensor are shown in Fig. 1.18. The sensing element is a capacitor composed of a sensitive electrode and a reference electrode. These can be, for example, a metallic disk and ring separated by a dielectric material. A cavity of dry air is usually placed behind the capacitive element to provide isolation. The rest of the sensor consists of electronic circuitry which can be included as an integral part of the unit, in which case it is normally embedded in a resin to provide sealing and mechanical support. There are a number of electronic approaches for detecting proximity based on a change in capacitance. One of the simplest includes the capacitor as part of an oscillator circuit designed so that the oscillation starts only when the capacitance of the sensor exceeds a predefined threshold value. The start of oscillation is then translated into an output voltage, which indicates the presence of an object. This method provides a binary output whose triggering sensitivity depends on the threshold value.

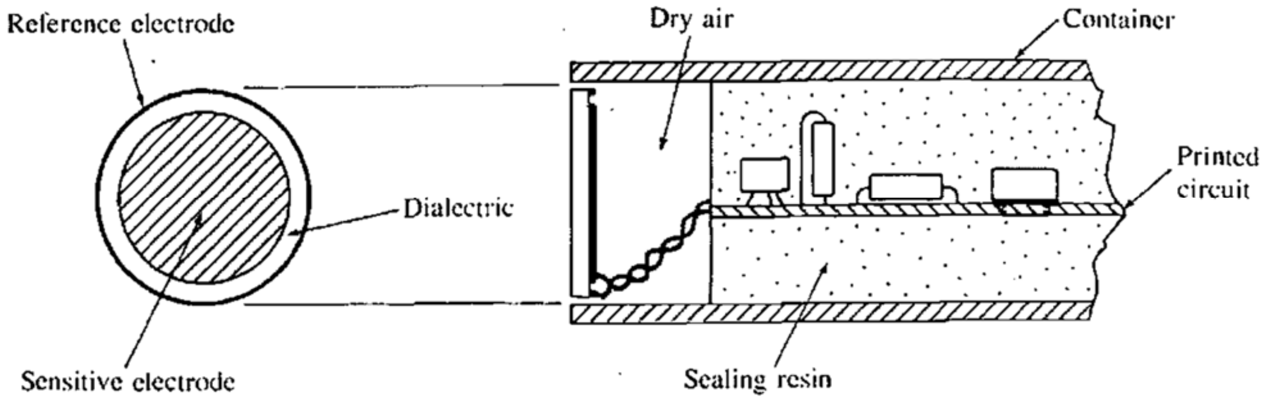


Fig. 1.18: A capacitive proximity sensor.

C) Ultrasonic Sensors

The response of all the proximity sensors discussed thus far depends strongly on the material being sensed. This dependence can be reduced considerably by using ultrasonic sensors. Figure 1.19 shows the structure of a typical ultrasonic transducer used for proximity sensing. The basic element is an electroacoustic transducer, often of the piezoelectric ceramic type. The resin layer protects the transducer against humidity, dust, and other environmental factors; it also acts as an acoustical impedance matcher. Since the same transducer is generally used for both transmitting and receiving, fast damping of the acoustic energy is necessary to detect objects at close range. This is accomplished by providing acoustic absorbers, and by decoupling the transducer from its housing. The housing is designed so that it produces a narrow acoustic beam for efficient energy transfer and signal directionality.

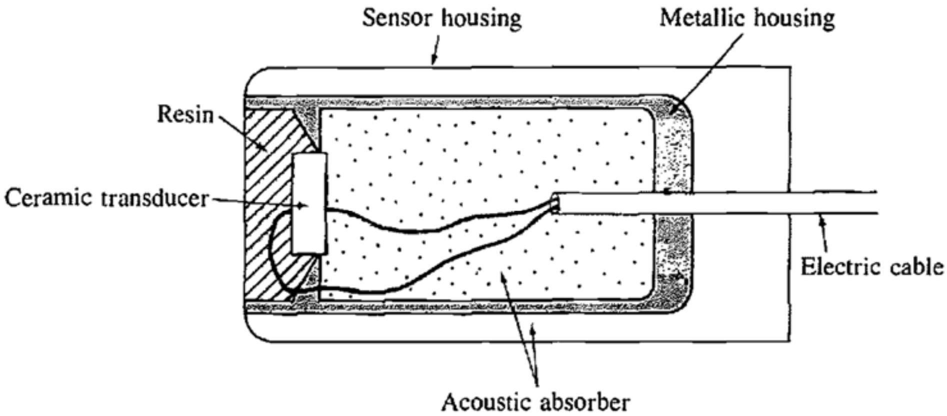


Fig. 1.19: An ultrasonic proximity sensor.

The operation of an ultrasonic proximity sensor is best understood by analysing the waveforms used for both transmission and detection of the acoustic energy signals. A typical set of waveforms is shown in Fig. 1.20. Waveform A is the gating signal used to control transmission. Waveform B shows the output signal as well as the resulting echo signal. The pulses shown in C result either upon transmission or reception. In order to differentiate between pulses corresponding to outgoing and returning energy, we introduce a time window (waveform D) which in essence establishes the detection capability of the sensor. That is, time interval Δt_l is the minimum detection time, and $\Delta t_1 + \Delta t_2$ the maximum. (It is noted that these time intervals are equivalent to specifying distances since the pro pagation velocity of an acoustic wave is known given the transmission medium.) An echo received while signal D is high produces the signal shown in E, which is reset to low at the end of a transmission pulse in signal A. Finally, signal F is set high on the positive edge of a pulse in E and is reset to low when E is low and a pulse occurs in A. In this manner, F will be high whenever an object is present in the distance interval specified by the parameters of waveform D. That is, F is the output of interest in an ultrasonic sensor operating in a binary mode.

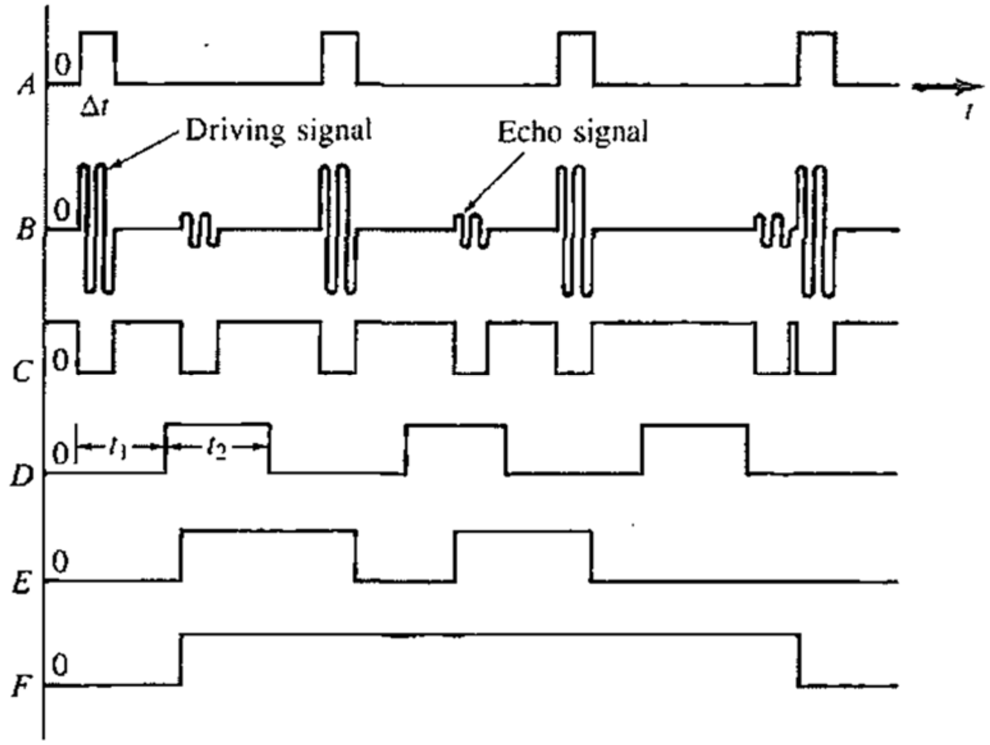


Fig. 1.20: Waveforms associated with an ultrasonic proximity sensor.