Basic Mechanical Engineering

(Credit: 3.00)

<u>EEE 1207</u>

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Contents

- Sources of energy: conventional and renewable;
- Introduction to IC engines,
- Refrigeration and Air conditioning systems.
- Statics of particles and rigid bodies;
- Forces in trusses and frames;
- Relative motion;
- Kinematics of particles: Newton's Second Law of Motion;
- Kinematics of rigid bodies.
- Introduction to Robotics; Plane, rotational and spatial motion with applications to manipulators;
- Geometric configurations: structural elements, linkage, arms and grippers;
- Motion characteristics.

Introduction to Robotics

TEXTBOOKS

1. Saeed B. Niku, “Introduction to robotics,” Prentice Hall, 2001.

2. John Craig, “Introduction to robotics,” 3rd ed. Prentice Hall, 2005.

Introduction

- What is a Robot?
- Why use Robots?
- Robot History
- Robot Applications

What is a robot?

- Origin of the word "robot"
  - Czech word "robota"– labor, "robotnik" – workman
  - 1923 play by Karel Capek – Rossum's Universal Robots
- Definition: (no precise definition yet)
  - Webster's Dictionary
    - An automatic device that performs functions ordinarily ascribed to human beings ➔washing machine = robot?
  - Robotics Institute of American
    - A robot (industrial 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.

What is a robot?

- By general agreement, a robot is:

  A programmable machine that imitates the actions or appearance of an intelligent creature–usually a human.

- To qualify as a robot, a machine must be able to:

  1) Sensing and perception: get information from its surroundings

  2) Carry out different tasks: Locomotion or manipulation, do something physical–such as move or manipulate objects

  3) Re-programmable: can do different things

  4) Function autonomously and/or interact with human beings.

Why Use Robots?

- Application in 4D environments
  - Dangerous
  - Dirty
  - Dull
  - Difficult
- 4A tasks
  - Automation
  - Augmentation
  - Assistance
  - Autonomous

Why Use Robots?

- Increase product quality
  - Superior Accuracies (thousands of an inch, wafer-handling: microinch)
  - Repeatable precision ➔ Consistency of products
- Increase efficiency
  - Work continuously without fatigue
  - Need no vacation
- Increase safety
  - Operate in dangerous environment
  - Need no environmental comfort – air conditioning, noise protection, etc
- Reduce Cost
  - Reduce scrap rate
  - Lower in-process inventory
  - Lower labor cost
- Reduce manufacturing lead time
  - Rapid response to changes in design
- Increase productivity
  - Value of output per person per hour increases

Robot History

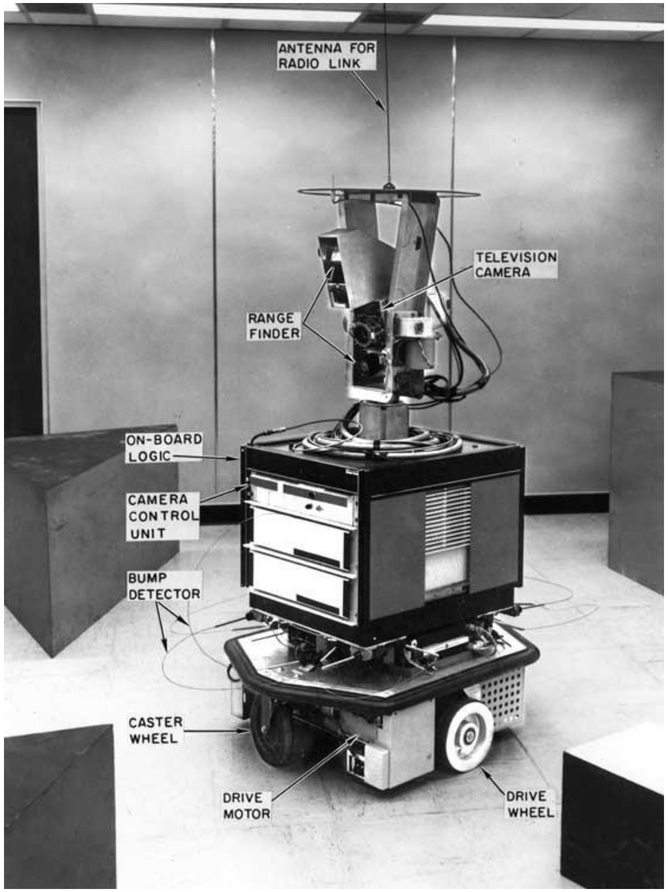
- 1961
  - George C. Devol obtains the first U.S. robot patent, No. 2,998,237.
    - Joe Engelberger formed Unimation and was the first to market robots
  - First production version Unimate industrial robot is installed in a die-casting machine
- 1962
  - Unimation, Inc. was formed, (Unimation stood for "Universal Automation")

Robot History

- 1968
  - Unimation takes its first multi-robot order from General Motors.

- 1966-1972
  - "Shakey," the first intelligent mobile robot system was built at Stanford Research Institute, California.

Robot History



- **Shakey** (Stanford Research Institute)
  - the first mobile robot to be operated using AI techniques
- **S**imple tasks to solve:
  - To recognize an object using vision
  - Find its way to the object
  - Perform some action on the object (for example, to push it over)

Robot History

- 1969
  - Robot vision, for mobile robot guidance, is demonstrated at the Stanford Research Institute.
  - Unimate robots assemble Chevrolet Vega automobile bodies for General Motors.
- 1970
  - General Motors becomes the first company to use machine vision in an industrial application The Consight system is installed at a foundry in St. Catherines, Ontario, Canada.

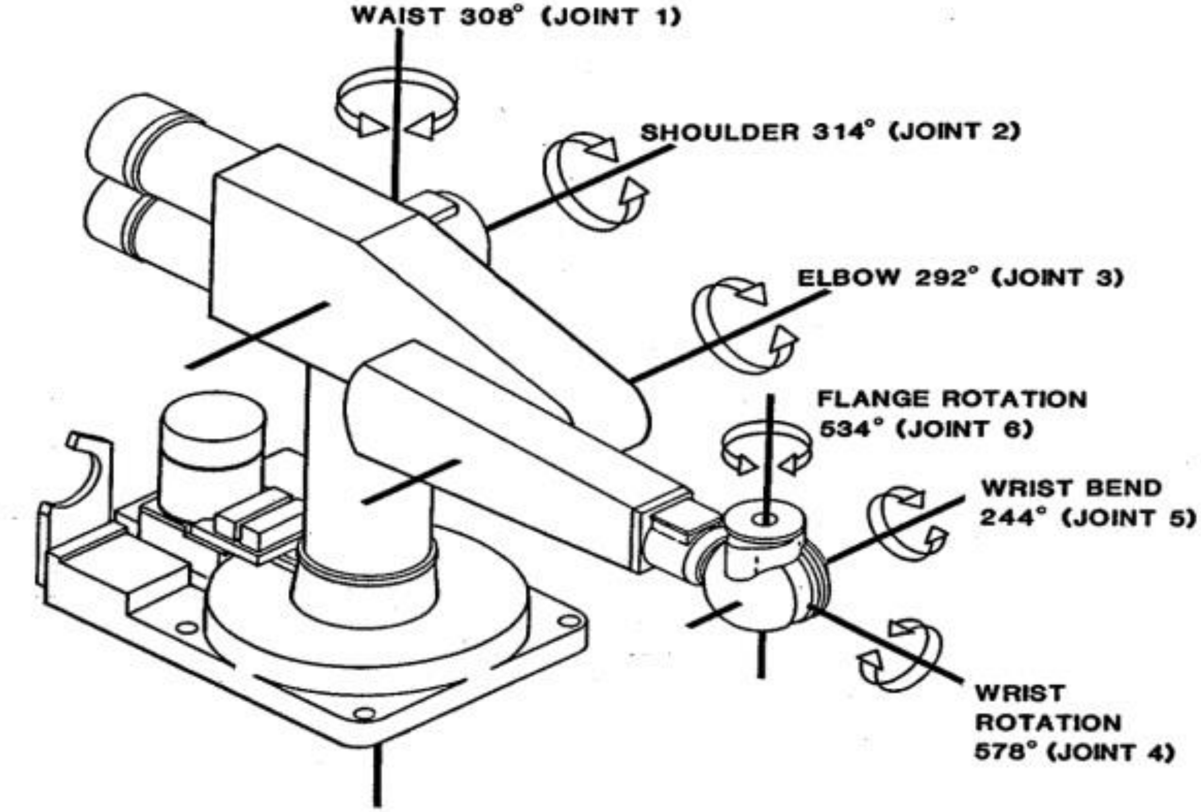
Robot History

- 1973-1979
  - Stanford Cart
  - Equipped with stereo vision.
  - Take pictures from several different angles
  - The computer gauged the distance between the cart and obstacles in its path

Robot History

- 1978
  - The first PUMA (Programmable Universal Machine for Assembly) robot is developed by Unimation for General Motors.
- 1981
  - IBM enters the robotics field with its 7535 and 7565 Manufacturing Systems.
- 1983
  - Westinghouse Electric Corporation bought Unimation, Inc., which became part of its factory automation enterprise. Westinghouse later sold Unimation to Staubli of Switzerland.

Industrial Robot - PUMA



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

How are they used?

- Industrial robots
  - 70% welding and painting
  - 20% pick and place
  - 10% others
- Research focus on
  - Manipulator control
  - End-effector design
    - Compliance device
    - Dexterity robot hand
  - Visual and force feedback
  - Flexible automation

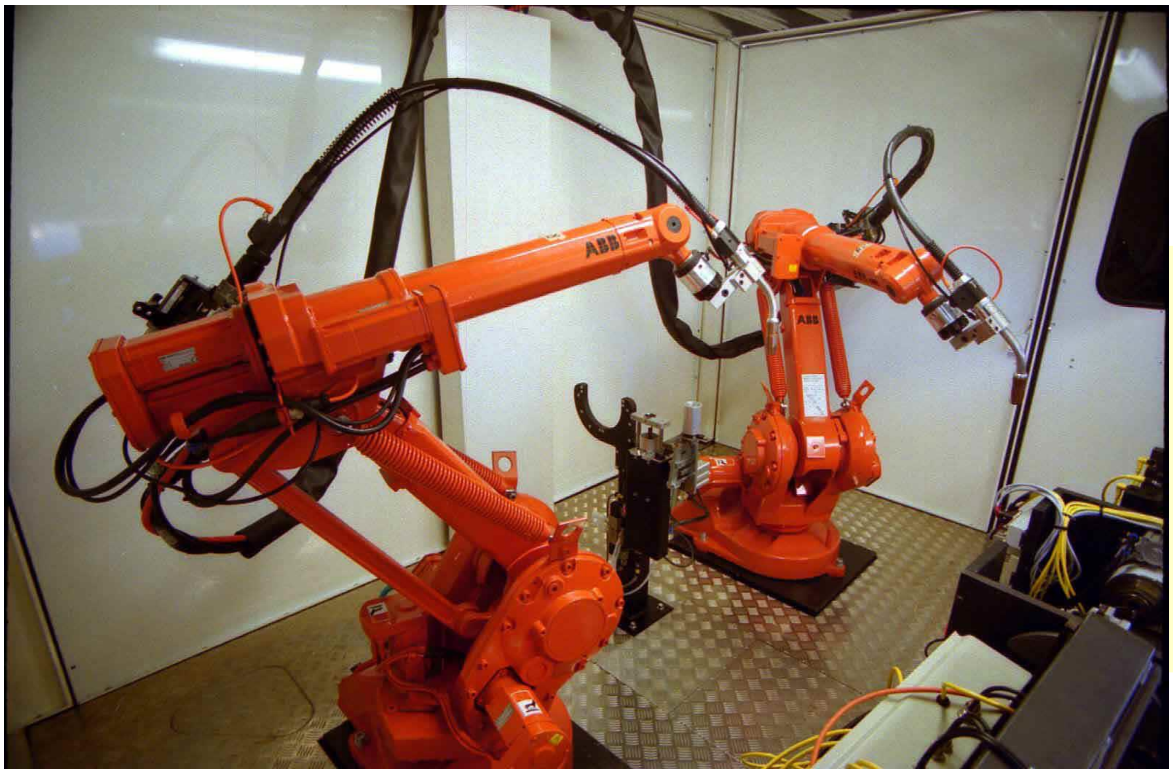
Robotics: a much bigger industry

- Robot Manipulators
  - Assembly, automation
- Field robots
  - Military applications
  - Space exploration
- Service robots
  - Cleaning robots
  - Medical robots
- Entertainment robots

Robot Manipulators

Manipulator

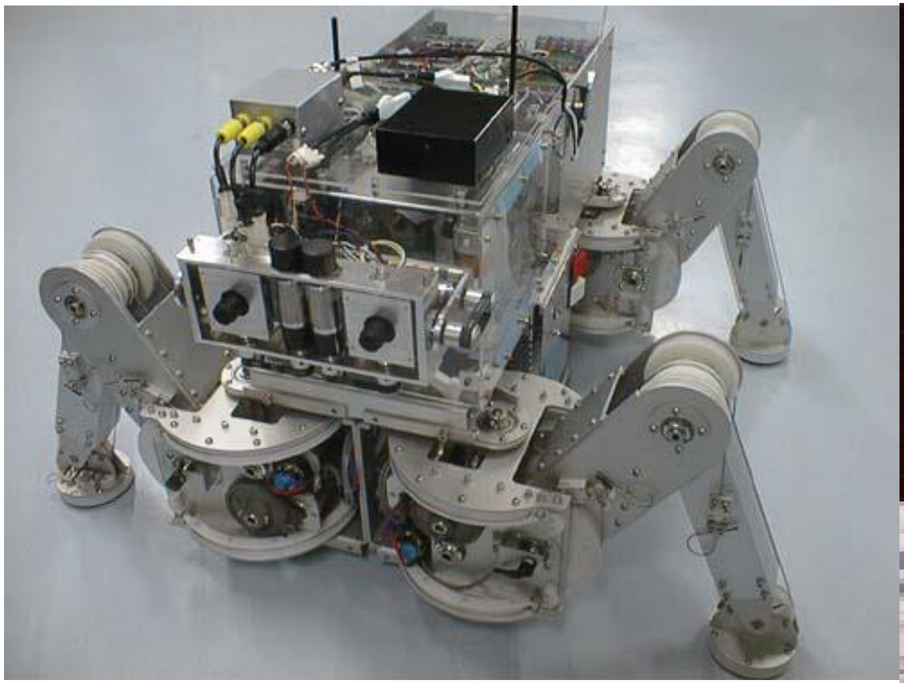
Robot Manipulators

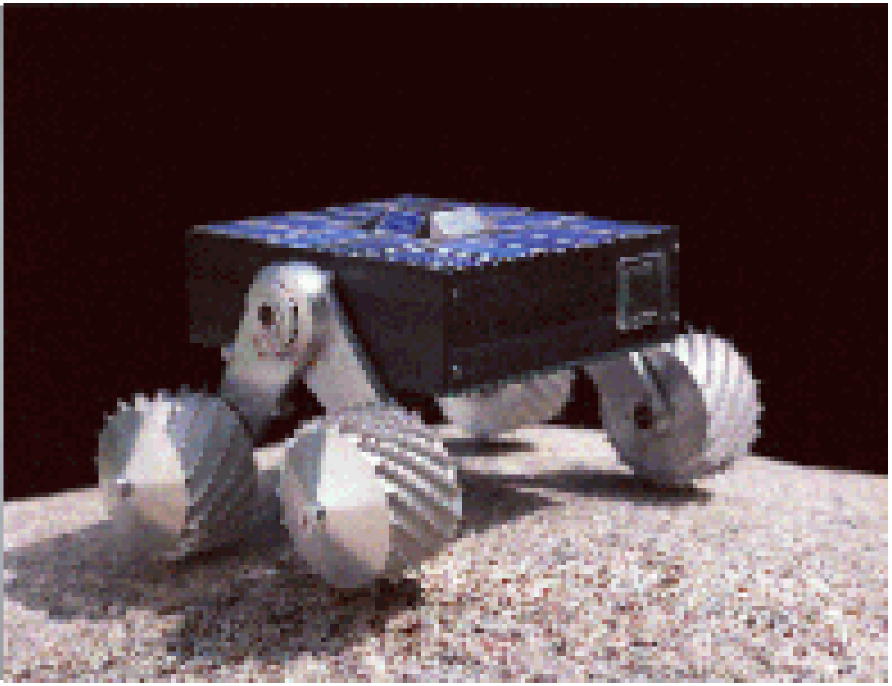


Repetitive jobs that are boring, stressful, or labor-intensive for humans

Welding Robot

Field Robots





Field Robots

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

Service robots

Jobs that are dangerous for humans

Decontaminating Robot

Cleaning the main circulating pump housing in the nuclear power plant

Service robots

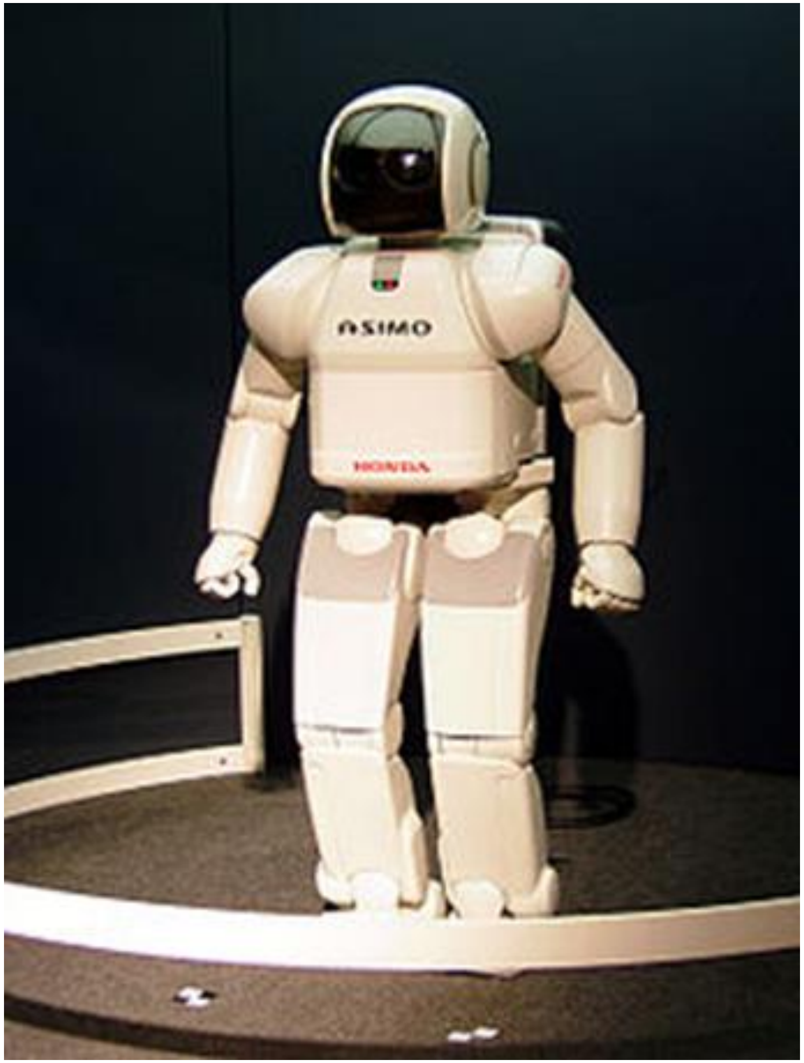
The SCRUBMATE Robot

The Roomba domestic vacuum cleaner Robot

Menial tasks that human don't want to do

Da Vinci Robot

Entertainment Robots



Entertainment Robots

Sony SDR-3X Entertainment Robot

Sony Aido

Robot Classification

- According to Japanese Industrial Robot Association (JIRA)
  Class 1: Multiple degrees of freedom, operated by an operator
  Class 2: works on predetermined method, hard to modify
  Class 3: same as class 2 but easy to modify
  Class 4: human motion recorded and then robot follows that motion
  Class 5: operator supplies the program rather than teaching it manually
  Class 6: understand its environment and complete its task despite the change in its surrounding
  Robotics Institute of America (RIA) **considers only class 3-6**.

- According to Association Francaise de Robotique (AFR)
  Type A: handling device with manual control
  Type B: automatic handling device with predetermined cycles
  Type C: programmable servo control with point to point trajectories
  Type D: same as C but it can acquire information from surrounding.

- Depending on types of applications:
  Pick and place - Moves items between points
  Continuous path control - Moves along a programmable path
  Sensory - Employs sensors for feedback

Robot Components

1. Manipulator
2. End effectors
3. Actuators
4. Sensors
5. Controller
6. Processors
7. Softwares

Robot manipulators

Manipulators are composed of **an assembly of links and joints**. Links are defined as the rigid sections that make up the mechanism and joints are defined as the connection between two links. The device attached to the manipulator which interacts with its environment to perform tasks is called the end-effector.

Manipulators can be classified depend on two criteria.

1. Motion characteristics

2. Kinematic Structure

Robot manipulators

By Motion Characteristics:

Planar manipulator: A manipulator is called a planar manipulator if all the moving links move in planes parallel to one another.

Spherical manipulator: A manipulator is called a spherical manipulator if all the links perform spherical motions about a common stationary point.

Spatial manipulator: A manipulator is called a spatial manipulator if at least one of the links of the mechanism possesses a general spatial motion.

Robot manipulators

By Kinematic Structure:

Open-loop manipulator (or serial robot): A manipulator is called an open-loop manipulator if its links form an open-loop chain.

Parallel manipulator: A manipulator is called a parallel manipulator if it is made up of a closed-loop chain.

Hybrid manipulator: A manipulator is called a hybrid manipulator if it consists of open loop and closed loop chains.

Robot End-Effectors

- End-effectors are the tools attached to the end of the robot arm that **enable it to do useful work**. Most robot manufacturers either do not include end-effectors with their robots or include a general purpose gripper to allow you to do simple tasks.
- Typically, the end-effectors must be purchased or designed separately. Also called end-of-arm-tooling, end-effectors are usually attached to the robot tool plate (after the last wrist joint) via a standard mechanical interface.
- Like robots themselves, **end-effectors require a power source**, often electric or pneumatic.

Robot End-Effectors

Grippers

Grippers are the most common end-effectors. They provide the equivalent of a thumb and an opposing finger, allowing the robot **to grasp small parts and manipulate them.**

Machine Tools Robot end-effectors can also be machine tools such as **drills, grinding wheels, cutting wheels etc.**

Laser and Water Jet Cutters Laser and water jet cutters are robot end-effectors that **use high-intensity laser beams or high pressure abrasive water jets** to cut sheet metal or fiberglass parts to shape.

Robot End-Effectors

Spray Painting Tools

Automatic spray painting is a useful application for robots, in the automotive and other industries.

Measuring Instruments

Measuring instruments are end-effectors that allow the robot to **precisely measure parts** by running the arm lightly over the part using a measuring probe or gauge.

Robot Control Methods

Robot control methods consists of a computer, robot, and sensors.

Lead-Through Programming

The human operator **physically grabs the end-effector** and shows the robot exactly what motions to make for a task, while the computer memorizes the motions (memorizing the joint positions, lengths and/or angles, to be played back during task execution).

Teach Programming

Move robot to required task positions via teach pendant; **computer memorizes these configurations and plays them** back in robot motion sequence. The teach pendant is a controller box that allows the human operator to position the robot by manipulating the buttons on the box. This type of control is adequate for simple, non-intelligent tasks.

Robot Control Methods

Off-Line Programming

Off-line programming is the use of **computer software with realistic graphics to plan and program motions** without the use of robot hardware (such as GRIP).

Autonomous

Autonomous robots are **controlled by computer, with sensor feedback**, without human intervention. Computer control is required for intelligent robot control. In this type of control, the computer may send the robot **pre-programmed** positions and even manipulate the speed and direction of the robot as it moves, based on sensor feedback. The computer can also communicate with other devices to help guide the robot through its tasks.

Robot Control Methods

Teleoperation

Teleoperation is **human-directed motion, via a joystick.** Special joysticks that allow the human operator to feel what the robot feels are called **haptic interfaces.**

Telerobotic

Telerobotic control is a **combination of autonomous and teleoperation control** of robot systems.

Robot Software

- Need to interface robot control system to external sensors, to provide "real time" changes based on sensory equipment
- computing based on geometry of environment
- ability to interface with CAD/CAM systems
- meaningful task descriptions
- off-line programming capability
- Large number of robot languages available AML, VAL, AL, RAIL, RobotStudio, etc. (200+)
- No standards exist

Sensors and Actuators

Sensors

- Sensor is a device that when exposed to a physical phenomenon (temperature, displacement, force, etc.) produces a proportional output signal (electrical, mechanical, magnetic, etc.).
- The term transducer is often used synonymously with sensors. However, ideally, a sensor is a device that responds to a change in the physical phenomenon. On the other hand, a transducer is a device that converts one form of energy into another form of energy.
- Sensors are transducers when they sense one form of energy input and output in a different form of energy. For example, a thermocouple responds to a temperature change (thermal energy) and outputs a proportional change in electromotive force (electrical energy). Therefore, a thermocouple can be called a sensor and or transducer.

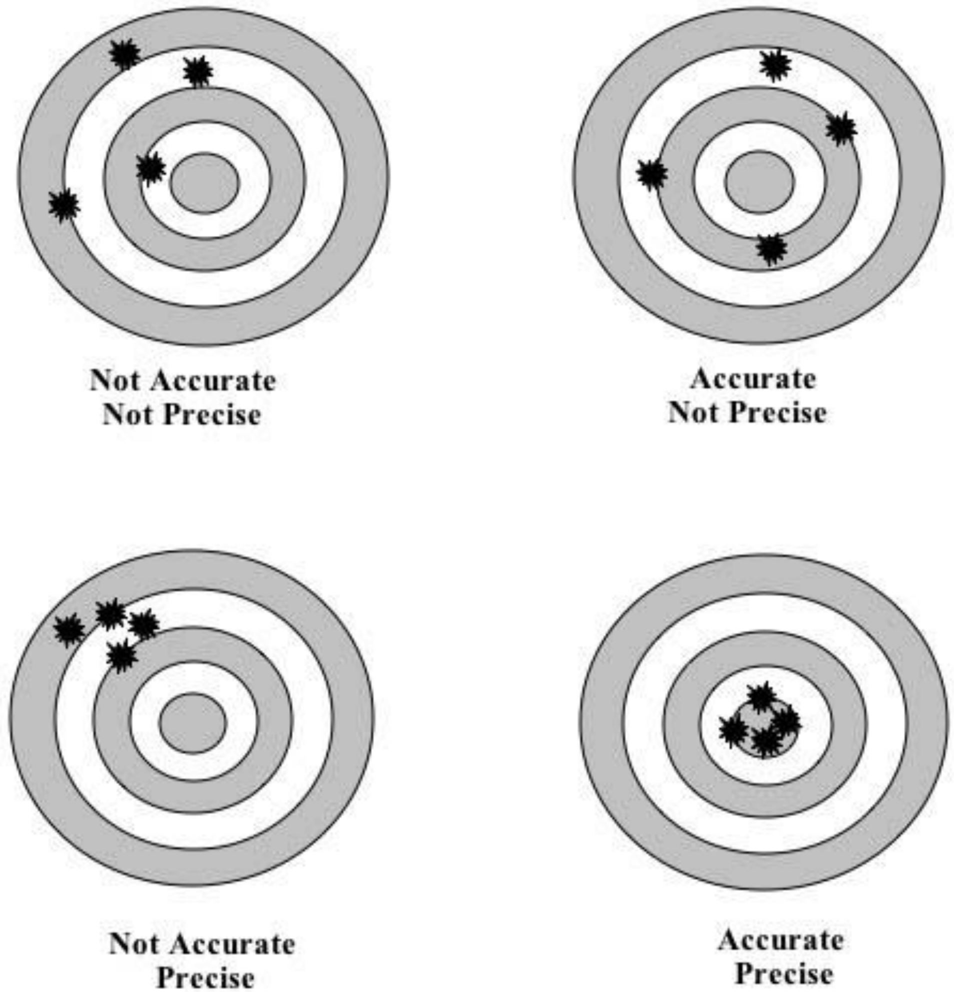
Sensor/Transducers Specifications

- Transducers or measurement systems are not perfect systems. Design engineer must know the capability and shortcoming of a transducer or measurement system to properly assess its performance.
- There are a number of performance related parameters of a transducer or measurement system. These parameters are called as sensor specifications.
- Sensor specifications inform the user about the deviations from the ideal behavior of the sensors.

Sensor Terminologies & Characteristics

- **Range:** Difference between the maximum and minimum value of the sensed parameter
- **Resolution:** The smallest change the sensor can differentiate
- **Accuracy:** Difference between the measured value and the true value
- **Precision:** Ability to reproduce the results repeatedly with a given accuracy
- **Sensitivity:** Ratio of change in output to a unit change of the input
- **Linearity:** Percentage of deviation from the best-fit linear calibration curve

Accuracy & Precision

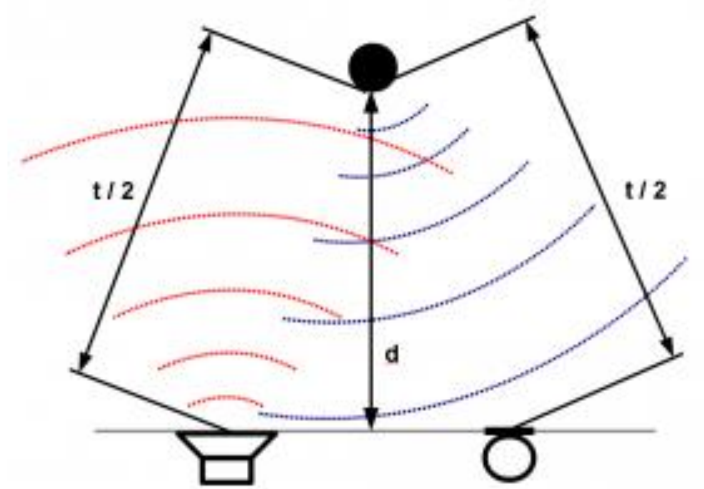


Types of Robot Sensors

- Distance Sensor (IR, Ultrasonic, Laser, Encoders, Stereo Camera)
- Proximity Sensor (IR, Ultrasound, Photo resistor)
- Contact Sensor
- Pressure Sensor
- Temperature Sensor
- Light Sensor
- Sound Sensor
- Tilt Sensor
- Navigation/ Positioning Sensor (GPS)
- So on….

Ultrasonic distance sensor

- The sensor emits an ultrasonic pulse and is captured by a receiver. Since the speed of sound is almost constant in air, which is 344m/s, the time between send and receive is calculated to give the distance between robot and the obstacle.
- The sound generator generates short ultrasonic impulses and triggers the timer. Second membrane registers the arrival of the sound impulse and stops the timer. From the timers time it is possible to calculate the distance traveled by the sound.

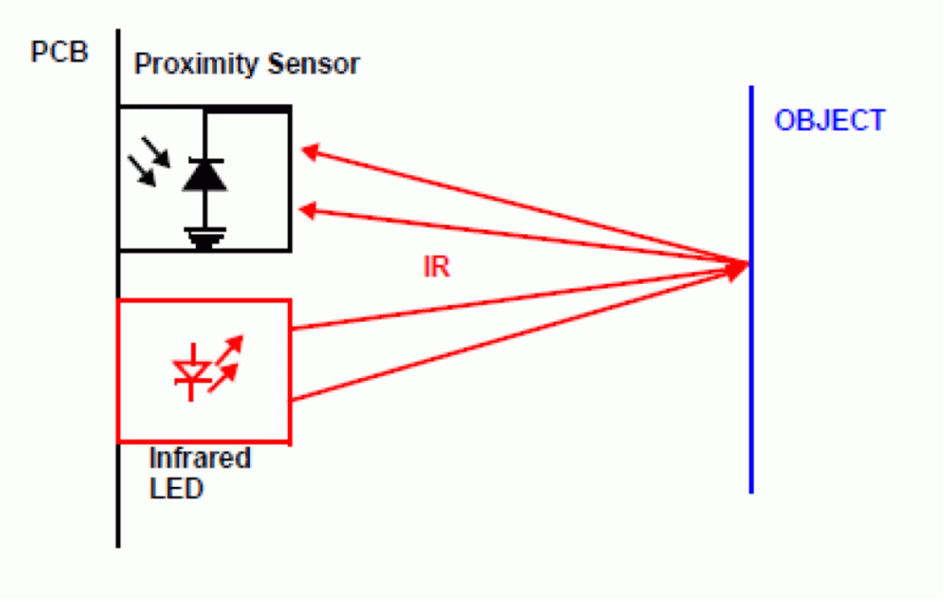


Ultrasonic distance sensor

- Ultrasound is reliable in any lighting environment and can be used inside or outside. Ultrasonic sensors can handle collision avoidance for a robot.
- Ultrasonic Sensors are best used in the non-contact detection of:
  - Presence , Level, Position, Distance
- Ultrasonics are Independent of:
  - Light, Smoke, Dust, Color
  - Material (except for soft surfaces, i.e. wool, because the surface absorbs the ultrasonic sound wave and doesn’t reflect sound.)
- Ultrasonic sensors are superior to infrared sensors because they aren’t affected by smoke or black materials, however, soft materials which don’t reflect the sonar (ultrasonic) waves very well may cause issues. It’s not a perfect system, but it’s good and reliable.

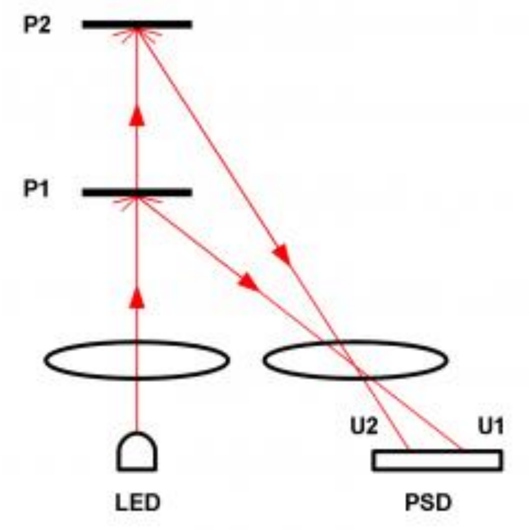
Infrared Distance sensor

- Infrared sensors work on the principle of reflected light waves. The reflected light is detected and then an estimate of distance is calculated between sensor and object.
- IR circuits are designed on triangulation principle for distance measurement. A transmitter sends a pulse of IR signals which is detected by the receiver if there is an obstacle and based on the angle the signal is received, distance is calculated.



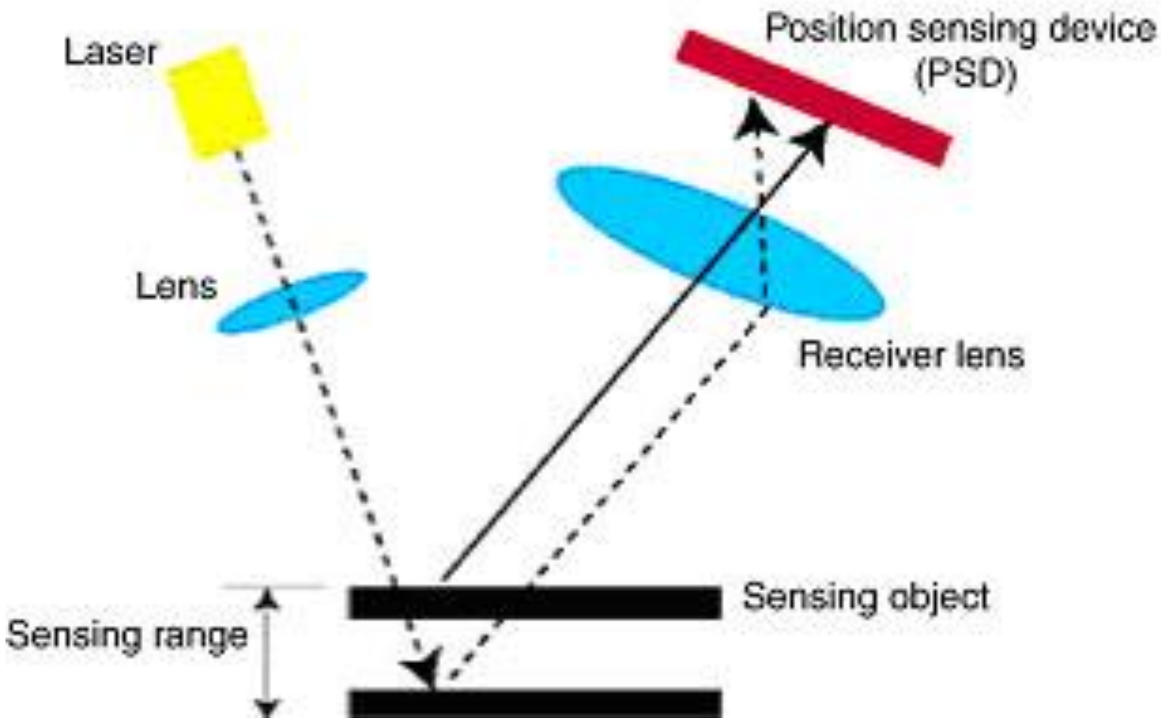
Infrared Distance sensor

- Infrared sensor values normally fluctuate in variant light conditions.
- There are a lot of limitations in infrared sensors, like the inability to use them in sunlight due to interference. It can make outdoor applications or dark indoor applications difficult.
- Ultrasonic sensors work using sound waves, detecting obstacles is not affected by as many factors. If reliability is an important factor in sensor selection, ultrasonic sensors are more reliable than IR sensors. If reliability is compromised for cost, infrared sensors are ideal.

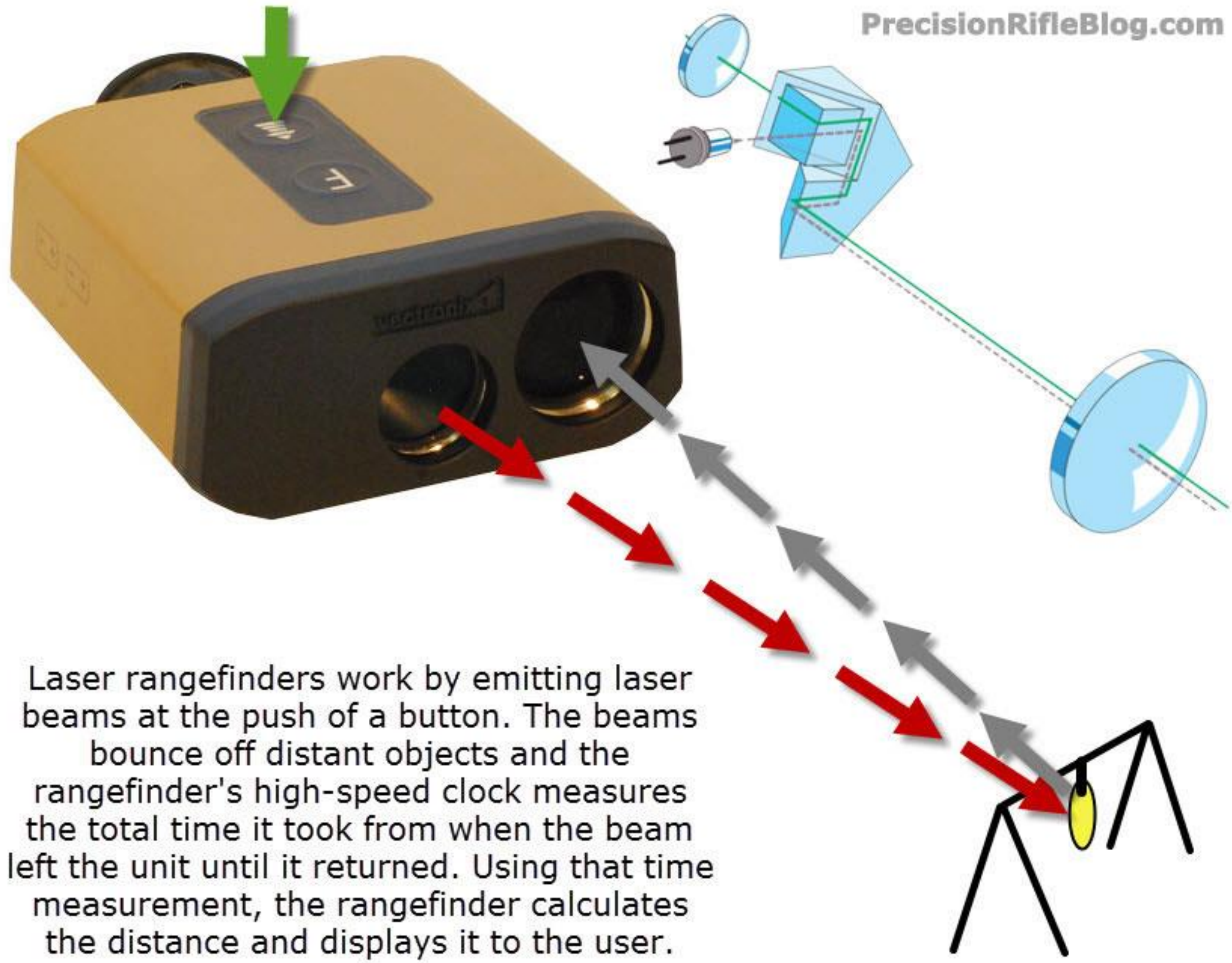


Laser range Sensor

- Laser light is transmitted and the reflected light is captured and analyzed.
- Distance is measured by calculating the speed of light and time taken for the light to reflect back to the receiver. These sensors are very useful for longer distances.

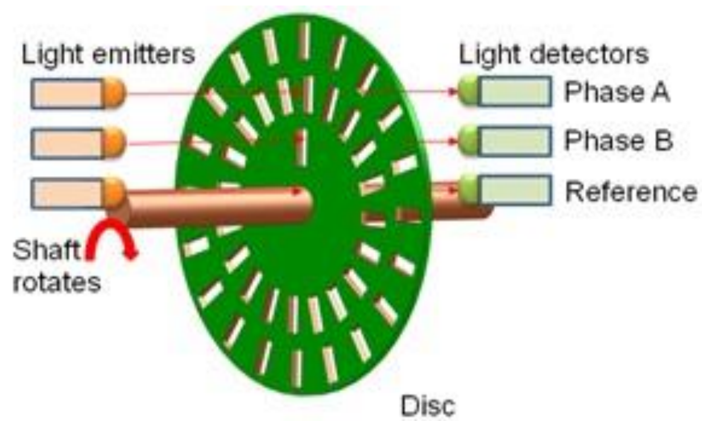


Laser range Sensor

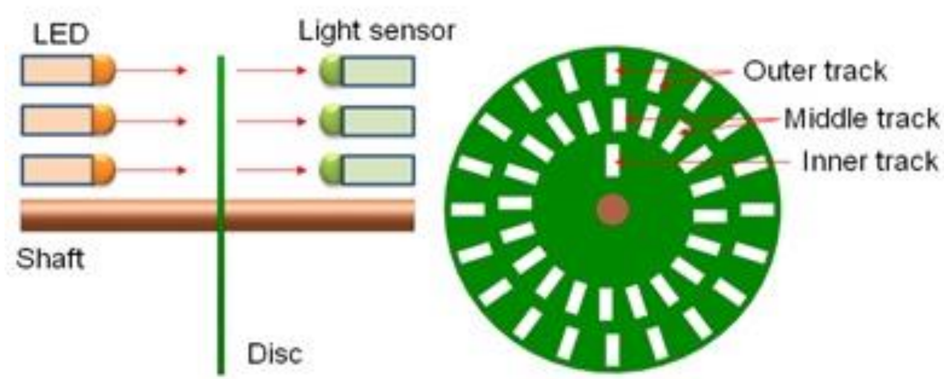


Optical encoders

- Optical encoders provide digital output as a result of linear / angular displacement.
- These are widely used in the Servo motors to measure the rotation of shafts.



- Figure shows the construction of an optical encoder. It comprises of a disc with three concentric tracks of equally spaced holes. Three light sensors are employed to detect the light passing thru the holes.

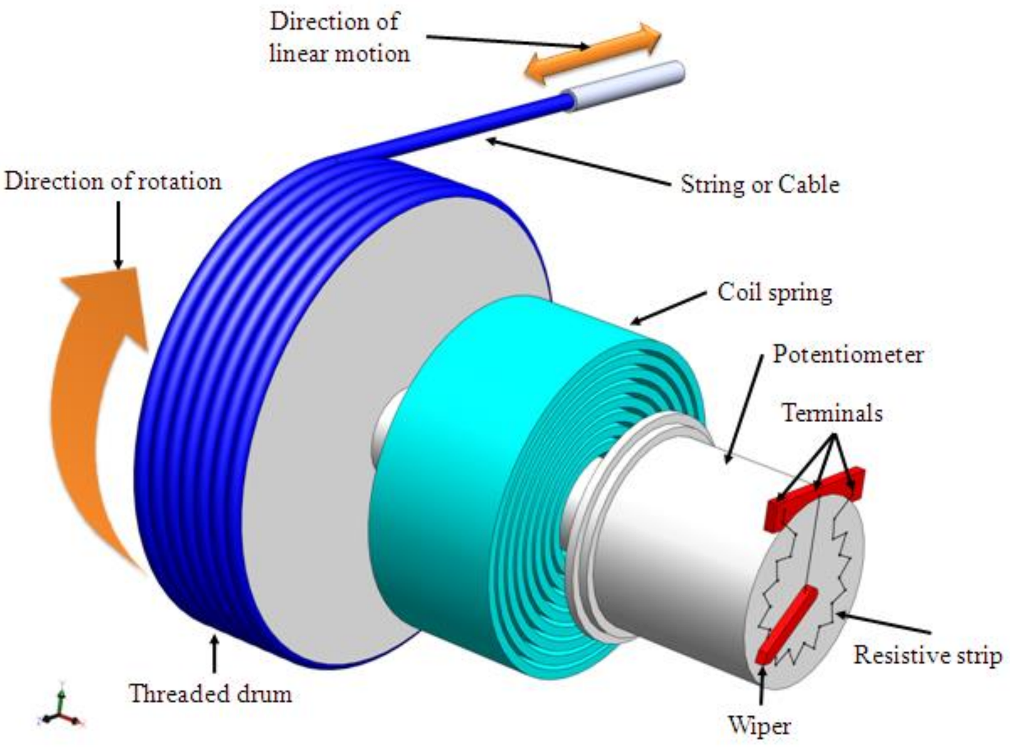


Optical encoders

- These sensors produce electric pulses which give the angular displacement of the mechanical element e.g. shaft on which the Optical encoder is mounted.
- The inner track has just one hole which is used locate the ‘home' position of the disc.
- The holes on the middle track offset from the holes of the outer track by one-half of the width of the hole. This arrangement provides the direction of rotation to be determined.
- When the disc rotates in clockwise direction, the pulses in the outer track lead those in the inner; in counter clockwise direction they lag behind. The resolution can be determined by the number of holes on disc. With 100 holes in one revolution, the resolution would be,
- $360°/100=3.6°$.

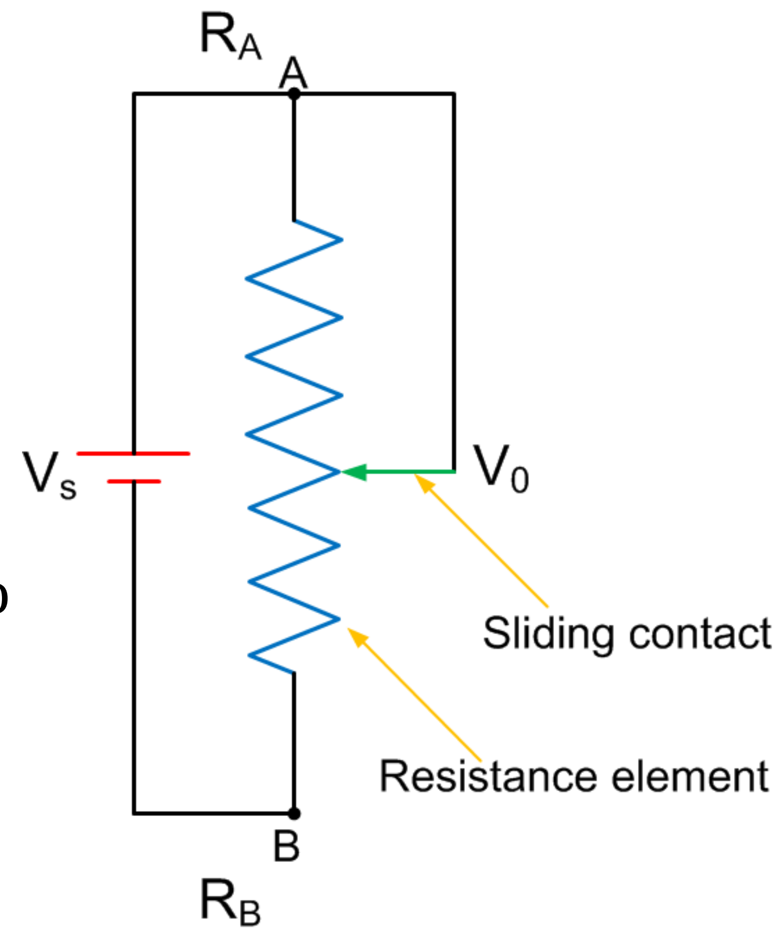
Potentiometer Sensors

- Figure shows the construction of a rotary type potentiometer sensor employed to measure the linear displacement. The potentiometer can be of linear or angular type.
- It works on the principle of conversion of mechanical displacement into an electrical signal.
- The sensor has a resistive element and a sliding contact (wiper).
- The slider moves along this conductive body, acting as a movable electric contact.



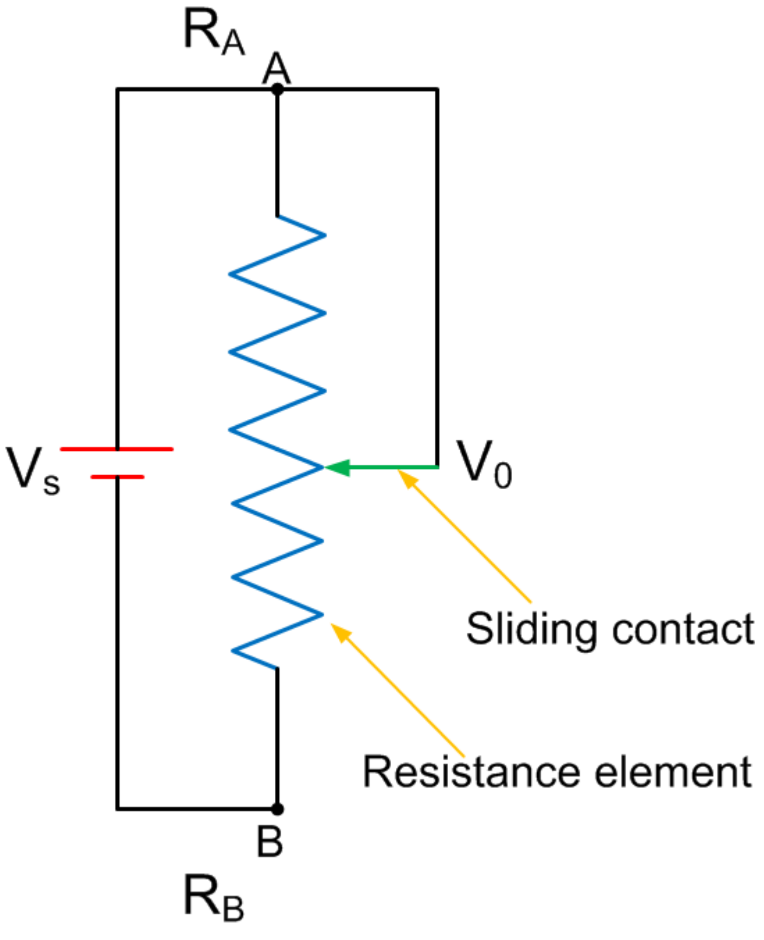
Potentiometer Sensors

- During the sensing operation, a voltage Vs is applied across the resistive element.
- A voltage divider circuit is formed when slider comes into contact with the wire.
- The output voltage (VA) is measured as shown in the figure. The output voltage is proportional to the displacement of the slider over the wire.
- Then the output parameter displacement is calibrated against the output voltage VA.



Potentiometer Sensors

- $V_A = I\ R_A$
- But $I = V_S / (R_A + R_B)$
- Therefore $V_A = V_S\ R_A / (R_A + R_B)$
- As we know that $R = \rho\ L / A$, where ρ is electrical resistivity, L is length of resistor and A is area of cross section
- $V_A = V_S\ L_A / (L_A + L_B)$



Applications of Potentiometer

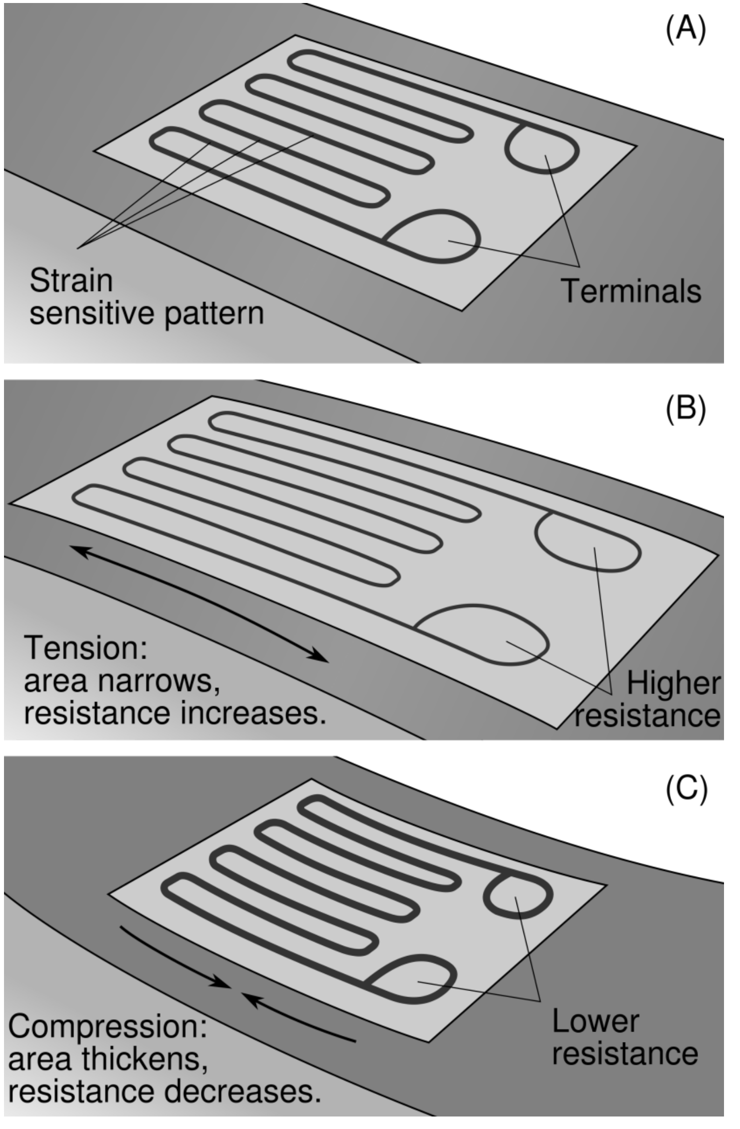
- These sensors are primarily used in the control systems with a feedback loop to ensure that the moving member or component reaches its commanded position.
- These are typically used on machine-tool controls, elevators, liquid-level assemblies, forklift trucks, automobile throttle controls.
- In manufacturing, these are used in control of injection molding machines, woodworking machinery, printing, spraying, robotics, etc.
- These are also used in computer-controlled monitoring of sports equipment.

Strain Gauges

- The strain in an element is a ratio of change in length in the direction of applied load to the original length of an element.
- The strain changes the resistance R *of the element. Therefore,*

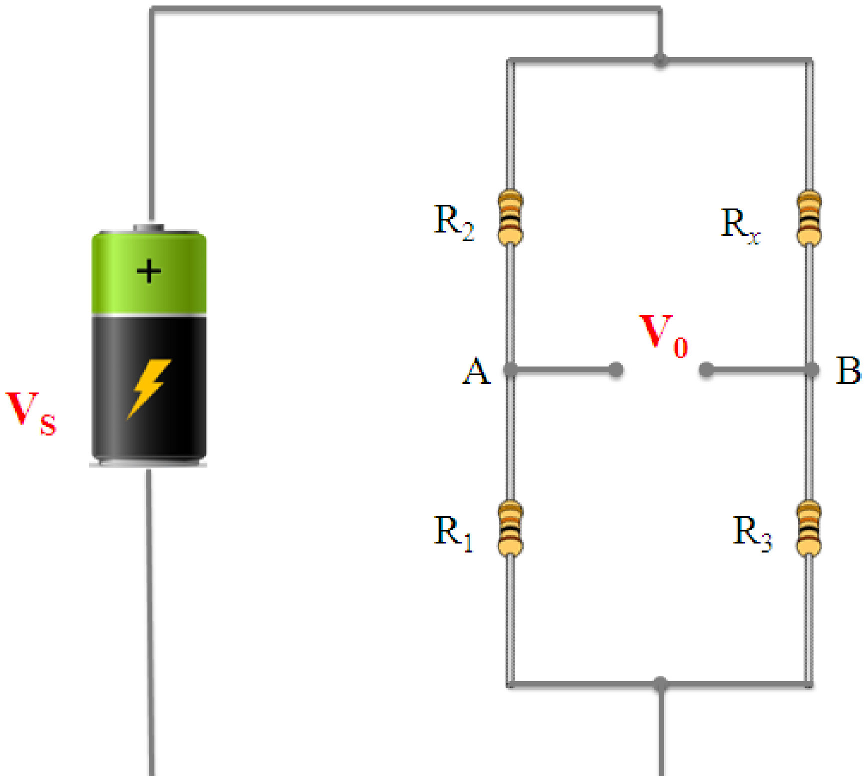
  $\Delta R/R \;\alpha\; \varepsilon$;

  $\Delta R/R = G\,\varepsilon$
- where G is the constant of proportionality and is called as gauge factor.
- Strain gauge comprises of a pattern of resistive foil arranged as shown in Figure



Strain Gauges

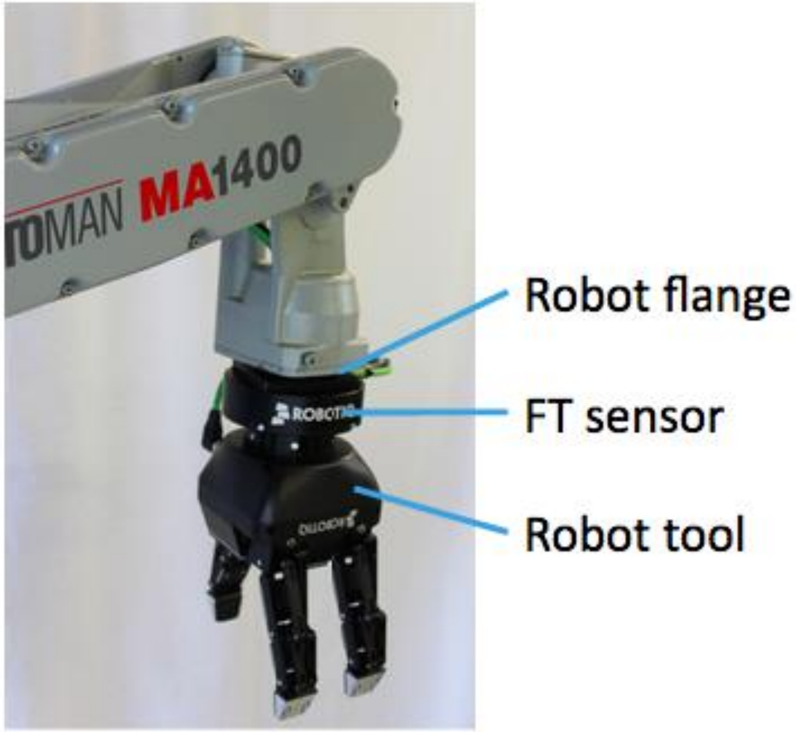
- These foils are made of Constantan alloy (copper-nickel 55-45% alloy) and are bonded to a backing material plastic (ployimide), epoxy or glass fiber reinforced epoxy.
- The strain gauges are secured to the work piece by using epoxy or Cyanoacrylate cement Eastman 910 SL.
- As the work piece undergoes change in its shape due to external loading, the resistance of strain gauge element changes.
- This change in resistance can be detected by a using a Wheatstone's resistance bridge as shown in Figure.



Strain Gauges

- In the balanced bridge we can have a relation,
- $R_2 / R_1 = R_x / R_3$
- where R_x is resistance of strain gauge element, R_2 is balancing/adjustable resistor, R_1 and R_3 are known constant value resistors.

- The measured deformation or displacement by the stain gauge is calibrated against change in resistance of adjustable resistor R_2 which makes the voltage across nodes A and B equal to zero.



Applications of Strain Gauges

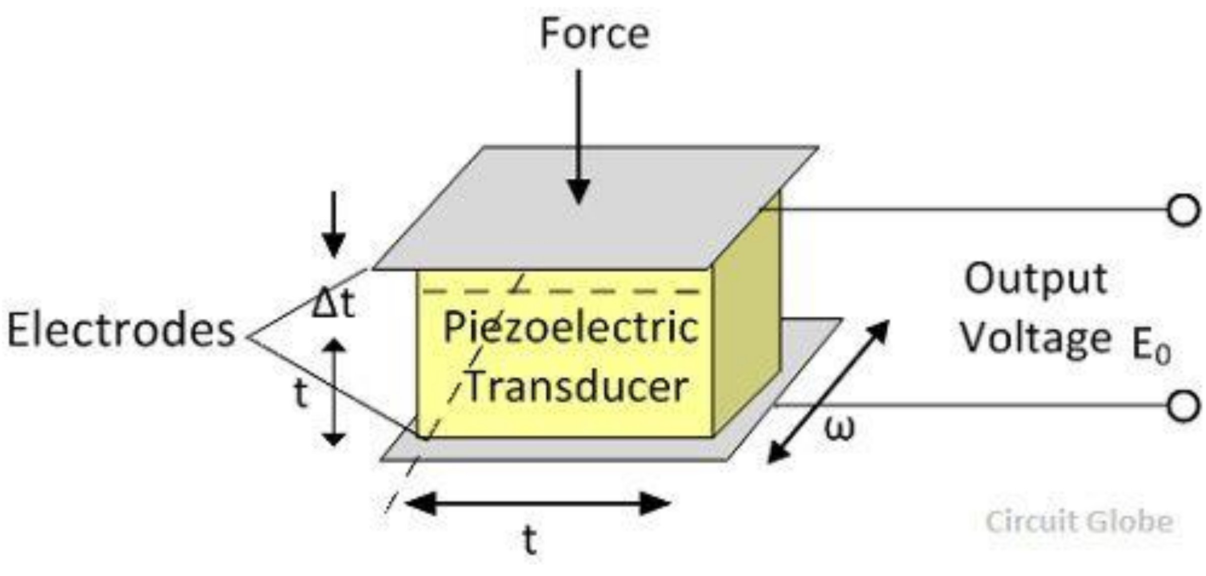
- Strain gauges are widely used in experimental stress analysis and diagnosis on machines and failure analysis.
- They are basically used for multi-axial stress fatigue testing, proof testing, residual stress and vibration measurement, torque measurement, bending and deflection measurement, compression and tension measurement and strain measurement.
- Strain gauges are primarily used as sensors for machine tools and safety in automotives.
- In particular, they are employed for force measurement in machine tools, hydraulic or pneumatic press and as impact sensors in aerospace vehicles.

Piezoelectric Sensor

- A sensor that utilizes the piezoelectric effect, to measure changes in acceleration, strain, pressure, and force by converting them into electrical charge is called as a piezoelectric sensor.
- The piezoelectric transducer uses the piezoelectric material which has a special property, i.e. the material induces voltage when the pressure or stress applied to it.
- Piezo is a Greek word which means ‘press’ or ‘squeeze’. The word piezoelectric means the electricity produces by the pressure. The Quartz is the examples of the natural piezoelectric crystals, whereas the Rochelle salts, ammonium dehydration, phosphate, lithium sulphate, dipotassium tartrate are the examples of the man made crystals.

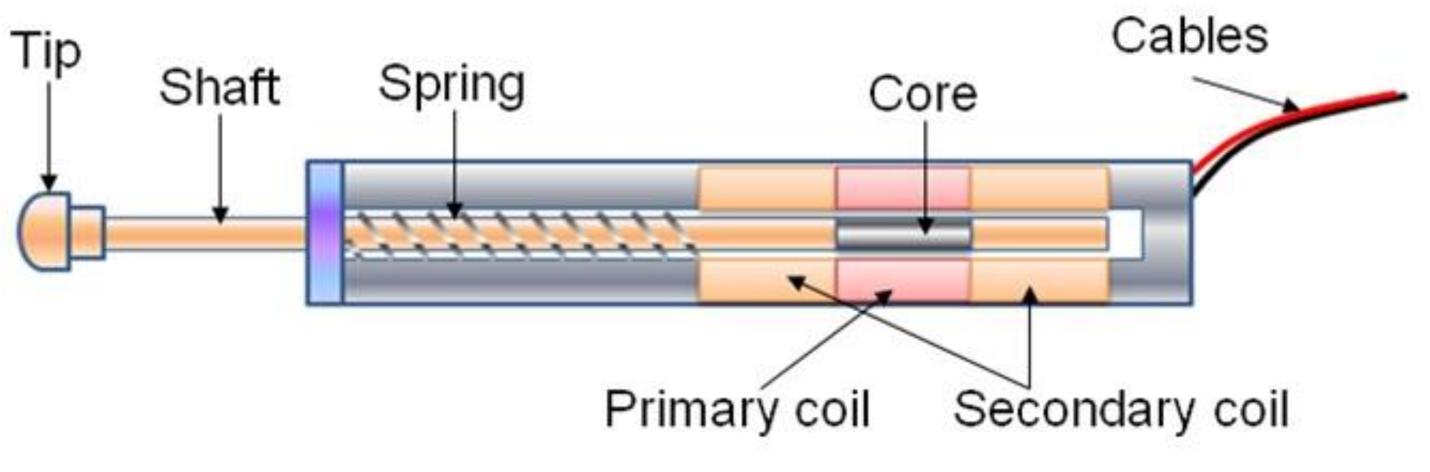
Piezoelectric Sensor

- The generated piezoelectricity is proportional to the pressure applied to the solid piezoelectric crystal materials.
- A piezoelectric force sensor, responds directly to an applied force: the associated deformation is in most cases negligibly small, assuring small loading errors in the force measurement.



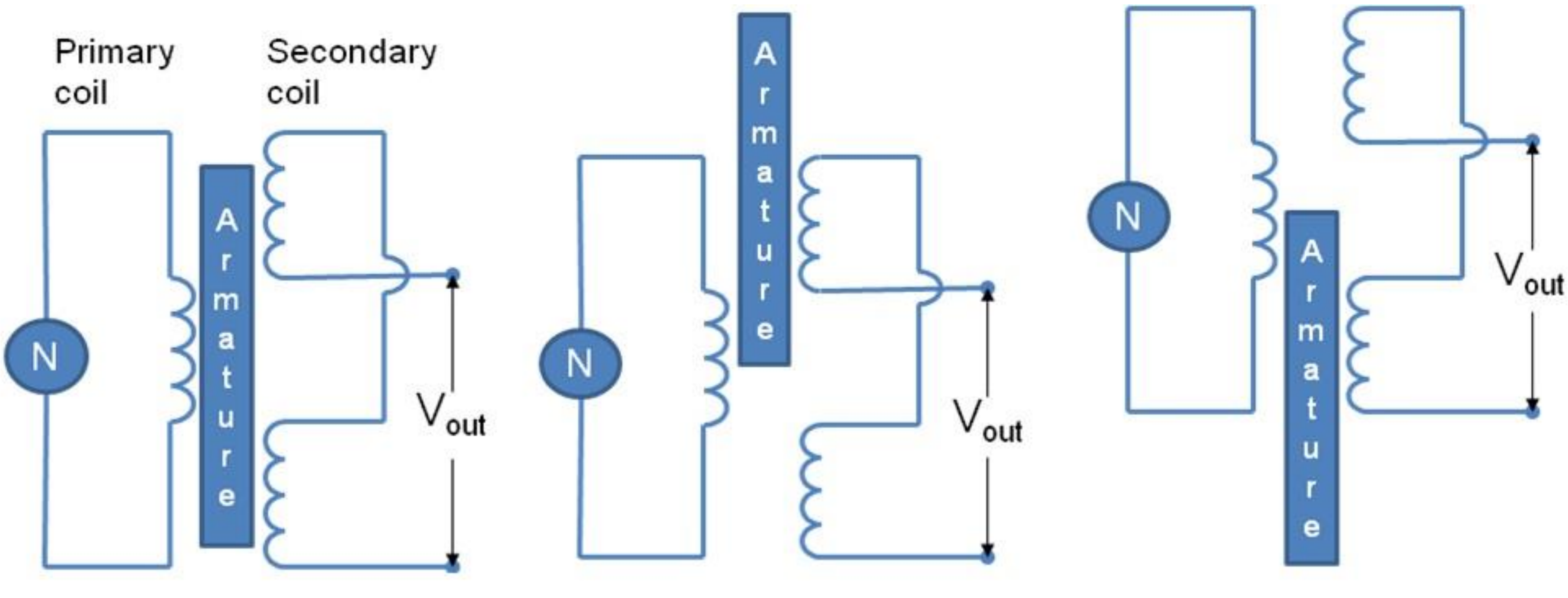
Linear Variable Differential Transformer (LVDT)

- Linear variable differential transformer (LVDT) is a primary transducer used for measurement of linear displacement with an input range of about ± 2 to ± 400 mm in general. It has non-linearity error ± 0.25% of full range.
- Figure shows the construction of a LVDT sensor. It has three coils symmetrically spaced along an insulated tube. The central coil is primary coil and the other two are secondary coils.
- A magnetic core attached to the element of which displacement is to be monitored is placed inside the insulated tube.



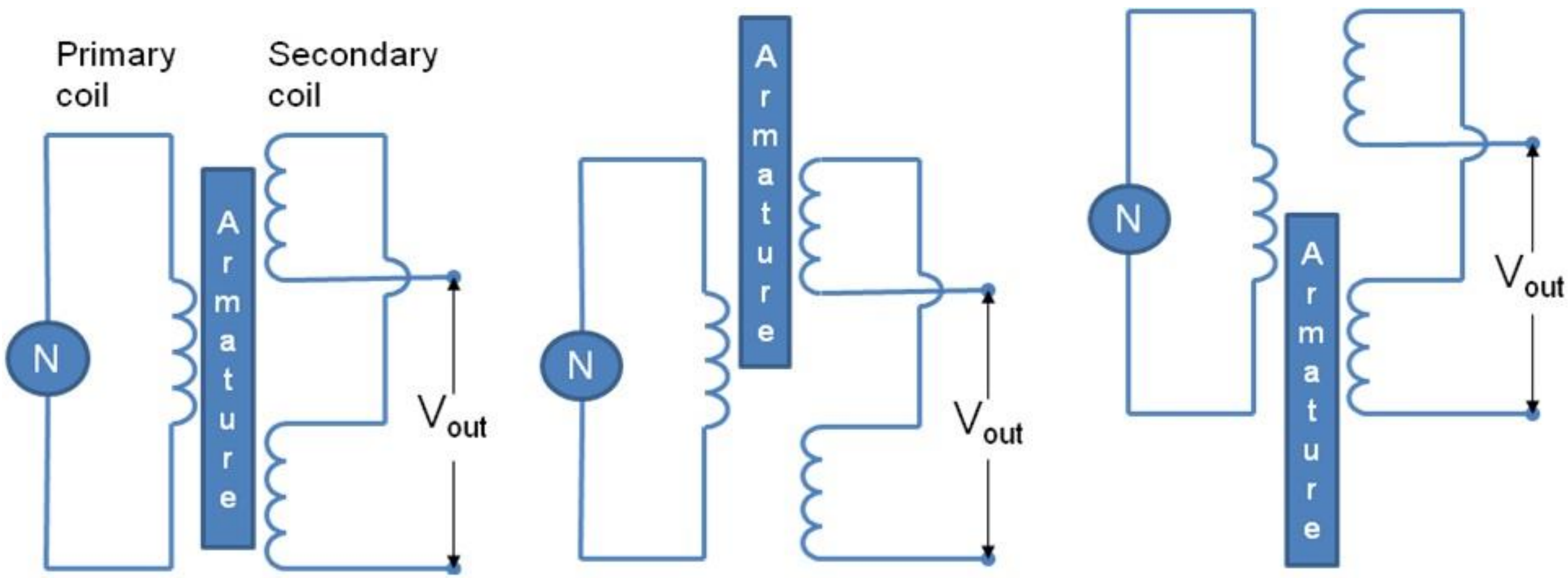
LVDT Sensors

- Due to an alternating voltage input to the primary coil, alternating electro-magnetic forces (emfs) are generated in secondary coils. When the magnetic core is centrally placed with its half portion in each of the secondary coil regions then the resultant voltage is zero.



LVDT Sensors

- If the core is displaced from the central position as shown in Figure, say, more in secondary coil 1 than in coil 2, then more emf is generated in coil 1 than the other, and there is a resultant voltage from the coils.
- If the magnetic core is further displaced, then the value of resultant voltage increases in proportion with the displacement.



LVDT Sensors

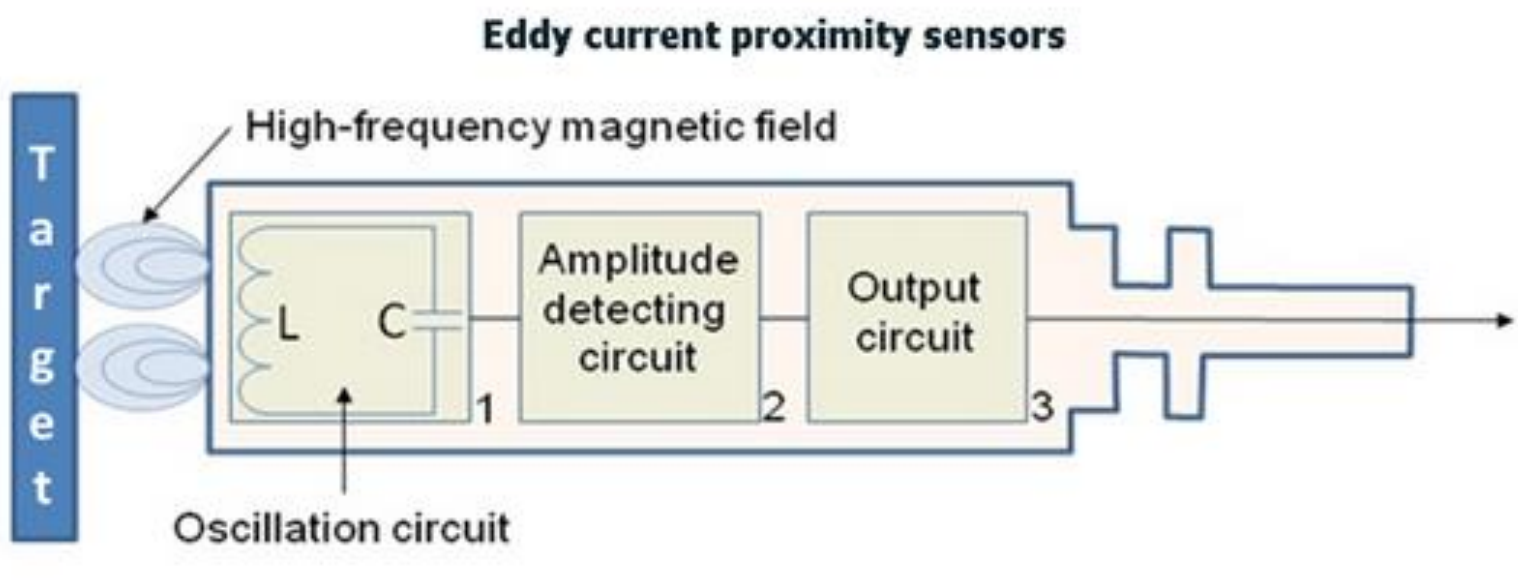
- With the help of signal processing devices such as low pass filters and demodulators, precise displacement can be measured by using LVDT sensors.
- LVDT exhibits good repeatability and reproducibility. It is generally used as an absolute position sensor. Since there is no contact or sliding between the constituent elements of the sensor, it is highly reliable. These sensors are completely sealed and are widely used in Servomechanisms, automated measurement in machine tools.

Applications of LVDT Sensors

- Measurement of spool position in a wide range of servo valve applications
- To provide displacement feedback for hydraulic cylinders
- To control weight and thickness of medicinal products viz. tablets or pills
- For automatic inspection of final dimensions of products being packed for dispatch
- To measure distance between the approaching metals during Friction welding process
- To continuously monitor fluid level as part of leak detection system
- To detect the number of currency bills dispensed by an ATM

Eddy current proximity sensors

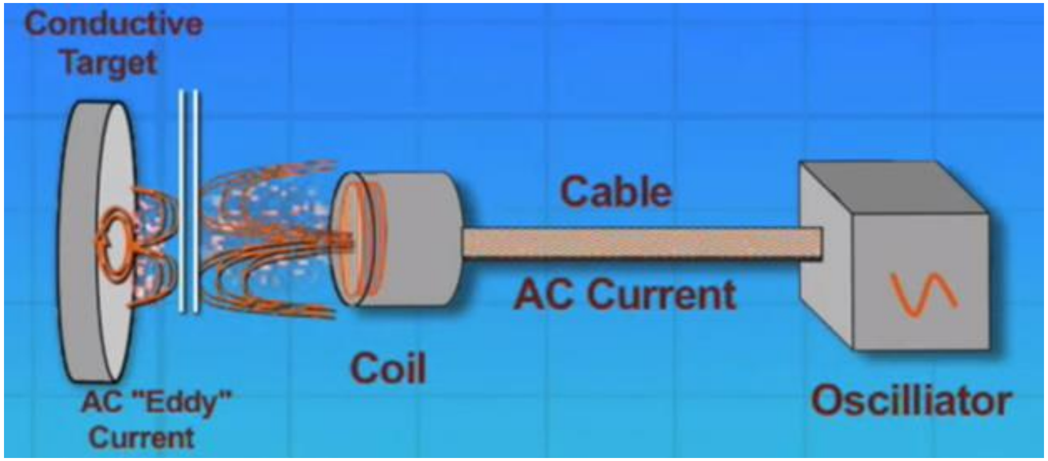
- Eddy current proximity sensors are used to detect non-magnetic but conductive materials. They comprise of a coil, an oscillator, a detector and a triggering circuit. Figure shows the construction of eddy current proximity switch.



Schematic of Inductive Proximity Sensor

Eddy current proximity sensors

- When an alternating current is passed thru this coil, an alternative magnetic field is generated.
- If a metal object comes in the close proximity of the coil, then eddy currents are induced in the object due to the magnetic field.
- These eddy currents create their own magnetic field which distorts the magnetic field responsible for their generation. As a result, impedance of the coil changes and so the amplitude of alternating current.



Eddy current proximity sensors

- This can be used to trigger a switch at some pre-determined level of change in current.
- Eddy current sensors are relatively inexpensive, available in small in size, highly reliable and have high sensitivity for small displacements.

Applications of eddy current proximity sensors

- Automation requiring precise location
- Machine tool monitoring
- Final assembly of precision equipment such as disk drives
- Measuring the dynamics of a continuously moving target, such as a vibrating element,
- Drive shaft monitoring
- Vibration measurements

Light sensors

- Photoresistor is a type of resistor whose resistance varies with change in light intensity; more light leads to less resistance and less light leads to more resistance. These inexpensive sensors can be easily implemented in most light dependant robots.
- Photovoltaic cells convert solar radiation into electrical energy. This is especially helpful to build a solar robot. Although photovoltaic cell is considered as an energy source, an intelligent implementation combined with transistors and capacitors can convert this into a sensor.


Photo Voltaic Cells (Solar Cells)


Photoresistors (LDR)

Sound Sensor

- This sensor (generally a microphone) detects sound and returns a voltage proportional to the sound level. A simple robot can be designed to navigate based on the sound it receives. Imagine a robot which turns right for one clap and turns left for two claps. Complex robots can use the same microphone for speech and voice recognition.
- Sound sensors generate a very small voltage difference which should be amplified to generate measurable voltage change.

Temperature Sensor

- What if your robot has to work in a desert and transmit ambient temperature? Simple solution is to use a temperature sensor. Tiny temperature sensor ICs provide voltage difference for a change in temperature. Few generally used temperature sensor IC's are LM34, LM35, TMP35, TMP36, and TMP37.

Contact Sensor

- Contact sensors are those which require physical contact against other objects to trigger. A push button switch, limit switch or tactile bumper switch are all examples of contact sensors.
- These sensors are mostly used for obstacle avoidance robots. When these switches hit an obstacle, it triggers the robot to do a task, which can be reversing, turning, switching on a LED, Stopping etc. There are also capacitive contact sensors which react only to human touch. Contact Sensors can be easily implemented, but the drawback is that they require physical contact.

Limit Switch (Contact Sensor)

Actuator

- An *actuator* is a specific type of a transducer which is a type of motor that is responsible for moving or controlling a mechanism or system that is operated by a source of energy, typically electric current, hydraulic fluid pressure, or pneumatic pressure, and converts that energy into motion.

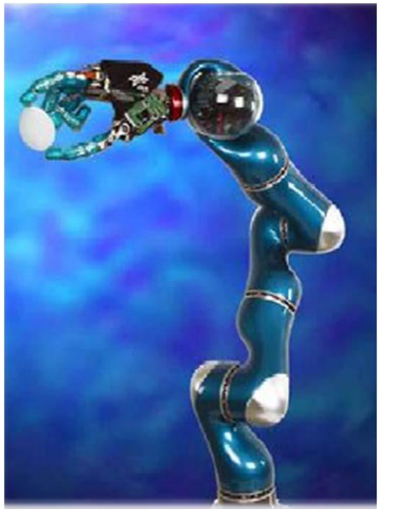
- Actuator plays a very important role while implementing control. The controller provides command signal to the actuator for actuation.
- The controller codes aim at deriving the actuator when an event has occurred.

Actuators for Robots

- Actuators are used in order to produce mechanical movement in robots.
- Actuators 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.
- Hydraulic actuators
- Pneumatic actuators
- Electric motor
  - DC motor, Servomotor, Stepper motor
- Direct drive motor
- Magnetostrictive actuators
- Shape memory metal actuators

Electric 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 motor 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, Pneumatic and other Actuators

- 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.

Important Properties of Actuators

- Power
- Weight

Power-to-Weight Ratio

- Price
- Accuracy
- Response Time
- Reliability
- Maintenance

Examples (important properties)

□ Underwater Robots

✓ waterproof operation

□ Space Robots

✓ liftoff weight, reliability

□ Industrial Robots

✓ power, accuracy

□ Entertainment Robots

✓ price

There is no ideal actuator, so it should be selected properly considering important properties.

Characteristics of Actuator Systems

- Power-to-Weight Ratio
  - Power-to-Weight ratio → Mobility of Robots
  - Ideal : low weight, high power
  - Hydraulic > Electric > Pneumatic
    - However hydraulic requires heavy power units (pump, reservoir, filters…)
- Stiffness vs. Compliance
  - Stiff System (Hydraulic)
    - Good : Rapid response, Accurate control
    - Bad : Dangerous
  - Compliant System (Pneumatic)
    - Good : Less dangerous
    - Bad : Slow response, Inaccurate control
- Direct Drive vs. Reduction Gear
  - Direct Drive (Hydraulic, Pneumatic)
    - Simple Structure → reduction of weight, cost, joint inertia, backlash, noise…
  - Reduction Gear (Electric)
    - Complex Structure → increase of weight, cost, joint inertia, backlash, noise…
    - But it also increases the resolution of the system. → very accurate control

Summary of Actuator Characteristics

	Hydraulic	Electric	Pneumatic
Good	• Good for large robots and heavy payload • Highest power/weight ratio • Stiff system, high accuracy, better response • No reduction gear needed • Can work in wide range of speeds without difficulty • Can be left in position without any damage	• Good for all sizes of robots • Better control, good for high precision robots • Higher compliance than hydraulics • Reduction gears used to reduce inertia on the motor • No leak, good for clean room • Reliable, low maintenance • Can be spark-free. Good for explosive environments	• Reliable components • No leaks or sparks • Inexpensive and simple • Low pressure compared to Hydraulics • Good for on-off applications and for pick and place • Compliant systems
Bad	• May leak. Not fit for clean room • Requires pump, reservoir, motor, hoses, etc. • Can be expensive and noisy. Requires maintenance • Viscosity of oil changes with temperature • Very susceptible to dirt and other foreign material in oil • Low compliance • High torque, high pressure, large inertia on the actuator	• Low stiffness • Needs reduction gears, increased backlash, cost, weight, etc. • Motor needs braking device when not powered. Otherwise, the arm will fall	• Noisy systems • Require air pressure, filter, etc. • Difficult to control their linear position • Deform under load constantly • Very low stiffness. Inaccurate response • Lowest power to weight ratio

Hydraulic and Pneumatic Actuator

- Actuators are output devices which convert energy from pressurized hydraulic oil or compressed air into the required type of action or motion. In general, hydraulic or pneumatic systems are used for gripping and/or moving operations in industry.
- Actuators can be classified into three types.
  - **Linear actuators**: These devices convert hydraulic/pneumatic energy into linear motion.
  - **Rotary actuators**: These devices convert hydraulic/pneumatic energy into rotary motion.
  - **Actuators to operate flow control valves**: these are used to control the flow and pressure of fluids such as gases, steam or liquid.
- The construction of hydraulic and pneumatic linear actuators is similar. However they differ at their operating pressure ranges. Typical pressure of hydraulic cylinders is about 100 bar and of pneumatic system is around 10 bar.

Hydraulic Actuators

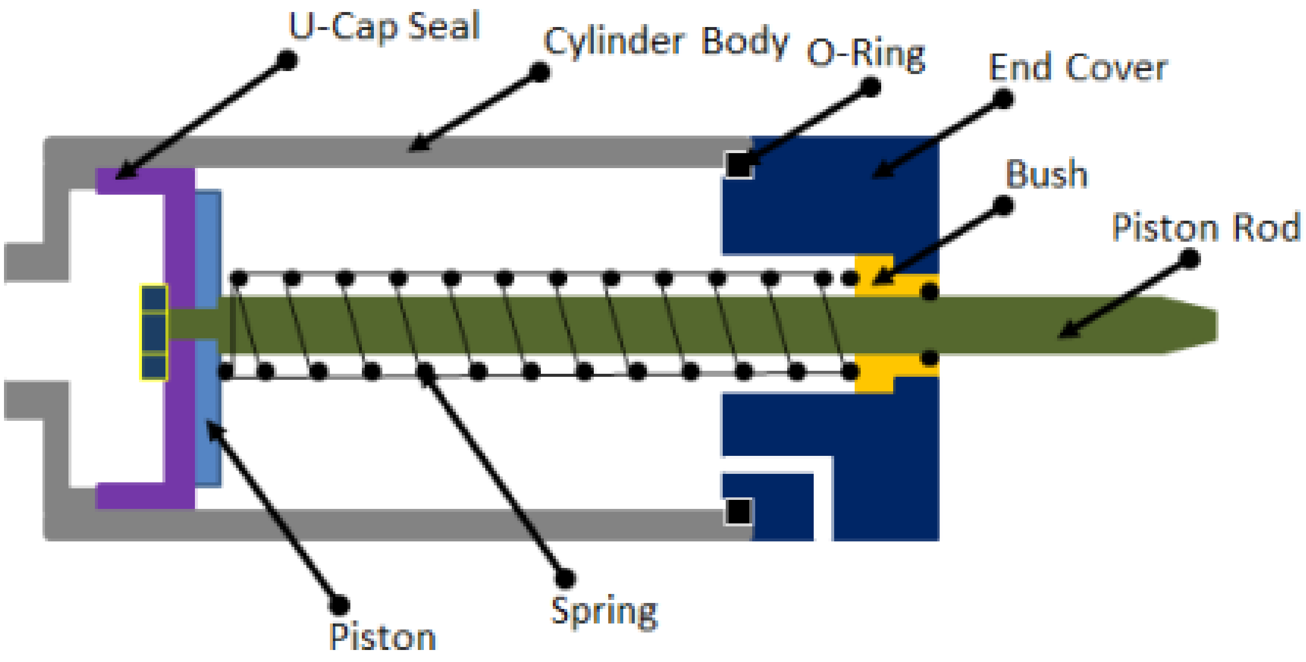
- A hydraulic system generally consists of the following parts:
  - Hydraulic linear or rotary cylinders to provide the force or torque needed to move the joints and are controlled by servo valve or manual valve.
  - A hydraulic pump to provide high pressure fluid to the system
  - Electric motor to operate the hydraulic pump.
  - Cooling system to get rid of heat.
  - Reservoir to keep fluid supply available to the system.
  - Servo valve which is a very sensitive valve that controls the amount and the rate of the fluid to the cylinders. The servo valve is generally driven by a hydraulic servomotor.
  - Sensors to control the motion of the cylinders (position, velocity, magnetic, touch,..)
  - Connecting hoses to transport the pressurized fluid.
  - Safety check valves, holding valves.

Pneumatic Actuators

- Similar principals to hydraulic systems
  - Pressurized air is used instead of hydraulic fluid.
  - Controlled by manual or electrically controlled solenoid valves.
- Compressible air
  - Accurate control is difficult.
  - The actuator is usually all the way forward or all the way backward; fully on or fully off.

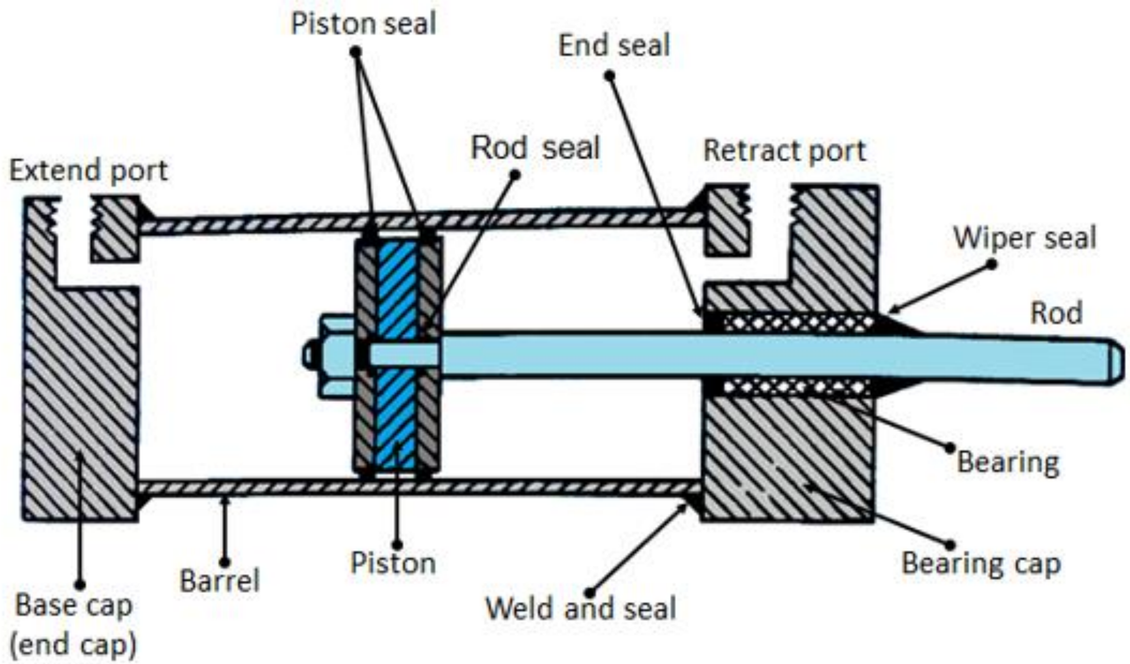
Single Acting Cylinder

- These cylinders produce work in one direction of motion hence they are named as single acting cylinders.
- The compressed air pushes the piston located in the cylindrical barrel causing the desired motion. The return stroke takes place by the action of a spring. Generally the spring is provided on the rod side of the cylinder.



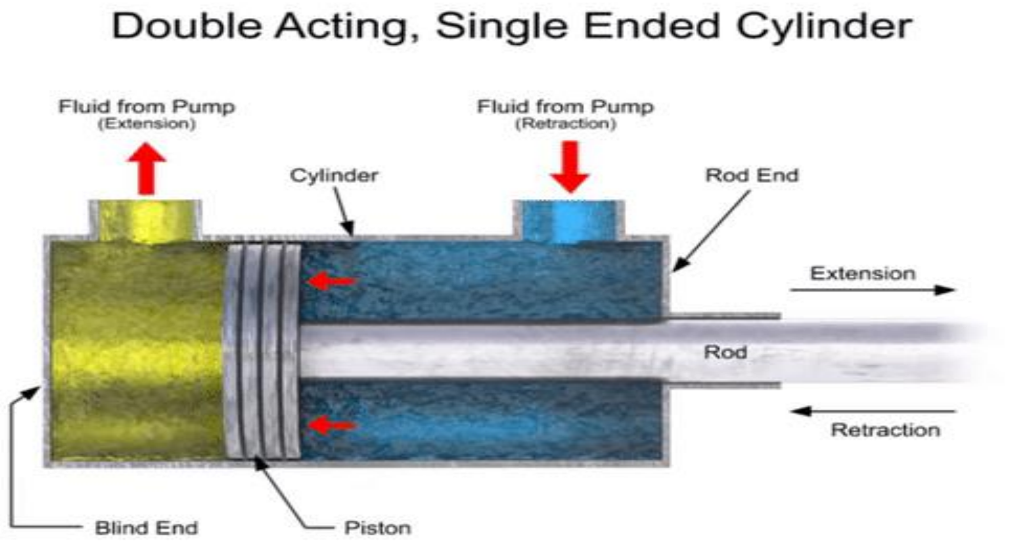
Double Acting Cylinder

- The main parts of a hydraulic double acting cylinder are: piston, piston rod, cylinder tube, and end caps. The piston rod is connected to piston head and the other end extends out of the cylinder. The piston divides the cylinder into two chambers namely the rod end side and piston end side. The seals prevent the leakage of oil between these two chambers. The cylindrical tube is fitted with end caps.



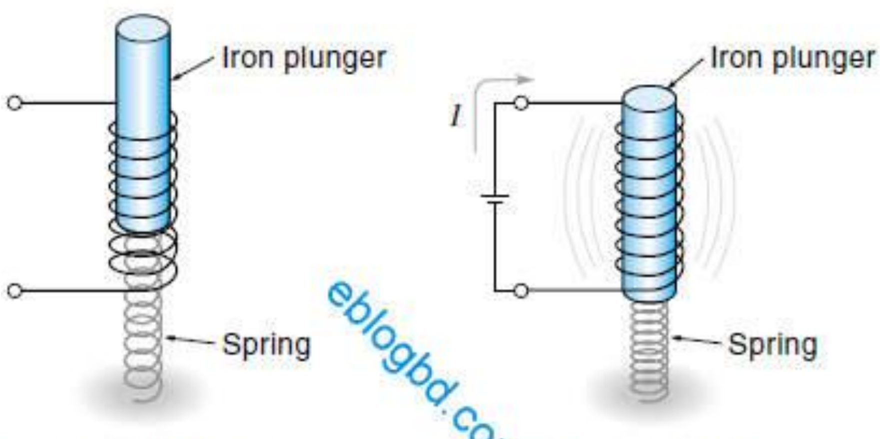
Double Acting Cylinder

- The pressurized oil, air enters the cylinder chamber through the ports provided. In the rod end cover plate, a wiper seal is provided to prevent the leakage of oil and entry of the contaminants into the cylinder. The combination of wiper seal, bearing and sealing ring is called as cartridge assembly. The piston seal prevents metal to metal contact and wear of piston head and the tube. These seals are replaceable. End cushioning is also provided to prevent the impact with end caps.

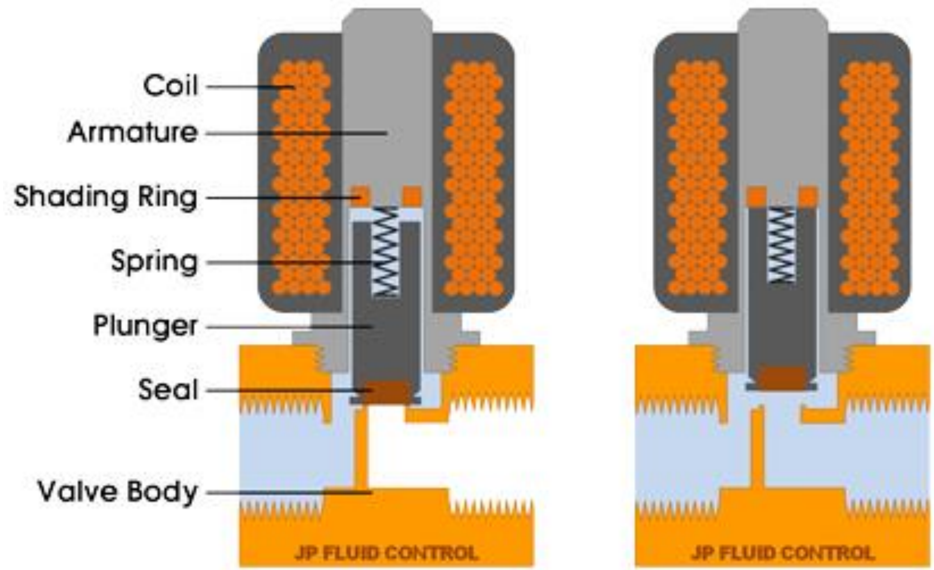


Solenoid Valve

- A **solenoid** is a simple electromagnetic device that converts electrical energy directly into linear mechanical motion, but it has a very short stroke (length of movement), which limits its applications.
- The solenoid consists of a coil of wire with an iron plunger that is allowed to move through the center of the coil.
- When the coil is energized, the resulting magnetic field pulls the plunger to the middle of the coil. The magnetic force is unidirectional — a spring is required to return the plunger to its un energized position.



(a) Unenergized (b) Energized



Electrical Actuators

- Advantages
  - Easy to control, low cost
  - Power supply available almost everywhere
  - Large variety of products
  - Normally high velocities 1000-10000 rpm
  - High power conversion efficiency
  - No pollution in working environment

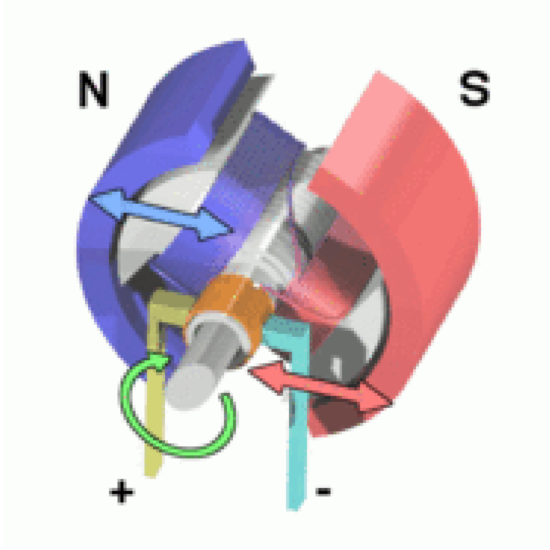
- Disadvantages
  - Overheating
  - Need special protection in flammable environments

Electrical Actuator Types

- 1. Servo Motor
- 2. DC-motors
- 3. Brushless DC-motors
- 4. Asynchronous motors
- 5. Synchronous motors
- 6. Stepper Motor
- Most of the time servo motor is used in the most of the robotics application.

Electric Motor

- An *electric motor* is a type of an electric actuator.
- Electric motors are based on the principle of electromagnetism.
- The mechanical construction uses two main components; a Stator and a Rotor.
- **Stator** is a stationary component of the motor and **rotor** is a rotating component. Stator generally has permanent magnets (in some cases electromagnetic windings), and rotor has electromagnets (in some cases permanent magnets) attached.



Electric Motor

- When electric current passes through the electromagnet, it creates a magnetic field generating a magnetic force between the stator and the rotor.
- The attractive and repulsive forces between the electromagnet and the permanent magnet make the rotor to turn and rotate.
- To get the rotor to turn, the electromagnets create a repulsive force at one end (pole) which attracts the permanent magnet towards the other end of the electromagnet.
- Once the rotor does a half-turn, the poles of the electromagnet flips (North to south or south to North) pushing the rotor further towards the other end. The process continues creating a circular motion.

Electric Motor

- The force created by the magnetic field between the rotor and the stator determines the **torque** of the motor.
- Number of times the rotor rotates in one minute determines the velocity of the motor, measured as Revolutions per Minute (**RPM**).
- Hence whenever you intend to buy a motor, always watch out for RPM and torque of the motor.
- Installing gears can increase either torque or velocity, but reducing the other.

AC motors and DC motors

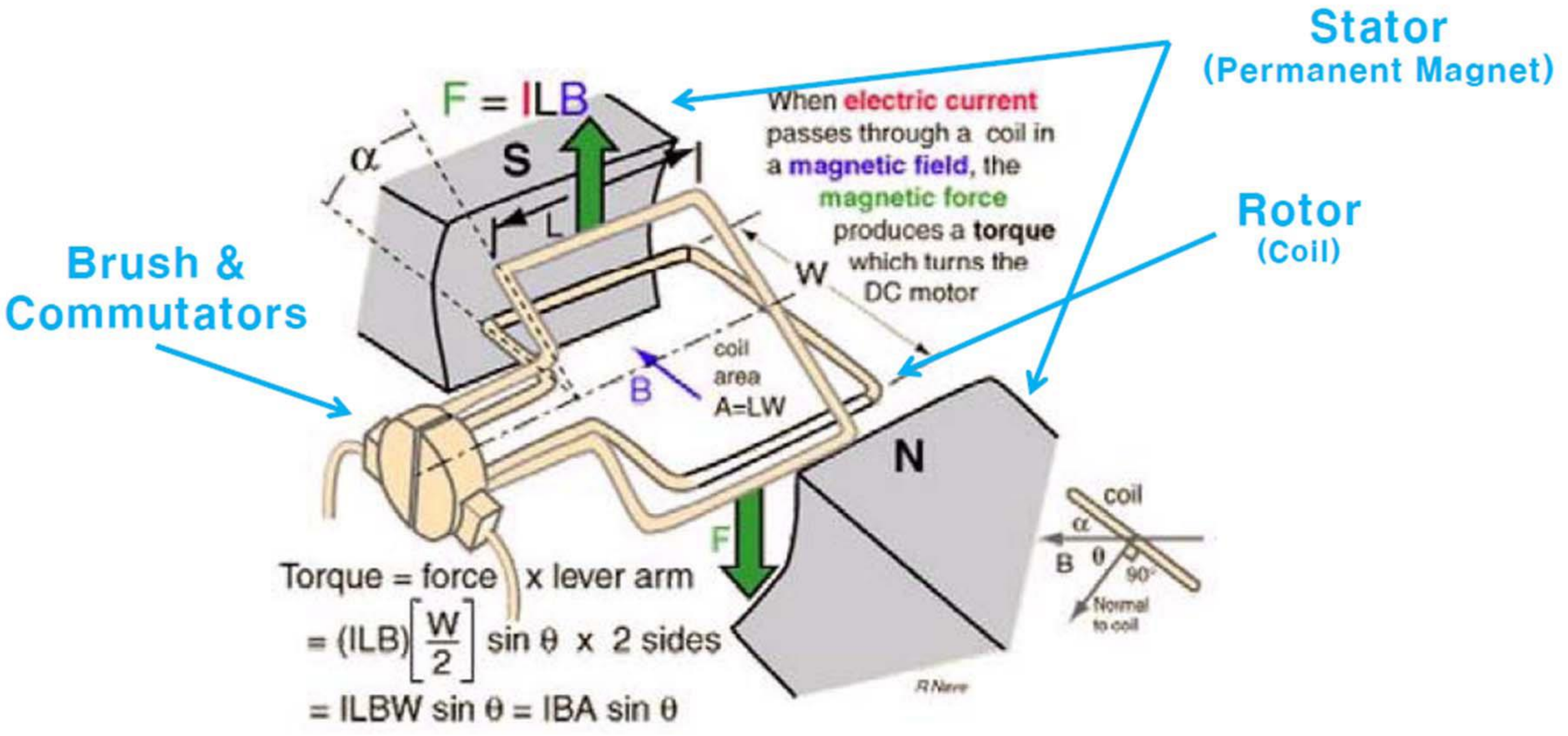
- **AC Motor**: Motors are designed to run on Alternate current (AC) or Direct Current (DC). However, it is very uncommon to use AC motors in mobile robots as they are harder to use, and most of the robots and circuits are DC powered. Therefore AC powered motor is limited to stationary and industrial robots.

- **DC motor**: DC motors are very easy to implement and most commonly used actuators in robots. There are different types of DC motors available.

- **Types of DC Motors:**
- Brushed DC motor, Brushless DC motor, Gear motor, Stepper motor, Servo motor, etc.

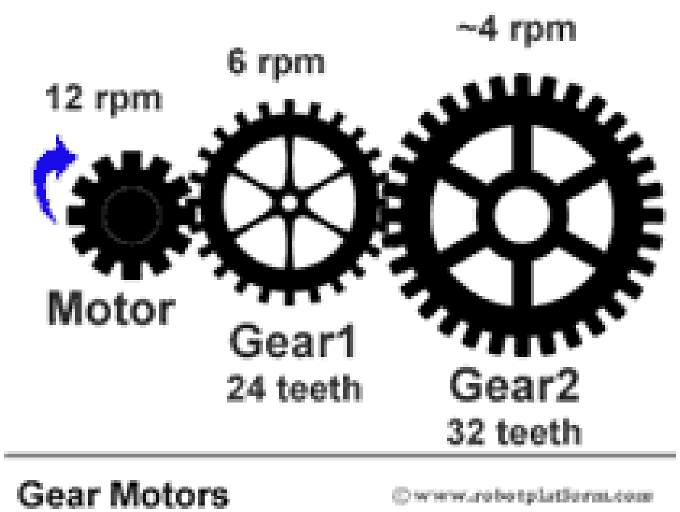
DC Motor

- The stator creates a fixed magnetic field.
- The rotor carries a current. → Magnetic Force
- Brushes and commutators change the direction of current causing the rotor to rotate continuously.
- Mechanical Switch: a) can be broken, b) generates noise signal



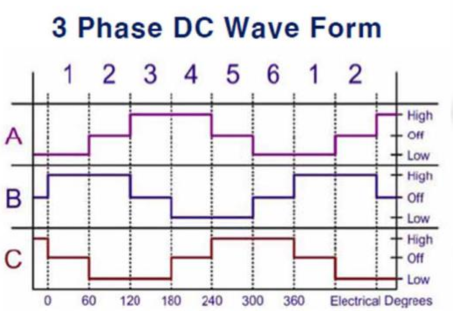
Geared DC motor

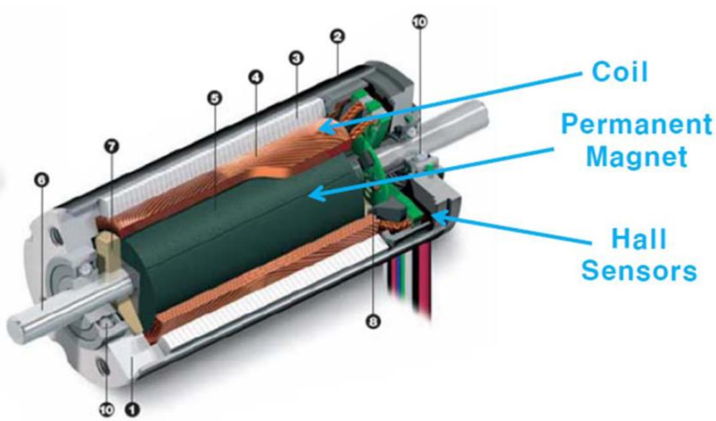
- DC motors are often coupled with gears which provide greater torque, but reducing speed. Normally all our robots would require a geared DC motor to pull the weight of our robot and any additional components placed.
- In DC gear motor, the motor shaft is connected to another bigger gear, which is further connected to a larger gear. As the motor rotates, the rotations per minute (rpm) of Gear1 is lesser than the motor. Gear2 has even less number of rotations per minute. However, each gear increases the torque of overall setup.

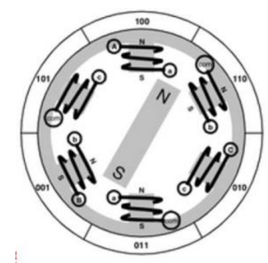


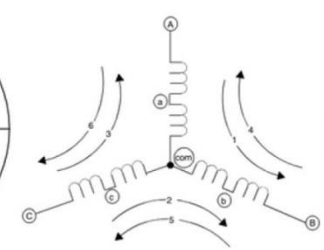
Brushless DC motors

- Hybrid between AC and DC motors - similar construction as AC
- Operated with an electronically switched DC waveform that is similar to AC current, not limited to 50 Hz
  - Can be operated at any speed
- Needs a controller circuit to electrically switch the DC waveform
  - Feedback from optical encoder or hall effect sensor
- Rotor usually has 3 phases
  - 3 currents, with 120° phase shift
- Brushless motors are very useful in robots as they are more capable; they provide enough torque, and greater speeds than brushed motors. Brushless motors are expensive due to their design complexity and need a controller to control their speed and rotation.



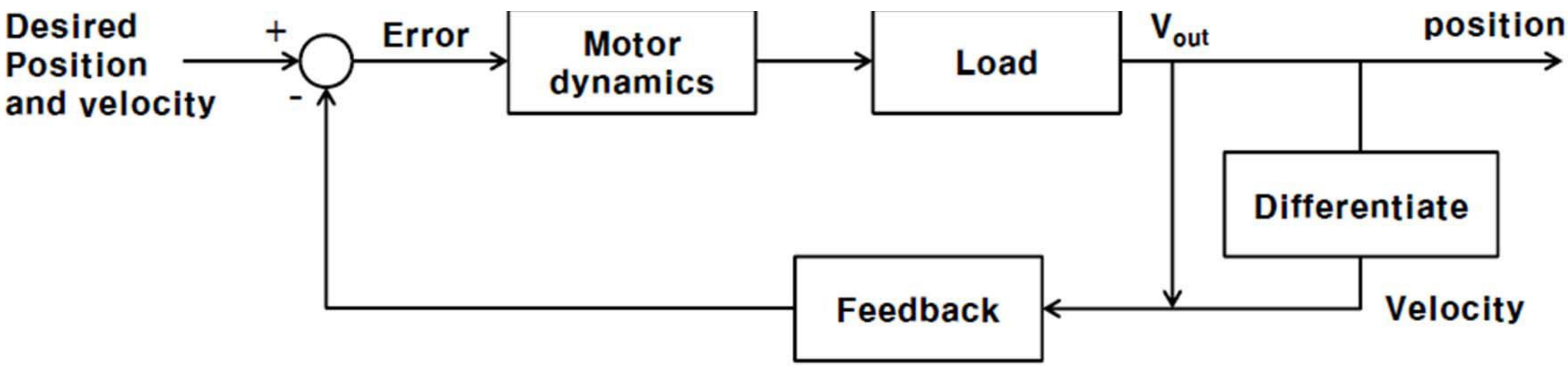






Servo System

- Servo is mechanism based on feedback control.
- The controlled quantity is mechanical.
- Properties of Servo Motor
  - High maximum torque/force allows high (de)acceleration
  - High zero speed torque/force
  - High bandwidth provides accurate and fast control
  - Works in all four quadrants
  - Robustness



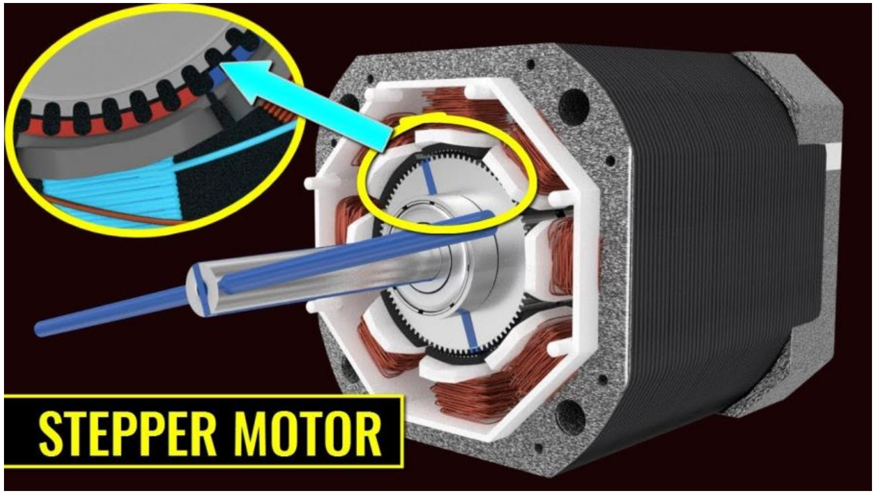
Servo Motors

- These are DC/AC/Brushless motors coupled with a feedback control circuitry, a gear system to increase torque and a position sensing device. When a signal (pulse) is sent, it moves the motor shaft to a desired position using the position feedback from a potentiometer. Servos do not exhibit continuous rotation, but are limited to a specific range (generally 200° back and forth) and requires us to modify it for continuous rotation.
- Since servos expect a control signal, there is an additional wire running into the servo which takes control pulses. Hence they have three wires; Ground, Power and Control pulse.
- Servos have a wide range of applications in robotics.

Output

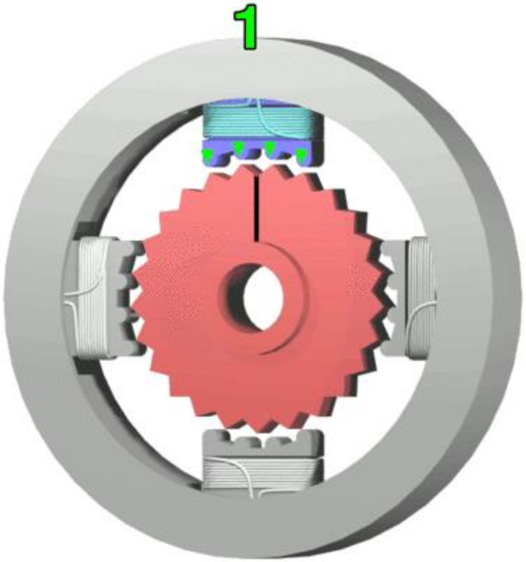
Stepper Motor

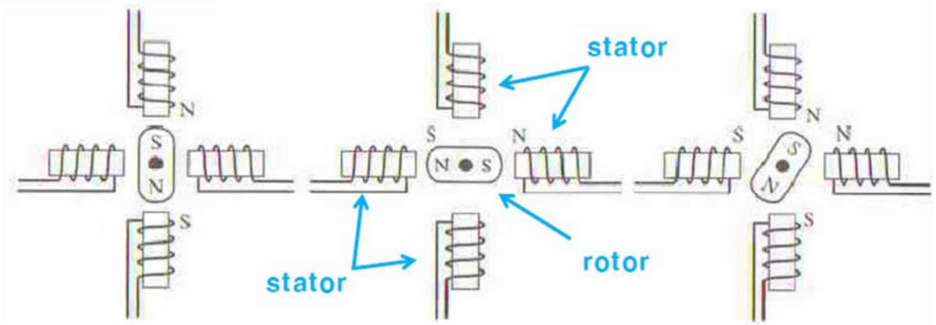
- Stepper motors are brushless motors which divides the rotor's rotation into discrete number of steps when electrical pulses are applied in an expected sequence.
- In other words, a brushless motor rotates continuously when voltage is applied across, but a stepper motor breaks it into steps per revolution and jumps each step for a certain pulse. Unlike a servo motor, stepper motor does not require any complex position feedback mechanism; on the torque side, stepper motors are similar to brushed DC motors with less torque.



Stepper Motor

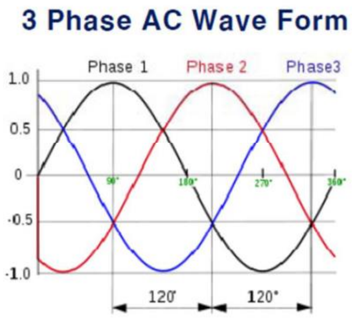
- A sequence of (3 or more) poles is activated in turn, moving the stator in small “steps”.
- Very low speed/high angular precision is possible without reduction gearing by using many rotor teeth.
- A Stepper motor is a digital actuator where input is in the form of programmed energization of stator winding and output is in the form of discrete angular position.
- Rotation of rotor occurs because of magnetic interaction between rotor pole and poles of sequentially energized stator winding.

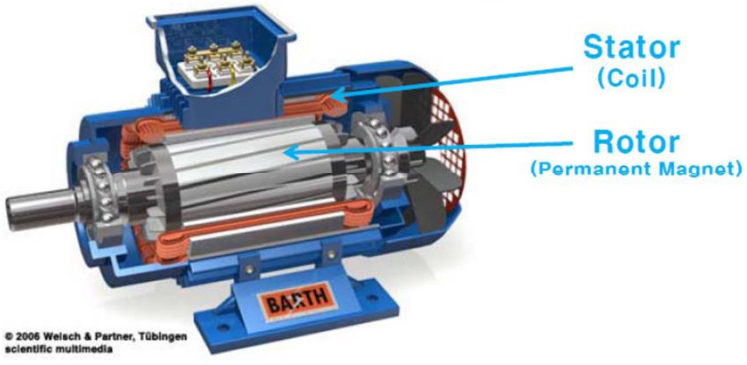




AC Motor

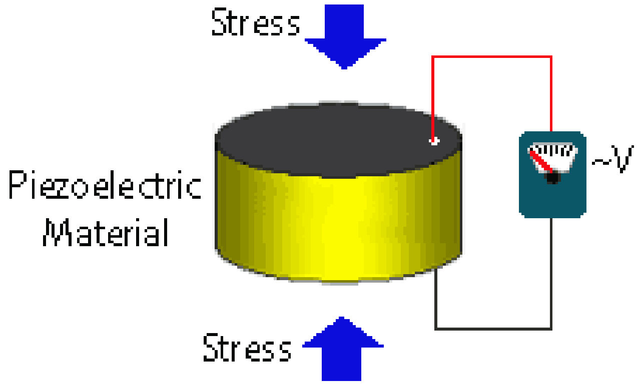
- Same as DC except rotor is permanent magnet, stator houses windings, no commutators or brushes.
  - No Brush : long working life
- As flux generated by AC current changes, rotor follows it and rotates.
- Fixed nominal speeds:
  - Functions of number of poles on rotor and line frequency (50 Hz)
- Better at dissipating heat than DC motors
  - Higher Power than DC Motors



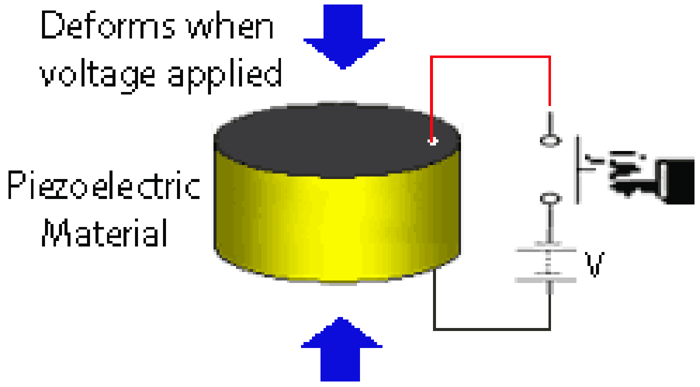


Piezoelectric Actuator

- When an electricity flows through a piezoelectric material, it creates a physical deformation which is proportional to the applied electric field, known as indirect piezoelectric effect.
- This precise deformation can be used to position objects with extreme accuracy, almost at µm accuracy.
- The strokes of these actuators can also be amplified if required, because direct strokes from these peizoelectric actuators are generally less than 100 µm.



Piezoelectric Effect



Piezoelectric Actuator

Degrees of Freedom

The degrees of freedom of a rigid body is defined its **total number of independent movements**. Each joint or axis on the robot introduces a degree of freedom.

The number of DOF is:

- Independent position variables needed to locate all parts of the mechanism
- Different ways in which a robot arm can move
- In robotics, DOF = number of independently driven joints
- **3D Space = 6 DOF** (3 position + 3 orientation)

Degrees of Freedom

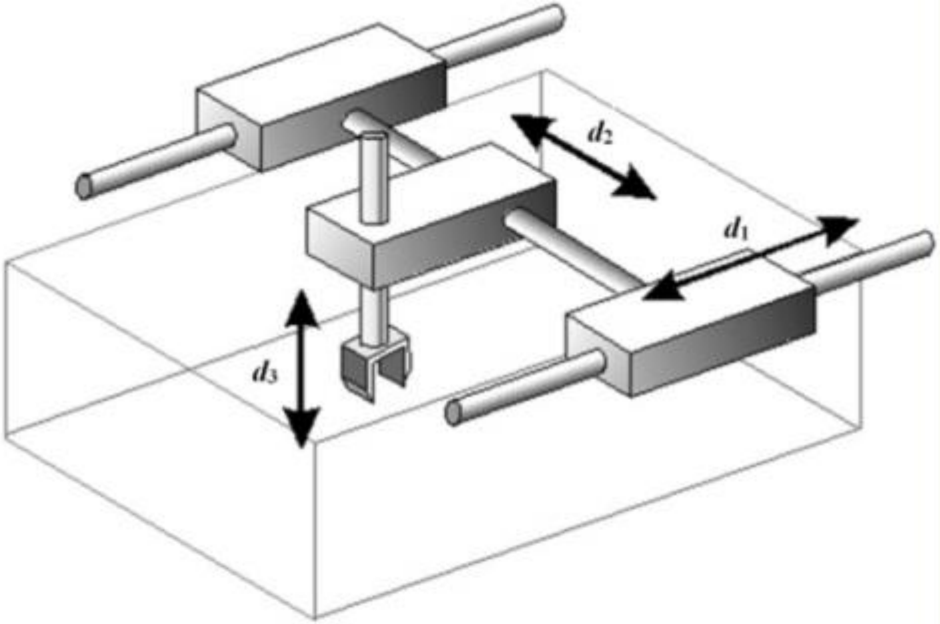
With increase of DOF

- positioning accuracy increases
- computational complexity increases
- cost increases
- Flexibility increases
- power transmission is more difficult

Robot axis

Cartesian Robot

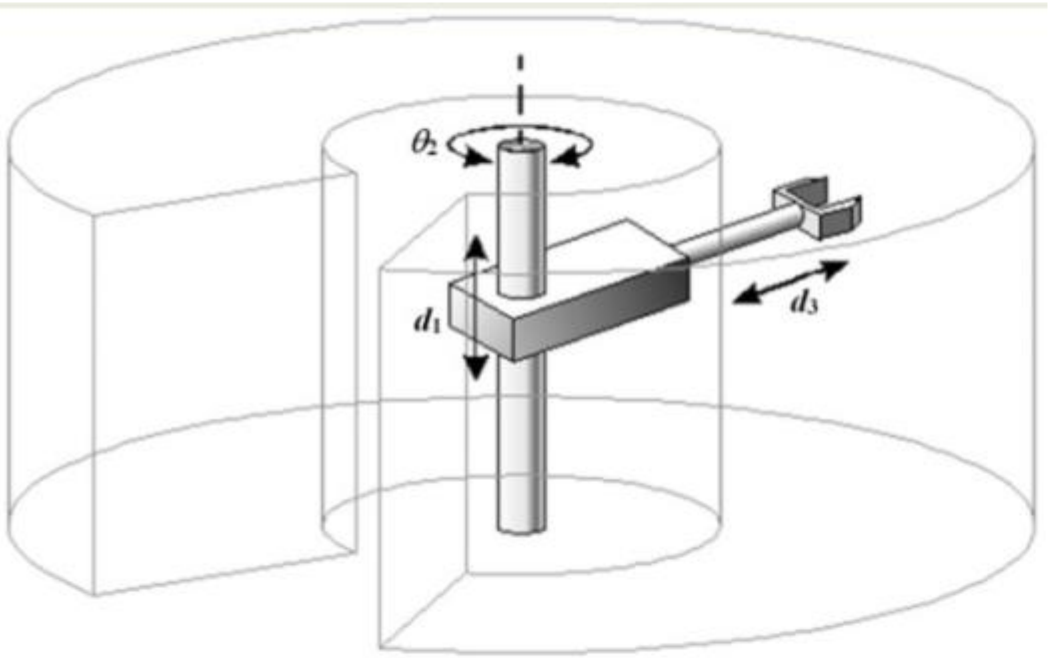
Cartesian robots have **three linear axes of movement** (X, Y, Z). They are constructed of three mutually-orthogonal P joints, with variable lengths L1, L2, L3. Used for pick and place tasks and to move heavy loads. They can also trace rectangular volumes in 3D space.



Robot axis

Cylindrical Robot

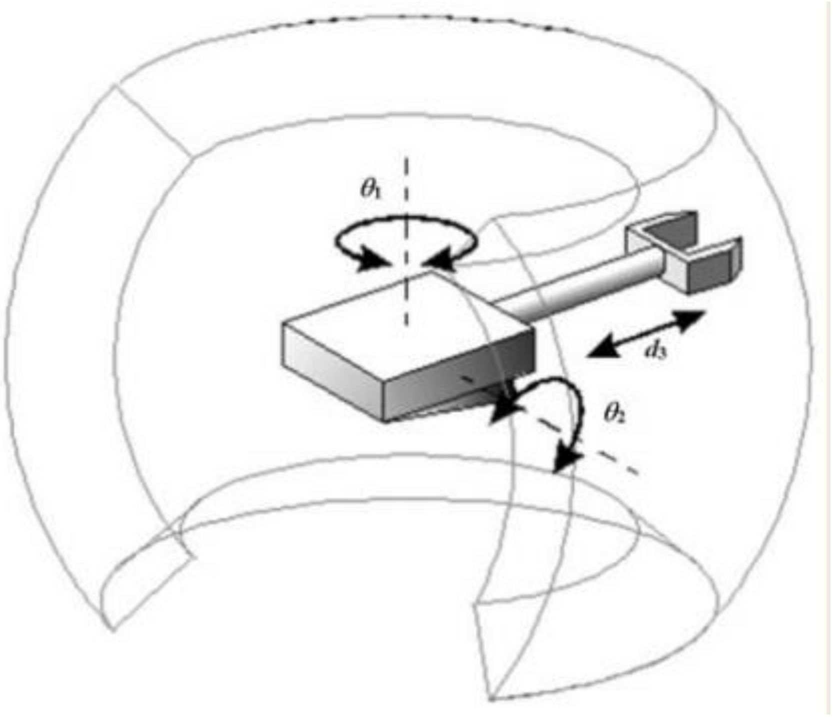
Cylindrical robot positions are controlled by a variable height L_1, an angle Θ_2, and a variable radius L_3 (P joint, R joint, P joint). These robots are commonly used in assembly tasks and can trace concentric cylinders in 3D space.



Robot axis

Spherical Robot

Spherical robots have two orthogonal rotational R axes, with variables Θ_1 and Θ_2, and one P joint, variable radius L3. The robots' end-effectors can trace concentric spheres in 3D space.



Kinematics

$$F(\textit{robot variables}) = \textit{world coordinates}$$

$$x = x(\xi_1, \ldots, \xi_n)$$

$$y = y(\xi_1, \ldots, \xi_n)$$

$$z = z(\xi_1, \ldots, \xi_n)$$

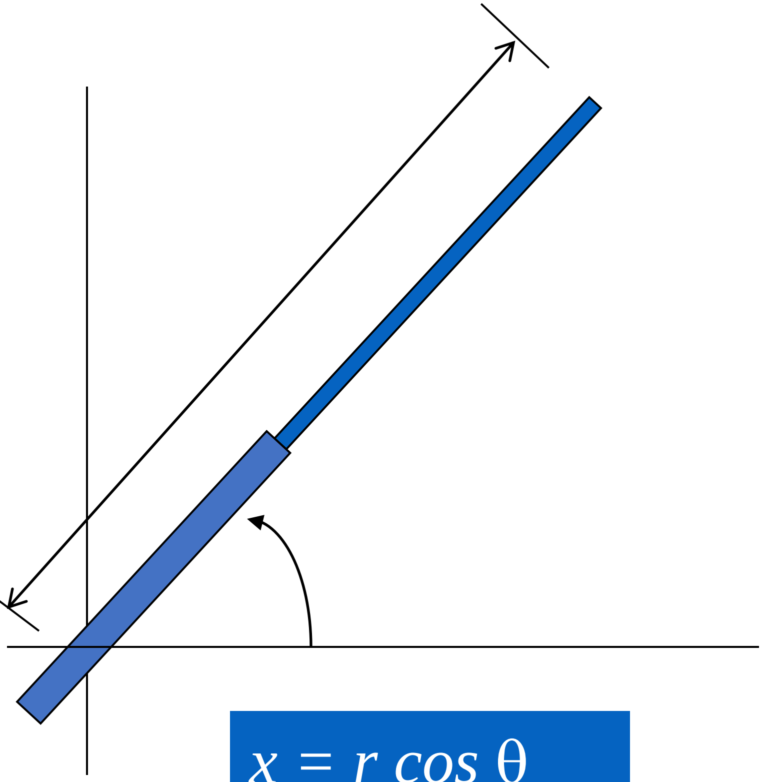
- In a “cascade” robot, Kinematics is a single-valued mapping.
- “Easy” to compute.

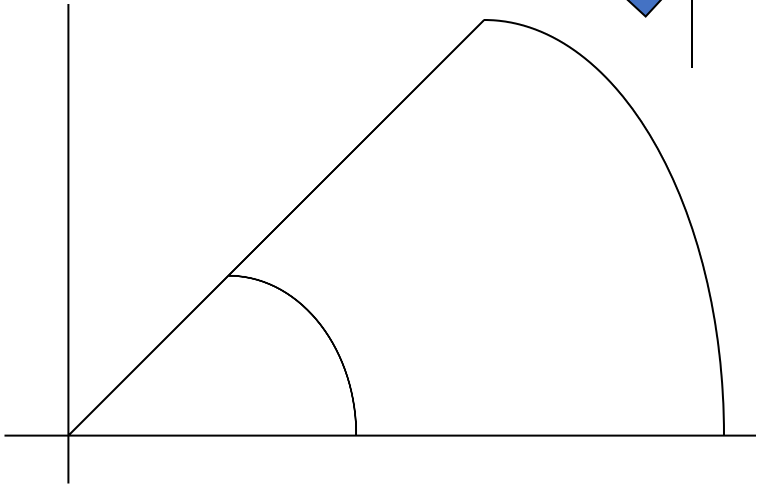
Kinematics: Example

$\xi_1 = \theta,\ \xi_2 = r$

$1 \leq r \leq 4.5$

$0 \leq \theta \leq 50^o$





$x = r \cos \theta$

$y = r \sin \theta$

Inverse Kinematics

- G(*world coordinates*) = *robot variables*

$$\xi_1 = \xi_1(x,y,z)$$
$$\vdots$$
$$\xi_1 = \xi_1(x,y,z)$$

- The inverse problem has a lot of geometrical difficulties
- inversion may not be unique!

Inverse Kinematics: Example