INTERNAL SENSORS

- are used to measure internal state of a robot
- i.e., its position, velocity, acceleration, etc., at a particular instant
- Depending on the quantities it measures, a sensor is termed as

- Position
- Velocity
- Acceleration
- Force sensor

Position Sensors

- Position sensors measure the position of each joint
- i.e., joint angle of a robot
- From these joint angles, one can find the end-effector configuration
- namely, its position and orientation,

- Different position sensors are-
  1. Encoder
  2. Potentiometer
  3. LVDT
  4. Synchros and Resolver

Encoder

- The encoder is a digital optical device
- that converts linear or angular displacement into an electrical signal.
- that converts motion into a sequence of digital pulses.
- 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.
- Further, each type may be again linear and rotary.

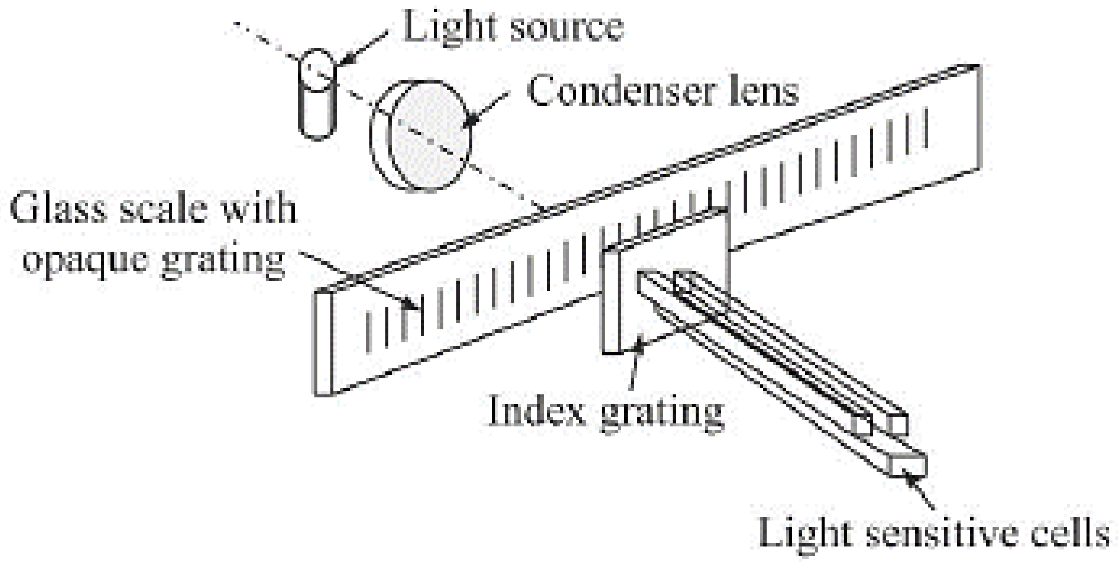
Incremental Linear Encoder

- As shown in Fig, it has a transparent glass scale with opaque grating.
- The thickness of grating lines and the gap between them is made same, which are in the range of microns.
- One side of the scale is provided with a light source and a condenser lens.
- On the other side there are light-sensitive cells.
- The resistance of the cells (photodiodes) decreases whenever a beam of light falls on them.
- Thus, a pulse is generated each time a beam of light is intersected by the opaque line.
- This pulse is fed to the controller
- grating is mounted on the shaft

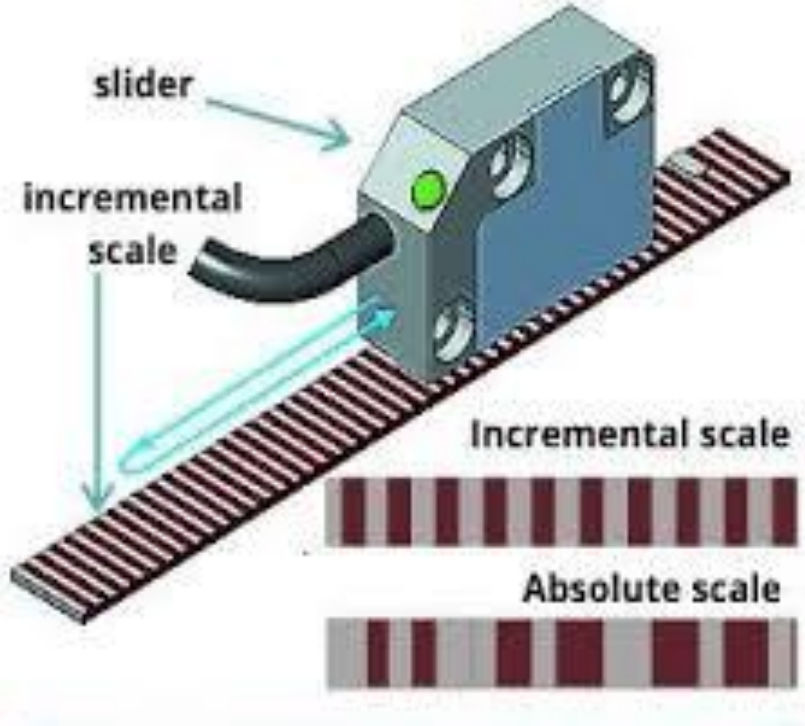
  whose position needs to be measured.
- The pattern of light and dark areas passing

  through the grating generates a sequence

  of electrical pulses.

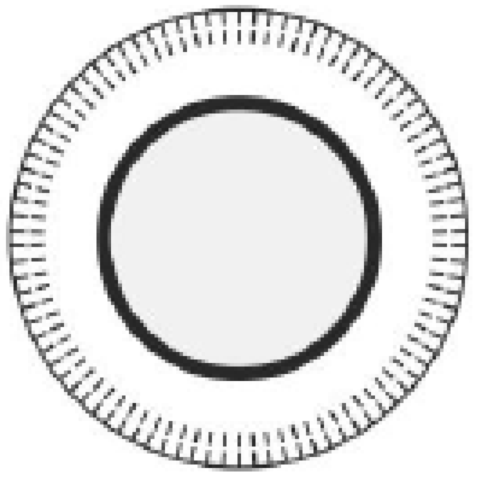


(a) Incremental linear type

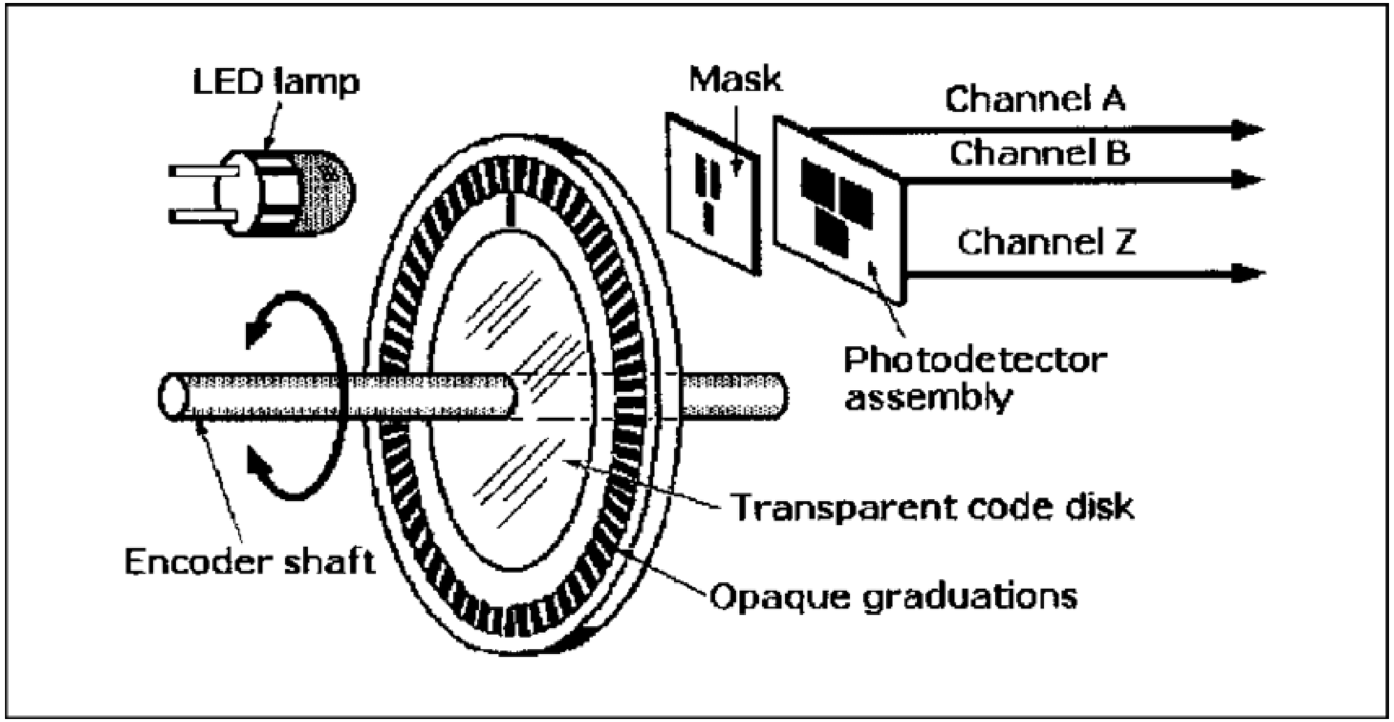


Incremental Rotary Encoder

- It is similar to the linear incremental encoder
- with a difference that the gratings are now on a circular disc, as in Fig.
- The common value of the width of transparent spaces is 20 microns.
- There are two sets of grating lines on two different circles which detect direction of rotation,
- and one can also enhance the accuracy of the sensor.
- There is another circle, which contains only one grating mark. It is used for measurement of full circles.



(c) Incremental rotary type


LED lamp
Mask
Channel A
Channel B
Channel Z
Photodetector assembly
Transparent code disk
Encoder shaft
Opaque graduations


ORANGE
ROTARY ENCODER
3806-OPTI-400-AB-OC

Absolute Linear Encoder

- It is similar in principle as the incremental linear encoder.
- The difference is that it gives absolute value of the distance covered at any time.
- Thus, the chance of missing the pulses at high speeds is less.
- The output is digital in this case.
- **The scale is marked in a sequence of opaque and transparent strips**, as shown in Fig.
- In the scale shown, if the opaque block represents

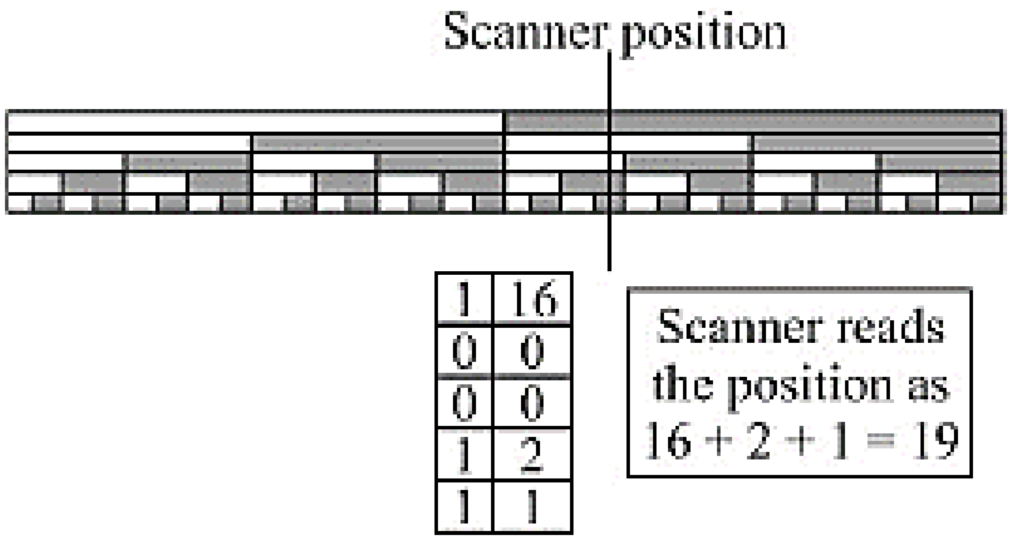
  1 (one) and the transparent block as 0 (zero)

  then the leftmost column will show a

  binary number as 00000, i.e., a decimal value of 0,

  and the rightmost column will show a binary number

  11111, i.e., a decimal value of 61.



(b) Absolute linear type

Absolute Rotary Encoder

- the circular disk is divided into a number of circular strips and each strip has definite arc segments,
- This sensor directly gives the digital output (absolute).
- The encoder is directly mounted on the motor shaft or with some gearing to enhance the accuracy of measurement.
- To avoid noise in this encoder, a gray scale is sometimes used.
- A Gray code, unlike binary codes, allows only one of the binary bits in a code sequence to change between radial lines.
- It prevents confusing changes in the binary output of the absolute encoder when the encoder oscillates between points.
- A sample Gray code is given in Table 4.1 for some numbers.

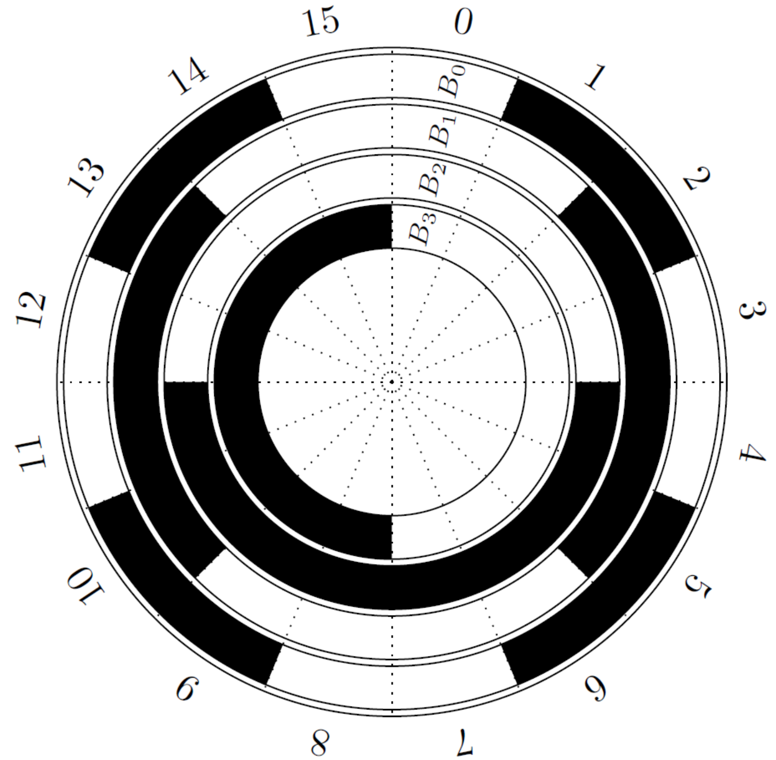

15
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
B_0
B_1
B_2
B_3

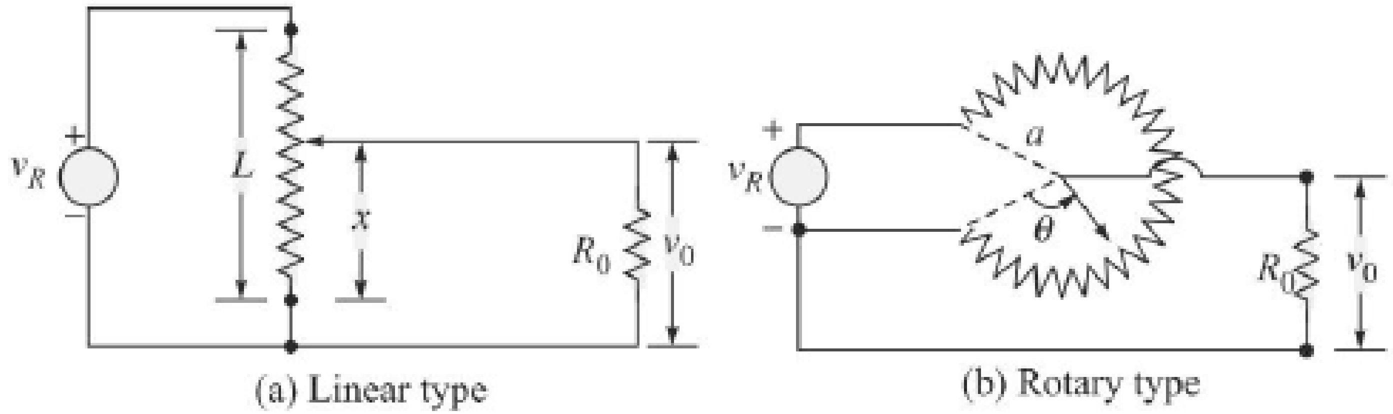
Table 4.1 Sample Gray codes

Decimal	Binary code	Gray code
0	0000	0000
1	0001	0001
2	0010	0011
3	0011	0010
4	0100	0110

- Different position sensors are-
  1. Encoder
  2. Potentiometer
  3. LVDT
  4. Synchros and Resolver

2. Potentiometer

- A potentiometer, **also referred as simply pot**
- is a variable resistance device that expresses linear or angular displacements in terms of voltage
- **It consists of a wiper** that makes contact with a resistive element
- as this point of contact moves, the resistance between the wiper and end leads of the device changes in proportion to the displacement

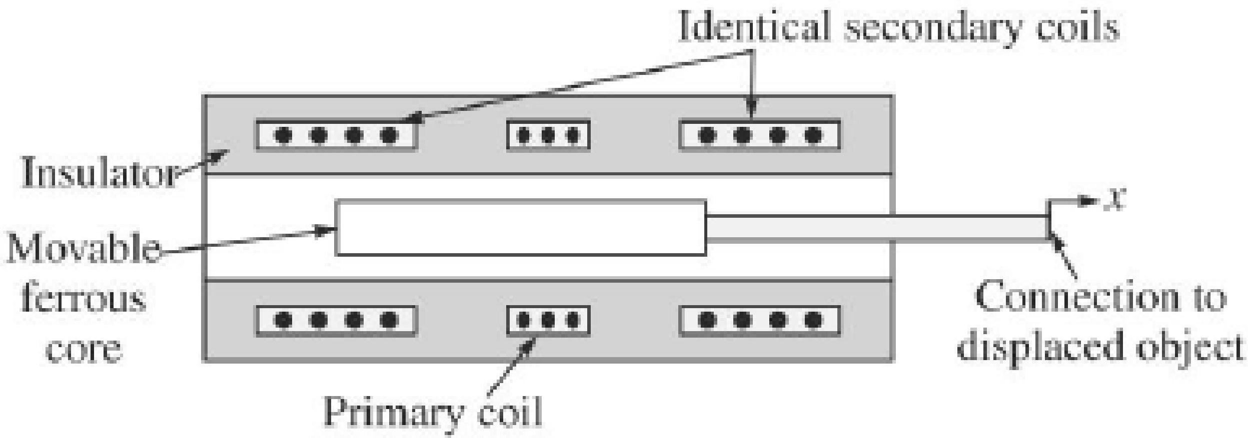


v_R: Reference voltage; v_0: Measured voltage
L, x, R_0, a, θ: Other physical parameters

Fig. 4.3 Potentiometers

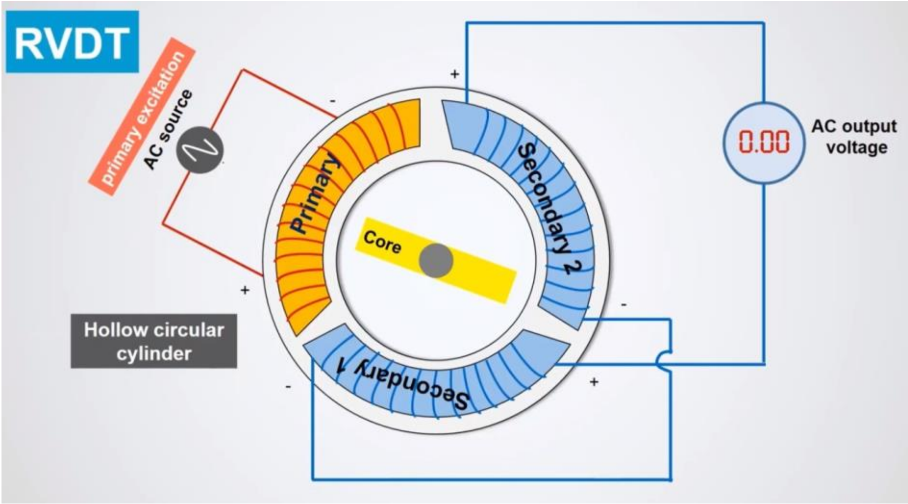
- Different position sensors are-
    1. Encoder
    2. Potentiometer
    3. LVDT
    4. Synchros and Resolver

3. LVDT



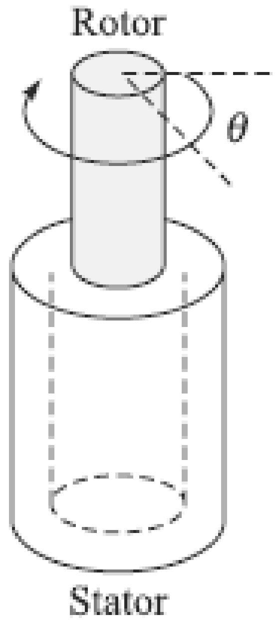
- **The Linear Variable Differential Transformer (LVDT)**
- is one of the most used displacement transducers, particularly when high accuracy is needed.
- It generates an ac signal whose magnitude is related to the displacement of a moving core,
- The basic concept is that of a ferrous core moving in a magnetic field
- the field being produced in a manner similar to that of a standard transformer.
- There is a central core surrounded by two identical secondary coils and a primary coil, as shown in Fig.

- As the core changes position with respect to the coils, it changes the magnetic fi eld, and hence the voltage amplitude in the secondary coil changes as a linear function of the core displacement over a considerable segment.
- A **Rotary Variable Differential Transformer (RVDT)** operates under the same principle



- Different position sensors are-
    1. Encoder
    2. Potentiometer
    3. LVDT
    4. Synchros and Resolver

4. Synchros and Resolver



- synchros and resolvers provide analog signal as their output.
- They consist of a rotating shaft (rotor) and a stationary housing (stator).
- Their signals must be converted into the digital form through an analog-to-digit
  converter before the signal is fed to the computer.
- synchros and resolvers employ single-winding rotors that revolve inside
  fixed stators.
- In a simple synchro, the stator has three windings oriented 120° apart and electrically connected in a Y-connection. (Difficult to manufacture and costly)
- Resolvers have only two windings oriented at 90°.
- In operation, synchros and resolvers **resemble rotating transformers.**

Velocity Sensors

4.2.2 Velocity Sensors

Velocity or speed sensors measure by taking consecutive position measurements at known time intervals and computing the time rate of change of the position values or directly finding it based on different principles.

1. All Position Sensors Basically, all position sensors when used with certain time bounds can give velocity, e.g., the number of pulses given by an incremental position encoder divided by the time consumed in doing so. But this scheme puts some computational load on the controller which may be busy in some other computations.

2. Tachometer Such sensors can directly find the velocity at any instant of time, and without much of computational load. This measures the speed of rotation of an element. There are various types of tachometers in use but a simpler design is based on the Fleming's rule, which states 'the voltage produced is proportional to the rate of flux linkage.' Here, a conductor (basically a coil) is attached to the rotating element which rotates in a magnetic field (stator). As the speed of the shaft increases, the voltage produced at the coil terminals also increases. In other ways, as shown in Fig. 4.6, one can put a magnet on the rotating shaft and a coil on the stator. The voltage produced is proportional to the speed of rotation of the shaft. This information is digitized using an analog-to-digital converter and passed on to the computer.

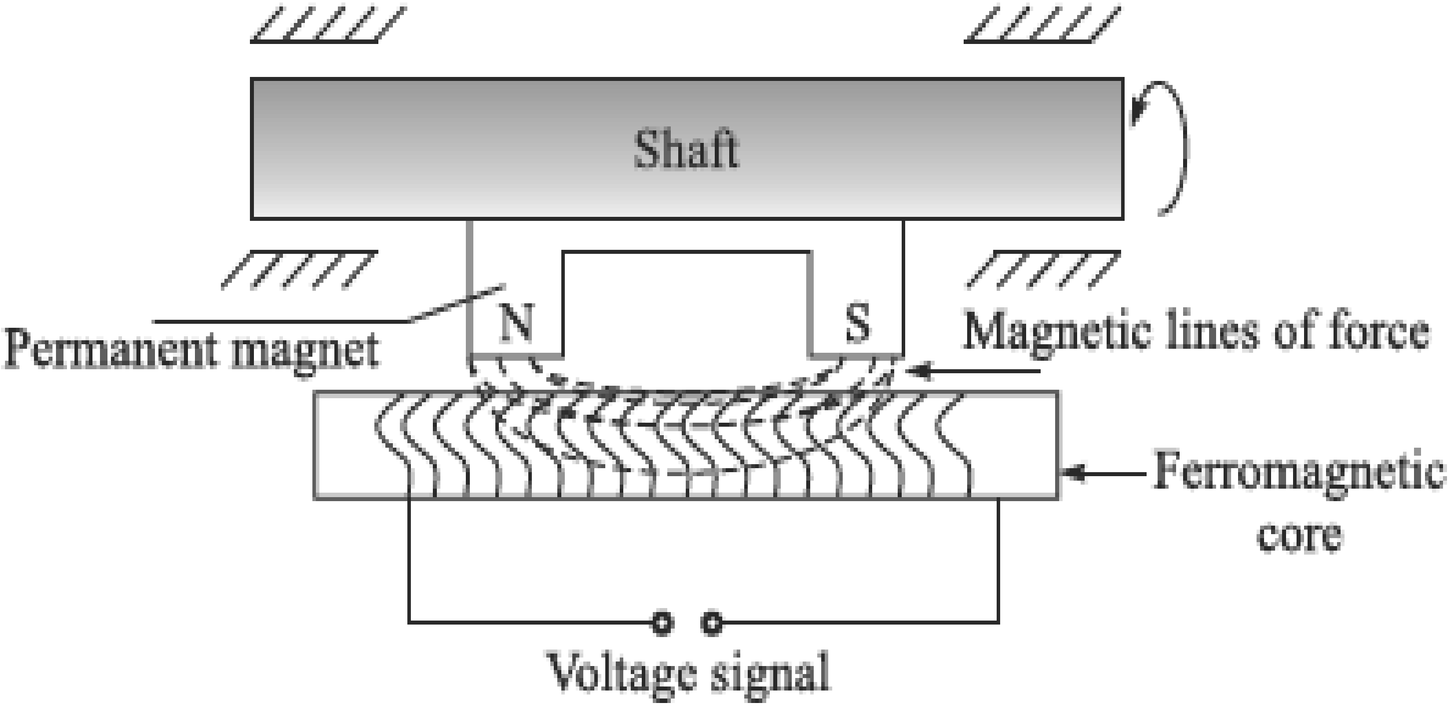


Fig. 4.6 Schematic diagram of a tachometer

3. Hall-effect Sensor Another velocity-measuring device is the Hall-effect sensor, whose principle is described next. If a flat piece of conductor material, called *Hall chip*, is attached to a potential difference on its two opposite faces, as indicated in Fig. 4.7 then the voltage across the perpendicular faces is zero. But if a magnetic field is imposed at right angles to the conductor, the voltage is generated on the two

other perpendicular faces. Higher the field value, higher the voltage level. If one provides a ring magnet, the voltage produced is proportional to the speed of rotation of the magnet.

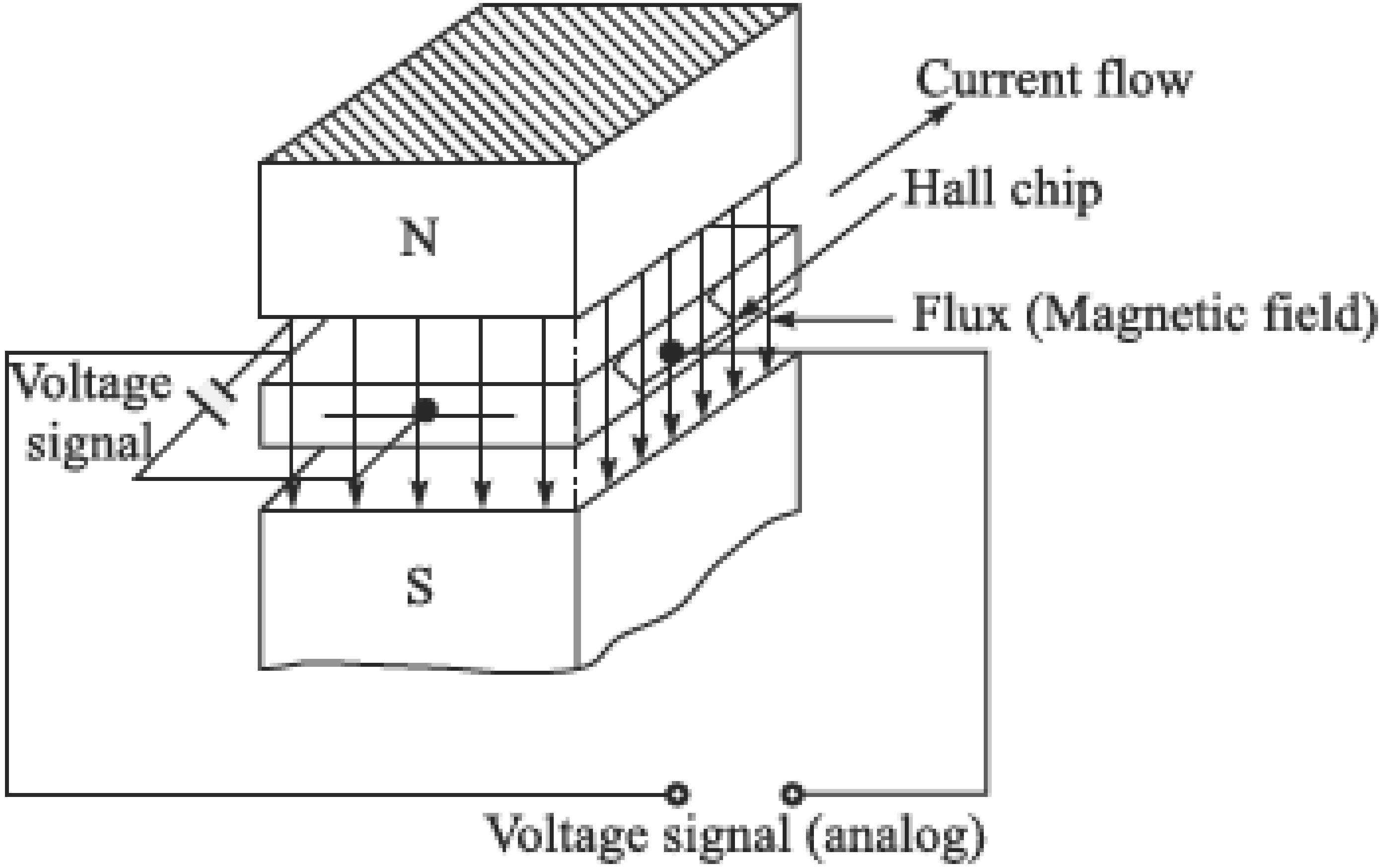
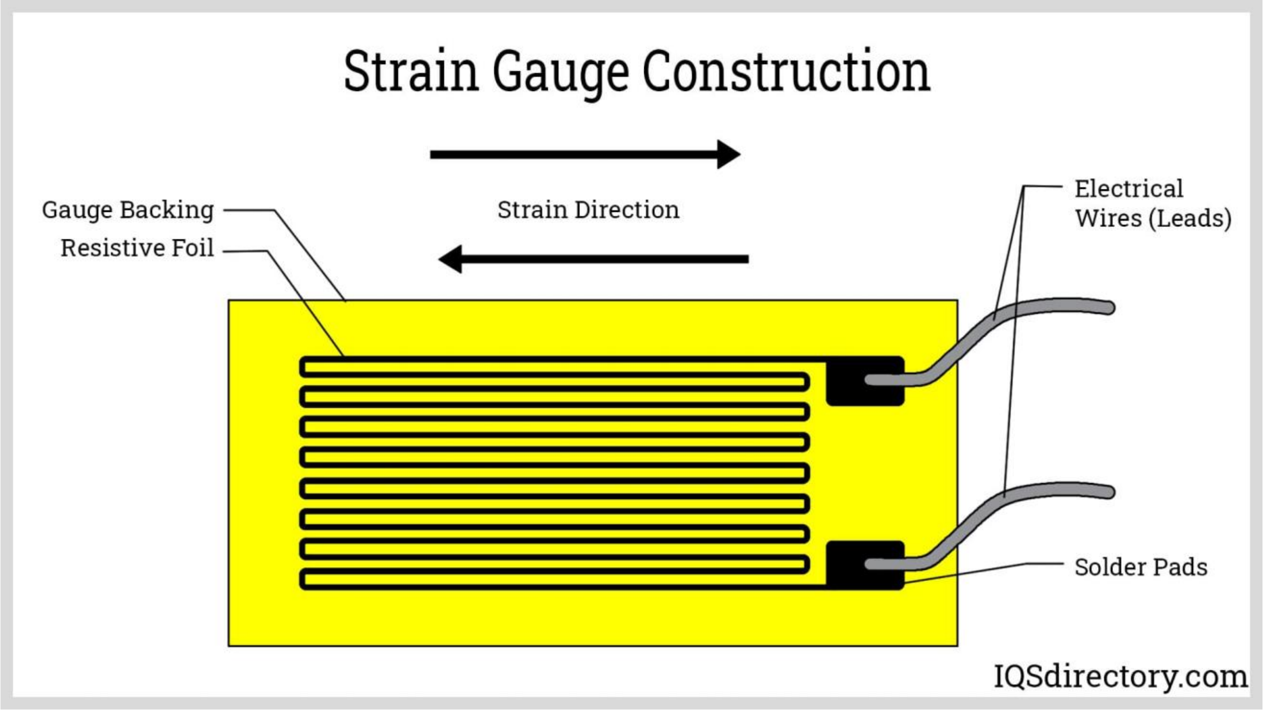


Fig. 4.7 Principle of Hall-effect sensor

In applications such as speed sensing in vehicles or machinery, a Hall effect sensor can be used along with a magnet attached to a moving part (like a wheel or gear). As the part moves, it causes the magnet to move relative to the Hall effect sensor.

As the magnet moves, it induces changes in the magnetic field detected by the Hall effect sensor. The rate of change of this magnetic field is directly related to the velocity of the moving part.

Acceleration Sensors



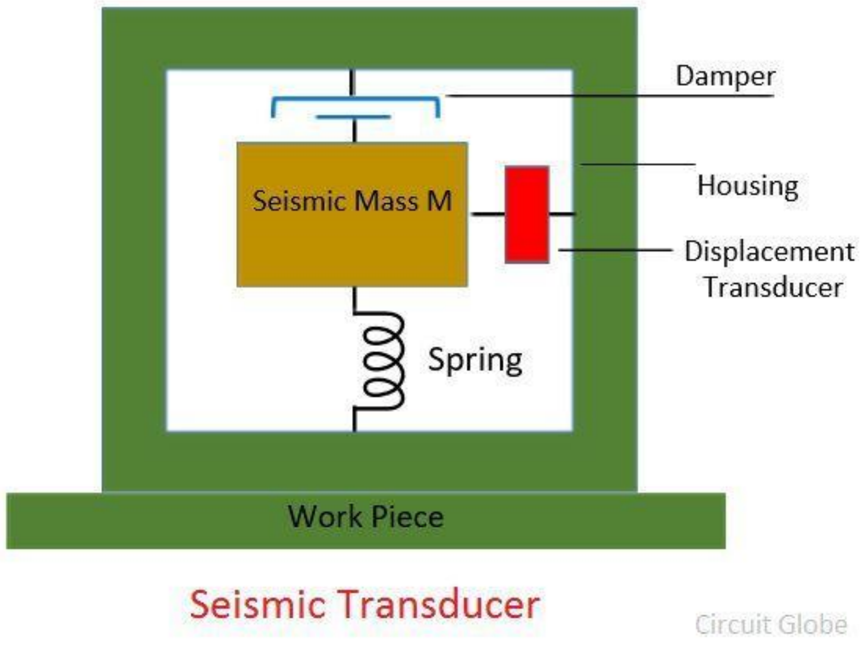
4.2.3 Acceleration Sensors

Similar to measurements of velocity from the information of position sensors, one can find the accelerations as the time rate of change of velocities obtained from velocity sensors or calculated from the position information. But this is not an efficient way to calculate the acceleration because this will put a heavy computational load on the computer and that can hamper the speed of operation of the system. Another way to compute the acceleration is to measure the force which is the result of mass times acceleration. Forces are measured, for example, using strain gauges for which the formula is

$$F = \frac{\Delta RAE}{RG} \tag{4.4}$$

where F is force, ΔR is the change in resistance of the strain gauge, A is the cross-sectional area of the member on which the force being applied, E is the elastic modulus of the strain-gauge material, R is the original resistance of the gauge, and G is gauge factor of the strain gauge. Then, the acceleration a is the force divided by mass of the accelerating object m, i.e.,

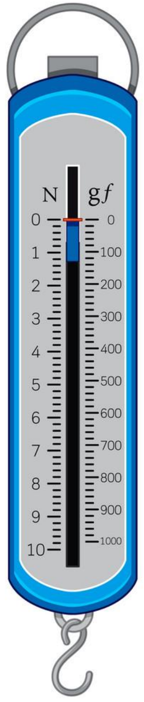
$$a = \frac{F}{m} = \frac{\Delta RAE}{RCm} \tag{4.5}$$



Force Sensors

4.2.4 Force Sensors

A spring balance is an example of a force sensor in which a force, namely, the weight, is applied to the scale pan that causes displacement, i.e., the spring stretches. The displacement is then a measure of the force. There exist other types of force sensors, e.g., strain-gauge based, Hall-effect sensor, etc.



1. Strain-gauge Based The principle of this type of sensors is that the elongation of a conductor increases its resistance. Typical resistances for strain gauges are 50–100 ohms. The increase in resistance is due to

- Increase in the length of the conductor; and
- Decrease in the cross-section area of the conductor.

Strain gauges are made of electrical conductors, usually wire or foil, etched on a base material, as shown in Fig. 4.8. They are glued on the surfaces where strains are to be measured, e.g., R_1 and R_2 of Fig. 4.9(a). The strains cause changes in the resistances of the strain gauges, which are measured by attaching them to the Wheatstone bridge circuit as one of the four resistances, $R_1 \ldots R_4$ of Fig. 4.9(b). The principle of a Wheatstone bridge is explained in Section 4.5.5. It is a cheap and accurate method of measuring strain. But care should be taken for the temperature changes. In order to enhance the output voltage and cancel away the resistance changes due to the change in temperature, two strain gauges are used, as shown in Fig. 4.9(a), to measure the force at the end of the cantilever beam.

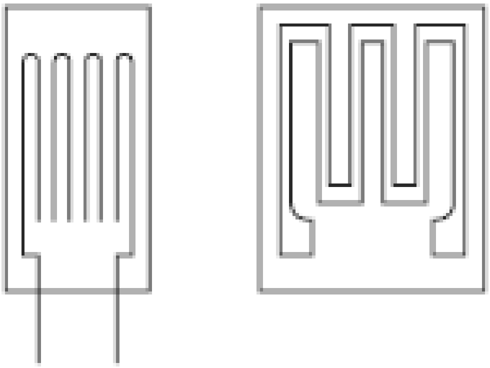
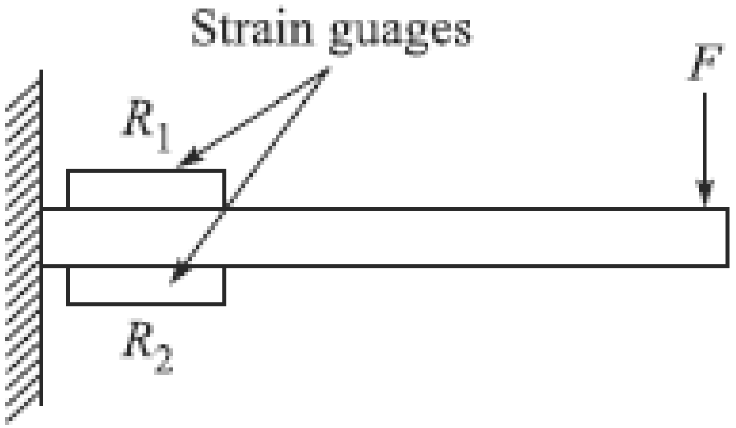


Fig. 4.8 Strain gauges



(a) Cantelever beam with strain gauges

2. *Piezoelectric Based* A piezoelectric material exhibits a phenomenon known as the *piezoelectric effect*. This effect states that when asymmetrical, elastic crystals are deformed by a force, an electrical potential will be developed within the distorted crystal lattice, as illustrated in Fig. 4.10. This effect is reversible. That is, if a potential is applied between the surfaces of the crystal, it will change its physical dimensions. The magnitude and polarity of the induced charges are proportional to the magnitude and direction of the applied force. The piezoelectric materials are quartz, tourmaline, Rochelle salt, and others. The range of forces that can be measured using piezoelectric sensors are from 1 to 20 kN and at a ratio of 2×10^5. These sensors can be used to measure an instantaneous change in force (dynamic forces).

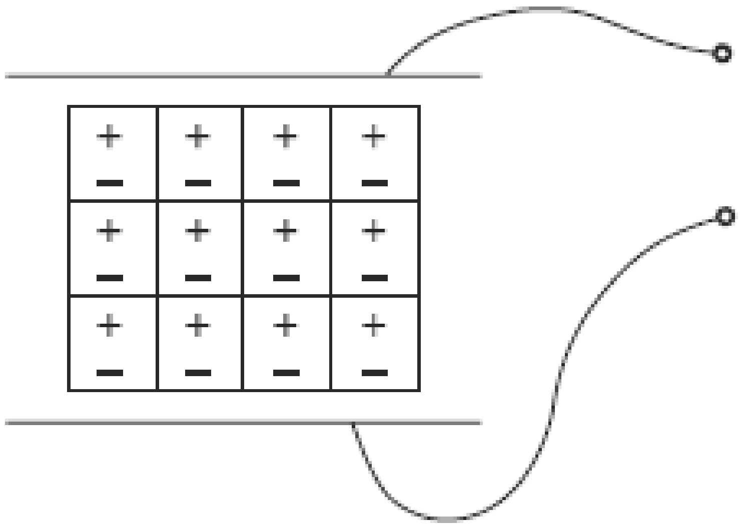


Fig. 4.10 Piezoelectric sensor

4.3 EXTERNAL SENSORS

External sensors are primarily used to learn more about a robot's environment, especially the objects being manipulated. External sensors can be divided into the following categories:

- Contact type, and
- Noncontact type.

Contact Type

a contact-type force sensor is explained.

Limit Switch A limit switch is constructed much as the ordinary light switch used at homes and offices. It has the same on-off characteristics.

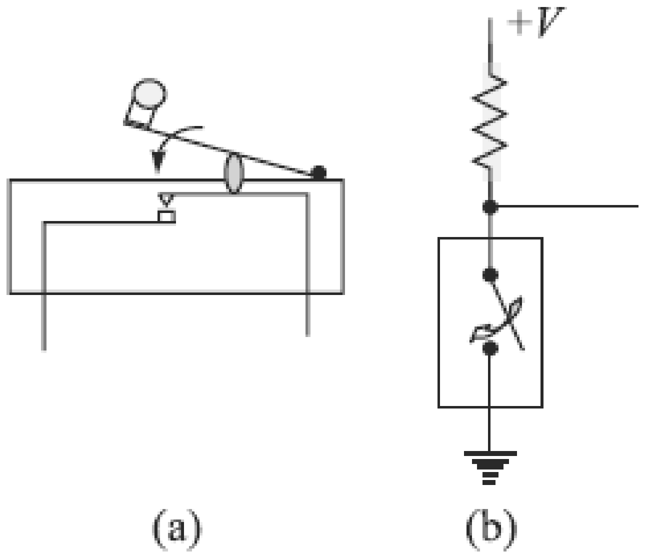


Fig. 4.11 Limit switch

Limit switches are used in robots to detect the extreme positions of the motions, where the link reaching an extreme position switches off the corresponding actuator, thus, safeguarding any possible damage to the mechanical structure of the robot arm.

The limit switch usually has a pressure-sensitive mechanical arm, as shown in Fig. 4.11(a). When an object applies pressure on the mechanical arm, the switch is energized. An object might have an attached magnet that causes a contact to rise and close when the object passes over the arm. As shown in Fig. 4.11(b), the pull-up register keeps the signal at +V until the switch closes, sending the signal to ground. Limit switches can be either Normally Open (NO) or Normally Closed (NC), and may have multiple-poles. A normally open switch has continuity when pressure is applied. A single-pole switch allows one circuit to be opened or closed upon contact, whereas a multi-pole switch allows multiple switch circuits to be open or closed. Limit switches are mechanical devices which have problems like

- they are subjected to mechanical failure,
- their mean time between failures is low compared to noncontact sensors, and
- the speed of operation is relatively slow compared to the speed of switching of photoelectric micro-sensors which is up to 3000 times faster.

4.3.2 Noncontact Type

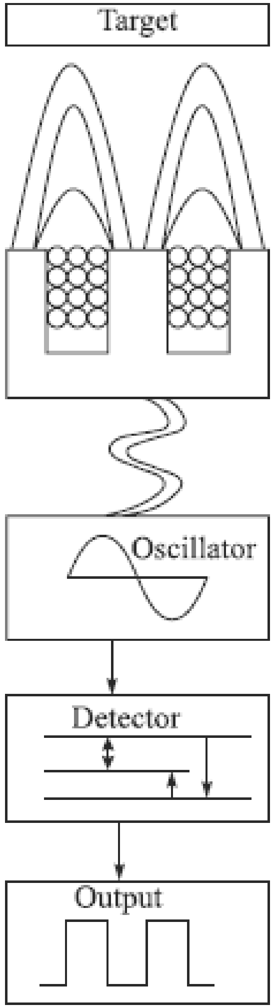
Here, noncontact-type force sensors and their principles are presented.

1. Proximity Sensor Proximity sensing is the technique of detecting the presence or absence of an object with an electronic noncontact-type sensor. Proximity sensors are of two types, *inductive* and *capacitive*. Inductive proximity sensors are used in place of limit switches for noncontact sensing of metallic objects, whereas capacitive proximity sensors are used on the same basis as inductive proximity sensors. However, these can also detect nonmetallic objects.

Inductive Proximity Sensor

- All inductive proximity sensors consist of four basic elements

- Sensor coil and ferrite core
- Oscillator circuit
- Detector circuit
- Solid-state output circuit



'ig. 4.12 Inductive proximity sensor

1. **Coil and Oscillator Circuit**: The main components of an inductive proximity sensor include a coil of wire and an oscillator circuit. The coil is typically wound around a ferrite core and connected to the oscillator circuit.
2. **Generation of Magnetic Field**: When an alternating current (AC) voltage is applied to the coil, it generates a fluctuating magnetic field around the sensor. This magnetic field extends outward from the coil's surface.
3. **Detection Principle**: When a metallic object enters the sensing range of the sensor, it disrupts the magnetic field generated by the coil. This disruption causes changes in the impedance of the coil and affects the oscillator circuit's frequency.
4. **Inductive Coupling**: The presence of the metallic object alters the inductance of the coil due to inductive coupling between the object and the coil. This change in inductance affects the frequency of the oscillator circuit.

1. **Output Signal**: The oscillator circuit is designed to produce an output signal that varies in response to changes in the coil's impedance or frequency. This signal can be processed further to indicate the presence or absence of the metallic object.
2. **Detection Range**: The sensing range of an inductive proximity sensor depends on factors such as the size and material of the target object, the coil's design, and the sensor's operating frequency. Typically, the sensing range ranges from a few millimeters to several centimeters.
3. **Output Types**: Inductive proximity sensors can have various output types, such as normally open (NO), normally closed (NC), or a digital signal (PNP or NPN). These output types indicate the presence or absence of the metallic object and can be interfaced with other control systems or devices.

Capacitive Proximity Sensor

- A capacitive proximity sensor operates based on changes in capacitance when an object enters its sensing field.

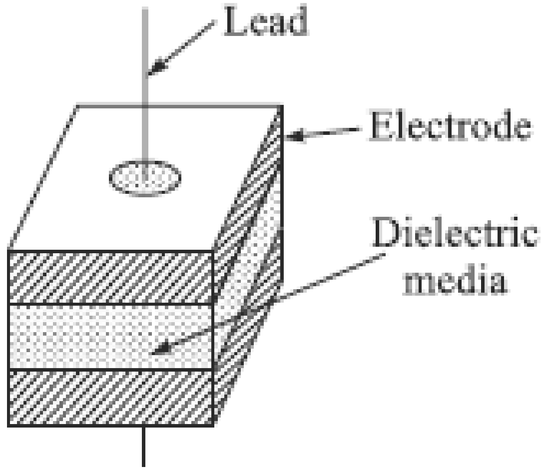


Fig. 4.13 Principle of capacitive sensors

1. **Capacitive Sensing Principle**: Capacitive sensors rely on the principle of capacitance, which is the ability of two conductive materials separated by a dielectric (insulating) material to store electrical energy. The capacitance is directly proportional to the area of overlap between the conductive materials and inversely proportional to the distance between them.
2. **Sensor Construction**: A capacitive proximity sensor typically consists of two electrodes—an emitting electrode (often referred to as the "active" electrode) and a receiving electrode (often referred to as the "ground" electrode). These electrodes are separated by an insulating material, forming a capacitor.
3. **Electrical Oscillation**: The sensor generates an electrical oscillation between the emitting and receiving electrodes. This oscillation occurs at a specific frequency determined by the sensor's design and operating parameters.
4. **Sensing Field Formation**: When no object is present in the sensor's proximity, the electric field between the electrodes extends into the surrounding environment, forming a sensing field.

5.Object Detection: When an object enters the sensing field, it interacts with the electric field. The object's dielectric properties (such as its permittivity) influence the capacitance between the electrodes.

6.Capacitance Change: The presence of the object alters the capacitance between the electrodes, leading to a change in the sensor's oscillation frequency. This change is detected by the sensor's electronics.

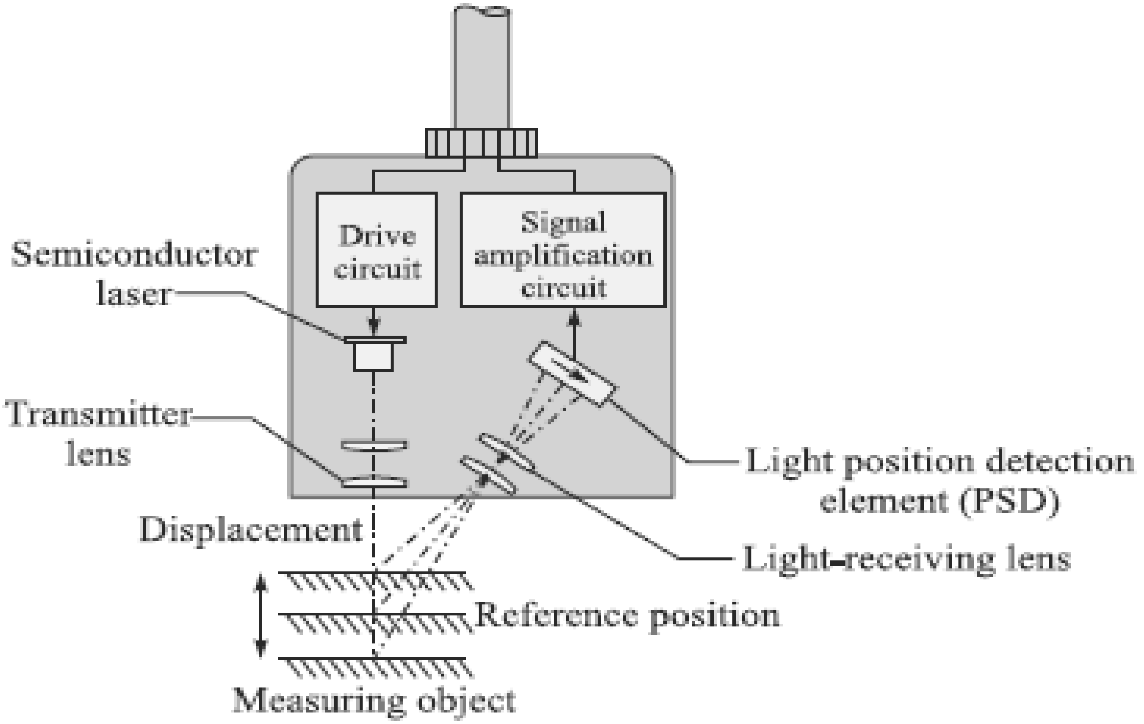
7.Output Signal: The sensor's electronics process the change in frequency and generate an output signal, indicating the presence of the object. Depending on the sensor's configuration, the output signal may be digital (indicating the presence or absence of the object) or analog (proportional to the detected capacitance change).

8.**Sensing Range and Sensitivity**: The sensing range of a capacitive proximity sensor depends on factors such as the sensor's design, operating frequency, and the dielectric properties of the target material. Sensitivity can be adjusted to detect objects of different sizes and materials.

Capacitive proximity sensors have two major limitations.

- The sensors are affected by moisture and humidity, and
- They must have extended range for effective sensing.

2. *Semiconductor Displacement Sensor* As shown in Fig. 4.14, a semiconductor displacement sensor uses a semiconductor Light Emitting Diode (LED) or laser as a light source, and a Position-Sensitive Detector (PSD). The laser



[Courtesy: http://www.sensorcentral.com/displacement/laser02.php]

Fig. 4.14 Semiconductor-based sensor

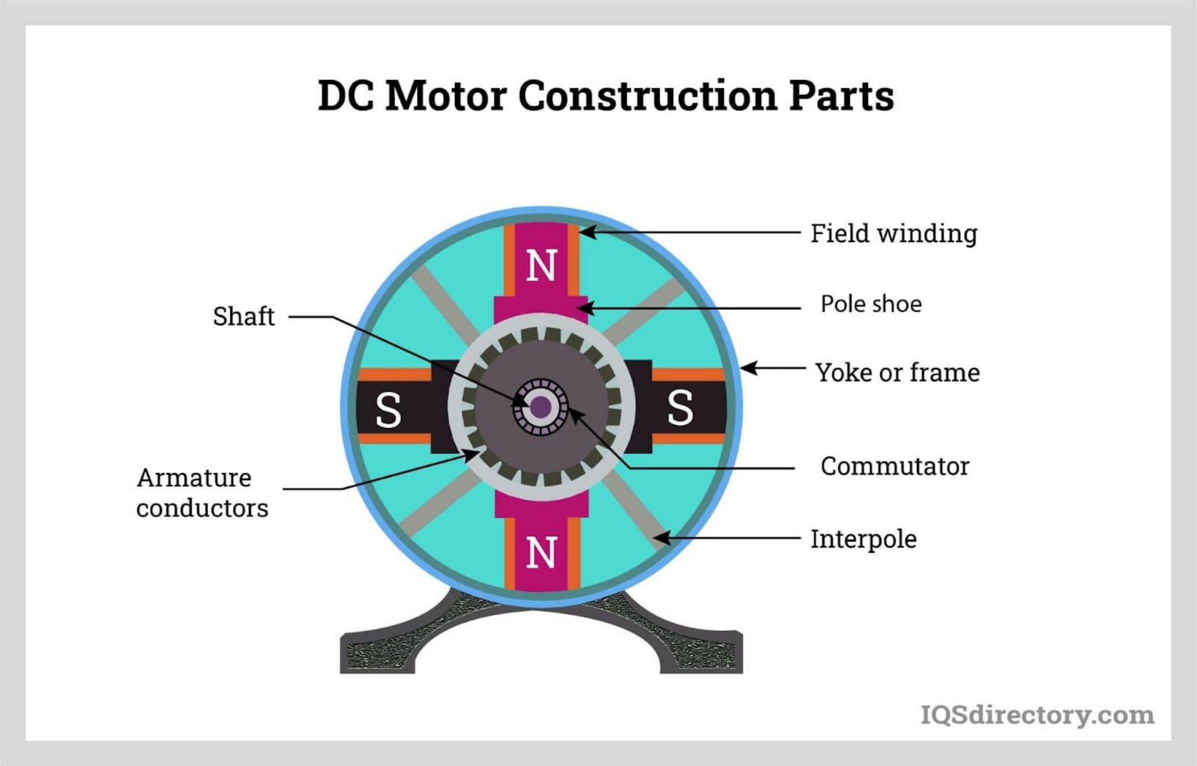
beam is focused on the target by a lens. The target reflects the beam, which is then focused on to the PSD forming a beam spot. The beam spot moves on the PSD as the target moves. The displacement of the workpiece can then be determined by detecting the movement of the beam spot.

Sensor Characteristics

- To choose an appropriate sensor for a particular need, we have to consider a number of different characteristics. These characteristics determine the performance, economy, ease of application, and applicability of the sensor.
- **Cost**: The cost of a sensor is an important consideration, especially when many sensors are needed for one machine. However, the cost must be balanced with other requirements of the design such as reliability, imp ortance of the data they provide, accuracy, life, and so on.
- **Size:** Depending on the application of the sensor, the size may be of primary importance.
- **Weight:** Since robots are dynamic machines, the weight of a sensor is very important. A heavy sensor adds to the inertia of the arm and reduces its overall payload.
- **Type of output (digital or analog):** The output of a sensor may be digital or analog and, depending on the application, this output may be used directly or have to be converted.
- **Interfacing:** Sensors must be interfaced with other devices such as microprocessors and controllers. The interfacing between the sensor and the device can become an important issue if they do not match or if other add-on components and circuits become necessary

- **Resolution**: Resolution is the minimum step size within the range of measurement of the sensor.
- **Sensitivity:** Sensitivity is the ratio of a change in output in response to a change in input. Highly sensitive sensors will show larger fluctuations in output as a result of fluctuations in input, including noise.
- **Linearity:** Linearity represents the relationship between input variations and outputnvariations. This means that in a sensor with linear output, the same change in input at any level within the range will produce a similar change in output.
- **Range:** Range is the difference between the smallest and the largest outputs the sensor can produce, or the difference between the smallest and largest inputs with which it can operate properly.
- **Response time:** the time required to observe the change in output as a result of a change in input.
- **Reliability:** Reliability is the ratio of how many times a system operates properly, divided by how many times it is used. For continuous, satisfactory operation it is necessary to choose reliable sensors that last a long time
- **Accuracy:** Accuracy is defined as how close the output of the sensor is to the expected value.
- **Repeatability:** If the sensor’s output is measured a number of times in response to the same input, the output may be different each time. Repeatability is a measure of how varied the different outputs are relative to each other.

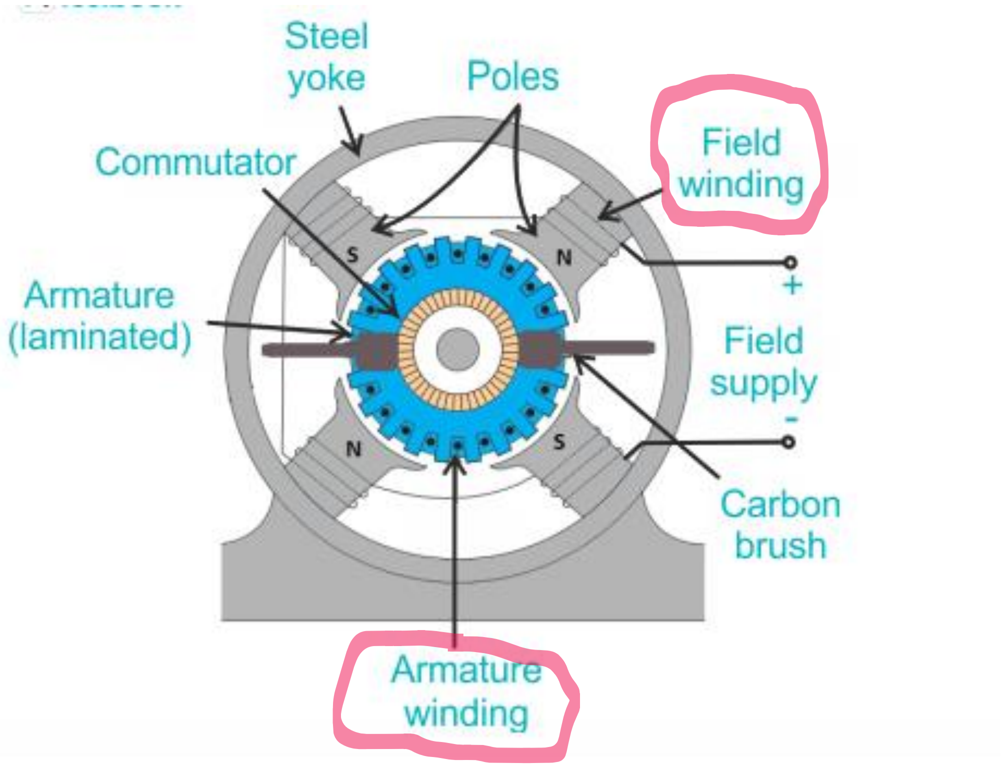
DC Motors

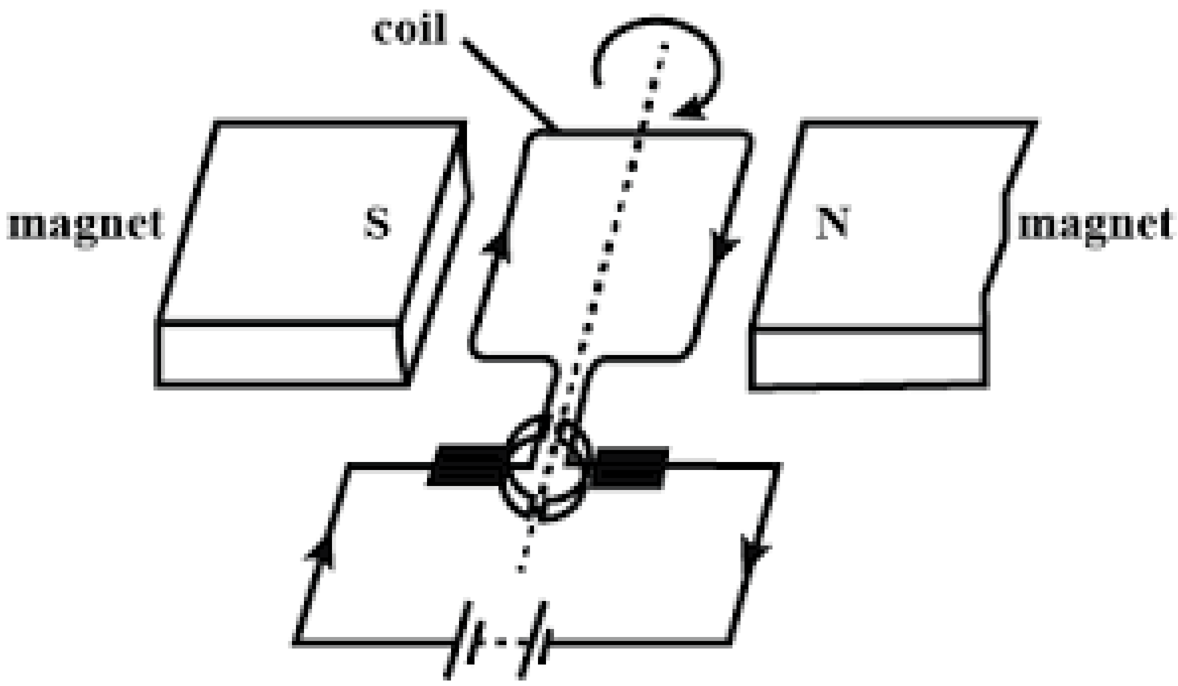


DC Motor Construction Parts
Field winding
Pole shoe
Yoke or frame
Commutator
Interpole
Shaft
Armature
conductors
N
S
S
N
IQSdirectory.com

Working

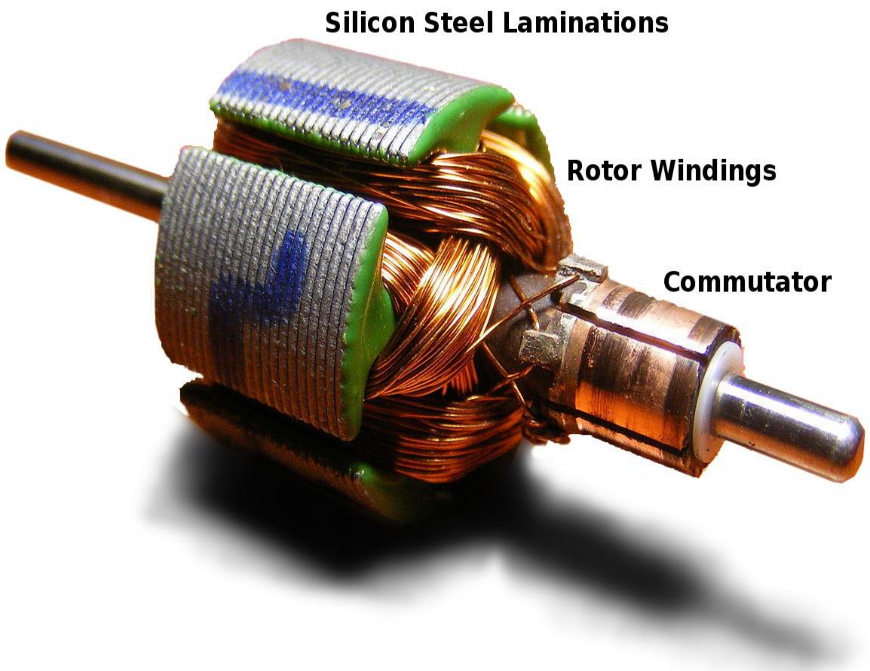
- A DC Motor is an electrical device that converts electrical energy into mechanical energy.
- The basic working principle of a DC motor is that whenever a current-carrying conductor is placed in a magnetic field, it experiences a force. This force is known as the **Lorentz force**, and it is responsible for the rotation of the motor's armature. Any electric motor that is operated using direct current or DC is called a DC motor

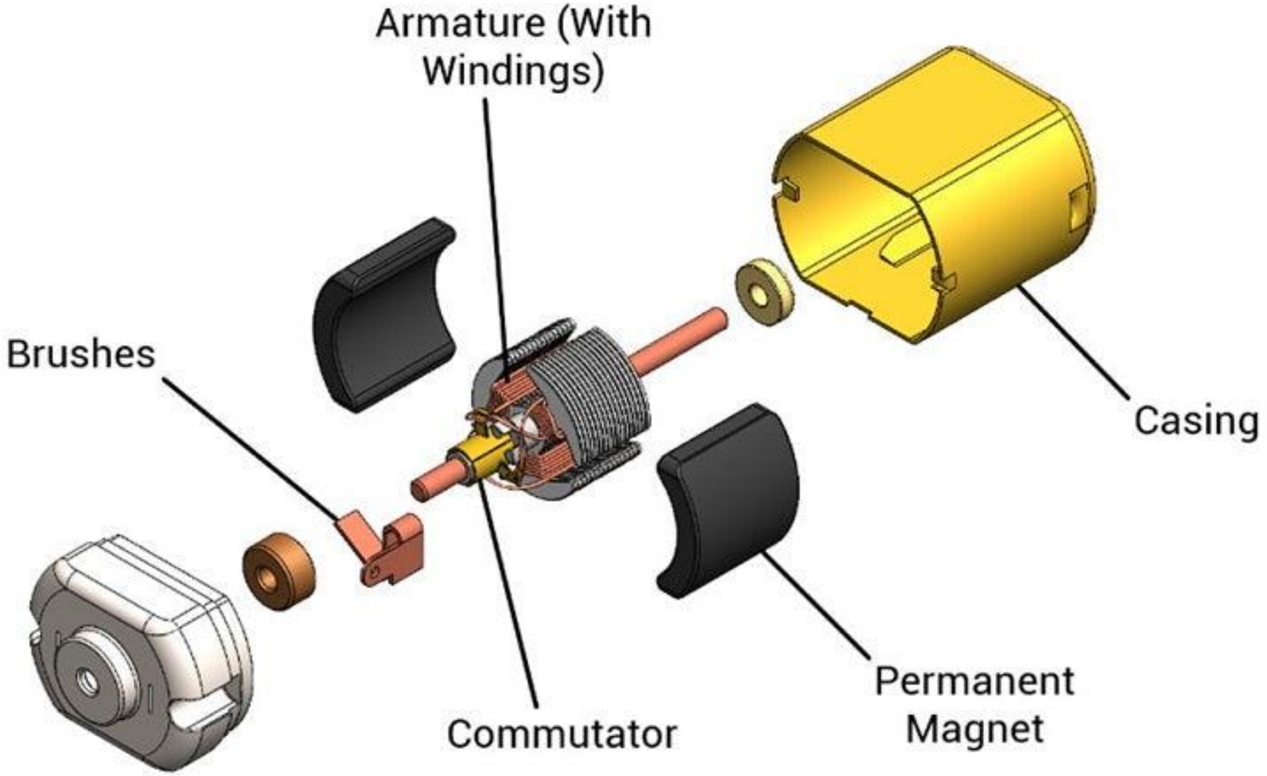




The main parts (or components) of a DC motor include:

- **Stator:** The stationary part of the motor, which creates the magnetic field. It usually consists of permanent magnets or electromagnets.
- **Rotor (Armature):** The rotating part of the motor that carries the windings, where the electromotive force (EMF) is generated.
- **Commutator:** A split ring device that reverses the direction of current flow through the armature windings, ensuring continuous rotation by maintaining the torque direction.
- **Brushes:** Carbon or graphite parts that maintain electrical contact with the commutator. Brushes allow current to flow into the armature windings while the motor is running.
- **Armature Windings:** Coils of wire wound around the armature that generate a magnetic field when current flows through them. This magnetic field interacts with the stator to produce motion.
- **Shaft:** A mechanical component that connects to the armature and transfers the rotational motion produced by the motor to the load (such as a fan or a pump).


Silicon Steel Laminations
Rotor Windings
Commutator


Armature (With Windings)
Brushes
Casing
Commutator
Permanent Magnet

Types of dc motors

They are classified into different types based on the field winding connections to the armature as:

- **Self Excited DC Motor**
- **Separately Excited DC Motor**

Self Excited DC Motor

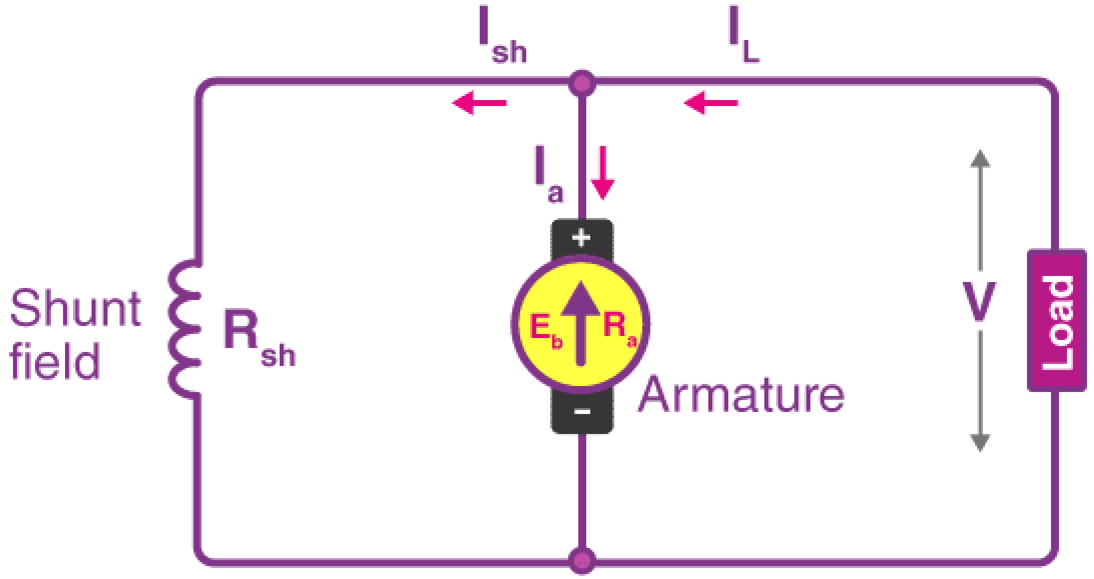
- In self-excited DC motors, the field winding is connected either in series or parallel to the armature winding. Based on this, the self-excited DC motor can further be classified as:
- **Shunt wound DC motor**
- **Series wound DC motor**
- **Compound wound DC motor**

separately-excited DC motor

- The field winding is supplied with a separate, independent source of DC power. This means the field winding is not directly connected to the armature circuit.

Shunt wound DC motor

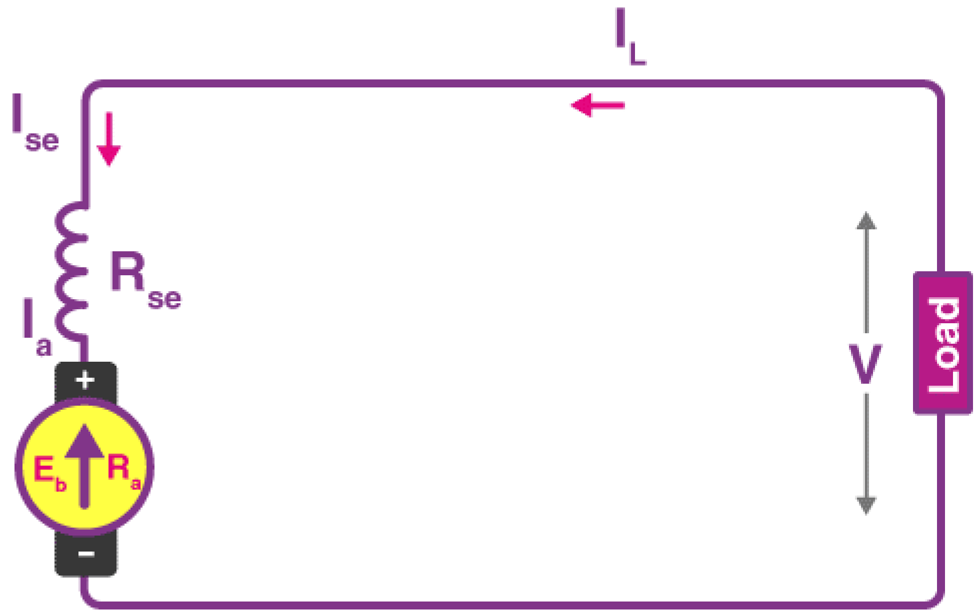
In a shunt wound motor, the field winding is connected parallel to the armature as shown in the figure.



Shunt wound DC motor

Series wound DC motor

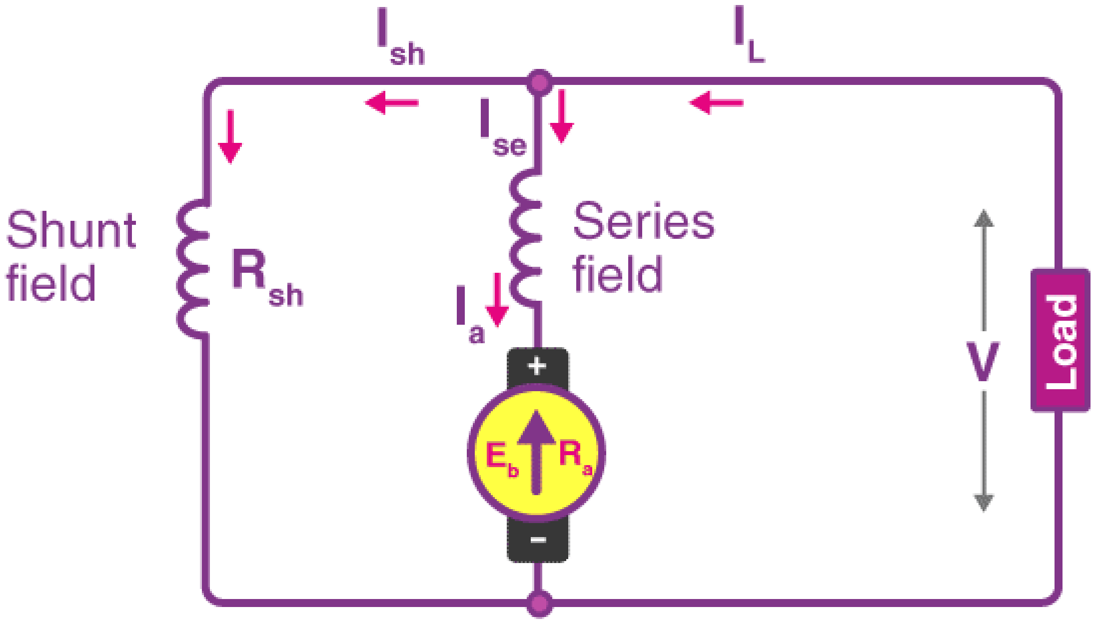
In a series wound DC motor, the field winding is connected in series with the armature winding as shown in the figure.



Series wound motor

Compound wound DC motor

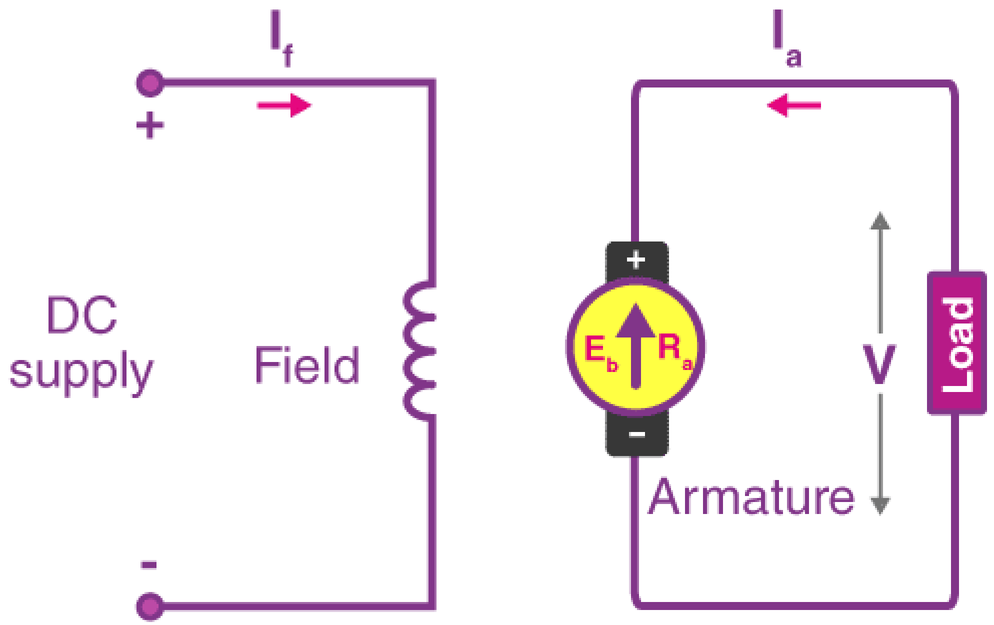
DC motors having both shunt and series field winding is known as Compound DC motor, as shown in the figure.



Compound wound DC motor

Separately Excited DC Motor

In a separately excited DC motor, the field coils are energized from an external source of DC supply as shown in the figure.



Separately excited DC motor

Serial No.	Windings in a dc motor	Field-coil resistance	Speed controllability	Starting torque
1	Shunt-wound	High	Good	Average
2	Series-wound	Low	Poor	High
3	Compound-wound	Parallel high, series low	Average	Average

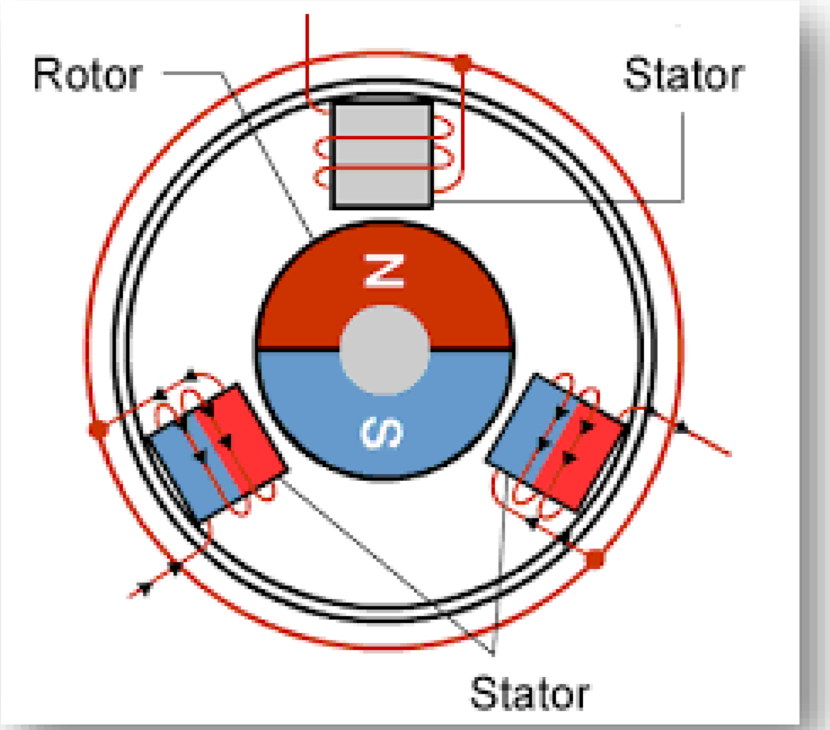
1. Permanent-Magnet (PM) dc Motors

- Here, no **fieldcoils are used and the field is produced by the permanent magnets themselves.**
- Permanent Magnet (PM) DC motors are electric motors that operate on direct current (DC) and utilize permanent magnets to generate the magnetic field required for their operation.
- Unlike traditional DC motors, which use wound field coils to create the magnetic field, PM DC motors have magnets embedded within or attached to the rotor.

2. Brushless Permanent-Magnet dc Motors

- A problem with dc motors is that they require a commutator and brushes in order to periodically reverse the current through each armature coil. The brushes make sliding contacts with the commutators and as a consequence sparks jump between the two and they suffer wear. Brushes Introduction to Robotics thus have to be periodically changed.
- To avoid such problems, brushless motors have been designed.

With the conventional dc motor, the magnet is fixed and the current-carrying conductors made to move. **With the brushless permanent-magnet dc motor the reverse is the case, the current-carrying conductors are fixed and the magnetic fi eld moves.**



Application of DC motor

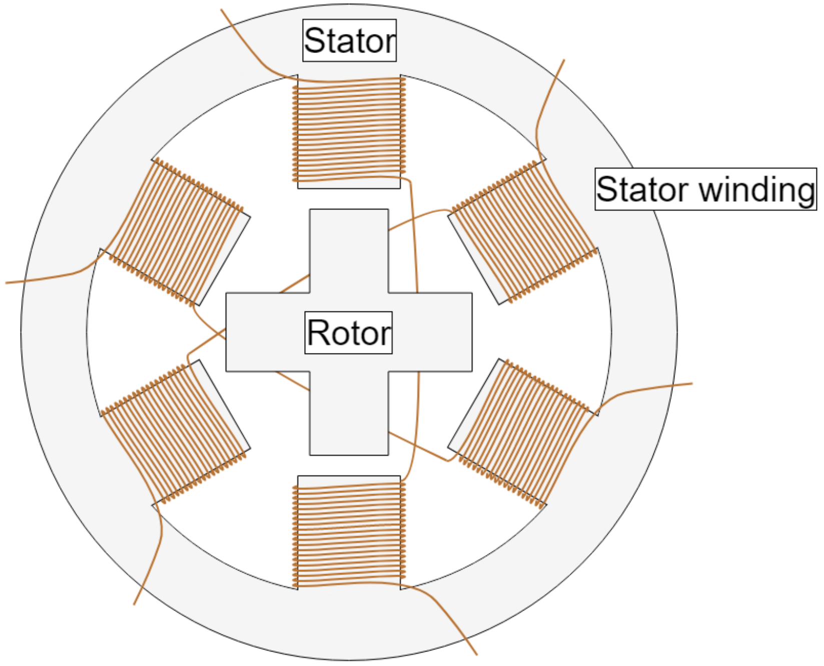
- Cranes
- Lifts
- Elevators
- Hair drier
- Vacuum cleaner
- Sewing machine
- Electric Vehicles
- Ceiling Fans

stepper motor

- A stepper motor is **a type of brushless DC electric motor** that divides a full rotation into a number of equal steps. Each step corresponds to a specific angular displacement, allowing precise control over the motor's position, speed, and rotation direction.
- **Stepper motors operate by energizing coils in a sequence**. They typically have multiple coils arranged around a rotor, and these coils are energized in a specific order to produce rotation.

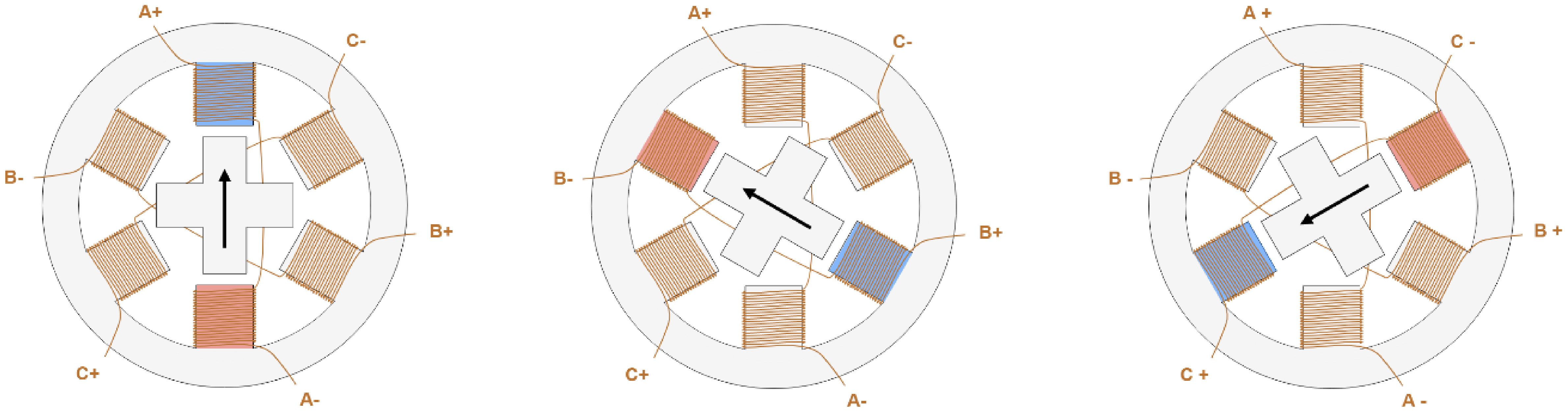
The unique feature of stepper motors is that they can be very accurately controlled in terms of speed and rotation angle.

- Stepper motors have a stationary part (the stator) and a moving part (the rotor).
- On the stator, there are teeth on which coils are wired, while **the rotor is either a <u>permanent magnet</u> or a variable reluctance iron core.**



- **Variable reluctance** refers to a principle in electromagnetism where the reluctance (or **resistance to magnetic flux**) of a material or system changes based on the physical position or configuration of the components involved.

- The basic working principle of the stepper motor is the following: By energizing one or more of the stator phases, a magnetic field is generated by the current flowing in the coil and the rotor aligns with this field. By supplying different phases in sequence, the rotor can be rotated by a specific amount to reach the desired final position.
- **Figure** shows a representation of the working principle. At the beginning, coil A is energized and the rotor is aligned with the magnetic field it produces. When coil B is energized, the rotor rotates clockwise by 60° to align with the new magnetic field. The same happens when coil C is energized. In the pictures, the colors of the stator teeth indicate the direction of the magnetic field generated by the stator winding.



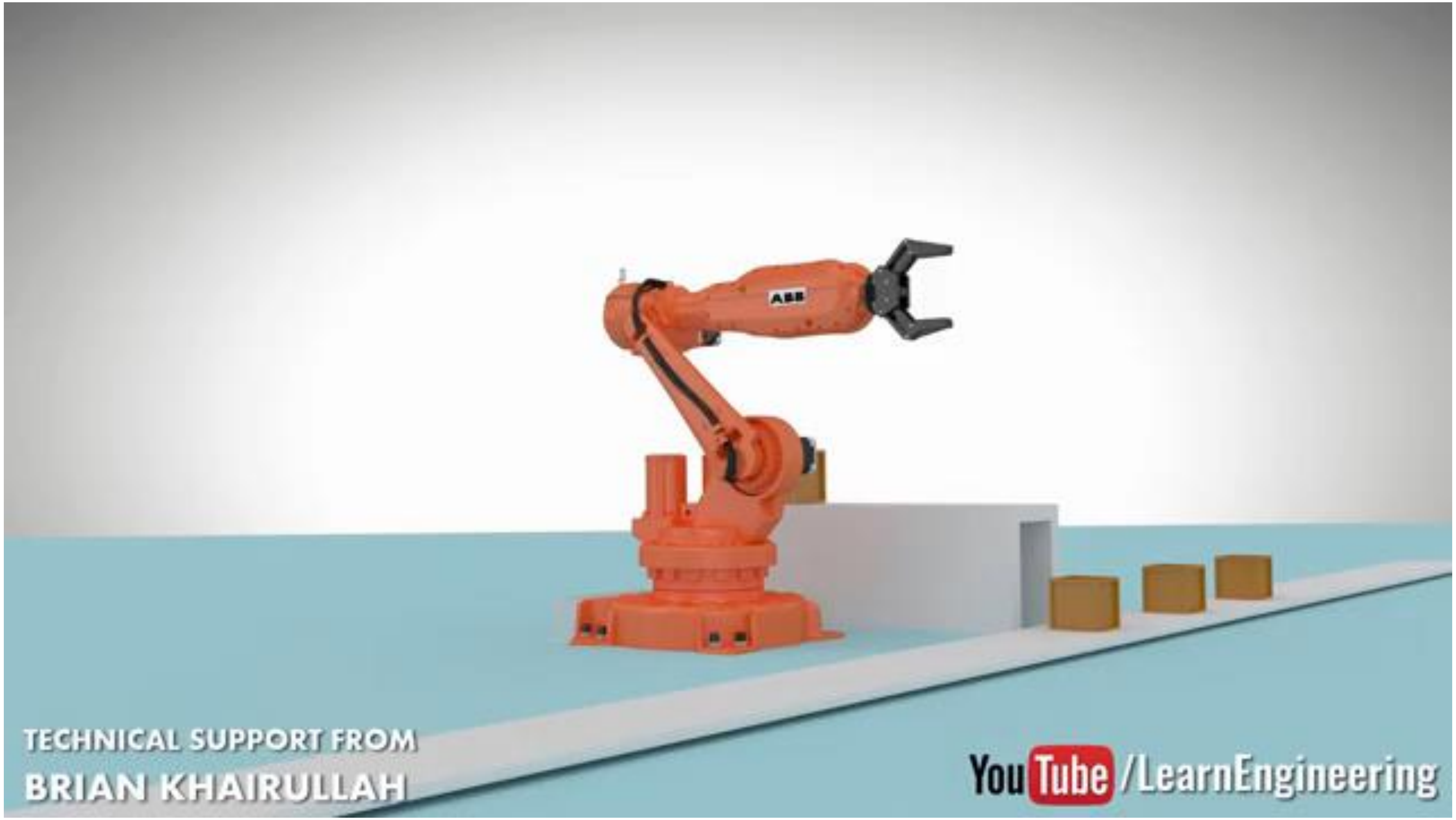


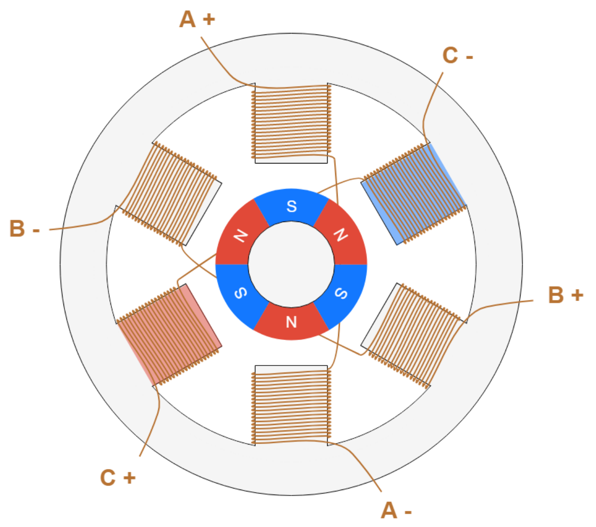
ABB
TECHNICAL SUPPORT FROM
BRIAN KHAIRULLAH
YouTube /LearnEngineering

1) Permanent-Magnet Stepper Motor

- A permanent magnet stepper motor is a type of stepper motor where the rotor contains permanent magnets. These magnets are typically arranged in a specific pattern, such as radial or diametric, to interact with the magnetic fields produced by the stator windings.

1. **Rotor**: **The rotor of a permanent magnet stepper motor contains permanent magnets**. These magnets are magnetized and maintain their magnetic field strength without the need for an external power source. The magnets are often arranged in a pattern that facilitates precise step movement when interacting with the stator's magnetic field.
2. **Stator**: The stator of a permanent magnet stepper motor contains multiple sets of coils or windings. These coils are energized in a specific sequence to create a rotating magnetic field. The interaction between the rotating magnetic field and the permanent magnets in the rotor causes the rotor to move in discrete steps.

Low resolution(smallest positional increment)
Low speed
Good torque (tendency to rotate)



2) Variable-Reluctance Stepper Motor

Magnetic reluctance, or simply reluctance, is the analog of electrical resistance. Just as current occurs only in a closed loop, so magnetic flux occurs only around, a closed path, (resistance to magnetic flux).

- **Rotor**: The rotor of a variable reluctance stepper motor is typically made of a **ferromagnetic material, such as iron or steel**. It does not contain any permanent magnets. Instead, the rotor is designed with teeth that create regions of high and low reluctance
- **Stator**: The stator of a variable reluctance stepper motor contains multiple sets of coils or windings. These coils are energized in a specific sequence to create a rotating magnetic field. As the stator coils are energized, the magnetic field interacts with the varying reluctance of the rotor, causing the rotor to move in discrete steps.

- The operation of a VR stepper motor is governed **by the principle of magnetic reluctance**, which is the resistance of a magnetic circuit to magnetic flux. **The rotor, which is an iron piece, tends to align itself along the path of least magnetic reluctance**, i.e., it tries to position itself in such a way that it faces more of the magnetized stator pole and less of the air gap.

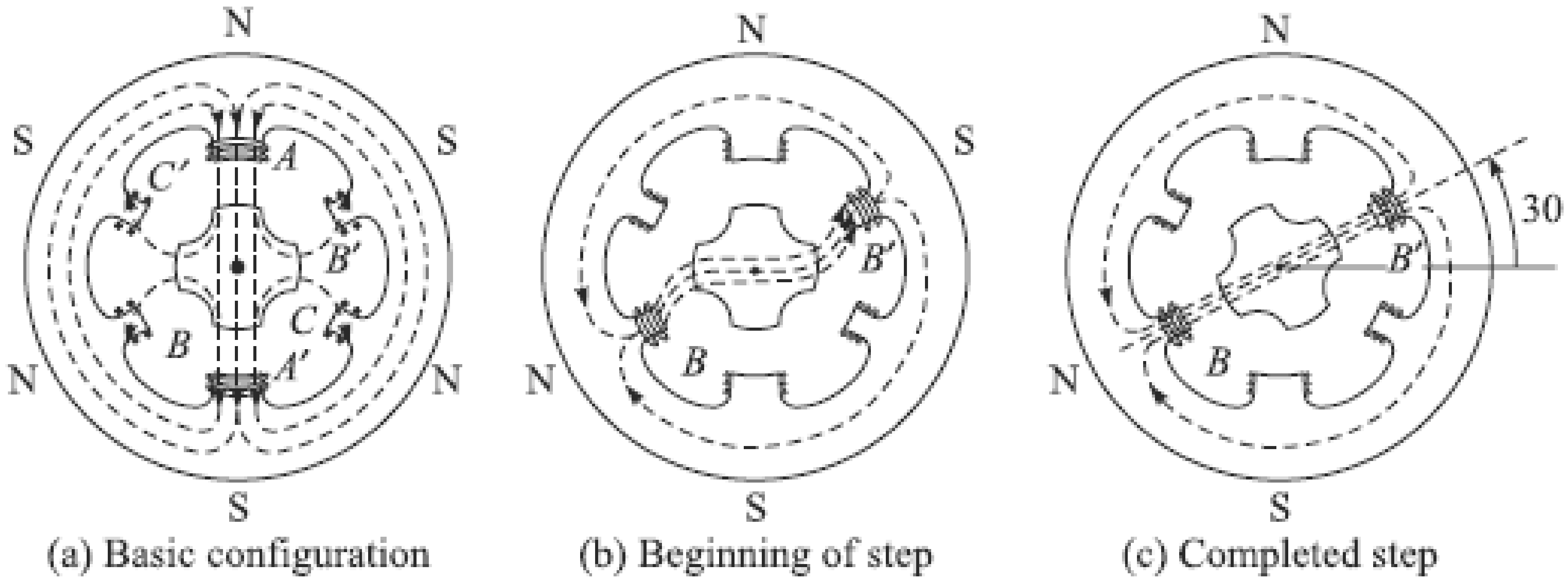


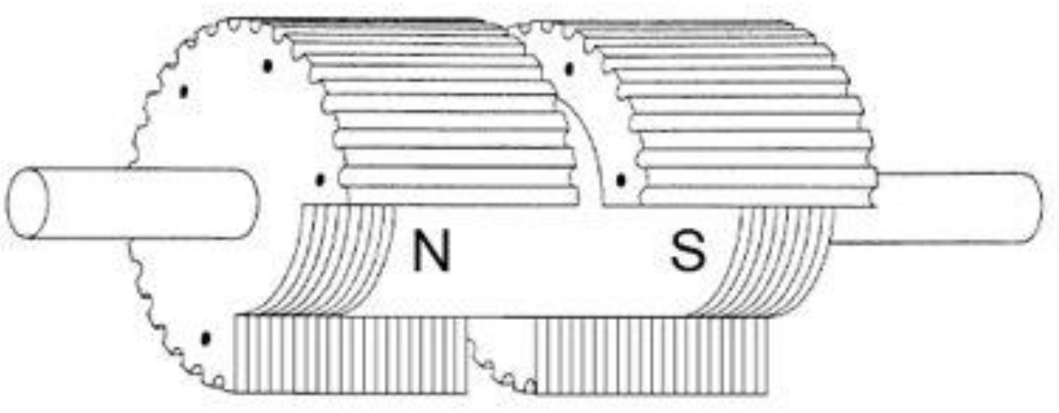
Fig. 3.5 Variable-reluctance stepper motor

Low torque
High resolution
High speed

3) Hybrid Stepper Motor

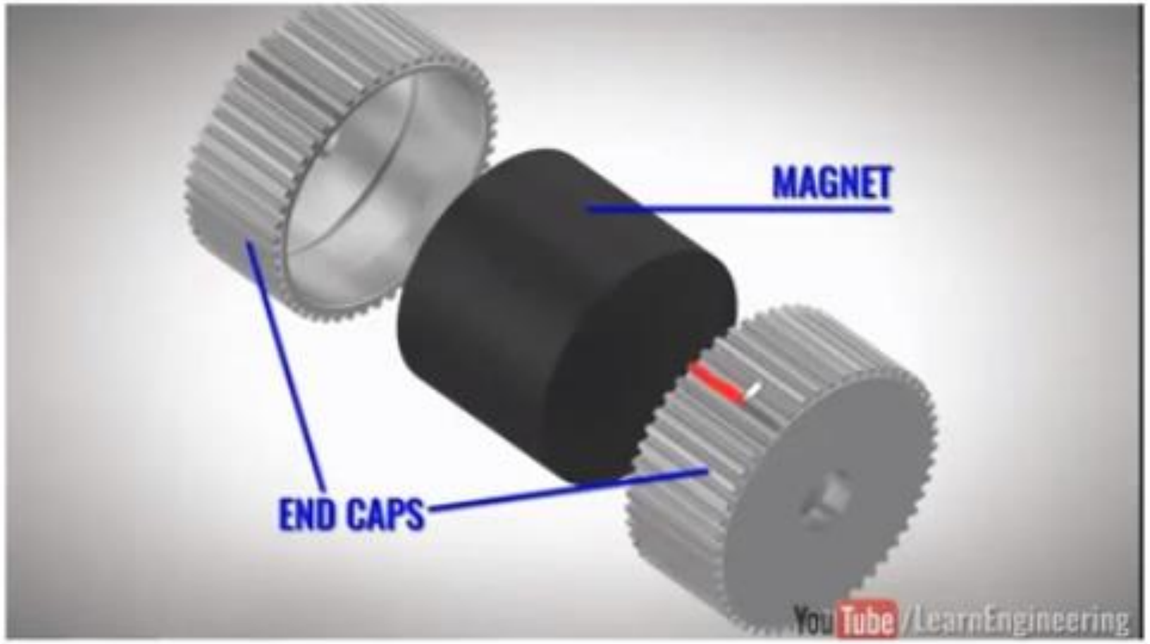
- They **combine the features of both the variable reluctance and permanent-magnet motors**
- Smooth control of motion with very small steps can be achieved
- High speed
- High resolution
- Good torque

- But circuit construction is complex
- And high cost

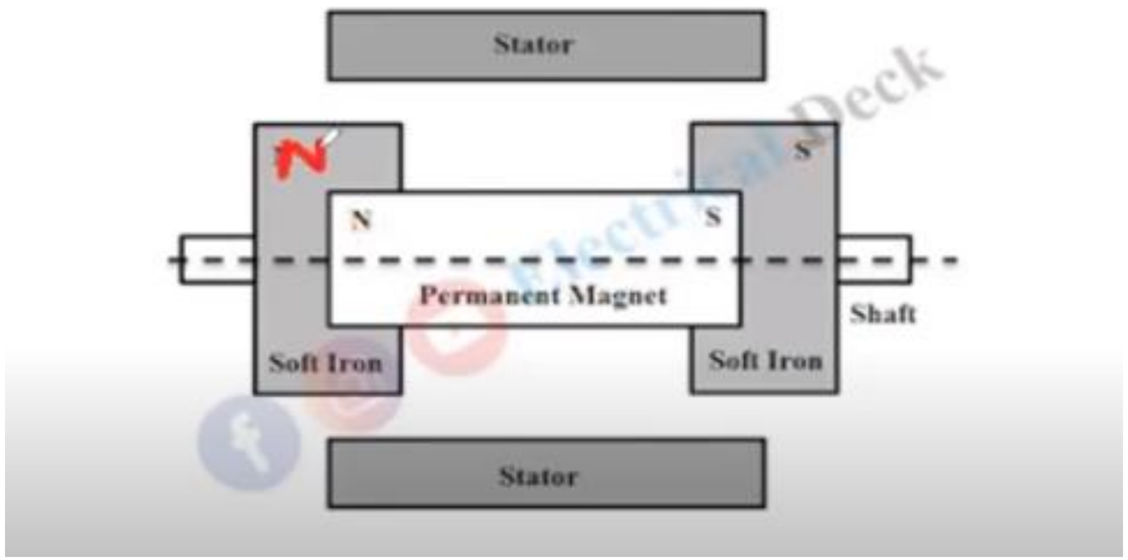


Hybrid Stepper Motor Rotor

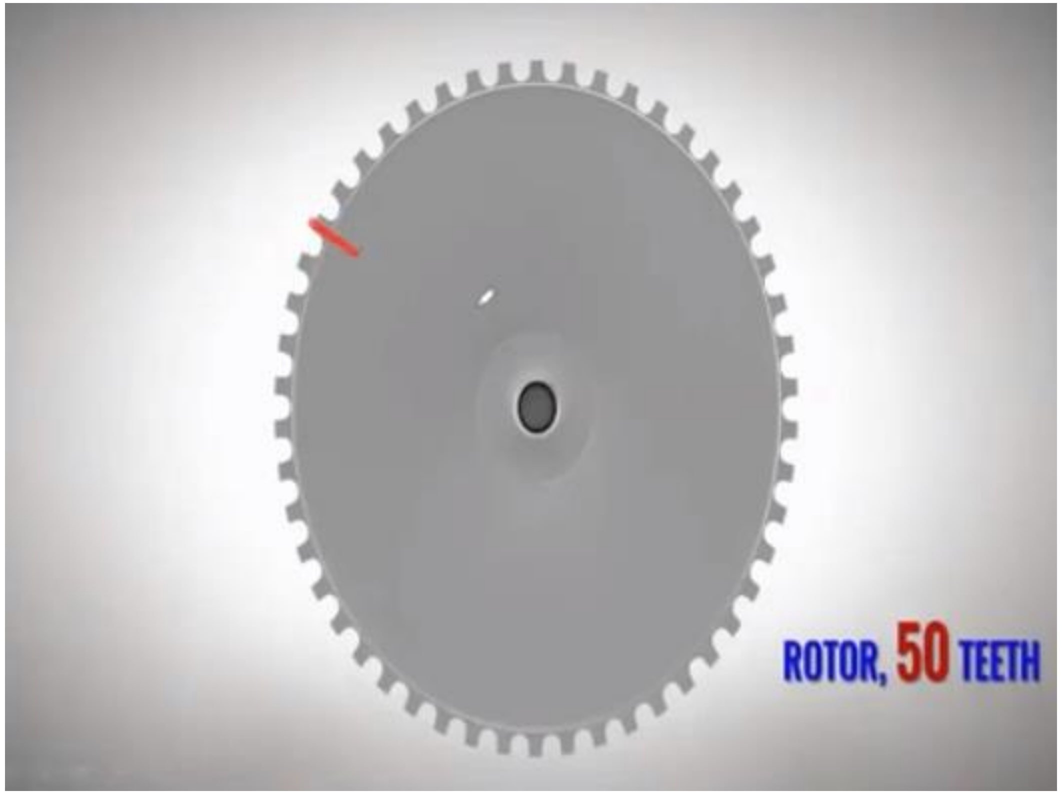
ROTOR

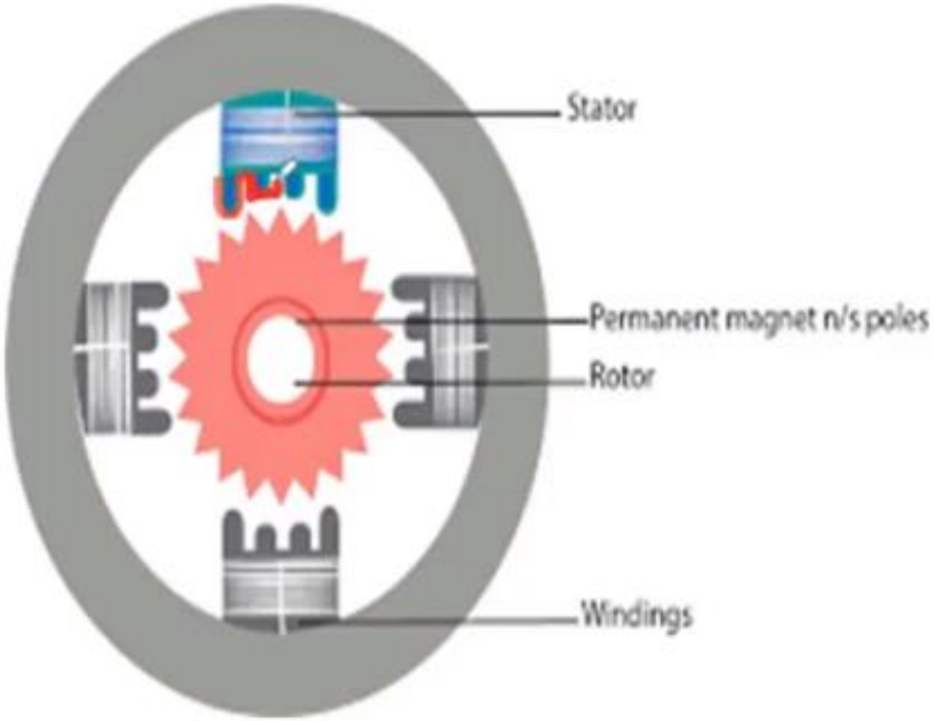


MAGNET
END CAPS
YouTube/LearnEngineering



Stator
N
N
S
S
Permanent Magnet
Shaft
Soft Iron
Soft Iron
Stator


ROTOR, 50 TEETH


Stator
Permanent magnet n/s poles
Rotor
Windings

Advantages

The **advantages of stepper motor** include the following.

- Ruggedness
- Simple construction
- Can work in an open-loop control system
- Maintenance is low
- It works in any situation
- Reliability is high

Disadvantages

The **disadvantages of stepper motor** include the following.

- Efficiency is low
- The Torque of a motor will declines fast with speed
- Accuracy is low
- Feedback is not used for specifying potential missed steps
- Small Torque toward Inertia Ratio
- Extremely Noisy

A servo motor is a type of rotary actuator or motor that allows for precise control of angular position, velocity, and acceleration. **It consists of a motor coupled with a sensor for position feedback**, often in the form of a potentiometer or an encoder. **This feedback mechanism enables the servo motor to accurately maintain its position** and respond to control signals, adjusting its rotational position as needed.

modern servo motors are capable of providing high performance and precision

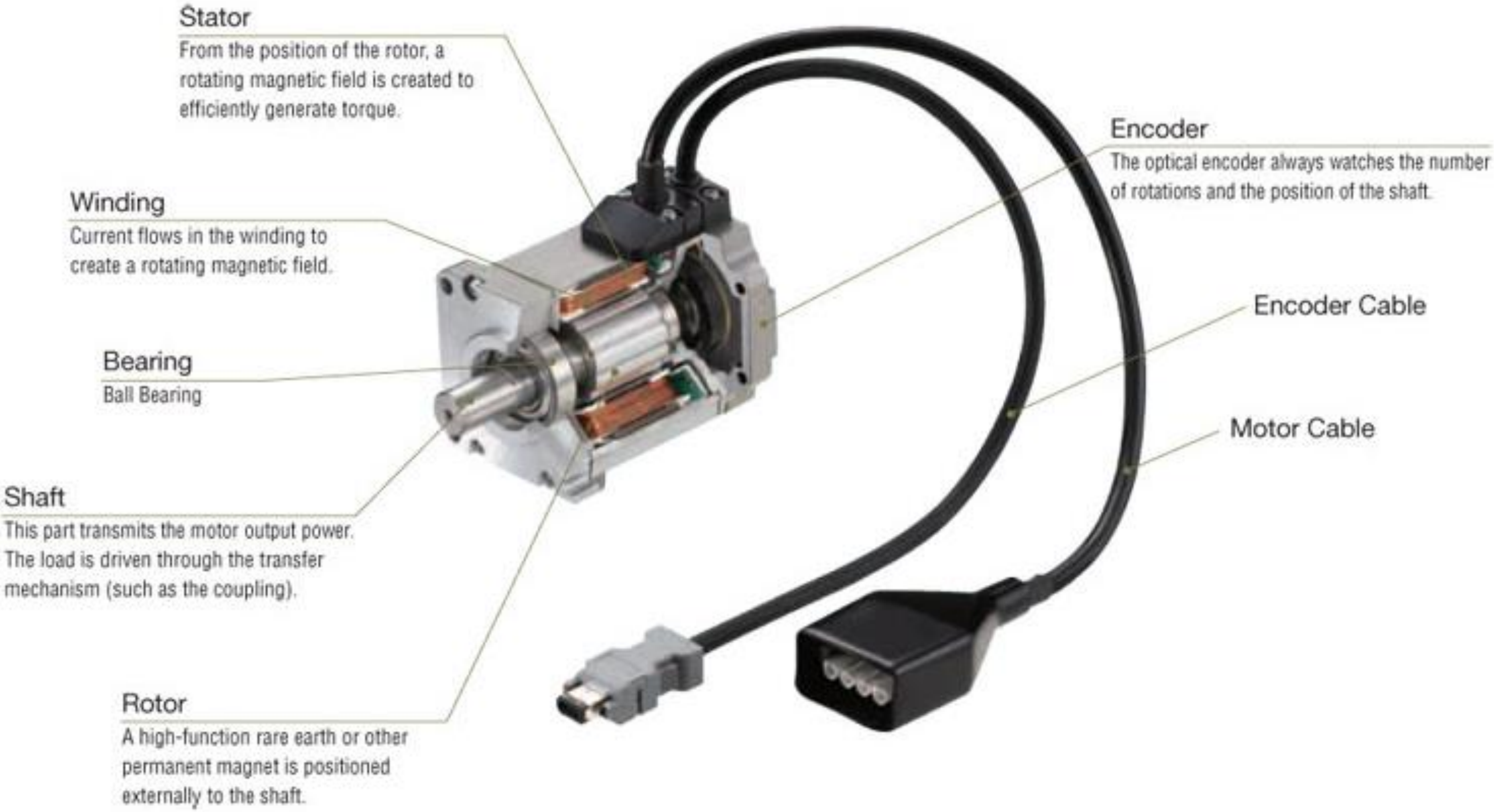
Components of servo motor

- **A motor:** This can be either a DC motor or an AC motor depending on the power source and the application requirements. The motor provides the mechanical power to rotate or move the output shaft.

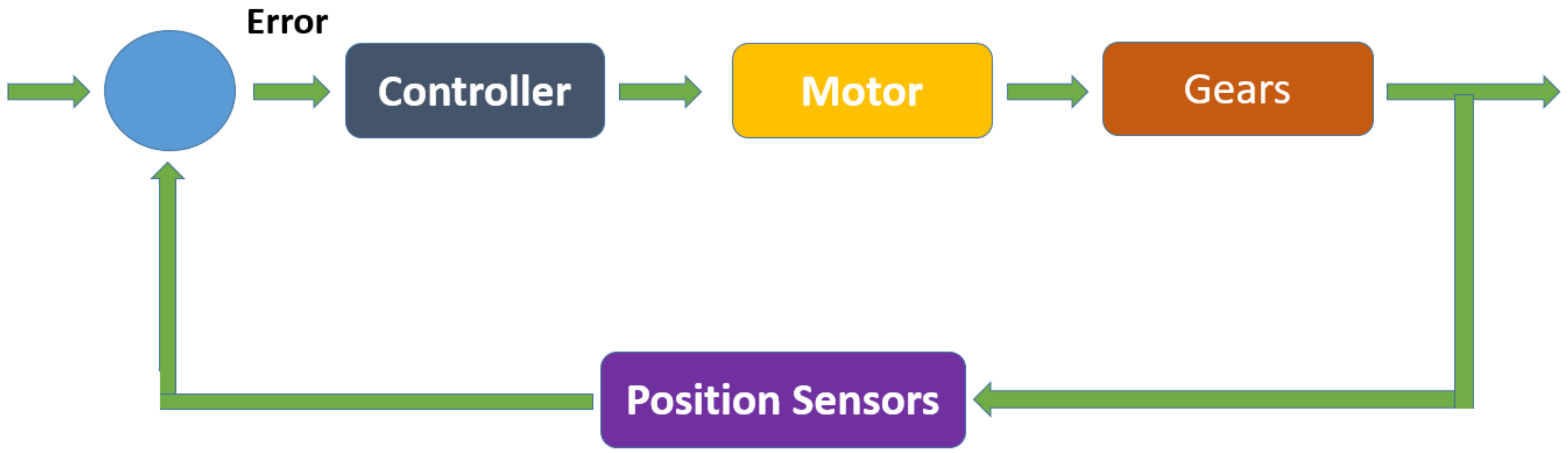
- **A gearbox: The gearbox allows the motor to transmit its power to the load at a different speed.** Some gearboxes are designed to provide finer control over the movement of the load. Gearboxes can provide mechanical isolation between the motor and the load. This can be beneficial for protecting the motor from shock loads(Shock loads refer to sudden and abrupt changes in the applied force) and reducing vibration

- **A sensor:** This can be either a potentiometer, an encoder, a resolver, or another device that measures the position, speed, or torque of the output shaft and sends feedback signals to the controller.

- **A controller:** This can be either an analog or a digital circuit that compares the feedback signals from the sensor with the desired setpoint signals from an external source (such as a computer or a joystick) and generates control signals to adjust the motor’s voltage or current accordingly.


Stator
From the position of the rotor, a rotating magnetic field is created to efficiently generate torque.
Winding
Current flows in the winding to create a rotating magnetic field.
Bearing
Ball Bearing
Shaft
This part transmits the motor output power. The load is driven through the transfer mechanism (such as the coupling).
Rotor
A high-function rare earth or other permanent magnet is positioned externally to the shaft.
Encoder
The optical encoder always watches the number of rotations and the position of the shaft.
Encoder Cable
Motor Cable

Closed Loop Control System (Feedback System)



Feedback System

How Does a Servo Motor Work?

- The basic working principle of a servo motor involves the controller receiving two types of input signals:
- **A setpoint signal:** This is an analog or digital signal that represents the desired position, speed, or torque of the output shaft.
- **A feedback signal:** This is an analog or digital signal that represents the actual position, speed, or torque of the output shaft measured by the sensor.
- The controller compares these two signals and calculates an error signal that represents the difference between them.
- The error signal is then processed by a control algorithm (such as PID) that generates a control signal that determines how much voltage or current should be applied to the motor.
- The control signal is sent to a power amplifier (such as an H-bridge) that converts it into an appropriate voltage or current level for driving the motor.
- The motor then rotates or moves according to the control signal and changes its position, speed, or torque, and sends a new feedback signal to the controller.
- The process repeats until the error signal becomes zero or negligible, indicating that the output shaft has reached the desired setpoint.

1. **Electrical Input**: The servo motor is connected to a power source, typically providing direct current (DC) electricity. This electrical input is controlled by a servo controller, which sends signals to the motor to specify the desired position or speed.
2. **DC Motor Operation**: Inside the servo motor, there's a DC motor, which is the primary component responsible for generating rotational motion. When electrical power is supplied to the motor, it creates a magnetic field that interacts with the motor's windings, causing the motor shaft to rotate.
3. **Gear Train**: Many servo motors incorporate a gear train, which consists of a set of gears that transmit and modify the rotational motion produced by the motor. The gear train helps adjust the speed and torque output of the motor, enabling precise control over the rotation of the motor shaft.

Types of Servo Motors

- Servo motors can be classified into different types based on their power source, construction, feedback mechanism, and application.

- **AC Servo Motors**
- **DC Servo Motors**

AC servo motors

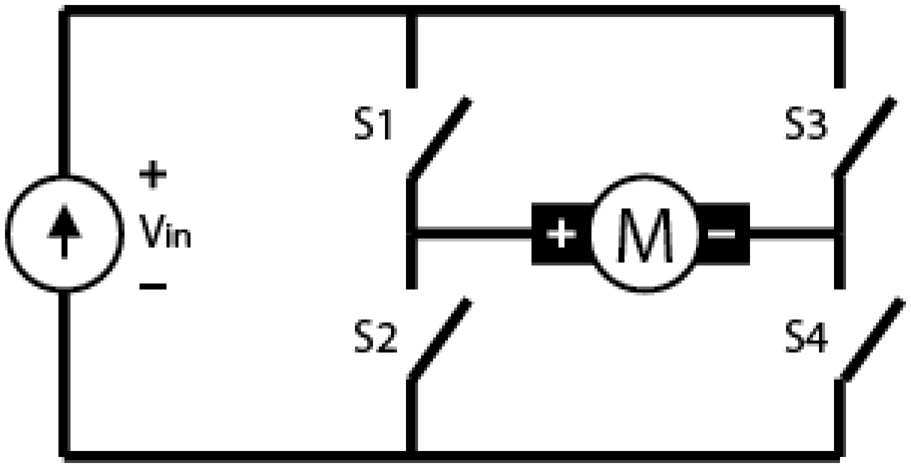
- AC servo motors are electric **motors that operate on alternating current** (AC). They have a stator that generates a rotating magnetic field and a rotor that follows the field.
- AC servo motors can be further divided into two types: **synchronous and asynchronous.**

- **Synchronous AC servo motors -** the rotor rotates at the same speed as the rotating magnetic field of the stator. They are more efficient, precise, and responsive than asynchronous motors, but they require a more complex controller and a position sensor.
- **Asynchronous AC servo motors-** the rotor doesn’t rotate at the same speed as the stator’s magnetic field. The rotor always lags behind the field’s speed,. They are simpler, cheaper, and more rugged than synchronous motors, but they have lower efficiency, accuracy, and speed.

DC Servo Motors

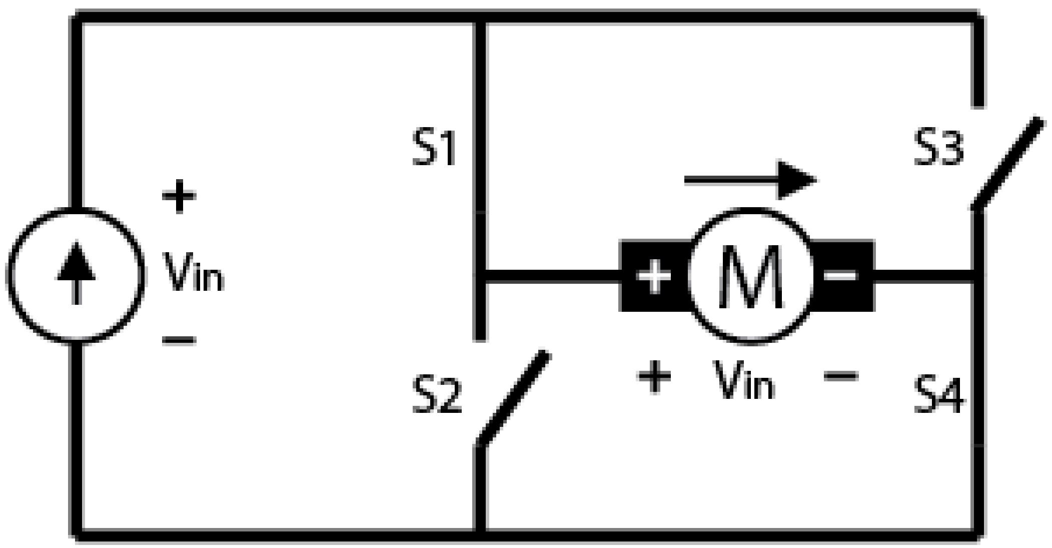
- DC servo motors are electric motors that operate on direct current (DC). They have a permanent magnet stator that generates a fixed magnetic field and a wound rotor that rotates when a current is applied.
- DC servo motors can be further divided into two types: **brushed and brushless.**
- **Brushed** DC servo motors **have a commutator and brushes** that switch the current direction in the rotor windings. They are simple, inexpensive, and easy to control, but they have lower efficiency, lifespan, and speed due to friction and wear of the brushes.
- **Brushless DC servo motors** have an **electronic controller that switches the current direction** in the stator windings. They are more efficient, durable, and fast than brushed motors, but they require a more sophisticated controller and a position sensor.

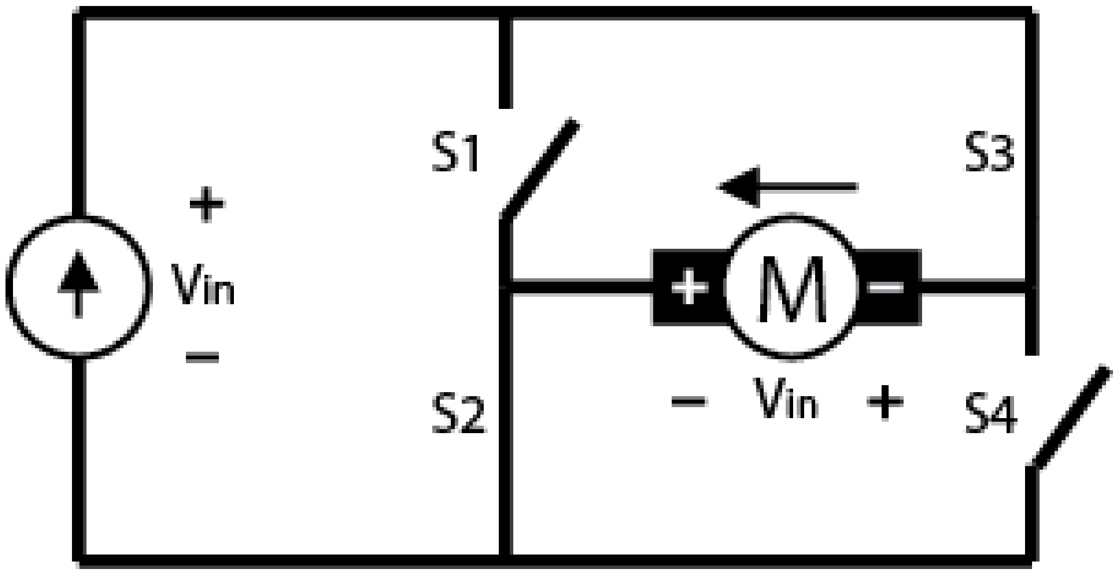
H-bridge



An H-bridge is a circuit configuration that is commonly used to control the direction and speed of a motor. It consists of four switches arranged in the shape of the letter "H." These switches can be transistors (such as MOSFETs or BJTs) or relays. **The H-bridge allows the motor to be driven forward or backward by changing the direction of the current flow through the motor windings.**

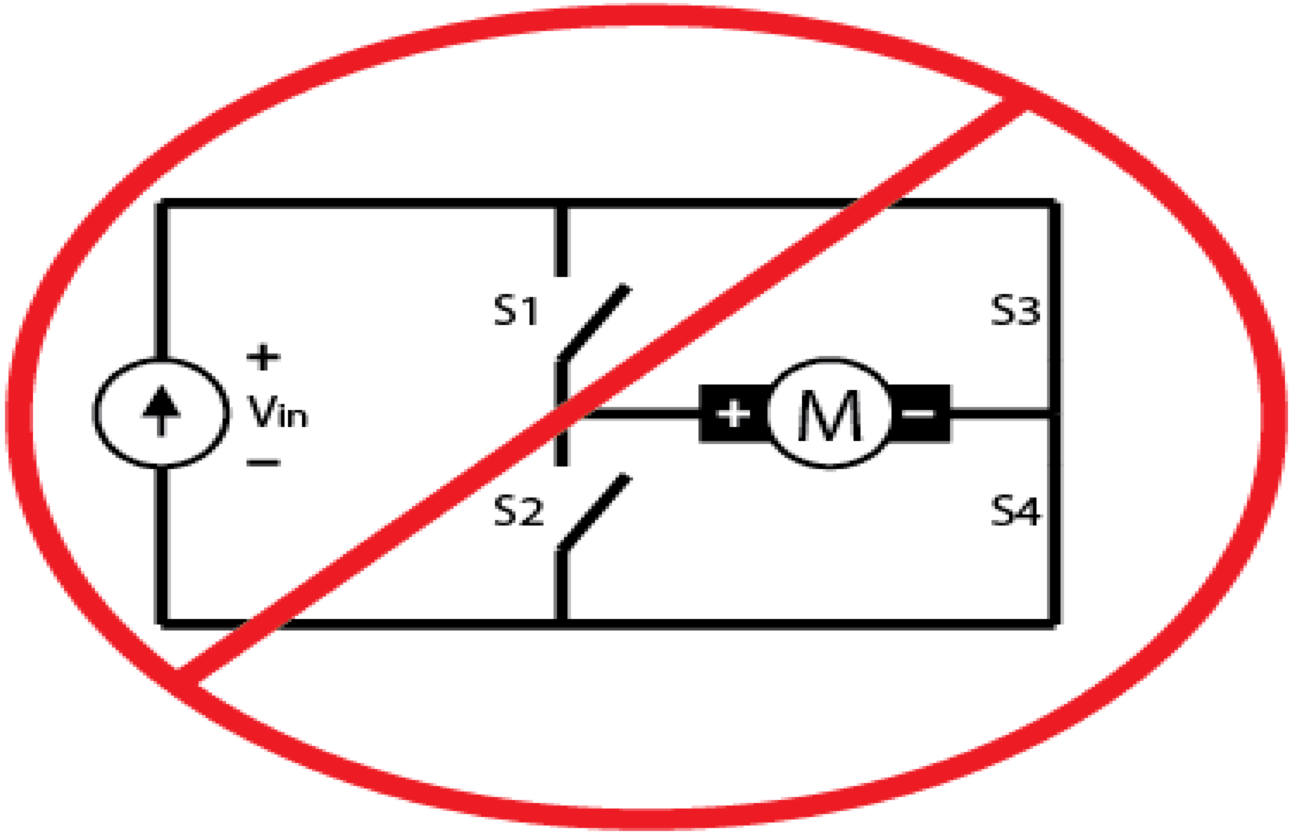
- If Switch 1 and 4 are closed, then the current will flow from the left to right on this image:
- If you close switch 1 and switch 4, the current will flow from the source, through switch 1, and then through the load, then through switch 4, and then back to the load.





- In the image above, the circuit has Switch 2 and switch 3 closed. This will cause the current to flow from the source, through switch 3, and then through the load, then through switch 2, then back to the load.

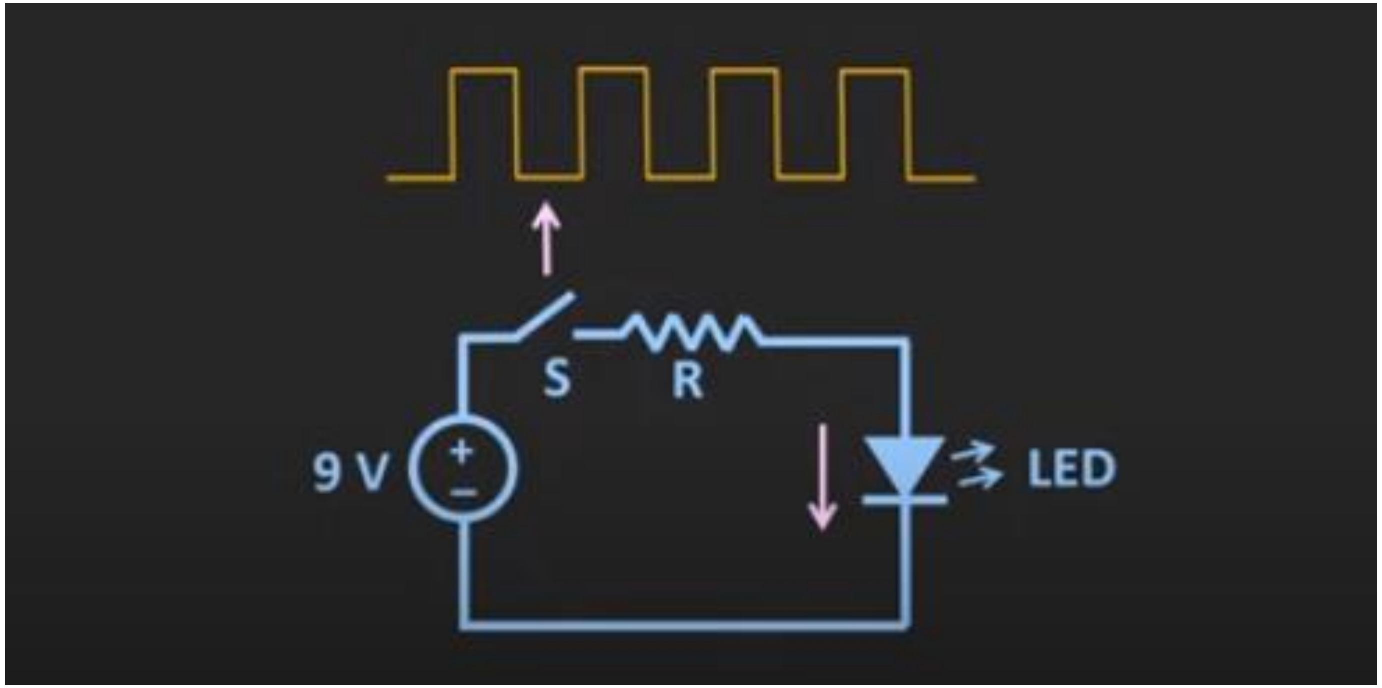
- If you drive current and close two switches in series, for example, switch 3 and 4 in the image below, you will cause a short and burn out the H-bridge

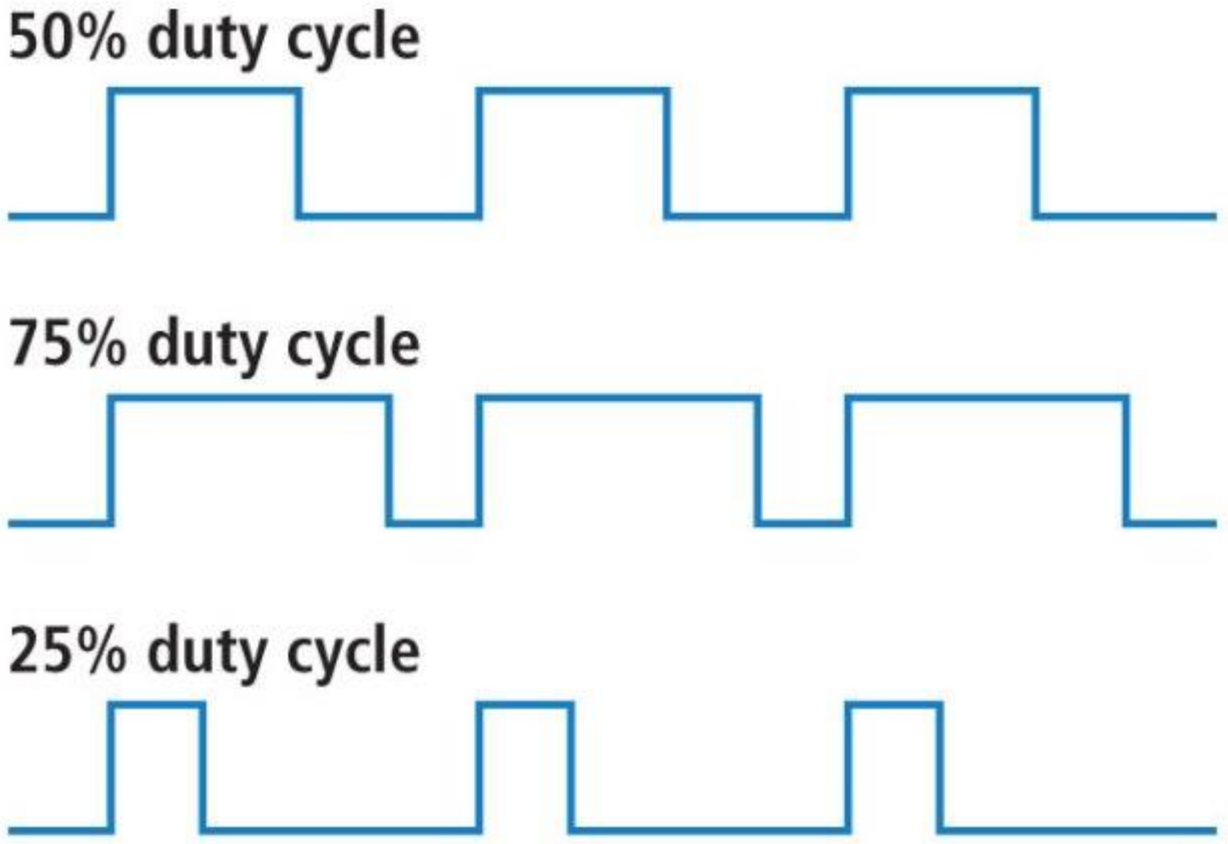


Pulse Width Modulation

- PWM stands for **Pulse Width Modulation.** It's a technique **used to control the average power delivered** to electrical devices, including motors. PWM works by varying the width of the pulse while keeping the frequency constant

- For dimming the LED lights
- Controlling the fan speed of CPU
- To control the brightness of the screen





By adjusting the duty cycle of the PWM signal (the ratio of pulse width to the period of the signal), you can control the average voltage and thus the speed of the motor.

- PWM is commonly used to control the speed of motors, including DC motors and certain types of AC motors. By adjusting the duty cycle of the PWM signal (the ratio of pulse width to the period of the signal), you can control the average voltage and thus the speed of the motor. A higher duty cycle corresponds to a **higher average voltage and faster motor speed, while a lower duty cycle results in a slower speed.**

- In addition to controlling speed, PWM can also be used to control the torque output of a motor. By adjusting the PWM signal, **you can vary the amount of power delivered to the motor,** thereby controlling its torque output. This is particularly useful in applications where precise control over motor torque is required, such as robotics and industrial automation.

- PWM control is more energy-efficient compared to traditional methods of motor control, such as resistive or rheostat-based speed control. By rapidly switching the power on and off, PWM allows for fine-grained control over the motor's operation while **minimizing energy loss and heat generation.**

- **PWM Basics**: PWM involves rapidly switching a digital signal on and off at a fixed frequency. The ratio of the time the signal is on (high) to the time it is off (low) within each period determines the average voltage applied to the motor. By adjusting this ratio, you can effectively control the motor speed.
- Pulse Width Modulation (PWM) signals are typically **applied to the motor through a motor driver circuit.** Here's how it generally works:
- **Motor Driver Circuit:** The motor driver circuit is responsible for delivering the appropriate voltage and current to the motor based on the PWM signal received. This circuit usually consists of power transistors (such as MOSFETs or BJTs) **configured in an H-bridge** configuration, as discussed earlier.
- PWM Input: **The PWM signal, generated by a microcontroller**, PLC (Programmable Logic Controller), or dedicated PWM generator, is fed into the motor driver circuit.
- Motor Connections: The motor connections are made to the motor driver circuit. The motor driver circuit controls the direction and speed of the motor based on the PWM signal received.

1. **Generating PWM Signal**: A PWM signal is generated by rapidly switching a voltage source (typically DC) on and off at a fixed frequency. The duration for which the voltage is ON during each cycle is called the "pulse width," and the ratio of this pulse width to the total period of the waveform is known as the "duty cycle.“

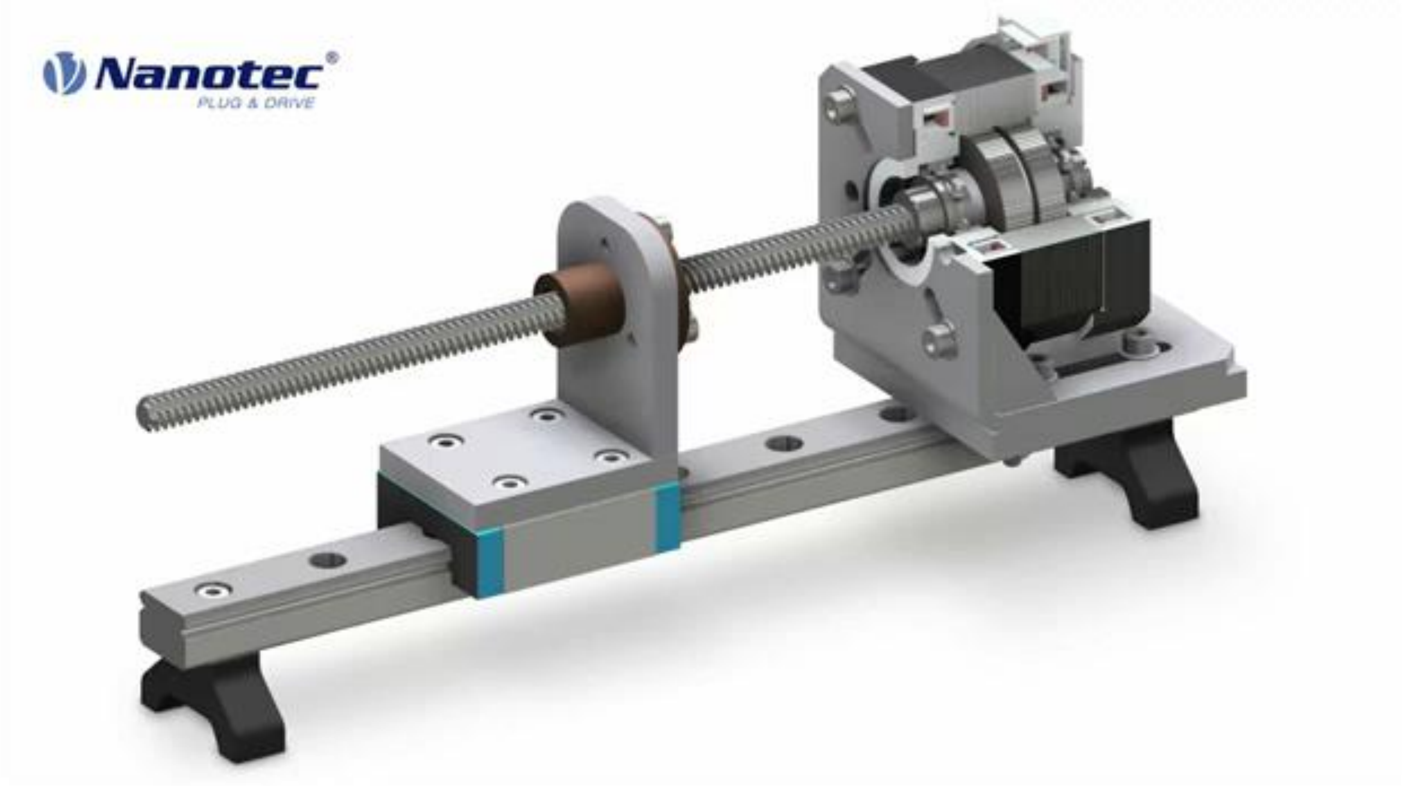
1. **Higher Duty Cycle = Higher Speed**: A higher duty cycle (i.e., longer ON time compared to OFF time) results in a higher average voltage applied to the motor, which leads to a higher motor speed. This is because the motor receives power for a greater portion of each cycle.

2. **Lower Duty Cycle = Lower Speed**: Conversely, a lower duty cycle (i.e., shorter ON time compared to OFF time) results in a lower average voltage applied to the motor, which leads to a lower motor speed. In this case, the motor receives power for a smaller portion of each cycle.

3. **Fine Control**: By adjusting the duty cycle of the PWM signal, you can achieve precise control over the motor speed. This allows for smooth and continuous speed adjustments across a wide range.

Actuator

An actuator in robotics is a component responsible for converting electrical energy into motion or physical manipulation. It's essentially the "muscle" of a robot, enabling it to perform tasks such as moving limbs, gripping objects, or rotating joints.



The actuators can be classified into three groups:

(Based on the source of input power)

1. Electric Actuators

The primary input power supply is the electric energy from the electric distribution system.

2. Hydraulic Actuators

They transform hydraulic energy stored in a reservoir into mechanical energy by means of suitable pumps. Hydraulic actuators are devices that use pressurized hydraulic fluid to produce mechanical motion.

3. Pneumatic Actuators

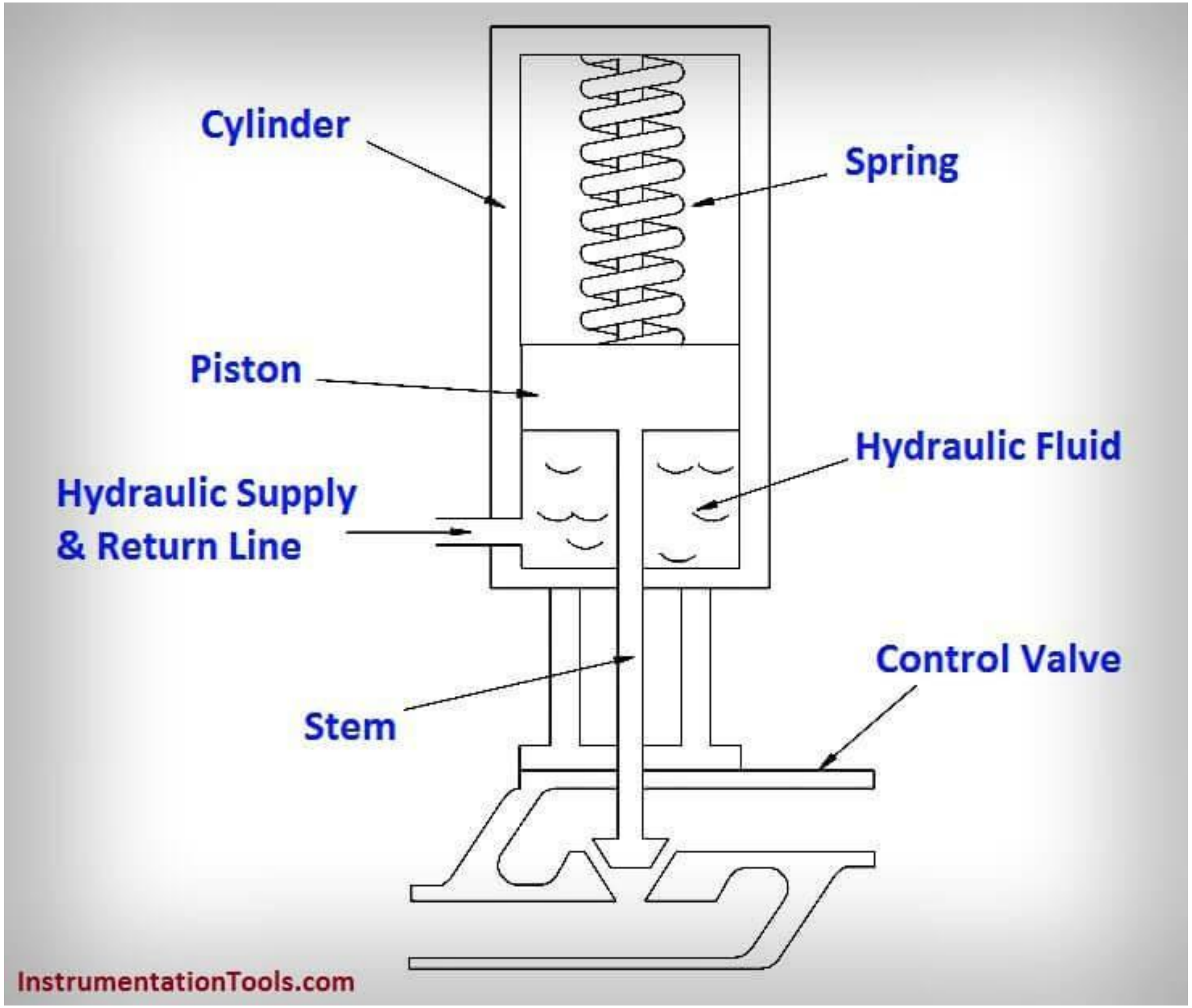
They utilize pneumatic energy, i.e., compressed air, provided by a compressor and transform it into mechanical energy by means of pistons or turbines.

In a robotic application, an actuator should have the following characteristics:

- **Low inertia** (Inertia is a fundamental property of matter that refers to the tendency of an object to resist changes in its state of motion.)
- **High power-to-weight ratio**
- **Possibility of overload and delivery of impulse torques** (a system or component may experience a load or force beyond its designed capacity, the capability of a system or component to apply sudden, high-magnitude torques or forces for a short duration.)
- **Capacity to develop high accelerations**
- **Wide velocity ranges**
- **High positioning accuracy**
- **Good trajectory tracking (**the ability of a system, such as a robotic arm or a moving vehicle, to accurately follow a predefined trajectory or path over time)

HYDRAULIC ACTUATORS

- Hydraulic actuators utilize **high-pressure fluid such as oil** to transmit forces to the point of application desired.
- Hydraulic actuators designed to operate at much higher pressures
- They are suitable **for high power applications.**
- Hydraulic actuators work **by converting the energy of pressurized fluid into mechanical motion**. They typically consist of a cylinder, a piston, and hydraulic fluid (usually oil).


Cylinder
Spring
Piston
Hydraulic Fluid
Hydraulic Supply
& Return Line
Control Valve
Stem
InstrumentationTools.com

1. **Cylinder and Piston**: The hydraulic actuator contains a cylinder with a piston inside it. The piston separates the cylinder into two chambers: the rod side and the cap side.
2. **Hydraulic Fluid**: The actuator is connected to a hydraulic system that supplies pressurized fluid, usually oil, to the cylinder. The fluid is stored in a reservoir and pumped into the cylinder by a hydraulic pump.
3. **Force Generation**: When hydraulic fluid is pumped into one side of the cylinder (either the rod side or the cap side), it applies pressure to the piston, causing it to move in the direction of the opposite chamber. This creates a pushing or pulling force, depending on the configuration of the actuator.
4. **Directional Control**: The direction of motion of the piston (and hence the actuator) is controlled by the direction of fluid flow into the cylinder. Directional control valves, such as spool valves or poppet valves, are used to regulate the flow of hydraulic fluid and control the movement of the actuator.
5. **Feedback Control**: In many applications, hydraulic actuators are equipped with sensors, such as position sensors or pressure transducers, to provide feedback to the control system. This feedback allows for precise control of the actuator's position, velocity, and force.

- **Advantages:**

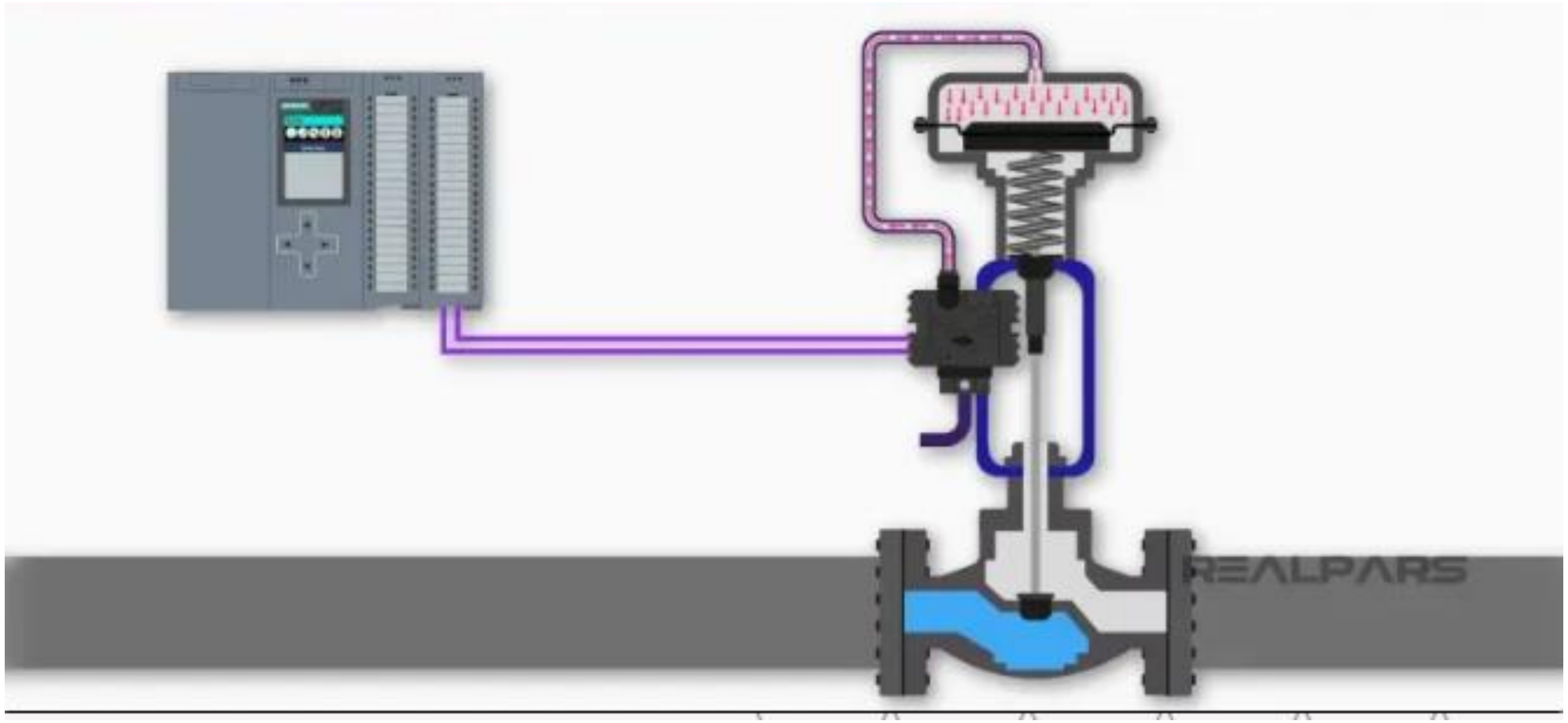
1. **High Force Output**: Hydraulic actuators **can generate high levels of force** due to the incompressibility of hydraulic fluid. This makes them suitable for **applications requiring heavy lifting or pushing**.
2. **Precise Control**: Hydraulic systems can provide **precise control over motion**, allowing for accurate positioning and movement. This precision is essential in applications such as industrial automation and robotics.
3. **Smooth Operation**: Hydraulic actuators **produce smooth and uniform motion**, which helps to minimize vibration and noise during operation. This characteristic makes them suitable for applications where smooth movement is crucial, such as in aerospace systems or precision machinery.
4. **Power Density**: Hydraulic systems have **a high power-to-weight ratio**, meaning **they can deliver significant power output** relative to their size and weight. This makes them suitable for applications where space and weight are constraints, such as in mobile equipment or aircraft.
5. **Ability to Handle High Loads**: Hydraulic actuators are capable of handling heavy loads without sacrificing performance. This makes them suitable for applications where high force is required, such as in construction equipment or material handling systems.

- **Disadvantages:**

1. **Complexity**: Hydraulic systems can be more complex and require more components compared to other actuation systems, such as electric or pneumatic systems. This complexity can increase installation, maintenance, and troubleshooting efforts.
2. **Fluid Leakage**: Hydraulic systems are prone to fluid leakage, which can result in reduced efficiency and environmental concerns. Proper maintenance and sealing techniques are necessary to minimize the risk of leakage.
3. **Potential for Fluid Contamination**: (Fluid contamination refers to the presence of unwanted substances or impurities in a fluid)Hydraulic systems are susceptible to contamination from dirt, debris, or moisture in the hydraulic fluid. Contamination can lead to reduced performance, increased wear and tear on components, and system failure if not adequately managed.
4. **Temperature Sensitivity**: **Hydraulic systems are sensitive to changes in temperature**, which can affect the viscosity and performance of the hydraulic fluid. Extreme temperatures can lead to issues such as fluid thickening or thinning, affecting the system's operation.
5. **Maintenance Requirements**: Hydraulic systems require regular maintenance, including fluid checks, filter replacements, and seal inspections, to ensure optimal performance and longevity. Failure to perform maintenance tasks can result in system failure or reduced efficiency over time.

PNEUMATIC ACTUATORS

- Pneumatic actuators are devices that **use compressed air** to produce mechanical motion. They are widely used in various industrial and automation applications due to their simplicity, reliability,



1. **Compressed Air Supply**: Pneumatic actuators require a source of compressed air, typically provided by a pneumatic system consisting of an air compressor, storage tank, and distribution network.
2. **Actuation Mechanism**: Pneumatic actuators contain a piston or diaphragm mechanism that converts the energy of compressed air into mechanical motion. When compressed air is introduced into the actuator, it creates pressure that moves the piston or diaphragm, causing linear or rotary motion, depending on the actuator design.
3. **Directional Control**: The direction of motion of the pneumatic actuator is controlled by valves, such as solenoid valves or manual valves, that regulate the flow of compressed air into and out of the actuator. Reversing the airflow direction allows the actuator to move in the opposite direction.
4. **Force and Speed**: The force and speed of pneumatic actuators can be adjusted by varying the pressure of the compressed air supplied to the actuator. Higher air pressure results in greater force and faster motion, while lower pressure yields lower force and slower motion.
5. **Applications**: Pneumatic actuators are used in a wide range of applications, including:
    1. Industrial automation: for tasks such as gripping, pushing, pulling, and lifting.
    2. Process control: for valve actuation in pipelines and fluid systems.
    3. Robotics: for simple pick-and-place operations and manipulation tasks.
    4. Automotive: for actuating components such as brakes, clutches, and doors.
    5. Aerospace: for actuating control surfaces, landing gear, and other mechanisms.

Advantages

- It is the **cheapest** form of all actuators. Components are readily available and compressed air is normally an already existing facility in factories.
- Compressed air can be stored and conveyed easily over long distances.
- **Compressed air is clean, explosion-proof** and insensitive to temperature fluctuations, thus, lending itself to many applications.
- They have few moving parts making them inherently reliable and reducing maintenance costs.
- Very quick in action and response time, thus, allowing fast work cycles.
- Pneumatics can be intrinsically safe in explosive areas as no electrical control is required.
- Individual components can be easily interconnected.

Disadvantages:

1. **Limited Precision**: Pneumatic actuators generally provide less precise control compared to other types of actuators, such as electric or hydraulic actuators.
2. **Limited Force and Speed Control**: While pneumatic actuators offer adjustable force and speed by varying the air pressure, their control range is often more limited compared to other actuation methods.
3. **Air Supply Dependency**: Pneumatic actuators rely on a **continuous supply of compressed air to operate.** Any interruption or failure in the air supply can result in the actuator becoming non-functional
4. **Noise and Vibrations**: Pneumatic systems can produce noise and vibrations during operation, especially at higher pressures or speeds
5. **Limited Energy Efficiency**: Pneumatic systems can be less energy-efficient compared to electric actuators, especially in applications where continuous operation or precise control is required. Compressing air consumes energy
6. **Temperature Sensitivity**: Pneumatic systems can be **sensitive to temperature fluctuations**, which can affect the density and performance of the compressed air. Extreme temperatures can lead to changes in the actuator's behavior, potentially impacting its reliability and efficiency.
7. **Maintenance Requirements**: Pneumatic systems **require regular maintenance** to ensure proper operation and reliability. This includes tasks such as checking for leaks, replacing seals and filters, and lubricating moving parts. Neglecting maintenance can lead to reduced performance, increased energy consumption, and premature component failure.

CONTROL

Control - On-Off Control - PID Control - Velocity Control and Position Control

BASICS OF CONTROL SYSTEM

- In a mechanical system, we are concerned with the response of the system to certain inputs. These inputs include commands to drive the system and disturbances from the environment. We can divide a system into five major components:
  1. The input (or inputs) to the system
  2. The controller and actuating devices
  3. The plant (the mechanism or process being controlled)
  4. The output (the controlled variable)
  5. Feedback elements (sensors)

Configuration of a Control System

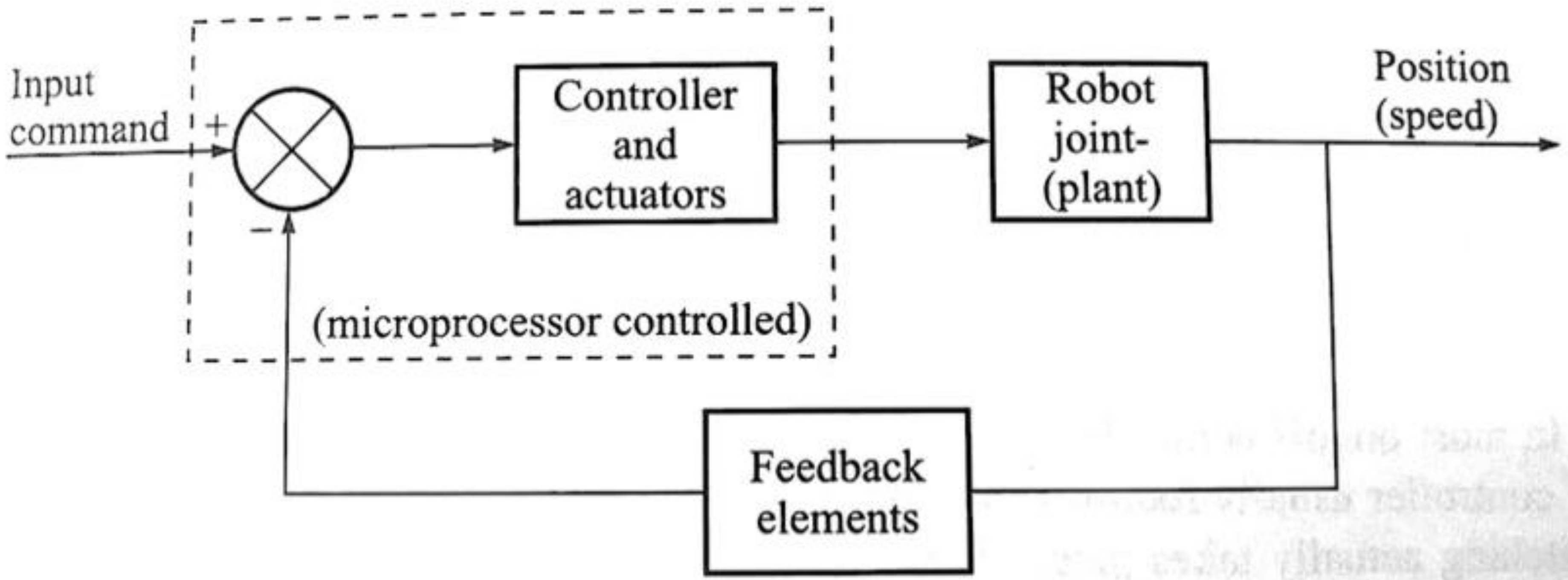


Fig. 3.8 *Typical block diagram configuration of a control system for a robot joint.*

- A general block diagram of the control system components for one joint of a robot manipulator is shown.
- The input command is the defined position (and possibly speed) to which the joint is directed to move.
- The output variable is the actual position (and speed) of the joint.
- The components of a control system include the controller and actuator.
- The purpose of the controller is to compare the actual output of the plant with the input command and to provide a control signal which will reduce the error to zero or as close to zero as possible.
- The controller generally consists of a summing junction where the input and output signals are compared, a control device which determines the control action, and the necessary power amplifiers and associated hardware devices to accomplish the control action in the plant.

- The actuator is used in robotics to convert the control action into physical movement of the manipulator.
- The controller and actuator may be operated by pneumatic, hydraulic, mechanical, or electronic means, or combinations of these.
- There are four basic control actions which are used singly or in combination to provide six common types of controller: on-off control, proportional control, derivative control and integral control.

- The six controller types are:
  1. On-off
  2. Proportional
  3. Integral
  4. Proportional-plus-integral (P-I)
  5. Proportional-plus-derivative (P-D)
  6. Proportional-plus-integral-plus-derivative (P-I-D)

ON-OF CONTROL

- On-Off Control In the on off controller, the control element provides only two levels of control, full-on or full-off.
- An example of a common implementation of this type of controller is the household thermostat.
- If the error which is present at the controller is e(t) and the control signal which is produced by the controller is m (t), then the on off controller is represented by
  - m(t) = M1, for e(t) > 0

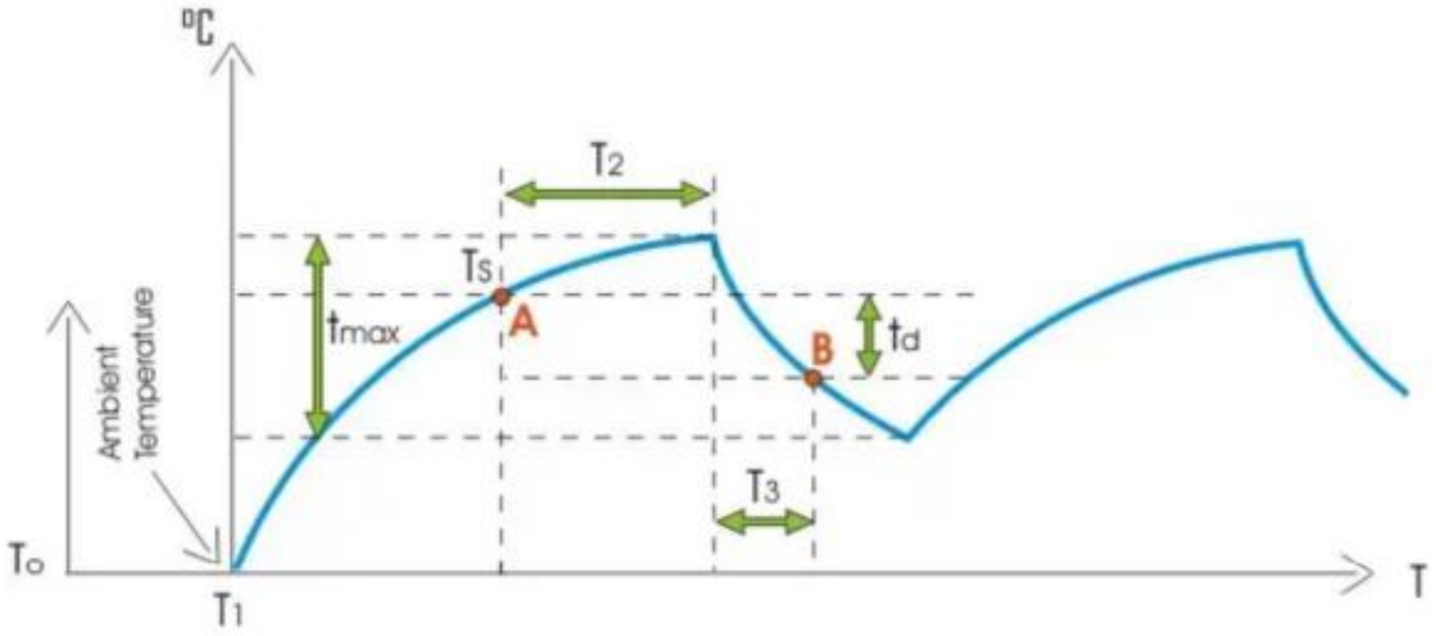
    = M2 for et) < 0

- On-Off control is the simplest form of feedback control.
- Sometimes, the control element has only two positions either it is fully closed or fully open.
- This control element does not operate at any intermediate position, i.e. partly open or partly closed position. Transmits only two output signal-ON (100%) & OFF(0%).
- Also known as Ban-Bang Controller or 2 –step controller.

- A very common example of on-off control theory is a fan controlling scheme of the transformer cooling system. When transformer runs with such a load, the temperature of the electrical power transformer rises beyond the pre-set value at which the cooling fans start rotating with their full capacity.
- As the cooling fans run, the forced air (output of the cooling system) decreases the temperature of the transformer. When the temperature (process variable) comes down below a pre-set value, the control switch of fans trip and fans stop supplying forced air to the transformer.

- After that, as there is no cooling effect of fans, the temperature of the transformer again starts rising due to load.
- Again when during rising, the temperature crosses the pre-set value, the fans again start rotating to cool down the transformer.
- Theoretically, we assume that there is no lag in the control equipment.
- That means, there is no time day for on and off operation of control equipment. With this assumption, if we draw a series of operations of an ideal on-off control system, we will get the graph given below.
- But in practical on-off control, there is always a non-zero time delay for closing and opening action of controller elements.
- This time delay is known as dead time. Because of this time delay, the actual response curve differs from the above shown ideal response curve.

Response Curve of On-Off Control System



the temperature of the transformer starts rising.

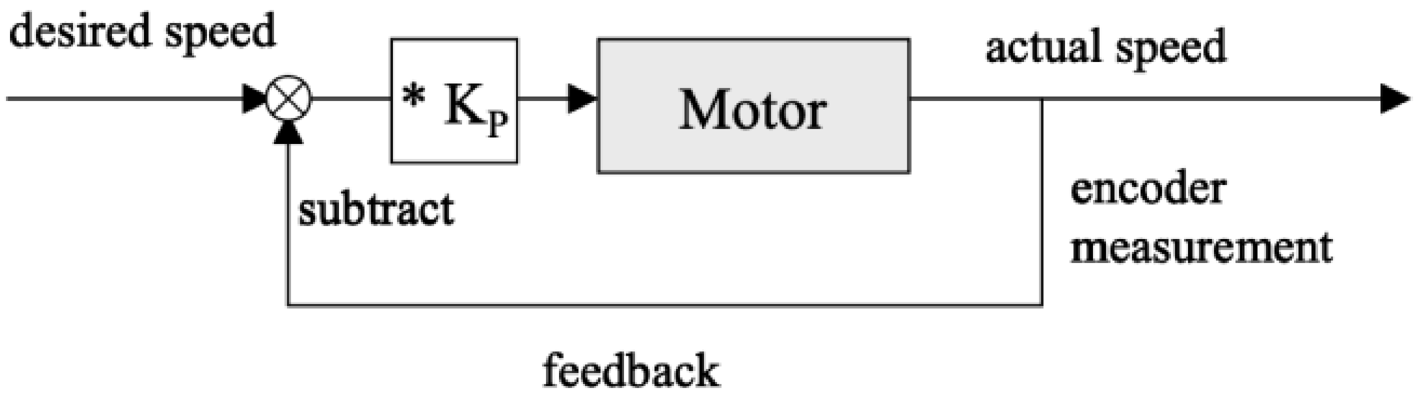
- This rising is exponential in nature. Let us at point A, the controller system starts actuating for switching on cooling fans, and finally, after the period of T2 the fans start delivering force air with its full capacity. Then the temperature of the transformer starts decreasing in an exponential manner.

- At point B, the controller system starts actuating for switching off the cooling fans, and finally after a period of T3 the fans stop delivering force air. Then the temperature of the transformer again starts rising in the same exponential manner.

PROPORTIONAL(P) CONTROL

- In cases where a smoother control action is required a proportional controller may be used.
- Proportional control provides a control signal that is proportional to the error. Essentially, it acts as an amplifier with a gain Kp.
- Its action is represented by
  - $m(t) = K_p e(t)$

- For many control applications, the abrupt change between a fixed motor control value and zero does not result in a smooth control behaviour. We can improve this by using a linear or proportional term instead. The formula for the proportional controller (P controller) is:
- $R(t) = K_P \cdot (v_{des}(t) - v_{act}(t))$
- Error Function: The difference between the desired and actual speed is called the "error function".



INTEGRAL(I) CONTROL

- In a controller employing an integral control action the control signal is changed at a rate proportional to the error signal. That is, if the error signal is large, the control signal increases rapidly, if it is small, the control signal increases slowly. This may be represented by
  - $m(t) = Ki \int e(t)\, dt$
  - where K, is the integrator gain.
- If the error were to go to zero, the output of the controller would remain constant. This feature allows integral controllers to be used when there is some type of constant load on the system. Even if there is no error the controller would still maintain an output signal to counteract the load.

PROPORTIONAL + INTEGRAL CONTROL (P-I)

- Sometimes it is necessary to combine control actions. A proportional controller is incapable of counteracting a load on the system without an error. An integral controller can provide zero error but usually provides slow response.

- One way to overcome this is with the P-I controller. This is represented by
  - $m(t) = K_p e(t) + K_p/T_i \int e(t)\, dt$
  - where Ti adjusts the integrator gain and Kp adjusts both the integrator and the proportional gain.

Proportional-Plus-Derivative Control

- Provides a control signal proportional to the rate of change of the error signal.
- Since this would generate no output unless the error is changing, it is rarely used alone.
- The P-D controller is represented by

$$m(t) = K_p e(t) + K_p T_d \frac{de(t)}{dt}$$

- The effect of derivative control action is to anticipate changes in the error and provide a faster response to changes.

P-I-D Controller

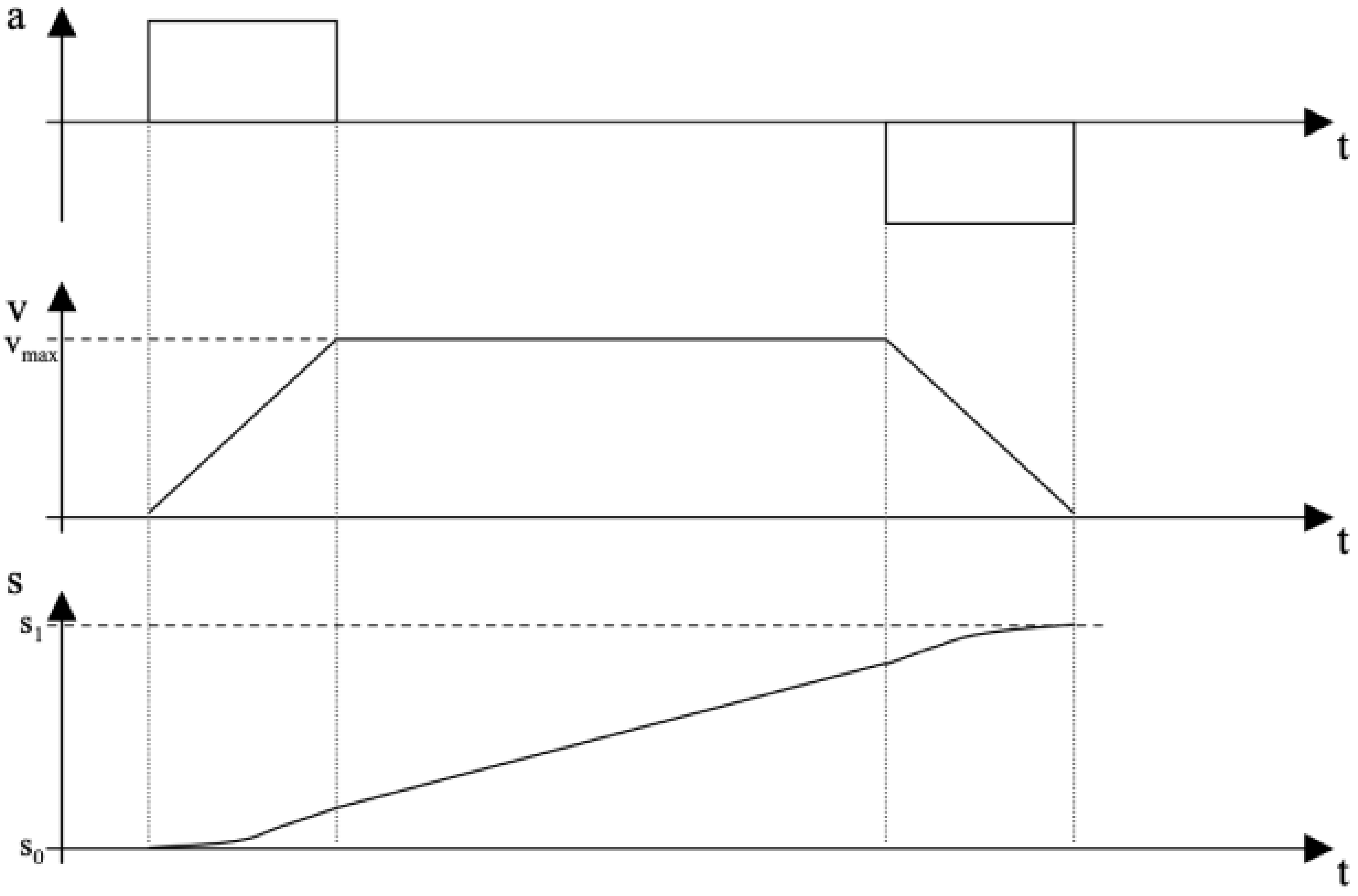
- Three of the control actions can be combined to form the P-I-D controller. The P-I-D controller can be represented by

$$m(t) = K_p e(t) + \frac{K_p}{T_i} \int e(t)dt + K_p T_d \frac{de(t)}{dt}$$

- P-I-D control is the most general control type and probably the most commonly used type of controller. It provides quick response, good control of system stability and low steady-state error. The computations associated with any of the above controllers are typically performed by microcomputers in a modern robot controller.

VELOCITY & POSITION CONTROL

- To drive a motor at a given speed for a number of revolutions and then come to a stop at exactly the right motor position we need velocity and position control.
- The former, maintaining a certain speed, is generally called velocity control, while the latter, reaching a specified position, is generally called position control.
- The position controller sets the desired velocities in all driving phases, especially during the acceleration and deceleration phases (starting and stopping).
- Let us assume a single motor is driving a robot vehicle that is initially at rest and which we would like to stop at a specified position.



a
t
v
v_{max}
t
s
s_1
s_0
t

- When ignoring friction, we only need to apply a certain force (here constant) during the starting phase, which will translate into an acceleration of the vehicle.
- The constant acceleration will linearly increase the vehicle's speed v (integral of a) from 0 to the desired value vmax, while the vehicle's position s (integral of v) will increase quadratically.
- When the force (acceleration) stops, the vehicle's velocity will remain constant, assuming there is no friction, and its position will increase linearly.

- During the stopping phase (deceleration, breaking), a negative force (negative acceleration) is applied to the vehicle. Its speed will be linearly reduced to zero (or may even become negative – the vehicle now driving backwards – if the negative acceleration is applied for too long a time).

- The vehicle's position will increase slowly, following the square root function.

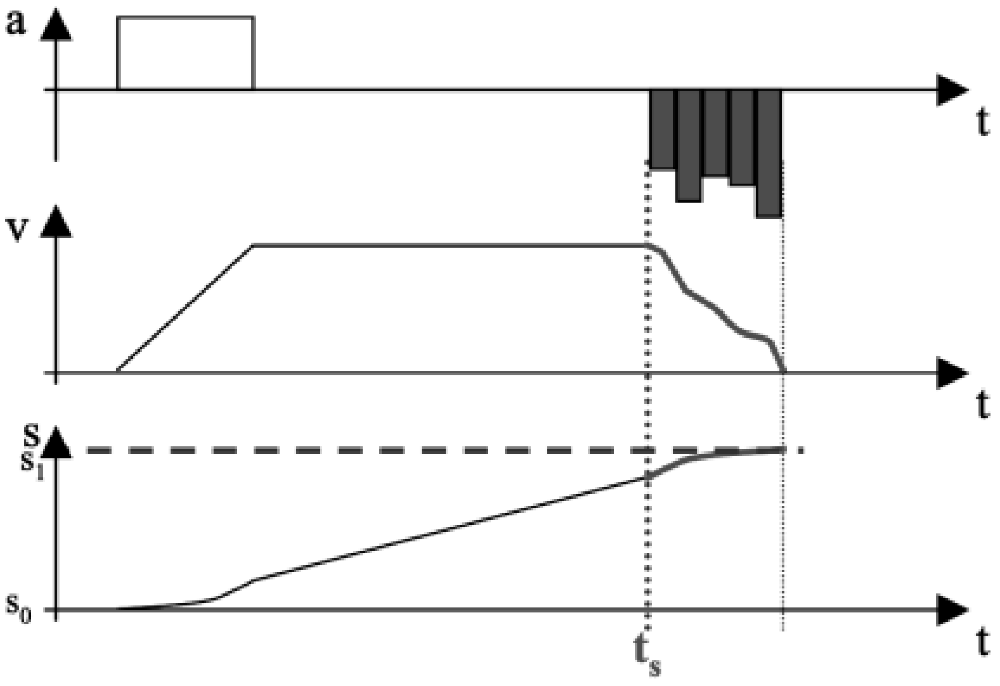


Figure 4.12: Breaking adaptation

- To control the amount of acceleration in such a way that the vehicle:
  1. Comes to rest (not moving slowly forward to backward).
  2. Comes to rest at exactly the specified position (for example we want the vehicle to drive exactly 1 meter and stop within 1mm).
- Figure shows a way of achieving this by controlling (continuously updating) the breaking acceleration applied. This control procedure has to take into account not only the current speed as a feedback value, but also the cur- rent position, since previous speed changes or inaccuracies may have had already an effect on the vehicle's position.

THE END
THANK YOU