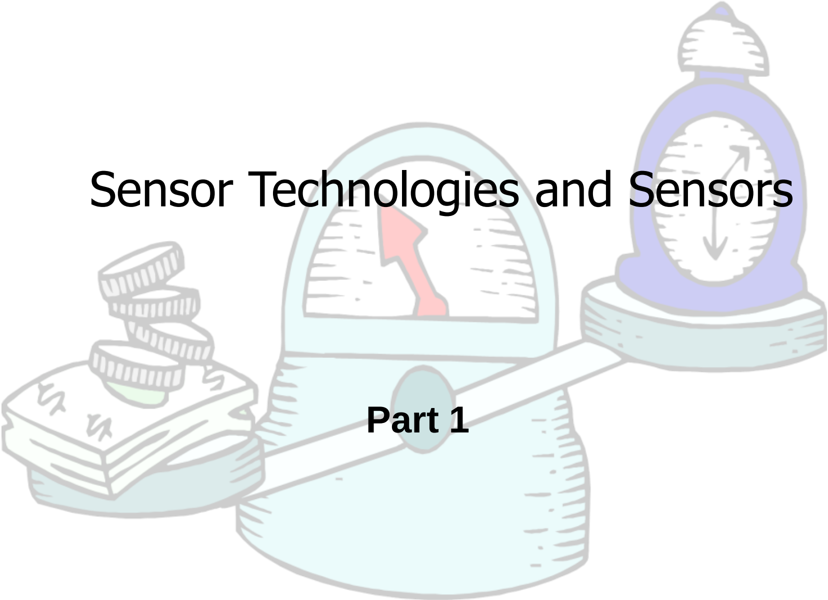
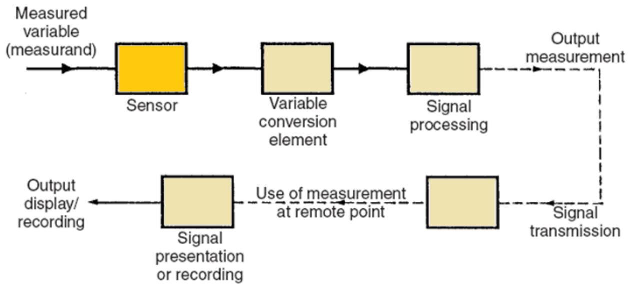


Sensor Technologies and Sensors

Part 1

Sensors in Measuring Instruments

- A sensor is that part of a measuring instruments which responds the changes in the measured variable by giving an output that is a function of the measurand.
- A sensor utilizes the interaction of the physical parameters with each other—most notably electric properties with stress, temperature thermal gradients, magnetic fields, and incident light—yields a multitude of sensing techniques which may be applied.

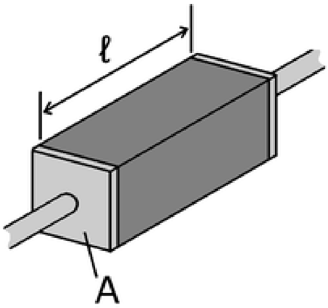


Resistive sensors

- ❑ Resistive sensors rely on the variation of the resistance of a piece of material when the measured variable is applied to it.
- ❑ Many resistors and conductors have a uniform cross section and their resistance, *R*, is given by:

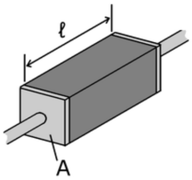
$$R = \rho(l/A)$$

where ρ is the resistivity of the element's material, *l* is its length and *A* is its cross sectional area.

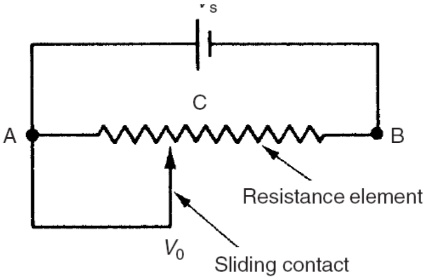


Resistive sensors: Potentiometers

- ❑ The resistive potentiometer is perhaps the best-known displacement-measuring device.
- ❑ It relies on changing the length *l* along which of the resistor is measured
- ❑ A linear relationship exists between the length and the resistance.

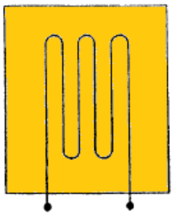


$$R = \rho(l/A)$$



Resistive sensors: Metal Strain Gauges

- Strain gauges are devices that experience a change in resistance when they are stretched or strained. They are typically used as part of other transducers, for example diaphragm pressure sensors that convert pressure changes into small displacements of the diaphragm.
- The traditional metal strain gauge consists of a length of metal resistance wire formed into a zigzag pattern and mounted onto a flexible backing sheet.
- The wire is nominally of circular cross-section. As strain is applied to the gauge, the shape of the cross-section of the resistance wire distorts, changing the cross-sectional area.
- As the resistance of the wire per unit length is inversely proportional to the cross-sectional area, there is a consequential change in resistance.
- The input–output relationship of a strain gauge is expressed by the gauge factor, which is defined as the change in resistance (R) for a given value of strain (S).



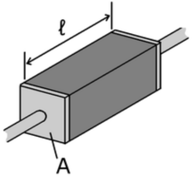
$$R = \rho(l/A)$$

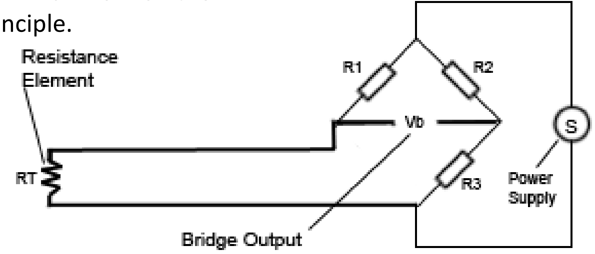
$$\text{gauge factor} = \frac{\delta R}{\delta S}$$

Resistive sensors:

- Many resistive sensors rely on the variation of the resistivity of the element's material when measured variable is changed. Common application of this principle is found in:
  - Resistance thermometers or resistive temperature detectors (RTDs)
  - Piezoresistive sensors and Piezoresistive strain gauges.
  - Some moisture meters which work on the resistivity-variation principle.

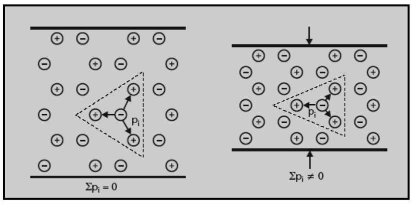
$$R = \rho(l/A)$$





Piezoresistive sensors

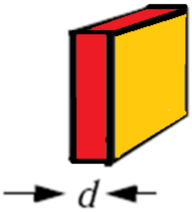
- A piezoresistive sensor is made from semiconductor material in which a p-type region has been diffused into an n-type base. The resistance of this varies greatly when the sensor is compressed or stretched.
- This is frequently used as a strain gauge, where it produces a significantly higher gauge factor than that given by metal wire or foil gauges. Also, measurement uncertainty can be reduced to ±0.1%.
- It is also used in semiconductor-diaphragm pressure sensors and in semiconductor accelerometers.



Capacitive sensors

- Capacitive sensors consist of two parallel metal plates in which a dielectric between the plates. A dielectric is an electrical insulator that can be polarized by an applied electric field. It is either air or some other medium.
- The capacitance C is given by:

$$C = \varepsilon_o \varepsilon_r \frac{A}{d}$$

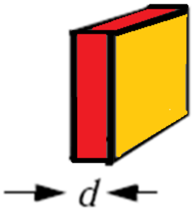


where ε_o is absolute permittivity, ε_r is the relative permittivity of the dielectric medium between the plates, *A* is the area of the plates and *d* is the distance between them.

Capacitive sensors

- Capacitive devices are often used as displacement sensors**, in which motion of a moveable capacitive plate relative to a fixed one changes the capacitance.**
- Often, the measured displacement is part of instruments measuring pressure, sound or acceleration.
- Alternatively, **fixed plate capacitors** can also be used as sensors, in which the capacitance value is changed by causing the measured variable **to change the dielectric constant** of the material between the plates in some way.
- **This principle is used in devices to measure moisture content, humidity values and liquid level.**

$$C = \varepsilon_o \varepsilon_r \frac{A}{d}$$

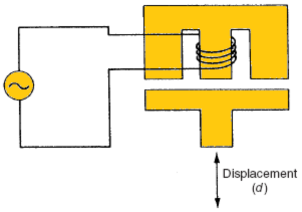


Magnetic Sensors

- **Magnetic sensors utilize the magnetic phenomena of:**
  - **inductance,**
  - **reluctance**
  - **and eddy currents**
- **to indicate the value of the measured quantity, which is usually some form of displacement.**

Inductive sensors

- ☐ In the inductive displacement transducer, the single winding on the central limb of an 'E'-shaped ferromagnetic body is excited with an alternating voltage.
- ☐ The displacement to be measured is applied to a ferromagnetic plate in close proximity to the 'E' piece.
- ☐ Movements of the plate alter the flux paths and hence cause a change in the current flowing in the winding. The current-voltage relationship in the winding is given by:
- ☐ For fixed values of ω and V, I depends only on *L*, which in turn, depends on the displacement *d* applied to the plate.
- ☐ The relationship between L and *d*, is a non-linear one, and hence the output-current/displacement characteristic has to be calibrated.



$$v = L\frac{di}{dt},$$

$$i = \frac{1}{L}\int v\,dt = \frac{V}{L}\int \cos\omega t\,dt$$

$$= \frac{V}{\omega L}\sin\omega t$$

$$I = \frac{V}{\omega L}$$

Magnetic Reluctance

- Magnetic Reluctance is analogous to resistance in an electrical circuit (although it does not dissipate magnetic energy).
- An electric field causes an electric current to follow the path of least resistance,
- **A magnetic field causes magnetic flux to follow the path of least magnetic reluctance**

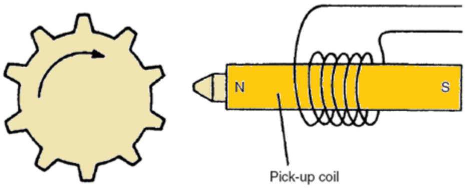
- The definition can be expressed as: $\mathcal{R}$=F/Φ

where

- ("$\mathcal{R}$") is the reluctance in ampere-turns per weber (a unit that is equivalent to turns per henry). "Turns" refers to the winding number of an electrical conductor comprising an inductor.
- ("F") is the magnetomotive force (MMF) in ampere-turns
- *Φ* ("Phi") is the magnetic flux in webers.

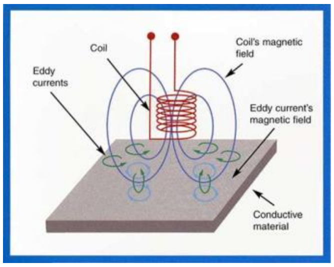
Variable Reluctance Sensors

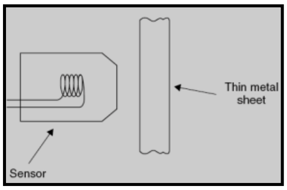
- Variable reluctance sensors are a class of magnetic sensors in **which a coil** is **wound on a permanent magnet** rather than on an iron core as in variable inductance sensors.
- Such devices are commonly used to measure rotational velocities.
- In a typical instrument a ferromagnetic gearwheel is placed next to the sensor.
- As the tip of each tooth on the gearwheel moves towards and away from the pick-up unit, the changing magnetic flux in the pick-up coil causes a voltage **to be induced in the coil** whose magnitude is proportional to the rate of change of flux.
- Thus, the output is a sequence of positive and negative pulses whose frequency is proportional to the rotational velocity of the gearwheel.



Eddy Current Sensors

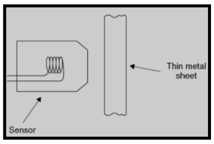
- Eddy current sensors are a third class of magnetic sensors and **consist of a probe containing a coil that is excited at a high frequency, which is typically 1MHz**.
- This is used to measure the displacement of the probe relative to a moving metal target.
- Because of the high frequency of excitation, eddy currents are induced in the surface of the target and the current magnitude reduces to almost zero a short distance inside the target.
- This allows the sensor to work with very thin targets, such as the steel diaphragm of a pressure sensor.





Eddy Current Sensors

- **The eddy currents alter the inductance of the probe coil, and this change can be translated into a d.c. voltage output that is proportional to the distance between the probe and the target**.
- Measurement resolution as high as 0.1 µm can be achieved.
- The sensor can also work with a non-conductive target if a piece of aluminum tape is fastened to it.



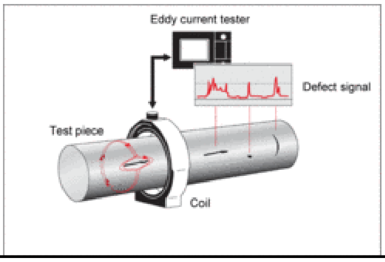
Effective Sensor Range
In practice, the effective range of an eddy current transducer is given by the vendor suggested range offset from the target surface by 20%.

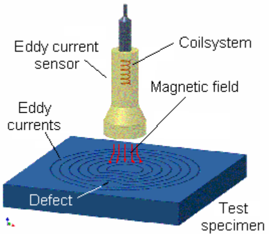
Eddy Current sensor applications

- The sensor can also work with a non-conductive target if a piece of aluminum tape is fastened to it.

Distance measurement

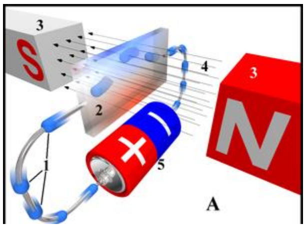
For product testing





Hall Effect Sensors

The Hall effect refers to the potential difference (Hall voltage) on the opposite sides of an electrical conductor through which an electric current is flowing, created by a magnetic field applied perpendicular to the current. Edwin Hall discovered this effect in 1879.

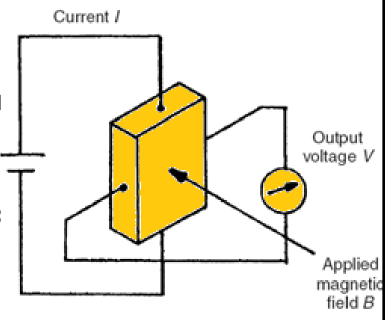


Hall effect diagram, showing electron flow (rather than conventional current).

Legend:
1. Electrons
2. Hall element, or Hall sensor
3. Magnets; 4. Magnetic field ;
5. Power source

Description:
In drawing "A", the Hall element takes on a negative charge at the top edge (symbolised by the blue color) and positive at the lower edge (red color).

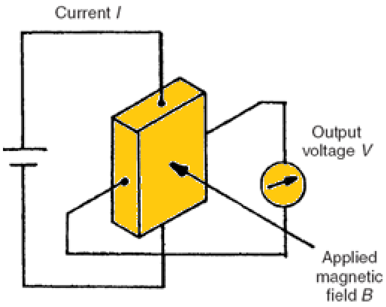
Hall-effect sensors



- A Hall-effect sensor is a device that is used to measure the magnitude of a magnetic field.
- It consists of a conductor carrying a current that is aligned orthogonally with the magnetic field.
- This produces a transverse voltage difference across the device that is directly proportional to the magnetic field strength.
- For an excitation current I and magnetic field strength B, the output voltage is given by
- **$V = KIB$**, where K is known as the Hall constant.
- The conductor in Hall-effect sensors is usually made from a semiconductor material as opposed to a metal, because a larger voltage output is produced for a magnetic field of a given size.

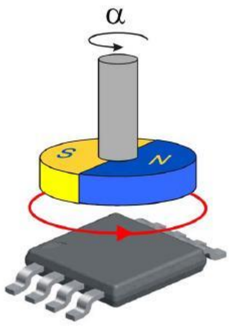
Hall-effect sensors

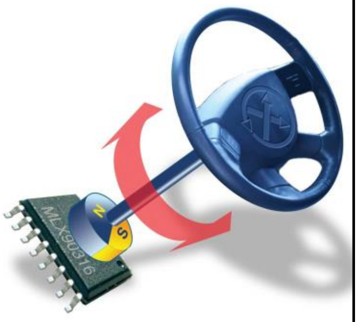
- ❑ In one common use of the device as a **proximity sensor**, the magnetic field is provided by a permanent magnet that is built into the device.
- ❑ The magnitude of this field changes when the device becomes close to any ferrous metal object or boundary.
- ❑ **The Hall effect is also commonly used in keyboard pushbuttons**, in which a magnet is attached underneath the button.
- ❑ When the button is depressed, the magnet moves past a Hall-effect sensor. The induced voltage is then converted by a trigger circuit into a digital output. **Such pushbutton switches can operate at high frequencies without contact bounce.**



Hall Sensor IC

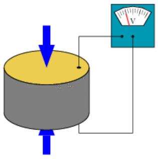
- The MLX90316 Non-contact absolute non-contacting rotary sensor IC allows simple implementation of rugged 360 degree position indicators.
- Applications include Throttle position sensing, pedal position drive by wire sensors, ride height, shaft position and othe 0 to 360 degree absolute rotary position indication applications.
- The IC is fully programmable to allow the user to set the angular range to any value and still have rail to rail signal for the chosen angular displacement. It also allows includes diagnostic options and is available in a dual redundant version for safety critical applications. See datasheet for complete list of specifications and programming options**.**





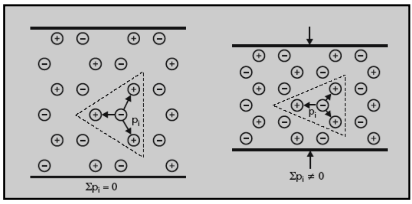
Piezoelectricity

- **Piezoelectricity** is the ability of some materials (notably crystals and certain ceramics) to generate an electric potential in response to applied mechanical stress. This may take the form of a separation of electric charge across the crystal lattice. If the material is not short-circuited, the applied charge induces a voltage across the material.
- The word is derived from the Greek *piezein*, which means to squeeze or press.
- The piezoelectric effect is reversible in that materials exhibiting the *direct piezoelectric effect* (the production of electricity when stress is applied) also exhibit the *converse piezoelectric effect* (the production of stress and/or strain when an electric field is applied).
- For example, lead zirconate titanate crystals will exhibit a maximum shape change of about 0.1% of the original dimension.



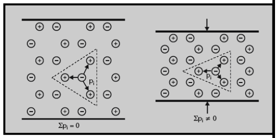
Piezoelectric transducers

- ❑ Piezoelectric transducers produce an output voltage when a force is applied to them.
- ❑ They are frequently used as ultrasonic receivers and also as displacement transducers, particularly as part of devices measuring acceleration, force and pressure.



Piezoelectric transducers

- Piezoelectric transducers are made from piezoelectric materials. These have an asymmetrical lattice of molecules that distorts when a mechanical force is applied to it.
- This distortion causes a reorientation of electric charges within the material, resulting in a relative displacement of positive and negative charges.



- The charge displacement induces surface charges on the material of opposite polarity between the two sides. By implanting electrodes into the surface of the material, these surface charges can be measured as an output voltage. For a rectangular block of material, the induced voltage is given by:

$$V = \frac{kFd}{A}$$

where F is the applied force, A is the area of the material, d is the thickness of the material and k is the piezoelectric constant. The polarity of the induced voltage depends on whether the material is compressed or stretched.

- Materials exhibiting piezoelectric behaviour include natural ones such as **quartz, synthetic ones such as lithium sulphate and ferroelectric ceramics such as barium titanate.**
- The piezoelectric constant varies widely between different materials. Typical values of k are 2.3 for quartz and 140 for barium titanate.
- Applying equation for a force of 1 g applied to a crystal of area 100 mm2 and thickness 1 mm gives an output of 23 μV for quartz and 1.4 mV for barium titanate.
- The piezoelectric principle is invertible, and therefore distortion in a piezoelectric material can be caused by applying a voltage to it.
- This is commonly used in ultrasonic transmitters, where the application of a sinusoidal voltage at a frequency in the ultrasound range causes a sinusoidal variation in the thickness of the material and results in a sound wave being emitted at the chosen frequency.

Strain gauges

- Strain gauges are devices that experience a change in resistance when they are stretched or strained.
- They are able to detect very small displacements, usually in the range 0–50 μm, and are typically used as part of other transducers,
- Measurement inaccuracies as low as +/- 0.15% of full-scale reading are achievable and the quoted life expectancy is usually three million reversals.
- Strain gauges are manufactured to various nominal values of resistance, of which 120, 350 and 1000 are very common. The typical maximum change of resistance in a 120 device would be 5 at maximum deflection.

Light energy

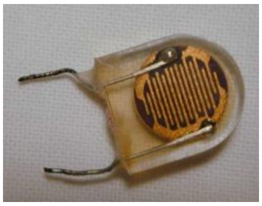
- For a sensor, we’re interested in the light power that falls on a unit area, and how well the sensor converts that into a signal.
- A common unit is the lux which measures apparent brightness (power multiplied by the human eye’s sensitivity).
- 1 lux of yellow light is about 0.0015 W/m^2.
- 1 lux of green light (50% eff.) is 0.0029 W/m^2.
- Sunlight corresponds to about 50,000 lux
- Artificial light typically 500-1000 lux

Light sensors

- Simplest light sensor is an LDR (Light-Dependent Resistor).
- Optical characteristics close to human eye.
- Common material is CdS (Cadmium Sulphide)
- Sensitivity:

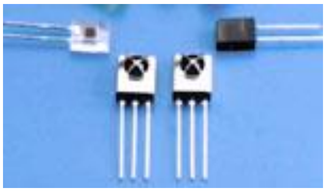
Typical

dark 1 MΩ,
10 lux 40 kΩ,
1000 lux 400 Ω.



Light sensors

- Semiconductor light sensors include: photodiodes, phototransistors, photodarlingtons.
- All of these have similar noise performance, but phototransistors and darlingtons have better sensitivity (more current for given light input).
- Phototransistor: 1 mA @ 1000 lux
- Photodarlingtons up to 100x this sensitivity.
- Photocells and phototransistors are particularly sensitive in the infrared region, and so are ideal partners for infrared LED and laser diode sources

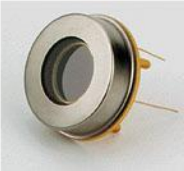


Light Detectors

- Photocells and phototransistors are particularly sensitive in the infrared region, and so are ideal partners for infrared LED and laser diode sources.
- Air-path optical sensors are commonly used to measure proximity, translational motion, rotational motion and gas concentration.

Light sensors – high end

- At the cutting edge of light sensor sensitivity are **Avalanche photodiodes**.
- Large voltages applied to these diodes accelerate electrons to “collide” with the semiconductor lattice, creating more charges.
- These devices have quantum efficiencies around 90% and extremely low noise.
- They are now made with large collection areas and known as LAAPDs (Large-Area Avalanche Photo-Diode)



Light sensors – cameras

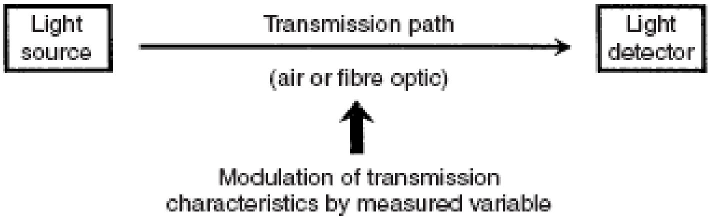
- Two solid-state camera types: CCD and CMOS.
- CCD is the more mature technology, and has the widest performance range.
  - Low noise/ high efficiency for astronomy etc.
  - Good sensitivity (low as 0.0003 lux, starlight)
- CCDs require several chips, but are still cheap ($50 +)
- Most CCDs work in near infrared and can be used for night vision **if** an IR light source is used.

Light sensors – cameras

- CMOS cameras are very compact and inexpensive, but haven't matched CCDs in most performance dimensions.
- Start from $20(!)
- Custom CMOS cameras integrate image processing right on the camera.
- Allow special functions like motion detection, recognition.

Optical sensors

- Optical sensors are based on the modulation of light travelling between a light source and a light detector.
- The transmitted light can travel along either an air path or a fibre-optic cable.
- Either form of transmission gives immunity to electromagnetically induced noise, and also provides greater safety than electrical sensors when used in hazardous environments.


Light source
Transmission path
(air or fibre optic)
Light detector
Modulation of transmission characteristics by measured variable

WHY OPTICAL SENSORS

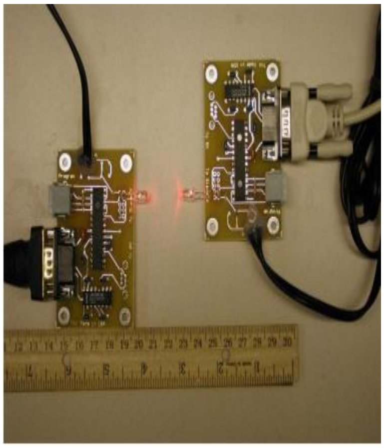
- ELECTROMAGNETIC IMMUNITY
- ELECTRICAL ISOLATION
- COMPACT AND LIGHT
- WIDE DYNAMIC RANGE
- AMENABLE TO MULTIPLEXING

OPTICAL SENSOR MEASURANDS

TEMPERATURE	CHEMICAL SPECIES
PRESSURE	FORCE
FLOW	RADIATION
LIQUID LEVEL	pH
DISPLACEMENT	HUMIDITY
VIBRATION	STRAIN
ROTATION	VELOCITY
MAGNETIC FIELDS	ELECTRIC FIELDS
ACCELERATION	ACOUSTIC FIELDS

Optical sensors

- Light sources suitable for transmission across an air path include tungsten-filament lamps, laser diodes and light-emitting diodes (LEDs).
- However, as the light from tungsten lamps is usually in the visible part of the light frequency spectrum, it is prone to interference from the sun and other sources.
- Hence, infrared LEDs or infrared laser diodes are usually preferred.
- These emit light in a narrow frequency band in the infrared region and are not affected by sunlight



Light Detectors

- Air-path optical sensors are commonly used to measure proximity, translational motion, rotational motion and gas concentration.

Optical sensors (fibre-optic)

- **As an alternative to using air as the transmission medium, optical sensors can use fibre-optic cable instead to transmit light between a source and a detector**.
- In such sensors, the variable being measured causes some measurable change in the characteristics of the light transmitted by the cable. The proportion of light entering the cable must be maximized
- The basis of operation of fibre-optic sensors is the translation of the physical quantity measured into a change in one or more parameters of a light beam.

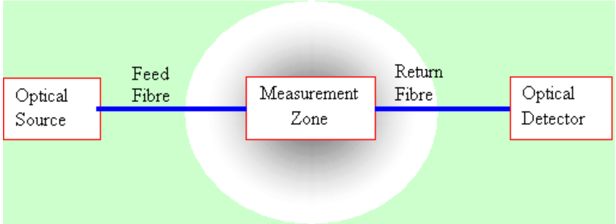
Fibre-optic sensors characteristic

- Fibre-optic sensors characteristically enjoy long life. For example, the life expectancy of reflective fibre-optic switches is quoted at ten million operations.
- Their accuracy is also good, with, for instance, +/- 1% of full-scale reading being quoted as a typical inaccuracy level for a fibre-optic pressure sensor.
- Further advantages are their simplicity, low cost, small size, high reliability and capability of working in many kinds of hostile environment.

OPTICAL SENSOR MEASURANDS

TEMPERATURE	CHEMICAL SPECIES
PRESSURE	FORCE
FLOW	RADIATION
LIQUID LEVEL	pH
DISPLACEMENT	HUMIDITY
VIBRATION	STRAIN
ROTATION	VELOCITY
MAGNETIC FIELDS	ELECTRIC FIELDS
ACCELERATION	ACOUSTIC FIELDS

WORKING PRINCIPLE



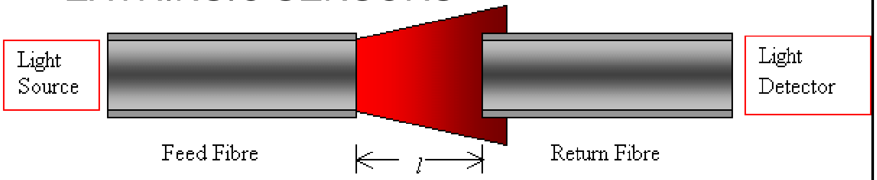
- LIGHT BEAM CHANGES BY THE PHENOMENA THAT IS BEING MEASURED
- LIGHT MAY CHANGE IN ITS FIVE OPTICAL PROPERTIES i.e INTENSITY, PHASE, POLARIZATION,WAVELENGTH AND SPECTRAL DISTRIBUTION

Fibre-optic sensors Classification

- Two major classes of fibre-optic sensor exist, intrinsic sensors and extrinsic sensors.
- In *intrinsic sensors*, the fibre-optic cable itself is the sensor,
- whereas in *extrinsic sensors*, the fibre-optic cable is only used to guide light to/from a conventional sensor.

CLASSIFICATION

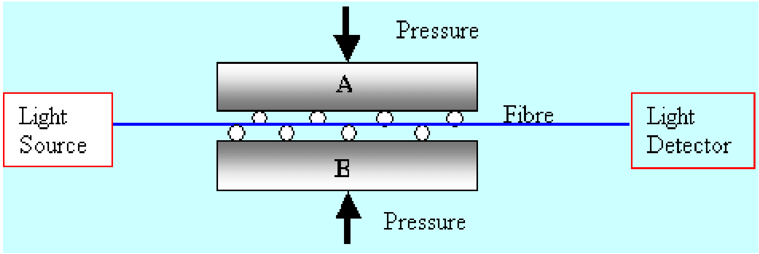
- EXTRINSIC SENSORS



WHERE THE LIGHT LEAVES THE FEED OR TRANSMITTING FIBER TO BE CHANGED BEFORE IT CONTINUES TO THE DETECTOR BY MEANS OF THE RETURN OR RECEIVING FIBER

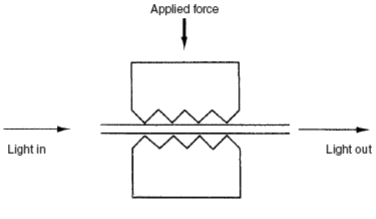
CLASSIFICATION (contd.)

- INTRINSIC SENSORS



INTRINSIC SENSORS ARE DIFFERENT IN THAT THE LIGHT BEAM DOES NOT LEAVE THE OPTICAL FIBER BUT IS CHANGED WHILST STILL CONTAINED WITHIN IT

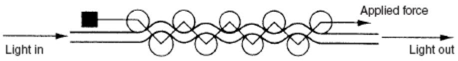
- In pressure sensors, the refractive index of the fibre, and hence the intensity of the light being transmitted, varies according to the mechanical deformation of the fibres caused by pressure
-



(a)

← simple pressure sensor

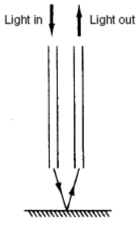
- Roller-chain pressure sensor →



Fibre-optic sensors

- Proximity sensor

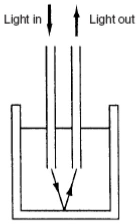
The amount of light reflected varies with the distance between the fibre ends and a boundary



(c)

- pH sensor

The amount of light reflected back into the fibers depend on the pH-dependant color of the chemical indicator in the solution around the probe tip



(d)