MECHATRONICS

(For B.E. / B.Tech Mechanical Engineering Students)

(As per Leading Universities New Revised Syllabus)

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Mechatronics - Syllabus

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Chapter 2: 8085 Microprocessor and 8051 Microcontroller

Introduction – Architecture of 8085 – Pin Configuration – Addressing Modes – Instruction set, Timing diagram of 8085 – Concepts of 8051 microcontroller – Block diagram

Chapter 3: Programmable Peripheral Interface


Chapter 4: Programmable Logic Controller

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Chapter 1

INTRODUCTION

1.1 INTRODUCTION TO MECHATRONICS

The word “Mechatronics” originated from Japanese-English. It was created by Tetsuro Mori a Japanese engineer of the “Yaskawa Electric Corporation”. The word “Mechatronics” was even registered as a trademark by the company in 1971. In course of time the company released the right of using the word in public. The word Mechatronics was coined by integrating Electronic controls in Mechanisms.

Mechanism is a machine or part of a machine which by virtue of its geometry and relative motion controls or transmits or constrains the movement of other parts. For example a cam mechanism can be used as timer as shown in Fig 1.1. By rotating the lever the toy moves up and down. In general the size of the cam or in other words any mechanical mechanism is large and heavy. This increases the cost and time of the end product. It also requires specialized tooling which cannot be used for any other purpose except for manufacturing only those components. Moreover, if there were space or weight constraints in the
design, then creating a conventional control mechanism becomes very challenging.

As the field of Electronic Engineering advanced the electronic components shrunk in size. These components have control application like counter, timer, etc. Another example, as shown in Fig. 1.2 is winding watch and smart watch. The winding watch requires precision parts of small size to make the mechanism which controls the movements of the watch hands indicating the time. Although the winding watch does not require any power source the engineering involved to make it is huge. Even to adding
function like a date or day or year or stop watch in it involves a lot of changes in the basic design and subsequent tooling. All this changed with the advancement of electronic components. Smart watch is one such example. It has no moving parts. It redefined the functionality of watch from just indicating time to limitless possibilities.

When engineers blended the advantages of electronic components with mechanisms the new field of Mechatronics emerged. The word is formed by taking “Mecha” from mechanisms and “Tronics” from Electronics. From the French standard NF E 01-010 Mechatronics is defined as an “approach aiming at the synergistic integration of mechanics, electronics, control theory, and computer science within product design and manufacturing, in order to improve and/or optimize its functionality”. Thus Mechatronics is (MCT) a multidisciplinary field of engineering. It is a system which brings together combination of systems engineering, mechanical engineering, electrical engineering, telecommunications engineering, control engineering and computer engineering.

1.2 NEED FOR MECHATRONICS:

Any engineering product is the end result of many branches of technologies brought together. Although an organisation may departmentalize the contribution of the different technologies, the boundaries between the technologies is a blur. For instance, let’s consider an Automobile Engine. In the early period to start an engine people have to mechanically crank it. To make thinks simpler people integrated the engine with a small motor powered by a battery power source, as a starter to replace
the function of cranking. This led to the usage of an ignition key. Now with the advancement in the information technology we can start an engine by remote control devices.

Hence, by integrating technologies, there is a huge advancement in the engineering product or system. Mechatronics is the resultant technology of integration. To incorporate the advantages of each technology in a product or in an engineering system it is necessary to lean on Mechatronics.

1.3 CONCEPTS OF MECHATRONICS APPROACH:

Mechatronics by nature is a unified approach to solve engineering problems or create engineering products or make engineering systems. Hence Mechatronic approach explores new possible way to incorporate the advantage of a new technology in applications which are already available. This upgrades the application to such a level that it was neither thought possible nor considered feasible earlier.

Every technology has its parameters. Parameters are nothing but a measurable quantity. For instance, in mechanical engineering the parameters are like
temperature, pressure, velocity, displacement, etc. In the same way electrical parameters are like voltage, current, resistance etc. Technologies are integrated concurrently by integrating these parameters. The relative information is used in a creative way to make a product or solve an engineering problem. Although the advancement in electronics and information systems is recent this methodology already exists.

For instance, let’s consider a Rheostat. A rheostat is a variable resistor which is used to control the current flowing in a circuit by moving the sliding contact called the wiper over the coil wound as shown Fig 1.4. With a mechanical sliding motion the flow of current is controlled. The mechanical movement is now replaced by electronics circuits and digital signals. Hence digital potentiometer is made available in the market.

1. Controlling system
2. Controlled system

Controlling System is the intelligence system which is programmable to suit the application needs. Here the
signals are perceived at the input, interpreted by knowledge and a proper response is directed through the planning and control.

The controlled system in general is the active system which can be mechanical or chemical or others where the system’s state is sensed by sensors and as per the requirement the actuators are activated to produce the desired results.

“World” is the end user requirement or can be considered as the desired output from the system. Hence the key conceptual approach in mechatronics is the way in which the parameters of different technologies interact with each other, thereby fusing different technologies
concurrently into one core system. This system thus emerged draws the advantages and flexibilities of all the technologies which are integrated.

1.4 CLASSIFICATION OF MECHATRONICS:

Mechatronics as discussed is a branch of engineering which is the result of fusing two or more engineering technologies. Hence Mechatronics can be classified based on the technologies which are fused together. Though such technological ideology may already exists will now be considered as a part of multidisciplinary field of
Mechatronics. Fig. 1.6 illustrates the how technologies are merged.

1. Based on the level of fusion let’s try to classify mechatronics

Level 1:
Here two major engineering technologies are fused hence level would comprise of:

- Electromechanical Engineering (Electrical and Mechanical)
- Digital Systems (Electrical and Computer)
- Digital controls (Computer and Control)
- Sensor and Actuators (Mechanical and Control)

Level 2:
Here three major engineering technologies are fused and they are:

- Micro-control
- Analog Systems
- Simulation
- Modeling

Level 3:
The Fig. 1.6 illustrates only a symbolic representation of fusion of technologies. When the boundary of engineering classification is no longer applicable then the products/systems/solutions is of Mechatronics level 3 classification.
2. Based on Mechatronics product it was classified by Japan society for Promotion of Machine Industry (JSPMI) into the following categories

Class I:
Mechanical products which are fused with electronics to enhance or increase functionality come under Class I. Example for this is a numerically controlled machine or a variable speed drives, etc.

Class II:
When traditional mechanical systems are upgraded with internal electronics then it comes under Class II. A modern sewing machines or a Digital Odometer is an apt example for that.

Class III:
Class III is systems that retain the functionality of the traditional mechanical system, but the internal mechanisms are replaced by electronics. A classic example is the digital watch.

Class IV:
Class IV products are designed with integrated mechanical and electronic technologies in a synergistic way. Examples include right from photocopiers, to smart washing machines.
3. Based on the Behavioral characteristic of the system

(a) Automated Mechatronic Systems:

An Automated mechatronic system is capable of handling materials and energy, communicating with its environment and is characterized by self-regulation, which enables it to respond to predictable changes in its environment in a pre-programmed fashion. An overwhelming majority of current mechatronic systems belong to this category.

(b) Intelligent Mechatronic Systems:

An Intelligent mechatronic system is capable of achieving given goals under conditions of uncertainty. In contrast to automated systems, which are, by definition, pre-programmed to deliver given behavior and are therefore predictable, intelligent systems may arrive at specified goals in an unpredictable manner.

(c) Intelligent Mechatronic Networks:

Intelligent mechatronic networks are capable of deciding on their own behavior by means of negotiation between constituent autonomous units (the network nodes). Each of constituent units is itself an intelligent mechatronic system.

1.5 EMERGING AREAS OF MECHATRONICS:

- Machine vision
- Automation and robotics
- Servo-mechanics
- Sensing and control systems
- Computer-machine controls
Expert systems
Industrial goods
Consumer products
Mechatronics systems
Medical mechatronics, medical imaging systems
Structural dynamic systems
Transportation and vehicular systems
Mechatronics as the new language of the automobile
Computer aided and integrated manufacturing systems
Computer-aided design
Engineering and manufacturing systems
Bio-mechatronics
Packaging
Microcontrollers / PLCs
Mobile apps
M&E Engineering
Consumer products: Security camera, microwave oven, etc.
Implant-devices: Artificial cardiac Pacemaker, etc.
Defense: Unmanned air, ground and underwater vehicles, jet engines, etc.
Robotics: Welding robots, Material handling robots etc.
Automotive industry: Anti-lock braking system (ABS), Multi-point fuel injection etc.
Non-conventional vehicles: electro-bicycles, electro scooters, invalid carriages, etc.
Office equipment: copy and fax machines etc.
Computer peripherals: printers, plotters, disk drives etc.

Photo and video equipment: Thermal Camera, Camcorders etc.

Simulators: Car simulator, Plane simulator, etc.

Entertainment Industry: sound and illumination systems

Network-centric, distributed systems

Aviation, space and military applications

**Advantages of Mechatronics:**

- Comparatively low cost without compromising quality
- Perform complicated and precise movements of high quality
- High reliability, durability and noise immunity
- Constructive compactness of modules
- Systems can be controlled and monitored remotely (Unmanned systems)
- Redesign functional modules of sophisticated and complex systems as per specific purposes of the customer
- Flexibility in the system design
- Increasing the optimal production limits by increasing the machine utility to the highest extent

**Disadvantages of Mechatronics:**

- Different expertise required
- System design relies more on innovation rather to the conventional method
- More complex safety issues
1.6 SYSTEM:

A system is defined as a set of interdependent or interacting components connected to form a complex/intricate whole which is designed for a specific purpose. A system consists of an object which is under study, enclosed by a boundary to the surrounding environment. By varying the input conditions of surrounding the output from the object under study is analyzed. This is illustrated in the Fig. 1.7.

System defined thus is a generalized one. Our whole universe is comprised of systems performing specific functions. In engineering context a system can be from simple home appliance like flat iron to a complex production line.

In Mechatronics where the fusion of engineering technology is there a simple example of a system is a Car. In a car there is the engine, transmission of motion from the engine to wheels and many other mechanical parts. There are electrical components like the batteries, lights etc. There are electronic control components in the stereo,
brake system, fuel injection systems etc. Now a day's modern cars are equipped with navigators, automated safety devices, anti-theft devices etc. On whole a Car is product of Mechatronics.

1.6.1 Elements of Mechatronic system:

Fig. 1.8 illustrates the elements of mechatronic system. The elements are summarized below for clarity.

1. Actuators and Sensors
2. Signals and Conditioning
3. Digital Logic System
4. Data Acquisition system and software
5. Computer and display devices

Process can be mechanical or chemical or any other in the mechatronic system. For understanding the elements
of a mechatronic system let us consider a mechanical system.

1. **Sensors:**

   The parameters of the mechanical system like pressure, temperature, displacement etc, are sensed by the respective sensor and are converted into a signal. This signal is input to a signal conditioning unit.

2. **Signal Conditioning:**

   The signal obtained from the sensor is converted according to the requirement. Signals are of two types one is an analog signal and the other is a digital signal. Hence there are two types of convertor DAC (Digital to Analog Convertor) and ADC (Analog to Digital Convertor).

3. **Digital Logic system:**

   This is actually the control unit where the signal is analyzed and proper response or feedback is given to the system. In this unit only PLC or Micro–controller or any other control circuit are there. With advancements in the system this unit is interfaced with a computer. This enables much easier control for the end user.

4. **Computer Systems:**

   In Computers data of the system is acquired by data acquisition units and stored as data logs. From this data logs one can monitor and analyze the overall functioning of the system. There are special data logger or other related devices which are now available with an interface to connect with a computer.

   Computers are also equipped with display unit. This display unit is now programed through software to control
the entire system. An apt example for this is BMS (Building Management System). BMS software shows the facility’s Air-condition system, CCTV, Electrical system, etc. With the control terminal of the BMS control room, one can control all the integrated system of the facility.

1.7 MEASUREMENT SYSTEM:

It is essential to know and the state of a system. State of the system is determined by the Properties/Parameters of the system. In a mechanical system the properties/parameters are temperature, pressure, displacement, etc. In electrical system the parameters are current, voltage, resistance, etc. Mechatronics systems are an integration of technologies, hence it is a must that parameters of one technology is read by another technology. To enable that capability a **Measurement system** is required. A measurement system is composed of three components as illustrated in **Fig. 1.9**.

![Diagram of Measurement System](image)

The parameters of the systems are read by an appropriate sensor or transducer. This is in the form of a signal which can either be digital or analog. As per the system requirement the signal is processed by a DAC or ADC units by the signal processor. This signal processed is shown on the display screen. The display panel has the control unit which sets the limits of the parameters or is pre-programed as per the reading. It also stores the data in log files in the form of readings, tables or graphs etc., as per the design.
Digital weighing machine can be considered as a simple example to illustrate the above system as shown in Fig. 1.10 (a).

When a load is placed on the machine it is actually placed on a strain gauge. This strain gauge is strained. The strain is converted into millivolts. This voltage signal is amplified. The amplified voltage is programed by the logic units to give the analogous reading in kilograms or pounds etc., at the display unit.

1.8 CONTROL SYSTEM:

In many systems, it is not enough just to measure a parameter. It is also required to control the parameter. A parameter is either maintained as constant or varied in a pre-programmed way. To control a parameter, say pressure, the following is required to be considered:

1. To control any parameter, the first requirement is the real-time reading of the parameter. Hence the first requirement is to know the pressure level in the system under observation to control that.

2. Once that parameter is measured, it must be compared to a standard. After measuring the pressure of system in bars or pascals, it must be compared to a standard to know if the pressure is high or low in the system.
3. After comparison, if the parameter is within the desired range, then it is maintained otherwise control action is taken. There are numerous ways to control the variable parameters.

A general control system is illustrated in Fig. 1.10(b)

1.8.1 Basic Terminology used in Control System:
(a) Reference Variable or Input: Reference variable is that benchmarked variable which is used to compare with the system output to know if the output is in the specified desired level. It is like when petrol is bought from the bunk, the operator types the amount say Rs.100/- in the counter. The counter runs a dispensing petrol until it reaches Rs.100/-. This Rs.100/- amount is ‘Reference Variable’ of the System.

(b) Output: It refers to the actual response of the system as per the input fed to the system.

(c) Feedback: The output of a system is measured. This measure is in the form of a signal which is fed to the control circuit. This path from the output to the control unit is considered as feedback. Refer Fig 1.12.

(d) Error: The difference between the reference variable and the system output is called error.
(e) **Disturbance:** Those signals which disturb the system by affecting the reference variable or other control features are considered as ‘Disturbance’.

(f) **Actuating Signal:** The response signal due to the error which actuates the system to change the output is called ‘Actuating Signal’.

(g) **Control or feed forward Elements:** The components which are connected between control unit and the output unit are considered as the feed forward elements.

(h) **Controlled Output:** The parameter (Pressure, Temperature, etc.) which is regulated/Guided/controlled for the system is called “Controlled Output”.

(i) **Feedback element:** The elements which are used to generate feedback in the system are the feedback elements.

**1.8.2 Types of Control System:**

Fig. 1.10 illustrates a general control system. It has not mentioned how the controlling is done. There are two basic ways in which a system is controlled and they are

(a) **Open Loop Control System:**

In this system, the control parameter is simply regulated. Just like a fan regulator which merely regulates the speed of fan with various settings. Here the output is
only regulated as per the pre-programed set up. An open loop control system can be illustrated as shown in Fig. 1.11.

**Advantages and Disadvantages of Open Loop Control System**

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) Manufacturing cost is low as it is very simple.</td>
<td>(a) Control is limited as per the pre-programing.</td>
</tr>
<tr>
<td>(b) Ease of control and Maintenance.</td>
<td>(b) Control is manually operated and hence it is slow and subjected to human error.</td>
</tr>
<tr>
<td>(c) Pre-programed as per the requirement.</td>
<td>(c) Output optimization is not possible as there is no feedback.</td>
</tr>
<tr>
<td>(d) Very useful in application where the output is difficult to measure or economically not feasible.</td>
<td>(d) This system cannot be automated.</td>
</tr>
<tr>
<td>(e) It is very economical to use in applications where the control output requirement levels are clear.</td>
<td>(e) Cannot be used in complex applications where the control output has to be monitored and maintained even with all variations.</td>
</tr>
</tbody>
</table>

(b) **Closed Loop Control System:**

In this system, as illustrated in Fig. 1.12, the control parameter is instantaneously controlled. This is achieved by the means of a feedback. From the output a feedback is generated. This generated signal is compared with the
set conditions in the control system. If there is a difference, an error is generated. To compensate the error, control is activated and output is varied to match the set condition. This process continues till the error is nil or zero.

A closed loop control system can be explained from the working principle of a compressor in an Air conditioning unit. On turning on an AC unit, an user sets the temperature as 21°C. Now the unit must maintain the room temperature to 21°C. The thermostat measures the temperature of the room and converts it to a signal. This signal is compared analogously with the set temperature 21°C. If the temperature of the room is more said 26°C then the error is positive. This results in activating or switching on the compressor which is a key component in the AC unit for regulating the temperature. The comparison of room temperature with the set temperature is continuous. As soon as the temperature of the room drops to 21°C the error becomes zero. Depending on the programing of the AC unit, the compressor will be switched off. Hence the compressor will cut-in or cut-off as per the fluctuations of the room temperature.
1.8.3 Basic terms used in Closed Loop Control System:

- **Process element:** It is the element of the system which is to be controlled. It can be a room where the temperature is controlled or a tank where water level is controlled etc.

- **Measurement Element:** The element which is used to measure the state of the process element is called Measurement Element.

- **Reference point or Set point:** It is the standard signal which is set in the system to control the output.

- **Comparison Element:** This element compares the reference value to the measured value. The difference between them is considered as error. 
  \[(\text{Error} = \text{Reference value} - \text{Measured value})\]

- **Control Element:** This element reads the error signal and produces a signal to correct the error.

- **Correction element:** It is that element which receives a signal from the control element and makes changes in the output accordingly.

- **Controlled Variable:** It is that parameter which is controlled by the control system. It is the temperature of the room which is controlled.

- **Manipulated Variable:** To control the output or the controlled variable there is a variable which is changed and it is called manipulated variable.
1.8.4 Comparison between Open loop and Closed loop Control System:

<table>
<thead>
<tr>
<th>Feature</th>
<th>Open loop System</th>
<th>Closed Loop system</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Cost</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>2. Feedback</td>
<td>No feedback is there</td>
<td>Feedback is there</td>
</tr>
<tr>
<td>3. Accuracy</td>
<td>Limited to pre-programing</td>
<td>As per the efficiency of feedback</td>
</tr>
<tr>
<td>4. Contraction</td>
<td>Simple</td>
<td>Complex</td>
</tr>
<tr>
<td>5. Non-linearity</td>
<td>System can malfunction</td>
<td>well within the specified range of non-linearity</td>
</tr>
</tbody>
</table>
### Feature

<table>
<thead>
<tr>
<th></th>
<th><strong>Open loop System</strong></th>
<th><strong>Closed Loop system</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>6. Stability</td>
<td>Stable as per the pre-program condition</td>
<td>Continuously active with feedback</td>
</tr>
<tr>
<td>7. Response time</td>
<td>Slow as it is manually operated</td>
<td>Instantaneous as it is automated</td>
</tr>
<tr>
<td>8. Output Optimization</td>
<td>Not possible</td>
<td>Possible within the limits of the control system</td>
</tr>
<tr>
<td>9. Maintenance</td>
<td>Easy</td>
<td>Difficult</td>
</tr>
<tr>
<td>10. Disturbance Handling</td>
<td>Chances of having a disturbance are limited.</td>
<td>Depends on the systems failsafe’s and signal filters efficiency.</td>
</tr>
</tbody>
</table>

### 1.8.5 Application which use Automatic Control System:

A closed loop control system is an Automatic control system. In such systems the control parameter is either pre-defined as per design specification or set by the user as per within the range of the designed specification. Some of applications which use Automatic control system are as follows.

**a) Automatic Tank level indicator control system:**

Fig 1.13(a) illustrates the schematic diagram of the Tank level indicator system. The water is stored in a tank. Inside the tank there is a float. This float raises or dips as per the level in the tank. This float is connected to a level transmitter which uses the property of the float to
measure the water level in the tank. This measured level is transmitted by the Level Transmitter as a signal to the Level controller. In the level controller, there is a comparison element which compares signal from the level transmitter with the standard pre-set signal. If there is a difference in two signals then error is generated. (Error = Reference value – Measured value) Based on the error that is if level is low, then control valve is activated to open and water flows into the tank. If the error is null or negative (In case of pre-design failsafe or malfunction) then the control valve is closed. Fig 1.13(b) illustrates the control system block diagram of the Tank level indicator system.

<table>
<thead>
<tr>
<th>Tank Level Indicator Control System</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process Element</td>
</tr>
<tr>
<td>Measurement Element</td>
</tr>
<tr>
<td>Reference Point</td>
</tr>
</tbody>
</table>
### Tank Level Indicator Control System

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Comparison Element</td>
<td>Level Controller</td>
</tr>
<tr>
<td>Control Element</td>
<td>Level Controller</td>
</tr>
<tr>
<td>Correction Element</td>
<td>Control valve open/close</td>
</tr>
<tr>
<td>Manipulated Variable</td>
<td>Water</td>
</tr>
<tr>
<td>Controlled Variable</td>
<td>Tank level</td>
</tr>
</tbody>
</table>

(b) **Lubrication Oil cooling system:**

Lubrication is very important for engines. It not only reduces the wear and tear, but also regulates the temperature of the engine. But lubricant’s mechanical properties like viscosity and density change completely if its temperature crosses a certain limit. Hence it is important to maintain the temperature of the lubricants within that limit in which its mechanical property remains unaffected. **Fig. 1.14** illustrates the Lubrication oil cooling system. From the engine hot lubricant comes out and enters the heat exchanger. In the heat exchanger the hot
lubricant’s heat is exchanged with cold water. The cool oil goes to the oil sump. The temperature of the oil at the sump is measured by a thermostat. This temperature is fed to the control valve. The control valve compares the temperature with set temperature. If there is difference then it adjusts the flow of water by adjusting the valve opening. Hence the flow rate of water changes as per the temperature of the oil in the sump. This oil is then pumped into the engine. If the lubricant’s temperature is beyond the limit, it means the lubricant is old and has lost its mechanical property and it is time to replace with fresh stock.

In order to safeguard the engine from entry of hot lubricant, there is a failsafe system in place. A thermostat measures the temperature of the lubricant entering into the engine. This temperature is compared with the set temperature range at the failsafe. If the temperature is excess, then the failsafe with trip/stop the engine.

<table>
<thead>
<tr>
<th>Lubrication oil cooling system</th>
<th>Engine failsafe system</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process Element</td>
<td>Lubricant</td>
</tr>
<tr>
<td>Measurement Element</td>
<td>Temperature of lubricant</td>
</tr>
<tr>
<td>Reference Point</td>
<td>Set temperature at valve</td>
</tr>
<tr>
<td>Comparison Element</td>
<td>Control valve</td>
</tr>
<tr>
<td>Control Element</td>
<td>Control Valve</td>
</tr>
</tbody>
</table>
Lubrication oil cooling system | Engine failsafe system
---|---
Correction Element | Control Valve open/close | Failsafe Tripper on/off
Manipulated Variable | Water flow rate | Engine tripper
Controlled Variable | Temperature of Lubricant | Engine On/Off (Emergency)

(c) Automatic shaft speed control system:

**Fig. 1.15** illustrates the schematic and block diagram of the control system used to control the speed of the shaft. The speed of the shaft is measured by the Tachogenerator. The measured speed is sent to the Differential Amplifier. Differential Amplifier boosts this signal and compare with set speed signal by the resistance potentiometer. If there is an error then accordingly a signal is given to the motor
to increase or decrease the speed. Thus the speed of shaft which is coupled with motor is increased or decreased to get in level with the set speed.

<table>
<thead>
<tr>
<th><strong>Shaft Speed Control System</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Process Element</td>
</tr>
<tr>
<td>Measurement Element</td>
</tr>
<tr>
<td>Reference Point</td>
</tr>
<tr>
<td>Comparison Element</td>
</tr>
<tr>
<td>Control Element</td>
</tr>
<tr>
<td>Correction Element</td>
</tr>
<tr>
<td>Manipulated Variable</td>
</tr>
<tr>
<td>Controlled Variable</td>
</tr>
</tbody>
</table>

1.8.6 Analogue and Digital Control systems:

There are two kinds of signal which can be used in the control process. They are digital and analogue signal. Analogue signal are continuous signal which varies with time. Digital signals are signals that represent a sequence of discrete values. They are illustrates in Fig. 1.16.

Based on the measuring device and control element these signals have to be converted into the other. Hence we have Digital to analogue Convertor (DAC) and Analogue
to Digital Convertor (ADC). Hence the control system with these convertors can be illustrated with previous example of Shaft speed controller as shown in Fig. 1.17.

The measured shaft speed by tachogenerator is in analogue which is convertor into digital by ADC before sending it to the differential amplifier which is in microprocessor unit. The response signal from microprocessor unit is converted from digital to analogue signal before feeding to motor through the signal amplifier. Thus both ADC and DAC are used in control system.

1.8.7 Sequential Controllers:
In process or a plant, there are operations which occur in a sequence. In some cases like a production line, the output of first operation becomes the input of second operation and in other cases the same object is subjected to different operations in a sequence like a product undergoing a series of quality checks. Each operation in the sequence must be controlled to get the desired end product/output. To facilitate that, these plants or process is equipped with sequential controllers. Let us understand this with the following example.
A. Domestic Washing Machine:

In an automatic domestic washing machine, once it is loaded with laundry, there are number operations machine has to perform to wash them. They can be listed out as

(a) **Pre-wash:** In this operation, the closed washing machine drum is filled with cold water by which laundry gets soaked. Then the machine spins the drum gently. As per the timer set by Program or by the user, this process continues.

(b) **Main wash:** In this operation first the cold water is drained. Then hot water (Temperature set by the user) along with detergent or any other washing agent fills the drum. Then the machine spins in normal wash speed (also set by the user) to wash the laundry. As per the timer set by program or user, the process goes on.
(c) **Rinsing:** In this operation, the washed water in the drum is drained and it is refilled with cold or hot water as per the settings. Then the drum again spins removing soapy detergent and dirt from the clothes. The time is again preset by the program or by the user. Depending on the kind of fabric, this cycle is repeated.

(d) **Drier:** The rinsed water is drained from the drum. Then the drum spins expelling water from the laundry. Once the drum comes to rest the drum door can be opened. The laundry washed will be wet but not soaking wet. Then the laundry removed from the machine and hung on a wire in the sun to get them dried manually.

The operations Pre-wash, Main-wash, Rinsing and Drier are carried out in sequence. Apart from that, there is also emergency stop and reset options in the washing machines. Each operation has its own control parameters and set points to conduct them.

The domestic washing machine controls the open/close of water inlet valve. It measures and senses the water level in the drum. It opens/closes the drain valve by sensing the level of the water in the drum. It also controls the temperature of the water and the speed of the drum. In all the operations all these parameters come into play. Every operation is also timed by timer switches.

In earlier days, the mechanical control was used. The function of the timer was performed by cam switches. The timer switch was made by synching a small motor with sliding or point contact which follows the profile of the cam as illustrated in the Fig. 1.19(a).
There are many limitations in cam switches. Today they are replaced by microprocessor control which is also referred as a microcontroller. A simple microprocessor with memory is integrated on one chip known as embedded microcontroller. Microcontrollers can be pre-programmed to perform the same logical operations that are required for a washing machine or any other applications. The advanced

**Fig:1.19 (a) Cam-operated switch**

**Fig:1.19 (b) Programmable Logic Controller**
adoptable form of the microcontroller is the “Programmable Logic Controller”. It is used for complicated system where the process condition varies and a great deal of flexibility is required. A PLC can be programmed and reprogramed as the situation demands for producing the desired output.

1.8.8 Microprocessor based Controllers:

A Microprocessor is also known as the Central Processing Unit (CPU). It is the brain of computer, household appliances and electronic devices. A Microprocessor is not a standalone device, it must be integrated with input/output device along with memory to perform functions.

When a microprocessor is integrated with memory unit, input, output units and programmed for a particular control application of a system or a plant, it becomes a Microcontroller. Different kinds of configured microcontrollers are used in applications as the control element.
When the demands of the application became complicated with higher flexibility, a pre-programmed micro-controller was not a viable option. To meet this demand, PLC (Programmable Logic Controller) came into the market. The main feature of a PLC is its programmable ability as per the requirement of the output. **Fig 1.20** gives the general architecture of a PLC.

Let us now study some of the commonly used applications which uses microprocessor based system for control.

(a) **Automatic camera:**

The automatic modern camera has automatic focusing and exposure. The microprocessor based system is used for controlling the focusing and exposure.

Switch is on to activate the automatic camera system. Then the camera is pointed at the object to be photographed. The microprocessor takes the input using the following interfaces:

- **Switch to activate system**
- **Shutter button pressed when photograph is to be taken**
- **Range sensor**
- **Light sensor**
- **Encoder to give lens position**
- **Battery Test**
- **Interface circuitry**
- **Motor drive**
- **To advance free space to capture image**
- **Solenoid**
- **Actuator to open shutter**
- **Solenoid**
- **Actuator to close shutter**
- **Lens position drive**
- **Aperture control drive**
- **Display of data in view finder**
- **Motor**

**Fig: 1.21** Basic elements of the control system for an automatic camera
range sensor and sends an output signal to the lens position drive in order to position the lens to achieve correct focusing. Then the lens position is fed back to the microprocessor so that this feedback signal will be used to modify the lens position according to the input from the range sensor.

As soon as the photograph is taken, the microprocessor sends signal to the motor drive to advance the free space for the next photograph.

(b) Copying Machine:

The copying machine is a best example for mechatronic system. This machine has analog and digital circuit, sensors, actuators, and microprocessors. The operating procedure is given here.

The operator places the original in a loading place and presses a button to start. The original is taken to the platen glass. A high intensity light source scans the original and transfers the original’s image to a drum. A blank piece of paper is taken from the loading cartridge and the image is transferred on to the paper. During this, ink toner powder is heated to bond to the paper according to the image. This is known as electrostatic deposition. Then the xerox copy is delivered to the appropriate bin which is known as sorting mechanism.

Analog circuits control the lamp, heater and other power circuits in the machine. Digital circuits control the digital displays, indicator lights, buttons, and switches forming the user interface. Other digital circuits include logic circuits and microprocessors which co-ordinate all of the functions in the machine. Optical sensors and
microswitches detect the presence or absence of paper, its proper positioning and whether (or) not doors and latches are in their correct positions. Other sensors include encoders used to track motor rotation. Actuators include servo and stepper motors that load and transport the paper, turn the drum and index the sorter.

(c) **Engine Management System:**

![Four Stroke Spark Ignition Engine Diagram](image)

**Fig:1.22 Four Stroke Spark Ignition Engine**
This system is useful to manage the ignition and fuelling requirements of the engine. Let us consider the four stroke internal combustion engine in which each cylinder has piston and connected to the common crankshaft. We have already studied the operation of 4 stroke engine which are given here briefly.

When the piston moves down, the inlet valve opens and air fuel mixture is sucked into the cylinder (suction stroke). When the piston moves up, the inlet valve closes and the airfuel mixture is compressed, (compression stroke). At the end of compression stroke, the spark is thrown on the airfuel mixture and gets ignited. Sudden explosion takes place and so the piston is pushed down to execute the expansion stroke. This is known as working stroke (or) power stroke. As soon as the piston reaches the bottom dead centre, it moves up again to execute exhaust stroke to send out the burnt gases. During this time, the exhaust valve is open.

The different pistons have their power strokes at different times to enable the common crank shaft rotate continuously.

The power and speed of the engine can be controlled by changing the ignition timing and airfuel mixture ratio. Now-a-days, the microprocessors are used for controlling ignition timing and air-fuel ratio.

The important elements of microprocessor are shown in Fig. 1.23.

To control the ignition timing, the crankshaft rotates and drives the distributor. The distributor makes electrical contacts for each spark plug in turn and a timing wheel.
The timing wheel produces pulses as the indication of the crankshaft position. The microprocessor then adjusts the timing so that at ‘right’ moments of time, the high voltage pulses are sent to the distributor.

To control the airfuel mixture, the microprocessor activates the solenoid valve to open the inlet valve according to the throttle position and engine temperature as inputs. The amount of fuel injected into the air stream are determined by an input from a sensor of mass rate of air flow and the microprocessor then gives an output to control a fuel injection valve.

1.9 SENSORS AND TRANSDUCERS

Sensors and transducers are used widely in describing measurement instruments. The usage of the word sensor is rooted from USA, whereas transducer is rooted from Europe. The meaning of the word Sensor is “to perceive” and Transducer is “to lead across”.

A Sensor is defined as a device that detects a change in a physical stimulus and turns it into a signal which can be measured or recorded.

A Transducer is defined as a device that transfers power from one system to another in the same or in the different form (Strain to voltage).
Hence a sensor by itself will sense the state of a system and a transducer with logic circuitry can be used to ascertain the same. All transducers would thus contain a sensor and most (though not all) sensors would also be transducers. **Fig. 1.24** shows the sensing process in terms of energy conversion. Most of the time the output signal generated would be a voltage analogous to the input signal. It sometimes may be in a wave form whose frequency is proportional to the input or a pulse train containing the information in some other form.

In Mechatronics sensing the parameters of system is key function to know the state of the system. Only by knowing/measuring the state of the system appropriate control measures requirements can be ascertained.

**1.9.1 Classification of Sensors:**

There are many ways sensors can be classified. Some of the ways are discussed as given here.

(a) *Based on the stimulus that is the response signal, sensors can be classified as per table given here.*
Table 5.1

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Stimulus</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Acoustic</td>
<td>Wave (Amplitude, Phase, Polarization), Spectrum, Wave Velocity</td>
</tr>
<tr>
<td>2</td>
<td>Electric</td>
<td>Charge, Current, Potential, Voltage, Electric field (amplitude, phase polarization &amp; spectrum)</td>
</tr>
<tr>
<td>3</td>
<td>Magnetic</td>
<td>Magnetic field (amplitude, phase, polarization, spectrum), Magnetic flux, Permeability</td>
</tr>
<tr>
<td>4</td>
<td>Optical</td>
<td>Wave (amplitude, phase, polarization, spectrum), Wave velocity, Refractive Index, Emissivity, Reflectivity, Absorption</td>
</tr>
<tr>
<td>5</td>
<td>Thermal</td>
<td>Temperature, Flux, Specific heat, Thermal conductivity</td>
</tr>
<tr>
<td>6</td>
<td>Mechanical</td>
<td>Position (Linear, Angular), Acceleration, Force, Stress, Pressure, Strain, Mass, Density, Moment, Torque, Shape, Roughness, Orientation, Stiffness, Compliance, Crystallinity, Structural</td>
</tr>
</tbody>
</table>

(b) Based on the Power requirement:

- **Active Sensor**: In these sensors, the output signal is generated by a physical phenomenon of transduction (Like a generation of voltage due to temperature difference at thermocouple or in a thermometer where the level of mercury raises
with the change in temperature). It does not require any power source to measure the parameter of the system. Hence it is also considered as Self-generating Transducer.

- **Passive Sensor:** These sensors require external power source to function. Most of them work on the principles which are dependent on electrical energy like resistance, inductance and capacitance. A simple example is digital weighing machine which uses a battery operated Wheatstone bridge to measure weight. The machine stops functioning when the battery is drained.

(c) Based on the type of output Signal:

- **Analog Sensors:** When the signal output of a sensor is in analog form, then those sensors are called analog sensors. Analog devices produces a continuous signal which is proportional to the measured parameter. A simple example is the Bourdon tube where pressure is measured by elastic property of the tube.

- **Digital Sensor:** When the signal output of a sensor is in digital form, then those sensors are called digital sensors. A simple example is piezoelectric transducer used measure stress by natural phenomenon piezoelectric effect.

(d) Based on conversion of a parameter to an electrical parameter:

- **Primary Sensor:** When a sensor's output signal is in the form of electrical quantity like current, voltage etc., then they are considered as the
primary sensor. Thermocouple sensor or Hall Effect sensor are typical examples of such kind of sensor.

- **Secondary Sensor:** When a sensor’s output signal is in any other form than electrical quantity like voltage and current, then such quantity (like displacement or strain) are transformed into voltage or current. The function of secondary sensor is to transform other quantities into electrical quantities like voltage or current.

(e) Based on the parameter measured:

Some of the common parameters which are measured to know the state of a system are

- Displacement
- Pressure
- Velocity
- Temperature
- Light
- Level
- Flow
- Proximity

1.9.2 Static and Dynamic Characteristics of a Sensor:

A system basically exists in two states. One is called the Transient state and the other is called Steady state. Transient state is a state where the system is subjected to a sudden change. Steady state is a state when the system reaches equilibrium. A sensor should work well in both these states. In the steady state, the system is in a static condition and hence the characteristics of a sensor in that
state are called as Static characteristics. In transient condition, the system is in a dynamic condition and hence the characteristics of a sensor in that state are called Dynamic characteristics.

A. Static Characteristics of a Sensor:

(i) **Accuracy:** It is the extent to which a sensor is capable of measuring the parameter's value to the actual/true value in the system. The accuracy of a sensor can be expressed in following ways:

   (a) Point accuracy: When accuracy is specified at only one particular point of scale it does not give any information about the accuracy at any other Point on the scale it is called point accuracy.

   (b) Accuracy as percentage of scale span: When asensor has a uniform scale, its accuracy can be expressed in terms of scale range.

   (c) Accuracy as percentage of true value: Accuracy can also be specified in terms of a percentage true value of the quantity being measured.

(ii) **Precision:** The ability of the sensor to give the same measurement at all time if the parameter measured remains constant in the system is considered as precision. Precision is related to the variance of a set of measurements taken by the sensor. For instance, a level indicator sensor will indicate the same level in real time unless there is an actual change in the level. But if the reading is changing when it senses the same level then the precision of the sensor is bad. Hence it is very much
related to the repeatability, reproducibility and reliability of the sensor. Precision are composed of two characteristics

(a) Conformity: Consider a weight of 3.451 Kg. When a weighing machine with a sensor reads that measure it reads as 3.5 Kg as it is scaled in that way. Though there is no deviation from the value this error is caused due to the limitation of the sensor.

(b) Number of Significant figures: When a set of reading of the same quantity is taken by a sensor then each reading is a significant figure. These significant figures convey the actual information about the magnitude & the measurement precision of the quantity. The precision can be mathematically expressed as

\[
P = 1 - \frac{|X_n - \bar{X}_n|}{X_n}
\]

\[
P = \text{Precision}
\]

\[
X_n = \text{Value of } n^{th} \text{ measurement}
\]

\[
\bar{X}_n = \text{Average of the set of measured values}
\]

For example let’s consider the following set of readings

<table>
<thead>
<tr>
<th>S.No</th>
<th>Reading Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>32</td>
</tr>
<tr>
<td>2</td>
<td>31</td>
</tr>
<tr>
<td>3</td>
<td>30</td>
</tr>
<tr>
<td>4</td>
<td>29</td>
</tr>
<tr>
<td>5</td>
<td>32</td>
</tr>
</tbody>
</table>
The average value $X_n = (32 + 31 + 30 + 29 + 32)/5 = 30.8$

The precision of the 4th reading is

$$P = 1 - [(30.8 - 29)/30.8] = 0.941 = 94.1\%$$

(iii) **Error**: The algebraic difference between the true value ($A_t$) and indicated value ($A_m$) of the parameter measured by the sensor is called error ($e$).

$$e = A_t - A_m$$

(iv) **Repeatability/Reproducibility**: The repeatability and reproducibility of a sensor are its ability to give the same output for repeated applications of the same input value. Repeatability is also defined as the measure of deviation of test results mean value.

(v) **Reliability**: The reliability of a sensor is defined as the possibility that it will perform its assigned functions for a specific period of time under given conditions. The reliability of the sensor is affected not only by the choice of individual part in it but also by the manufacturing methods, quality of maintenance and the type of user.

(vi) **Sensitivity**: The sensitivity denotes the smallest change in the measured variable to which the instrument responds. It is defined as the ratio of the changes in the output of an instrument to a change in the value of the quantity to be measured. Mathematically it is expressed as

$$\text{Sensitivity} = \frac{\text{Infinitesimal change in output}}{\text{Infinitesimal change in input}} = \frac{\Delta q_0}{\Delta q_1}$$
(vii) **Linearity:** Linearity is defined as the ability of the sensor to reproduce the input characteristics of the measured parameter of the system in a linear and symmetrical manner.

Graphically an ideal relationship between the input and output would be like the straight line as shown in Fig. 1.24(a). Practically the relationship between the input and output would be like the actual curve which is called as the calibration curve of the sensor.

Linearity as mathematical quantity is defined as the percentage ratio of maximum deviation between the ideal line and actual calibration curve to full scale deflection.

\[
\% \text{ Linearity} = \frac{\text{Maximum deviation of output from idealized straight line}}{\text{Full scale deflection}} \times 100
\]

It is expected to have a sensor as linear as possible as it is very much related to its accuracy.

(viii) **Resolution:** Resolution is defined as the smallest increment in the assured value that can be detected by the sensor. The smallest value of input change which will produce an observable change in the
output of the sensor is called resolution. It is also referred as the discrimination of the sensor. It is also known as the degree of fineness with which measurements can be made. For example, if a micrometer with a minimum graduation of 1 mm is used to the nearest 0.5 mm, then by interpolation, the resolution is estimated as 0.5 mm.

(ix) **Threshold**: If the input quantity is varied from zero onwards, the output does not change until some minimum value of input is exceeded. This minimum value of input is called Threshold. Hence resolution is the smallest measurable input change and threshold is the smallest measurable input.

(x) **Drift**: The drift is the gradual shift in the sensor's output over an extended period of time during which the value of input variable does not change. Drift may be classified into three categories:

(a) **Zero Drift**: It is defined as the deviation in the sensor's output with time, from its zero value when the variable measured is a constant.

(b) **Span drift** or **sensitivity drift**: If there is proportional change in the indication all along the upward scale, the drifts is called span drift or sensitivity drift.

(c) **Zonal drift**: In case the drift occurs only at a portion of span of a sensor, it is called zonal drift.

(xi) **Stability**: The ability of a sensor to retain its performance throughout its specified operating life and the storage life is defined as stability.
(xii) **Tolerance:** The maximum allowable error in the measurement is specified in terms of some value is called tolerance. It is closely related to accuracy as many sensors manufactured specify accuracy in terms of tolerance values. Hence tolerance indicates the maximum allowable deviation of the manufactured sensor from a specified value.

(xiii) **Range or span:** The range of a sensor is defined as the limits between which the input can vary, the difference between the limits (maximum value – minimum value) is known as span. For example a load cell is used to measure force. The load cell can only measure from 20 to 100 N. Below 20 N or above 100 N it will not show any reading. Hence the range of the load cell is between 20 to 100 N. and span is 80 N (i.e., 100-20).

(xiv) **Bias:** The constant error that exists in the sensor throughout its range is called bias. It can be eliminated by calibrating the sensor.

(xv) **Hysteresis:** If the input variable is increased the output of the measuring sensor also increases. This is given by curve 1. When the input variable is decreased the output of the sensor also decreases. This is given by curve 2. The difference between the two curves is called hysteresis. Hysteresis is generally expressed as a percentage of full scale reading.

(xvi) **Dead Space:** There will be no output response for certain range of input values in a sensor which is known as Dead space/Dead band. Backlash in gears is a good example of dead space. There will be no
output until the input has reached a particular value. The time taken by a sensor to respond with an output after providing an input is called Dead time.

B. Dynamic Characteristics of Sensor:

(i) Response time:
When a sensor is suddenly given an input (by turning it on) or subjected to sudden change in the input, then there will considerable delay before it indicates a specified percentage (98%) of actual measure of the input as output. This delay/lag is called the Response time of the sensor.
(ii) **Time Constant:** It is 63.2% of the response time when subjected to step input.

(iii) **Rise Time:** The time taken for the sensor's output to rise to a specified percentage of the steady state output. It is mostly considered as the time taken to rise from 10% of steady state value to 90-95% of the steady state value.

(iv) **Settling time:** The time taken for the output of a sensor to settle within a specified percentage of the steady state value is called settling time.

### 1.10 POTENTIOMETERS:

The Potentiometer is a displacement transducer. It uses a variable resistance transduction principle to indicate the position or track the displacement.

**Construction:**

As illustrated in Fig 1.25, potentiometer consists of three terminals. The one in the middle is known as the wiper/slider, and the other two are known as ends. The wiper is a movable contact where resistance is measured with respect to it and either one of the end terminals.

![Fig. 1.25: Linear Potentiometer and Rotary Potentiometer](image-url)
Working Principle:

“The potential difference across any length of a wire of uniform cross-section and uniform composition is proportional to its length when a constant current flows through it.”

A battery is connected to a potentiometer wire “AB” with a switch control. Current ‘I’ from the battery flows through potentiometer wire AB forming the primary circuit.

A primary cell of potential difference ‘E’ is connected in series with a positive terminal of the battery along with a galvanometer, High resistor and a jockey forming the secondary circuit.

If the potential difference between AJ and the potential difference of the primary cell (E) is same then there will be no deflection in the galvanometer. AJ is called balancing length.

The potential difference between AJ ($V_{AJ}$) is expressed as

$$V_{AJ} = I \times r \times l$$

Where

- $I$ – Current in the primary circuit
- $r$ – Resistance of unit length of potentiometer wire
- $l$ – Varying length on the balancing length of the potentiometer
Hence

\[ E = I \times r \times l \]

Since ‘I’ and ‘r’ are constant \( E \) is proportional to \( l \). This voltage ‘E’ is what is measured in real time application which is directly calibrated to indicate the length/displacement.

**Some applications of Potentiometer:**

- It is used to adjust the level of analog signals.
- It is used as a control input for electronic circuits.
- It is used as a light dimmer in lamps.
- Preset potentiometers are widely used throughout electronics wherever adjustments must be made during manufacturing or servicing.
- User-actuated potentiometers are widely used as user controls, and may control a very wide variety of equipment functions.
- In consumer electronics, it is used as such as volume controls and position sensors. *Audio control linear potentiometers (“faders”)*
- Low-power potentiometers, both linear and rotary, are used to control audio equipment, changing loudness, frequency attenuation and other characteristics of audio signals.
- The ‘log pot’ is used as the volume control in audio power amplifiers, where it is also called an “audio taper pot”, because the amplitude response of the human ear is approximately logarithmic. Potentiometers used in combination with filter networks act as tone controls or equalizers.
Television Potentiometers were formerly used to control picture brightness, contrast, and color response.

A potentiometer was often used to adjust “vertical hold”, which affected the synchronization between the receiver's internal sweep circuit (sometimes as a multi-vibrator) and the received picture signal, along with other things such as audio-video carrier offset, tuning frequency.

Motion Control Potentiometers can be used as position feedback devices in order to create “closed loop” control, such as in a servo mechanism.

Potentiometers are also very widely used as a part of displacement transducers because of the simplicity of construction and because they can give a large output signal.

Computation in analog computers, high precision potentiometers are used to scale intermediate results by desired constant factors, or to set initial conditions for a calculation.

A motor-driven potentiometer may be used as a function generator, using a non-linear resistance card to supply approximations to trigonometric functions.

Linear Track Systems, Gate Positioning, Injection Molding Machines, Spray Painting Robots, Liquid Level Measurement, Railroad Track Laying Equipment
Medical - Cat Scan Tables, Bone Densitometers, MRI Tables,

- In Automobiles - Brake Position, Clutch Position, Steering Position, Throttle Position, Suspension Flexure, Body Movement, Crash Testing

### 1.11 LINEAR VARIABLE DIFFERENTIAL TRANSFORMER (LVDT):

LVDT is also called as Differential transformer or Linear Variable Displacement transformer. It is an electrical transformer used for measuring linear displacement. There is also a transformer used to measure angular displacement referred to as Rotary Variable Displacement Transformer (RVDT). These transducers are non-contact type hence they have long life and they produce very accurate results. They work using AC supply, hence there are no electronic components in it. Even in extreme temperatures they can be used. LVDT uses an electromagnet coupling to convert linear displacement into an equivalent electrical signal.

**Construction:**

It consists of primary coil wound on the middle of a hollow cylindrical rod which is connected to AC supply. On the same hollow cylindrical rod, two secondary coils of equal turns are wound at an equal distance from the primary coil.
on either side. The two secondary coils are connected in series in opposition to each other to get net induced EMF as the difference between them.

\[ E_0 = E_{S1} - E_{S2} \]

Where

- \( E_0 \) - Net Emf
- \( E_{S1} \) - EMF induced at secondary coil S1
- \( E_{S2} \) - EMF induced at secondary coil S2

A movable soft iron core is placed inside this hollow cylinder.

**Working Principle:**

When supply is given to the primary coil, current flow through the coil creating a varying magnetic field in it. This magnetic field interacts with the secondary coil producing EMFs in them. When the movable iron core is in the center the EMF produced by both the coils are equal. Hence the net EMF of the coil is zero. The position of the iron core is considered as Null position.
If the core moves forward towards the secondary coil $S_2$, then the EMF induced in that coil will become greater hence the net EMF will be negative.

$$E_{S_1} < E_{S_2}, E_0 = E_{S_1} - E_{S_2} = -\text{ve}$$

If the core moves backward towards the secondary coil $S_1$, then the EMF induced in that coil will become greater hence the net EMF will be positive.

$$E_{S_1} > E_{S_2}, E_0 = E_{S_1} - E_{S_2} = +\text{ve}$$

Thus by using the magnitude and polarity of the net EMF induced, LVDT measures the displacement of the core from the Null position.

**Some applications of LVDT:**

- Displacement- extensometers, temperature transducers, butterfly valve control, servo valve displacement sensing, Precision gap between torch and surface of Welding work
- Deflection of Beams, Strings, or Rings
- Load cells, force transducers, pressure transducers
- Thickness Variation of Work Pieces-dimension gauges, thickness, surface irregularities and profile measurements, product sorting by size
- Fluid Level-fluid level and fluid flow measurement, position sensing in hydraulic cylinders
- Velocity & Acceleration-automotive suspension control
1.12 CAPACITANCE SENSORS:

A capacitance sensor is a variable capacitor. It is used for measuring displacement, pressure, etc.

**Construction:**

The capacitance sensor shown in fig 1.29 consists of two parallel metal plates separated by substance like air called dielectric. In normal capacitor the distance between the plates are fixed and this makes the capacitance of the capacitor constant. In a capacitance sensor the distance between the plates is a variable and hence there will be change in the capacitance which can be measured easily.

---

**Working Principle:**

In capacitance transducers, the value of the capacitance changes when there is a change in the input parameter's value which is to be measured. This change in capacitance is measured and calibrated against the input parameter's value. Thus the value of the input quantity is measured.
The capacitance $C$ between the two plates of a capacitance transducer is

$$C = \varepsilon_o \times \varepsilon_r \times \left( \frac{A}{d} \right)$$

Where

- $\varepsilon_o$ – Absolute permittivity
- $\varepsilon_r$ - Relative permittivity
- $A$ – Area of the plate
- $d$ – Distance between the plates

The product of $\varepsilon_o \times \varepsilon_r$ is called Dielectric Constant of the capacitor. Hence as per the formula of calculating capacitance, the value of capacitance varies due to

(a) Dielectric Constant
(b) Area of the plate
(c) Distance between the plates
Hence depending on the parameter which is used to change the capacitance of the capacitance transducer, there are three types of capacitance transducers.

1. Changing Dielectric Constant type:

The dielectric material between the two plates is changed (fig 1.30), due to which the capacitance of the transducer also changes. When the input value changes, corresponding to that the value of the dielectric constant also changes. Hence the capacitance of the transducer also changes. This capacitance change is calibrated to measure the input parameter value directly. This principle is used for measurement of level in the hydrogen container, where the change in level of hydrogen between the two plates results in change of the dielectric constant of the capacitance transducer. This principle can also be used for measurement of humidity and moisture content of the air.

2. Changing Area of the Plates type:

When the area of the plates changes, the capacitance of the variable capacitance transducer also changes. This principle is used in the torque-meter, used for measurement of the torque on the shaft. This comprises of the sleeve that
has teeth cut axially and the matching shaft that has similar teeth at its periphery.

3. Changing Distance (Linear/Angular) between the Plates type:
In these capacitive transducer, distance between the plate is variable, while the area of the plates and the dielectric constant remain constant. This is commonly used variable capacitance transducer. For measurement of the displacement of the object, one plate of the capacitance transducer is kept fixed, while the other is connected to the object. When the object moves, the plate of the capacitance transducer also moves, this results in change in distance between the two plates and the change in the capacitance. The changed capacitance is measured easily and it is calibrated against the input quantity, which is displacement. This principle can also be used to measure pressure, velocity, acceleration etc.

**Some applications of Capacitance Sensors:**

- Level Control of Liquids, Solids
- Pile-up Control
- Monitoring at Hazardous Area Environments, High Temperature Environments, High Pressure Wash-down Environments
- Feed Hopper Level Monitoring
- Small Vessel Pump Control
- Suitable for use in Environments with Inconsistent Power Supplies
- Grease Level Monitoring
- Pharmaceuticals Manufacturing
- Suitable for Use with Chemicals
- Pipeline Leak Detection
- Vessel Leak Detection
1.13 STRAIN GAUGES:

Strain gauges are used for measuring displacement, stress, strain and force. These are classified as mechanical, optical or electrical gauges depending on the principle of operation. Among them, the most commonly used and modernized gauge is the electrical resistance type gauge. It is popular as the process of measurement is simple and advantageous over all other gauges.

Construction: Electrical resistance type strain gauge

![Diagram of strain gauge](image)

The strain gauge shown in Fig 1.33 has sensing element in the form of a thin metallic resistive foil grid made of about 3 to 6 \( \mu \)m thick. This grid is put on the base of a plastic film of 15 to 16 \( \mu \)m thick and is laminated with another thin film on the top. Gauge sensing length is marked along with center markings on the length and width of the grid. Leads to the gauge are soldered to wire made of silver clad copper of 120-160 \( \mu \)m diameter and
2500 μm of length. The strain gauge is bonded to the measuring object with a dedicated special adhesive. Strain occurring on the measuring site is transferred to the strain sensing element via the gauge base through the leads which are normally connected to Wheatstone's bridge or any other resistance measuring device. For accurate measurement, the strain gauge and adhesive should match the measuring material and operating conditions including temperature.

**Working Principle:**

![Diagram of Strain Gauge Working Principle](image)

Strain gauge is basically a wire which goes back and forth as in **Fig. 1.34**. Depending on the direction of deformation the active axis is aligned with the object on which strain is to be measured. The input can be anything like force, torque or pressure which can deform the element on which measurement is to be made. This deformation is transferred to the strain gauge which changes the resistance of the gauge which is measured in the Wheatstone's bridge or any other resistance measuring
device. This is directly calibrated to indicate the parameter which is to be measured by the sensor.

The strain is measured by the following equation

\[
\frac{\Delta R}{R} = G_f \varepsilon
\]

Where

- \( R \) – Base Resistance
- \( \Delta R \) – Change in Resistance
- \( G_f \) – Gauge factor which is the constant of proportionality
- \( \varepsilon \) – Strain

Based on the type of element there are different forms of strain gauge as shown in Fig. 1.35.

![Fig:1.35 Strain gauged elements](image)

The strain is affected by temperature. Due to thermal stress, the expansion and contraction of the wire changes the resistance of the wire. Hence proper material is used
to withstand this and an appropriate correction factor is used to improve accuracy of the gauge.

**Strain gauges are used for measuring**
- Stress analysis
- Forces
- Moments
- Pressures
- Accelerations
- Displacements
- Vibrations

### 1.14 EDDY CURRENT SENSORS:

Eddy current is a circular current which is induced by a conductor when it is kept in a changing magnetic field. Eddy current sensors are used as proximity sensors to detect the presence or absence of non-magnetic conductive material. It is a non-contact sensor.

**Construction:**

The eddy current sensor consists of a coil wound on a ferrite core connected to a signal amplifier and a signal processor as shown in Fig. 1.36. The coil has an AC supply. The coil and the core arrangement are made inside a probe. This probe is connected to the signal processing unit with the signal amplifier and signal analyzer. As per the application, the signal processing unit can be calibrated to indicate the parameter which is to be measured.

**Working Principle:**

When supply is given to the sensing coil, it produces a magnetic field. When this magnetic field cuts the work
piece, it generates Eddy current in it. The Eddy current in the work piece generates a magnetic field opposite to the sensing coil’s magnetic field. Eddy current is very weak. Hence the magnetic field it produces is also very weak. When two magnetic field clashes, it produces a small distortion which is detected by the signal processing unit. These small distortion signals with are recognized when it is amplified and analyzed. Based on the applications, this sensor is used with the signal processing unit programmed.

This sensor is very accurate and cost of construction is low. It can be used in extreme conditions as it is not
temperature sensitive. Only problem is the distance from the target must be less.

**Some Applications of Eddy Current Sensor:**

- Automation requiring precise location
- Machine tool monitoring
- Final assembly of precision equipment such as disk drives
- Precision stage positioning
- Drive shaft monitoring
- Vibration measurements

### 1.15 HALL EFFECT SENSOR:

‘Hall Effect’ is used to measure magnetic field. The sensor applying ‘Hall effect’ principle is used to measure position, displacement, level and flow. It is also a non-contact sensor.

**Hall Effect Principle:**

When a thin conductor is powered by battery, then current will pass through the conductor in a straight line. But when that conductor is subjected to a magnetic field, then current flow will be disturbed by a force called Lorentz force. Hence electrons will move to one side of the plate and the positive poles to the other side of the plate, creating a potential difference in between the two sides of the plate. This is measured with a multimeter. This process of obtaining a measurable voltage is called Hall Effect.
Basic types of Hall Effect Sensors:

There are basically two kinds of Hall Effect sensors based on the output signals which can be either analog or digital. Any Hall Effect sensor has a Hall element which produces the voltage due to Hall Effect. This voltage is very low, hence it is amplified by a High Gain Amplifier. The amplified voltage is an analog signal. When the application requires analog output, this circuitry is enough. However, if the application demands a digital output, then this analog signal is fed to a Schmitt Trigger. It converts analog signal into a digital signal.

Hall Effect Switch:

The Hall Effect switch is nothing but a digital Hall Effect sensor with pre-set output condition. Fig. 1.39 illustrates a typical Hall Effect Switch. The voltage output
of the sensor is conditioned. If the voltage is less than the set standard, then it is in the ‘off’ state and if it is more than the set standard, then it is in the ‘on’ state. Thus, it is used as a switch.
Hall Effect Sensor for determining RPM of Wheel:

Here the Hall Element with a permanent magnet is placed near disc of a rotating disc. The gap between the sensor and the teeth of the disc is fixed and very less. Hence, when the disc is in motion the teeth cuts the magnetic field at regular intervals forming a pattern. This pattern gives an output in the form of a square wave signal.
which can be easily processed to determine the RPM of the shaft.

**Hall Effect Sensor for determining Liquid Level:**

Hall effect transducers are used for sensing position, displacement and proximity when the object to be sensed is fit with a small permanent magnet. Normally, the fuel level in an automobile fuel tank is determined by this Hall effect transducer as shown in Fig. 1.41.

The magnet will be attached to a float. As the fuel level raises (or) lowers, the float with magnet distance from the Hall effect sensor changes. Due to this, Hall voltage will be induced which measures the distance of the float from the sensor. Hence the fuel level can be determined.

**Some applications of Hall effect Sensor:**

- Wheel Speed sensors - RPM
- Crankshaft/Camshaft position sensors
- Hall Effect Switches
- MEMS Compasses
- Proximity Sensors
1.16 TEMPERATURE SENSORS:

Temperature can be measured by using any one of the following principle.

1. Materials change in length, volume (or) pressure of the system as a result of change in temperature.
2. By measuring change in electrical resistance as a result of change in temperature.
3. By measuring voltage between two dissimilar metals as a result of difference in temperature.
4. By measuring change in radiated energy as a result of change in temperature.

(a) Liquid in glass Thermometer:

Liquid in Glass Thermometers make use of thermal expansion of a liquid enclosed in a bulb when it is exposed to the system for which temperature has to be measured. The temperature can be determined by measuring the level of the liquid (mercury (or) alcohol) in the capillary attached to the bulb.

The standard clinical thermometer is the example for the liquid in Glass thermometer.

Liquid filled mechanical thermometer is shown in Fig. 1.42.
It consists of:

1. Temperature sensor in the form of an immersible bulb
2. Spiral spring (measuring element) coupled to the bulb through a capillary tube and
3. An indicating (or) recording attachment (pointer).

When the temperature sensor bulb is exposed to the thermal medium, the mercury enclosed in the bulb expands and this change in volume drives the spiral spring through a capillary link. The pointer coupled to the spring deflects as a function of temperature and it indicates the exact temperature.

(b) **Resistance Temperature Detector:**

Most of the metal’s resistance will increase with the increase of temperature [But carbon’s resistance will decrease with the increase of temperature]. The resistance of a highly conducting material increases with an increase in temperature. But, the resistance of semiconductor generally decreases with an increase in temperature.

The temperature sensing device is placed in contact with the system for which the temperature is to be measured.

The measure of its resistance indicates the temperature of the system.

The **Resistance Temperature Detector (RTD)** is used to measure temperature with the variation of metal resistance, where as, the **thermistor** is used to measure temperature with the variation of semiconductor resistance.
RTD is used to measure temperature ranging from cryogenic (−200°C) to 600°C. This is sensitive and highly stable. These RTDs are made up of materials such as platinum, Cu, Ni and tungsten. The RTD consists of a wire which is wound in the shape of coil to achieve small size and improve thermal conductivity.

Several forms of RTDs have been developed for temperature measurements depending upon their requirement, such as speed of response, environmental conditions and ability to withstand vibration (or) corrosion.

The Fig. 1.43(a) shows open wire RTD in which platinum wire is wound in the form of a free spiral (or) held in place by an insulated carrier such as silica (or) ceramic in the form of a perforated coil former. The lead wires are in direct contact with the gas (or) liquid for which the temperature has to be measured. Such RTD has an excellent response time, small conduction errors and small heating errors.

Resistance Vs temperature for most of the metals are given by quadratic equations.

\[ R = R_0 (1 + \alpha (T - T_0) + \beta (T - T_0)^2 + \ldots ) \]
where $R_0$ is the resistance at absolute temperature $T_0$ and $\alpha$ and $\beta$ are material constants depending on the purity of the material used.

The resistance Vs temperature curve is shown in Fig. 1.43 (b) which shows RTD’s characteristics for different metals.

(c) Thermistor:

Thermistor is used to measure temperature based on the principle of change in semiconductor resistance with change in temperature. The characteristics of thermistor depend on the particular behaviour of semiconductor resistance versus temperature.

When the temperature of the material is increased, the molecules starts vibrating. Further more increase of temperature causes more vibrations and as a result, the volume occupied by the atoms in the metal lattice will increase. Electron flow through the lattice becomes very difficult, which causes electrons in the semiconductor to detach, resulting in increased conductance.

Final conclusion is that an increase in temperature improves conductance.

The semiconductor becomes good conductor of current when its temperature is increased. And also the change in semiconductor’s resistance with respect to temperature is highly nonlinear. But for metal, its resistance is increased (ie conductance is decreased) when its temperature is increased.

The thermistor curves are plotted by the following non-linear equation.
\[
\frac{1}{T} = A + B \ln R + C (\ln R)^3
\]

where \( T = \) Temperature in K

\( R = \) Resistance of thermistor

\( A, B, C = \) Curve fitting constants

The temperature range of thermistor is in between \(-250^\circ C\) and \(650^\circ C\). The advantage of the thermistor is its high sensitivity. Because of the non-linear behaviour of the thermistor, it makes difficult to use the thermistor as a primary measurement device.

The thermistor can be fabricated in many forms, including discs, beads and rods as shown in Fig. 1.44.

The thermistors vary in size from a bead of 1mm diameter to a disc of several centimeters in diameter and several centimeters thick. By varying manufacturing process and using different semiconducting materials, a
manufacturer can provide a wide range of resistance values at any particular temperature. Because of thermistor's small size, they respond very rapidly to changes in temperature. But the main disadvantage of the thermistor is its non-linearity. Generally, the resistance-temperature relationship for a thermistor are given by the equation

\[ R = K e^{\beta/t} \]

where \( R \) = Resistance at temp \( t \)

\( K \) and \( \beta \) are constants

(d) Thermocouples:

Thermocouples are used to measure temperature. They are based on the principle that a current flows in a closed circuit made up of two dissimilar metals, if the junctions of the two metals are kept at different temperatures.

When two conductors of dissimilar material are joined to form a circuit, the following effect is noted.

When the two junctions are at different temperatures \( T_1 \) and \( T_2 \), small emf's are produced at the junctions, and the algebraic sum of these causes a current. This effect is known as Seebeck effect.

If both junctions are at the same temperature, there is no net emf. But, if there is a difference in temperature between the two junctions, there is an emf. This thermocouple voltage is proportional to the junction temperature difference.

\[ V = \alpha (T_1 - T_2) \]

where \( \alpha \) is called Seebeck coefficient.
The standard thermocouple configuration is shown in Fig. 1.46.

Thermocouple consists of two different metallic wires, A and B. These two wires are attached to a voltage measuring device. There are two junction 1 and 2. Junction 2 is normally maintained at 0°C by being immersed in ice water. This junction is known as reference junction temperature \(0°C\). The other junction 1 has to be installed at a point where temperature has to be measured. This junction is known as measuring junction.

By measuring the voltage difference, we can determine the temperature at the measuring junction. For a given pair of thermocouple metals and a reference
temperature, a standard reference table can be compiled for converting voltage measurements to temperatures.

The following examples show how to find temperature by measuring the voltage. A standard two junction thermocouple configuration is used to measure the temperature.

**Example 1:** The reference junction is held at constant temperature of 10°C. But we have thermocouple table with respect to the reference temperature 0°C as shown here.

<table>
<thead>
<tr>
<th>Junction temperature (°C)</th>
<th>Output voltage (mV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>10</td>
<td>0.507</td>
</tr>
<tr>
<td>20</td>
<td>1.019</td>
</tr>
<tr>
<td>30</td>
<td>1.536</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>80</td>
<td>4.186</td>
</tr>
<tr>
<td>90</td>
<td>4.725</td>
</tr>
<tr>
<td>100</td>
<td>5.268</td>
</tr>
</tbody>
</table>

What is the output voltage when the measuring junction is exposed to 100°C?

By applying law of intermediate temperature, we can write \( V_{100/0} = V_{100/10} + V_{10/0} \). The voltage measured for the temperature of 100°C relative to the reference junction at 10°C can be calculated as follows

\[
V_{100/10} = V_{100/0} - V_{10/0} \\
= (5.268 - 0.507) \text{ mV} \\
= 4.761 \text{ mV}
\]
**Example 2:** The reference junction is held at constant temperature of 20°C. Use thermocouple table referenced to 0°C. What is the output voltage when measuring junction is exposed to 80°C

By applying law of intermediate temperature, we can write.

$$V_{80/0} = V_{80/20} + V_{20/0}$$

The voltage measured for the temperature of 80°C relative to the reference junction at 20°C can be calculated as follows.

$$V_{80/20} = V_{80/0} - V_{20/0}$$
$$= 4.186 - 1.019$$
$$= 3.167 \text{ mV}$$

**(e) Radiative Temperature Sensing**

A body at a temperature greater than 0K radiates electromagnetic energy in an amount that depends on its temperature and physical properties. Radiative temperature sensor need not be in contact with the surface to be measured. Because the radiation emitted by a body is proportional to the fourth power of its temperature.

$$Q_{\text{radiation}} = \sigma T^4$$

where $\sigma = \text{Stefan Boltzman Constant} = 5.67 \times 10^{-8} \frac{W}{m^2 K^4}$

An **optical pyrometer** identifies the temperature of a surface by the colour of the radiation emitted by the surface. When a body is heated, it initially becomes dark
red, turns to orange and finally attains a white colour. The actual temperature measurement is based upon the determination of the variations in colour of the object, and comparing it with known values generated with a heated element.

Optical pyrometer is shown in Fig. 1.47.

![Fig: 1.47 Heated filament Optical pyrometer](image)

The radiation from the source is viewed through a lens and filter arrangement, along with a standard lamp placed in the optical path of the incoming radiation. A red filter is used to eliminate source of the uncertainties resulting from variation of radiation properties with wavelengths. By suitable adjustment of the lamp current, the colour of the lamp filament is made to match with the colour of the incoming radiation. When balance conditions are attained, the filament will disappear in the total incoming radiation field. At this moment, by measuring the lamp heating current, we can measure the temperature of the radiating body.
1.17 LIGHT SENSORS:

The Light Sensors are passive devices which convert “light energy” (visible or invisible like the infra-red) to electrical signals. Light sensors are also known as “Photoelectric Devices” or “Photo Sensors” as they convert light energy (photons) into electricity (electrons). Photoelectric devices can be grouped into two main categories, one which generate electricity when illuminated, such as Photo-voltaic or Photo-emissive, and the other which change their electrical properties in some way such as Photo-resistors or Photo-conductors. Hence they are classified as:

A. Photo-emissive Cells:

Principle:

These photo-devices are light sensitive materials like caesium that releases free electrons when struck by a photon of sufficient energy. The energy of the photons depends on the frequency of the light. Higher the frequency, greater is the energy of the photons which converts light energy into electrical energy.
Construction and Working:

The photo emissive cell consists of a glass envelope with a vacuum inside. The envelope also contains a light sensitive cathode and an anode. When light strikes the cathode, negative electrons are emitted and are attracted by the positive anode. The value of this current is proportional to the intensity of light falling on the cathode. The PEC (Photo Emissive cells) can be used as part of a potential divider circuit. This basic design is called a photo emissive cell or phototube. In a slightly different design it is called a photomultiplier where there is a series of plates (each plate consisting of the above components in it) are arranged so that one incoming photon releases multiple electrons—effectively amplifying an incoming light signal so it produces a bigger electrical response. Photoemissive cells are the oldest and most elaborate way of turning light into electricity.

B. Photo-conductive Cells:

Principle:

These photo-devices when exposed to light, their electrical resistance varies. When a semiconductor material is exposed to light, current flows through it and this phenomenon is referred to as Photoconductivity. Hence exposure to light increases the current for a given applied voltage in the circuits connected with these devices. This change can be measured to sense the intensity of light. The most common photoconductive material is Cadmium Sulphide used in LDR photocells.
Construction and Working:

Photoconductive Cell is also called the Photoresistor or Light Dependent Resistor or LDR. The snake-like track shown in Fig. 1.49 (a) is the Cadmium Sulphide (CdS) film which also passes through the sides. On the top and bottom are metal films which are connected to the terminal leads. It is designed in such a way as to provide maximum possible contact area with the two metal films. The structure is housed in a clear plastic or resin case, to provide free access to external light. The main component for the construction of LDR is Cadmium Sulphide (CdS), which is a photoconductor and contains no or very few electrons in the absence of light. In the absence of light, it is designed to have a high resistance in the range of mega ohms. When the sensor is exposed to light, the electrons becomes free due to photoconductivity. Hence the
conductivity of the material increases. When the light intensity exceeds a certain frequency, the photons absorbed by the semiconductor give band electrons the energy required to jump into the conduction band. This causes the free electrons or holes to conduct electricity and thus dropping the resistance dramatically (1 Kiloohm). The equation to show the relation between resistance and illumination can be written as

\[ R = A \times E^a \]

Where

- \( E \) – Illumination (lux), \( R \) – Resistance (Ohms), \( A, a \) – constants

The value of ‘\( a \)’ depends on the CdS used and on the manufacturing process. Values usually range between 0.7 and 0.9.

C. Photo-voltaic Cells:

Principle:

These photo-devices generate an emf which is proportional to the radiant light received. They are similar in effect to photoconductivity. Here two semiconductor materials are sandwiched and exposed to light which creates a voltage of approximately 0.5 V. The most common photovoltaic material is Selenium used in solar cells.

Construction and Working:

A typical silicon solar cell is composed of a thin wafer consisting of an ultra-thin layer of phosphorus-doped (N-type) silicon on top of a thicker layer of boron-doped (P-type) silicon. Hence form a PN junction. When the cell
surface is exposed to sunlight a potential difference is created in PN junction. Hence there is a flow of electrons. Individual solar cells can be connected together in series to form solar panels which increases the output voltage or connected together in parallel to increase the available current. Commercially available solar panels are rated in Watts, which is the product of the output voltage and current (Volts times Amps) when fully lit.
D. Photo-junction Devices:

**Principle:**
These photo-devices are mainly true semiconductor devices such as the photodiode or phototransistor which use light to control the flow of electrons and holes across their PN-junction. Photo-junction devices are specifically designed for detector application and light penetration with their spectral response tuned to the wavelength of incident light.

**Construction and working:**

![Diagram showing the construction of a photodiode light sensor.](image)

The construction of the Photodiode light sensor is similar to that of a conventional PN-junction diode, except that the diodes outer casing is either transparent or has a
clear lens to focus the light onto the PN junction for increased sensitivity. The junction will respond to light, particularly longer wavelengths such as red and infra-red rather than visible light.

The current-voltage characteristic (I/V Curves) of a photodiode with no light on its junction (dark mode) is very similar to a normal signal or rectifying diode. When the photodiode is forward biased, there is an exponential increase in the current, the same as for a normal diode. When a reverse bias is applied, a small reverse saturation current appears which causes an increase of the depletion region, which is the sensitive part of the junction.

When used as a light sensor it operates in the reverse biased mode. When the photodiode is exposed to light the PN junction in diode produces more hole/electron pairs and this increases the leakage current. As per the materials used for making the diode light sensitivity levels are set along with the corresponding leakage current at various levels of exposure to light. Thus, the photodiode’s current is directly proportional to the light intensity it is exposed to.