Basic Sensors

ENGG 6150: Bio-Instrumentation

Basic Sensors

- Under Displacement Measurement
- Proximity sensors
    - Inductive Proximity Sensors
    - Capacitive Proximity Sensors
    - Photoelectric Sensors
    - Ultrasonic Sensors
- Piezoelectric Sensors
- BioMEMS Sensors

Proximity Sensors

Proximity Sensors

- Proximity sensing is the technique of detecting the presence or absence of an object. There are different types of proximity sensors:

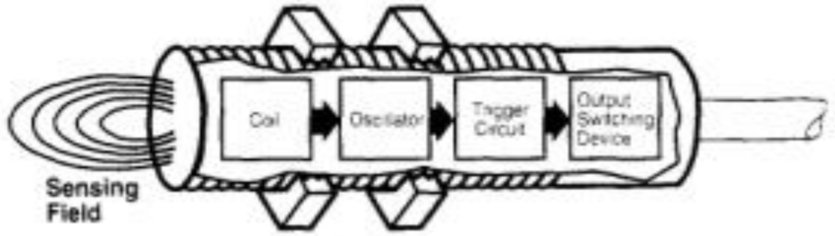
1. Inductive,
2. Capacitive,
4. Photoelectric,
5. Ultrasonic

Inductive Proximity Sensors

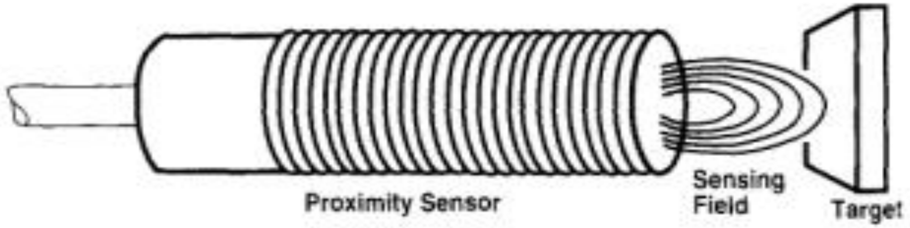
- Inductive sensors are used to detect the presence of metallic objects.
- These sensors require DC or AC voltage for the power to drive circuitry to generate the fields and to produce output signal.

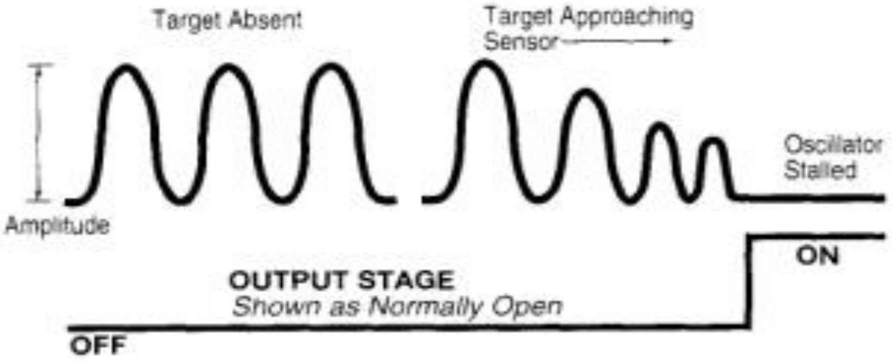
Inductive Proximity Sensors

- An inductive proximity sensor consists of four basic elements:



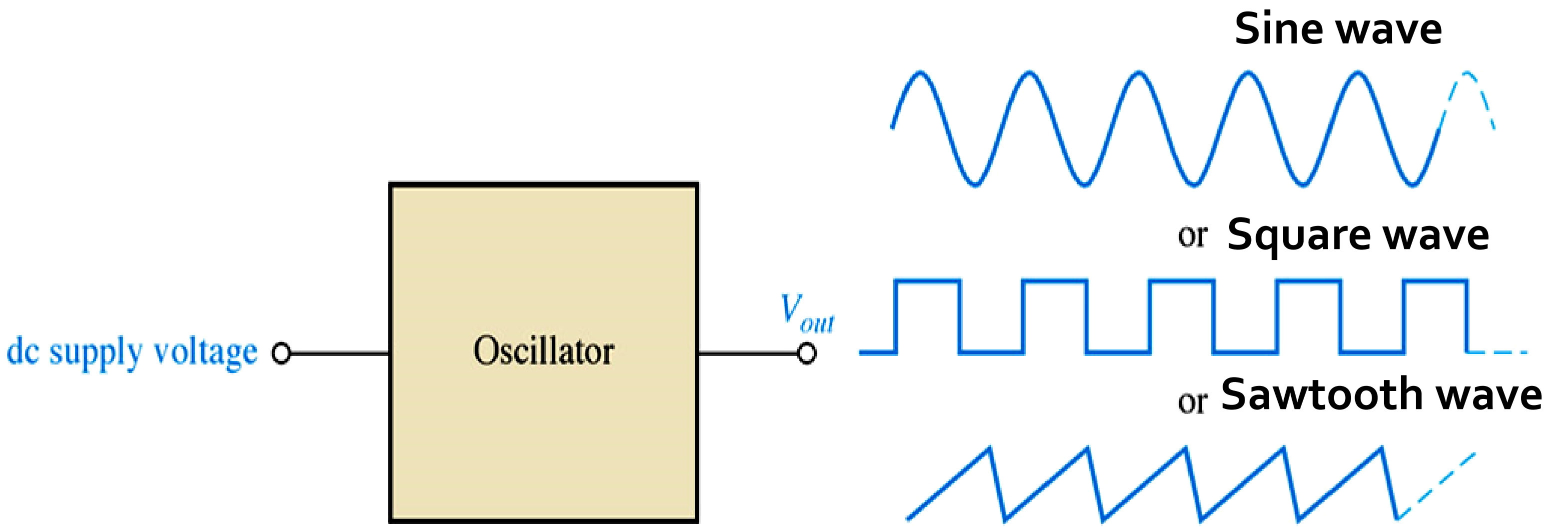
1. Sensor coil and ferrite core
2. Oscillator circuit
3. Trigger/Detector circuit
4. Solid-state output circuit





What is an oscillator

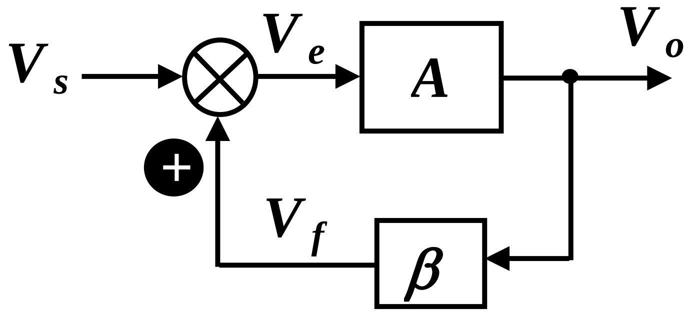
- An oscillator is a circuit that produces a repetitive signal from a dc voltage.
- The feedback oscillator relies on a positive feedback of the output to maintain the oscillations.



Basic principles for oscillation

- An oscillator is an amplifier with positive feedback.

$$V_e = V_s + V_f \quad (1)$$



$$V_f = \beta V_o \quad (2)$$

$$V_o = AV_e = A(V_s + V_f) = A(V_s + \beta V_o) \quad (3)$$

$$(1 - A\beta)V_o = AV_s \Rightarrow A_f \equiv \frac{V_o}{V_s} = \frac{A}{(1 - A\beta)}$$

Basic principles for oscillation

In general A and β are functions of frequency and thus may be written as;

$$A_f(s) = \frac{V_o}{V_s}(s) = \frac{A(s)}{1 - A(s)\beta(s)}$$

$T(s) = A(s)\beta(s)$ is known as loop gain

$$\Rightarrow \quad A_f(s) = \frac{A(s)}{1 - T(s)}$$

Replacing s with $j\omega$ $\Rightarrow$ $A_f(j\omega) = \dfrac{A(j\omega)}{1 - T(j\omega)}$

Basic principles for oscillation

At a specific frequency f_0

$$T(j\omega_0) = A(j\omega_0)\beta(j\omega_0) = 1$$

At this frequency, the closed loop gain;

$$A_f(j\omega_0) = \frac{A(j\omega_0)}{1 - A(j\omega_0)\beta(j\omega_0)}$$

will be infinite, i.e. the circuit will have finite output for zero input signal - oscillation

Basic principles for oscillation

Thus, the condition for sinusoidal oscillation of frequency f_0 is;

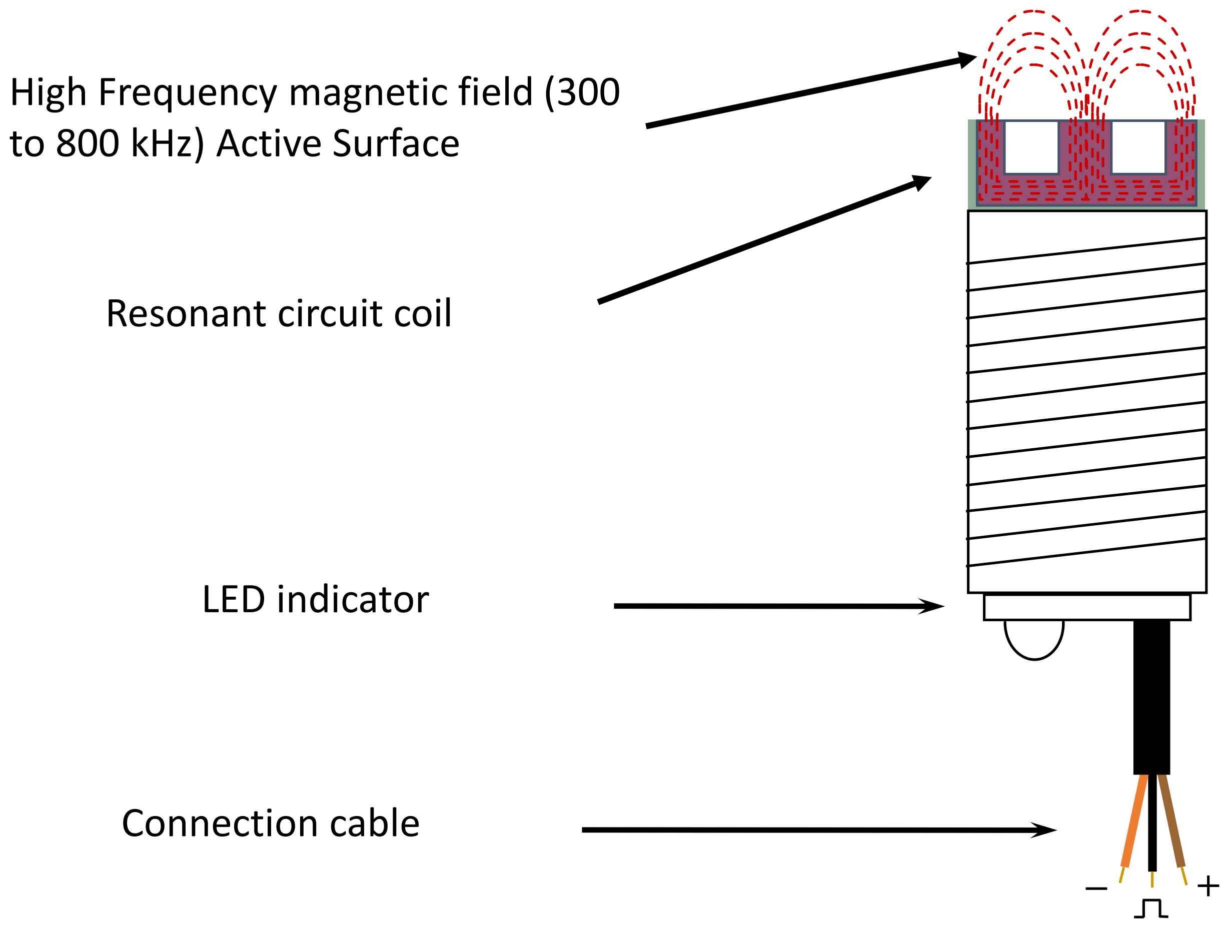
$$A(j\omega_0)\beta(j\omega_0) = 1$$

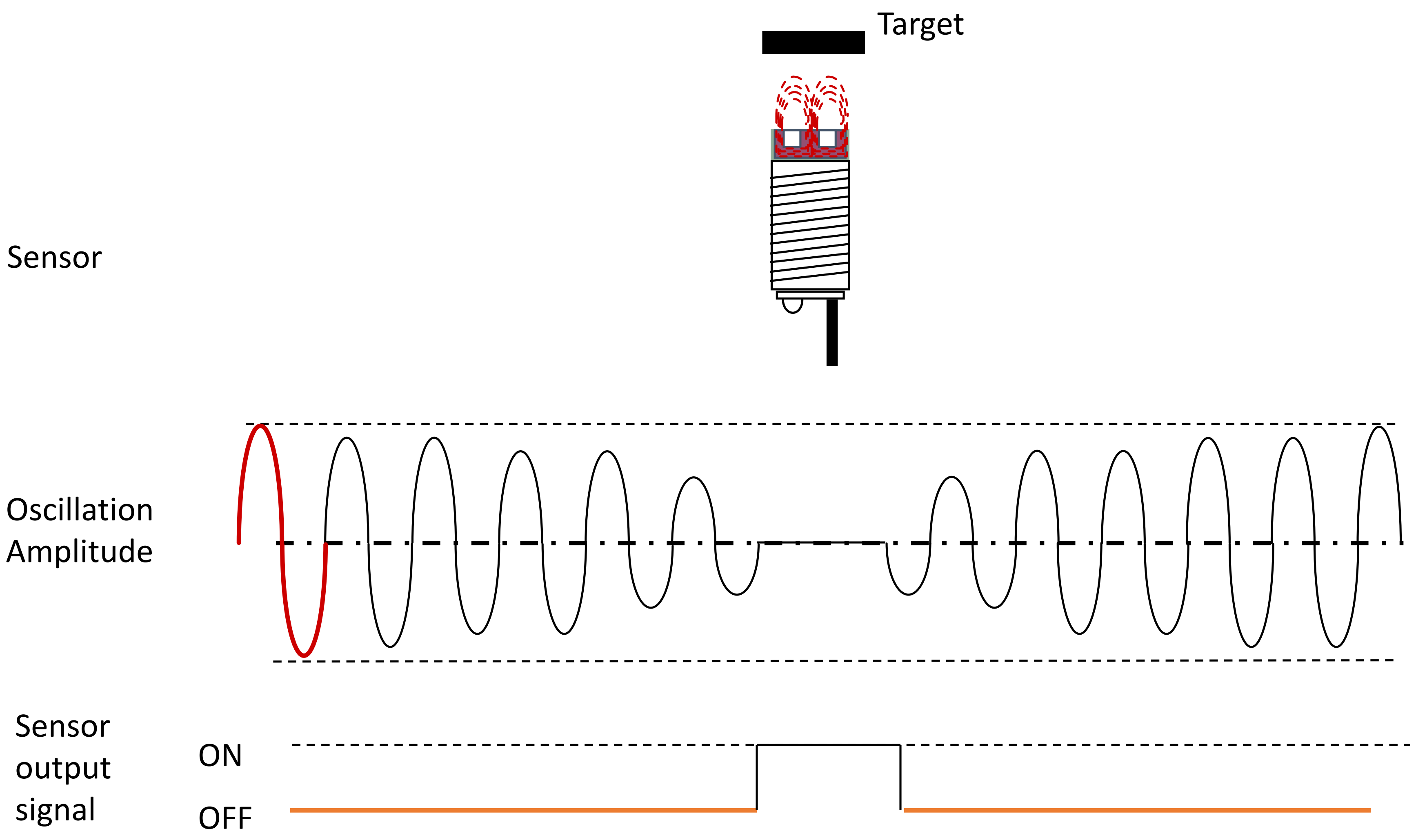
- This is known as Barkhausen criterion.
- The frequency of oscillation is solely determined by the phase characteristic of the feedback loop – the loop oscillates at the frequency for which the phase is zero.

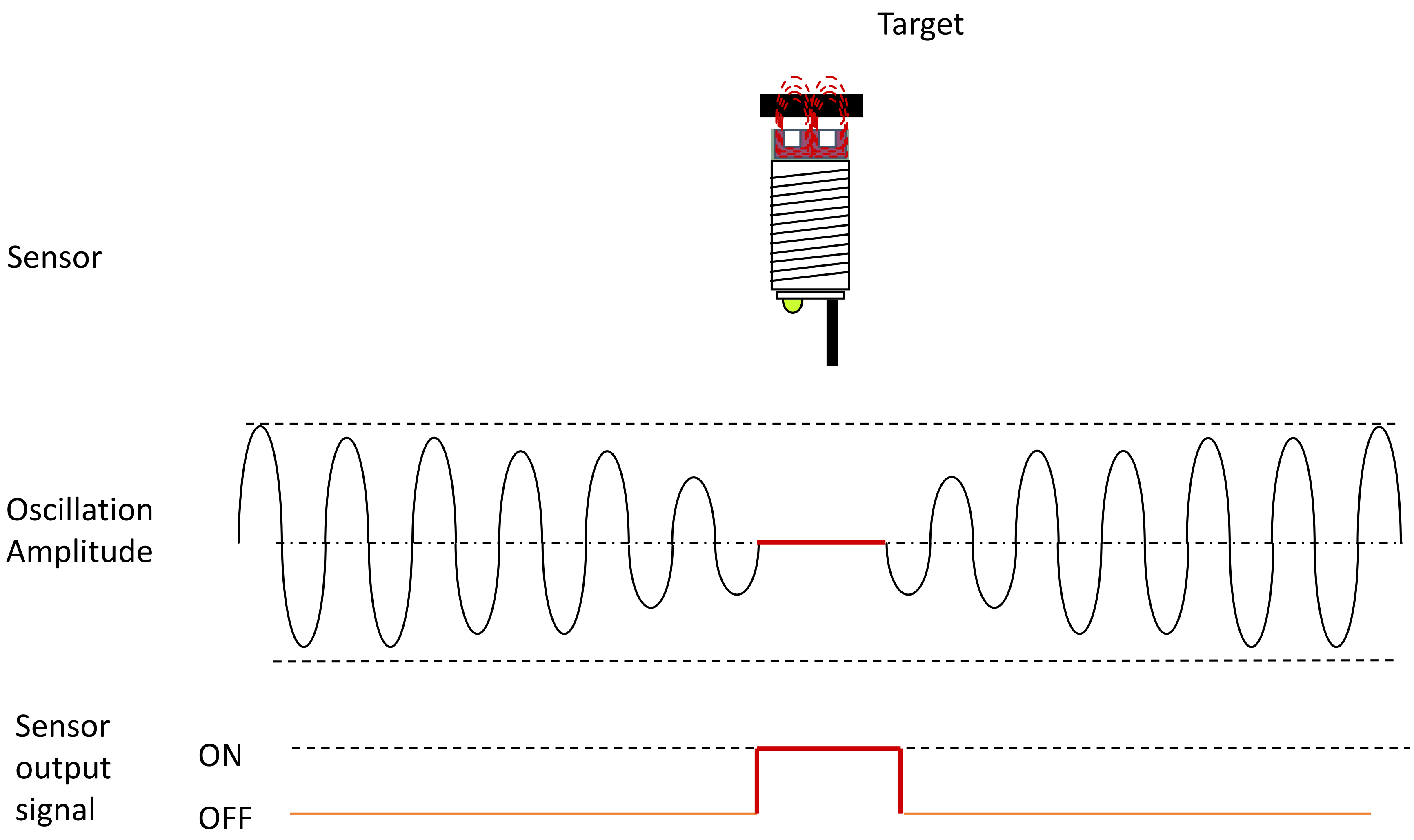
How does the oscillation get started?

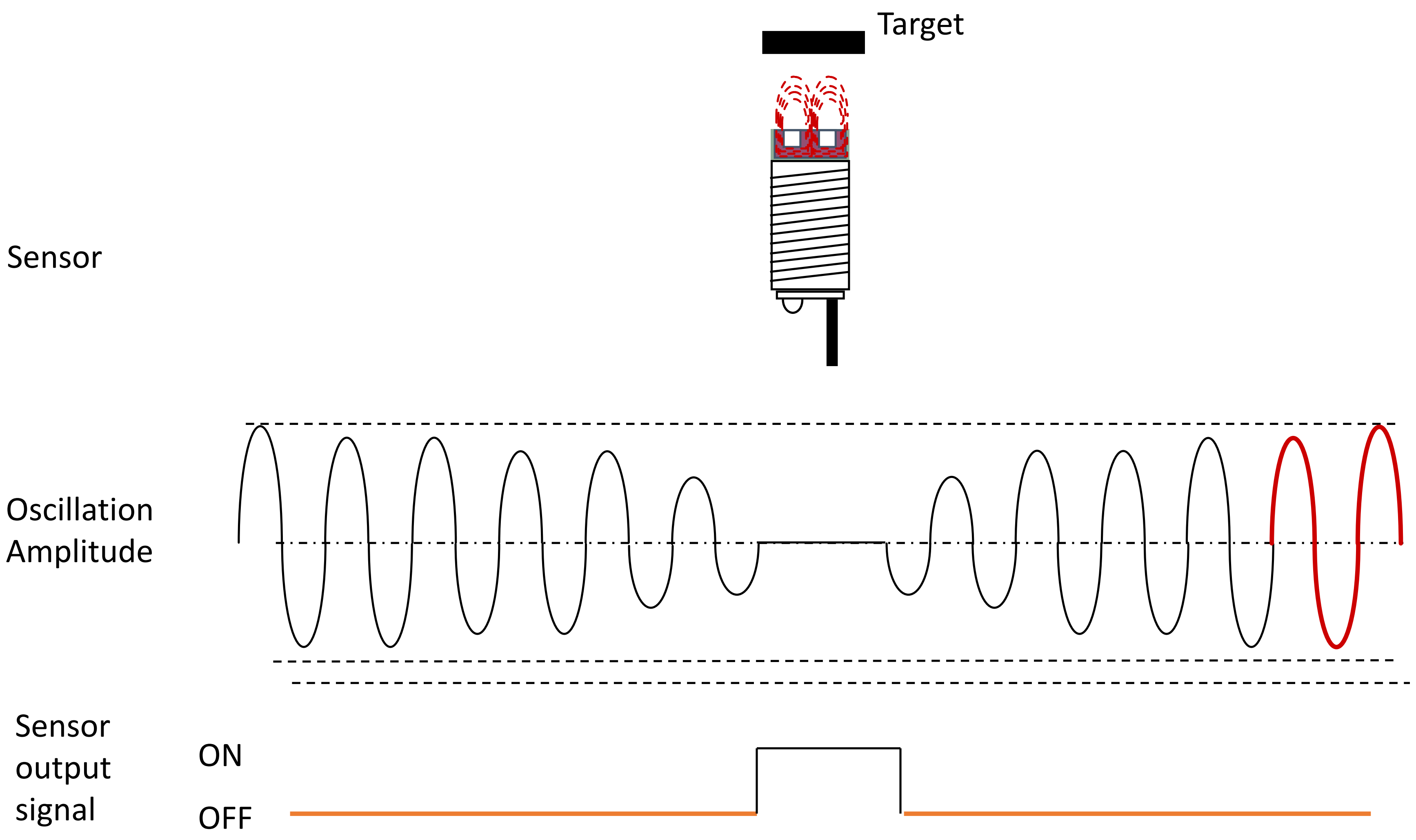
- Noise signals and the transients associated with the circuit turning on provide the initial source signal that initiate the oscillation

Inductive Proximity Sensors




Target
Sensor
Oscillation
Amplitude
Sensor
output
signal
ON
OFF


Target
Sensor
Oscillation Amplitude
Sensor output signal
ON
OFF


Target
Sensor
Oscillation
Amplitude
Sensor
output
signal
ON
OFF

Inductive Proximity Sensor
working principle

- The oscillator circuit generates a radio-frequency electromagnetic field that radiates from the ferrite core and coil assembly.

- The field is centered around the axis of the ferrite core, which shapes the field and directs it at the sensor face.

- When a metal target approaches and enters the field, eddy current are induced into the surfaces of the target.

Inductive Proximity Sensor

working principle

- This results in a loading effect, or “damping” that causes a reduction in amplitude of the oscillator signal.
- The detector circuit detects the change in oscillator amplitude. The detector will switch ON at specific operate amplitude.
- This ON signal generates a signal to turn ON the solid state output. This is often referred to as the *damped* condition.

Inductive Proximity Sensor
working principle

- As the target leaves the sensing field, the oscillator responds with an increase in amplitude.
- As the amplitude increases above a specific value, it is detected by the detector circuit, which switches OFF, causing the output signal to return to the normal or OFF(*undamped*) state.

Inductive Proximity Sensor

- Typical applications of inductive proximity sensors in control systems:

  - Motion position detection
  - Motion control
  - Machine control
  - Verification and counting

Capacitive Proximity Sensors

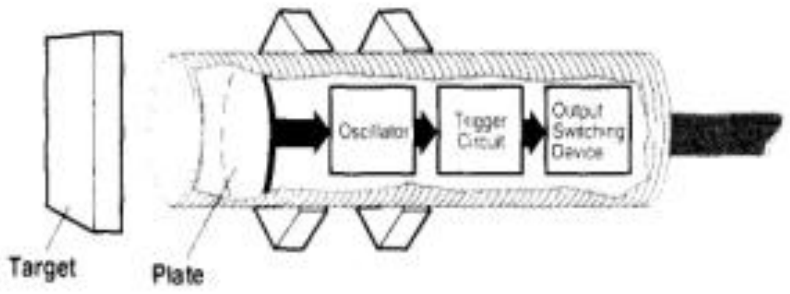
Capacitive Proximity Sensors

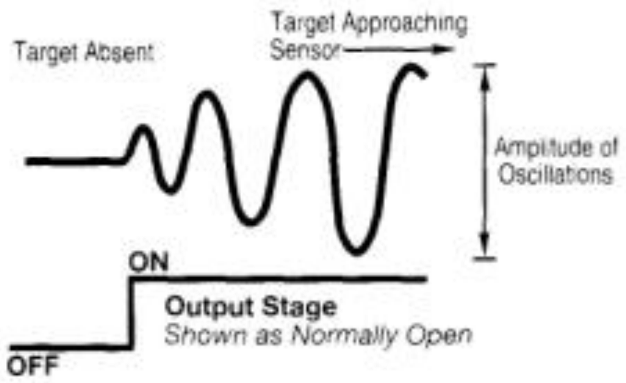
- Capacitive sensing is based on dielectric capacitance.
- Capacitance is the property of insulators to store an electric charge.
- A capacitor consists of two plates separated by an insulator, usually called a dielectric.
- When the switch is closed a charge is stored on the two plates.
- The distance between the plates determine the ability of a capacitor to store a charge and can be calibrated as a function of stored charge to determine a digital ON and OFF switching action or analog response based on the stored charge.

Capacitive Proximity Sensors

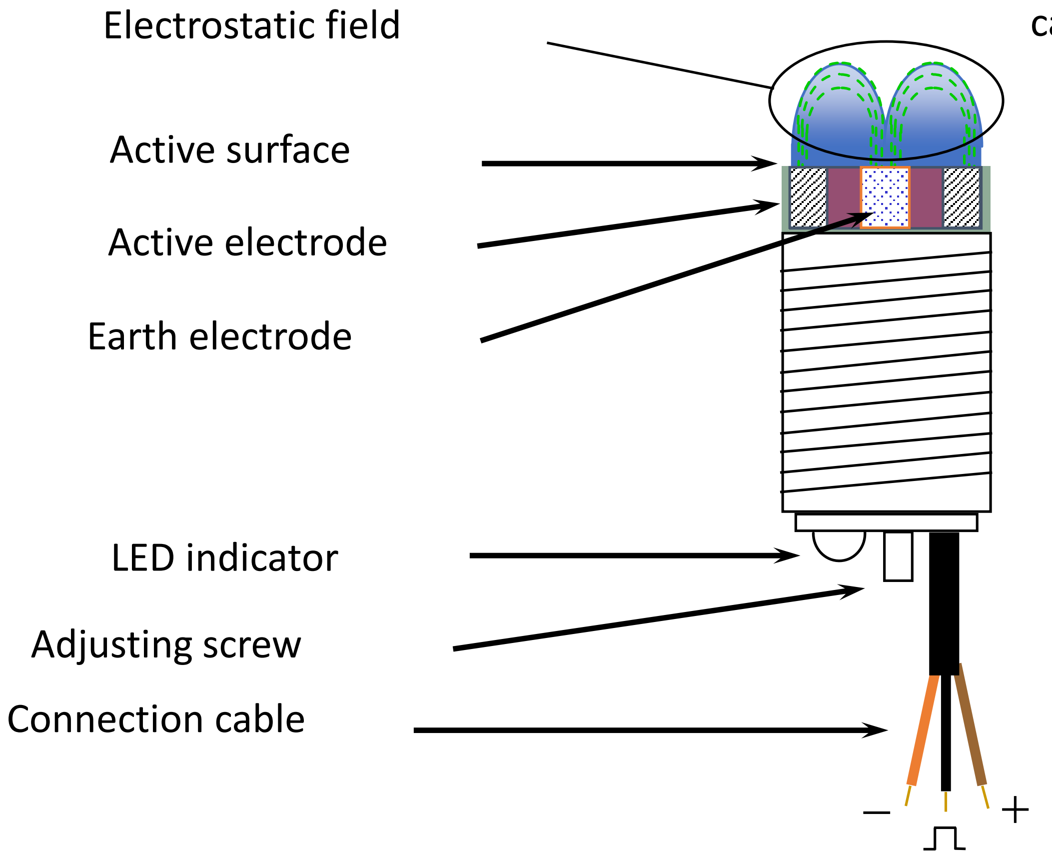
- The capacitive proximity sensor has the same four basic elements as an inductive sensor:

1. Sensor (the dielectric plate)
2. Oscillator circuit
3. Detector circuit
4. Solid-state output circuit

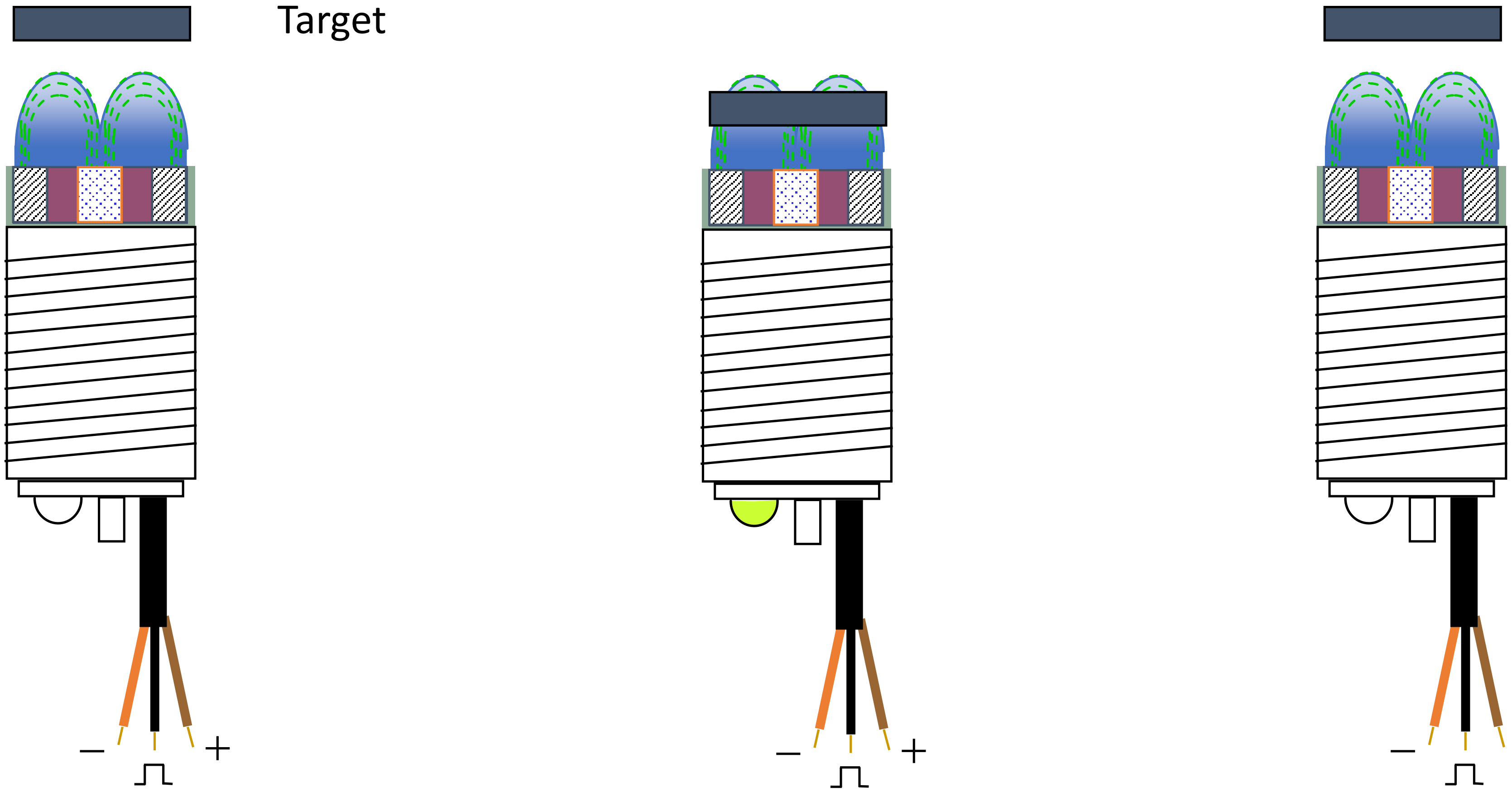




Capacitive Proximity Sensors



Sensor is looking for a change in capacitance in the active field


Target
–
+

Capacitive Proximity Sensors

- The oscillator circuit includes feedback capacitance from the external target plate and the internal plate.
- In a capacitive switch, the oscillator starts oscillating when sufficient feedback capacitance is detected.
- The oscillation begin with an approaching target until the value of capacitance reaches a threshold.
- At threshold point the trigger circuit will turn on the output switching device.
- Thus the output modules function as normally open or normally closed.

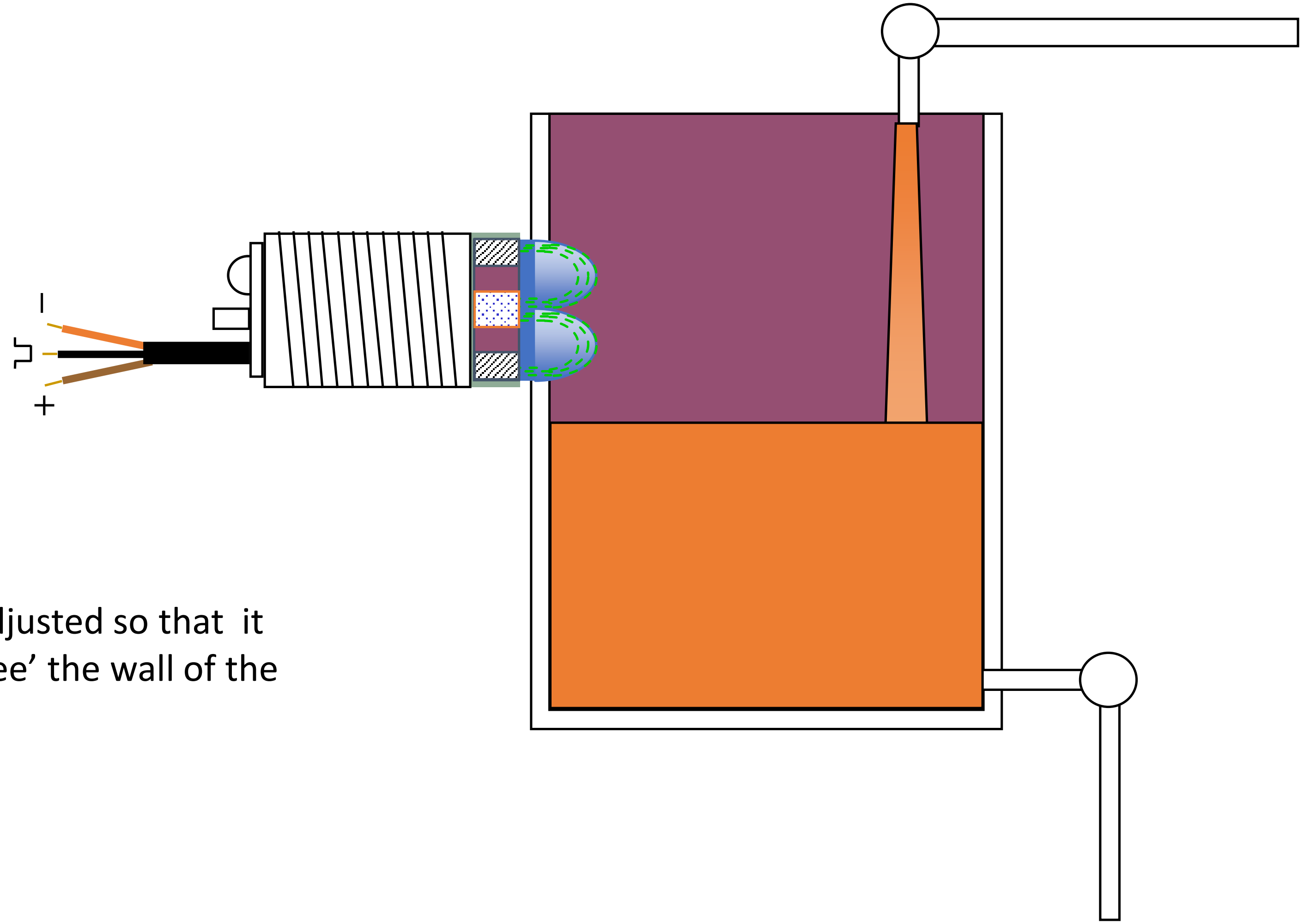
Capacitive Proximity Sensors

Features of capacitive sensors:

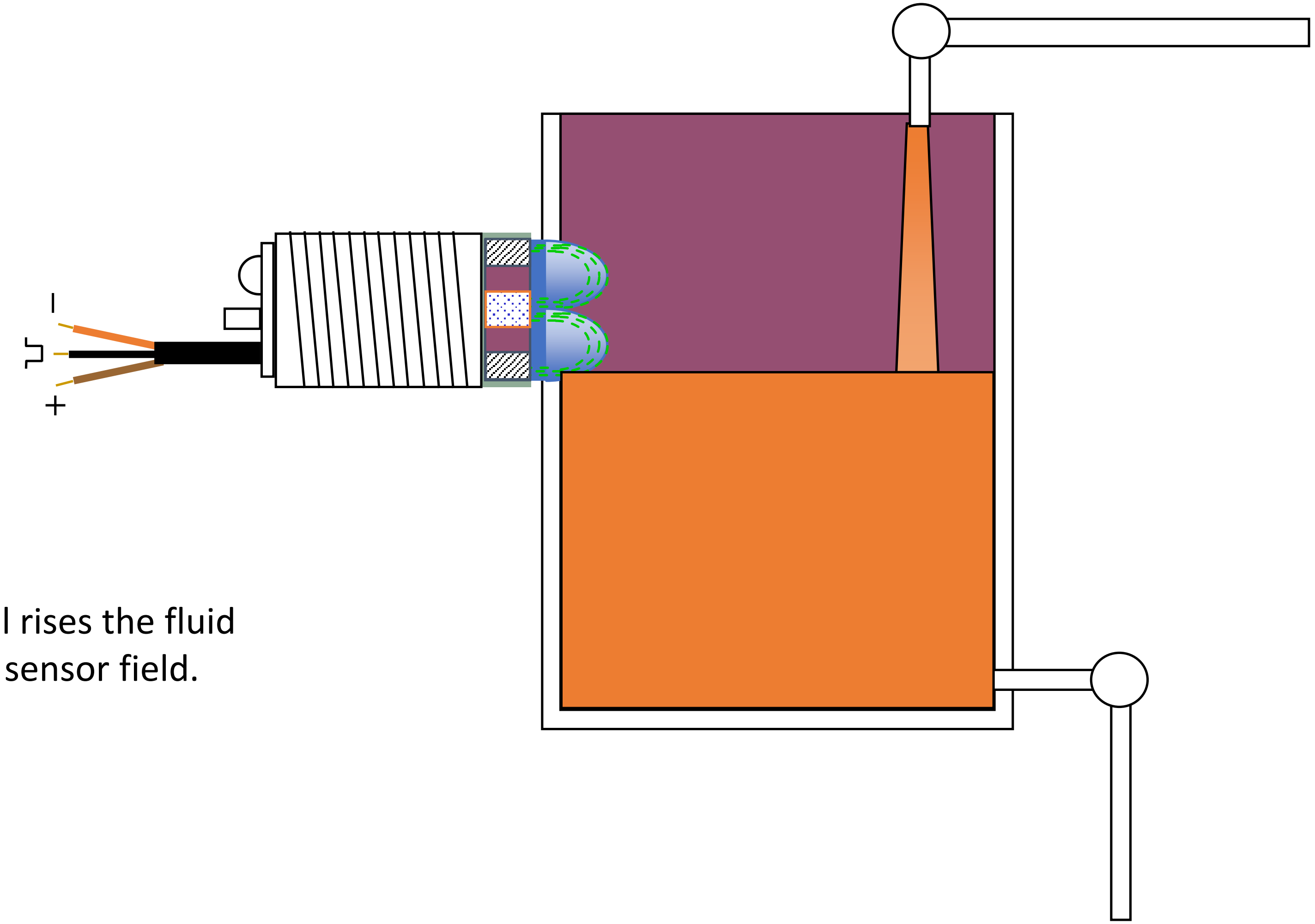
- They can detect non-metallic targets
- They can detect lightweight or small objects that annot be detected by mechanical limit switches
- They provide a high switching rate for rapid response in object counting applications.
- They can detect liquid targets through non-metallic barriers, (glass, plastic, etc)
- They have long operational life with a virtually unlimited number of operating cycles.
- The solid-state output provides a bounce-free contact signal

Capacitive Proximity Sensors

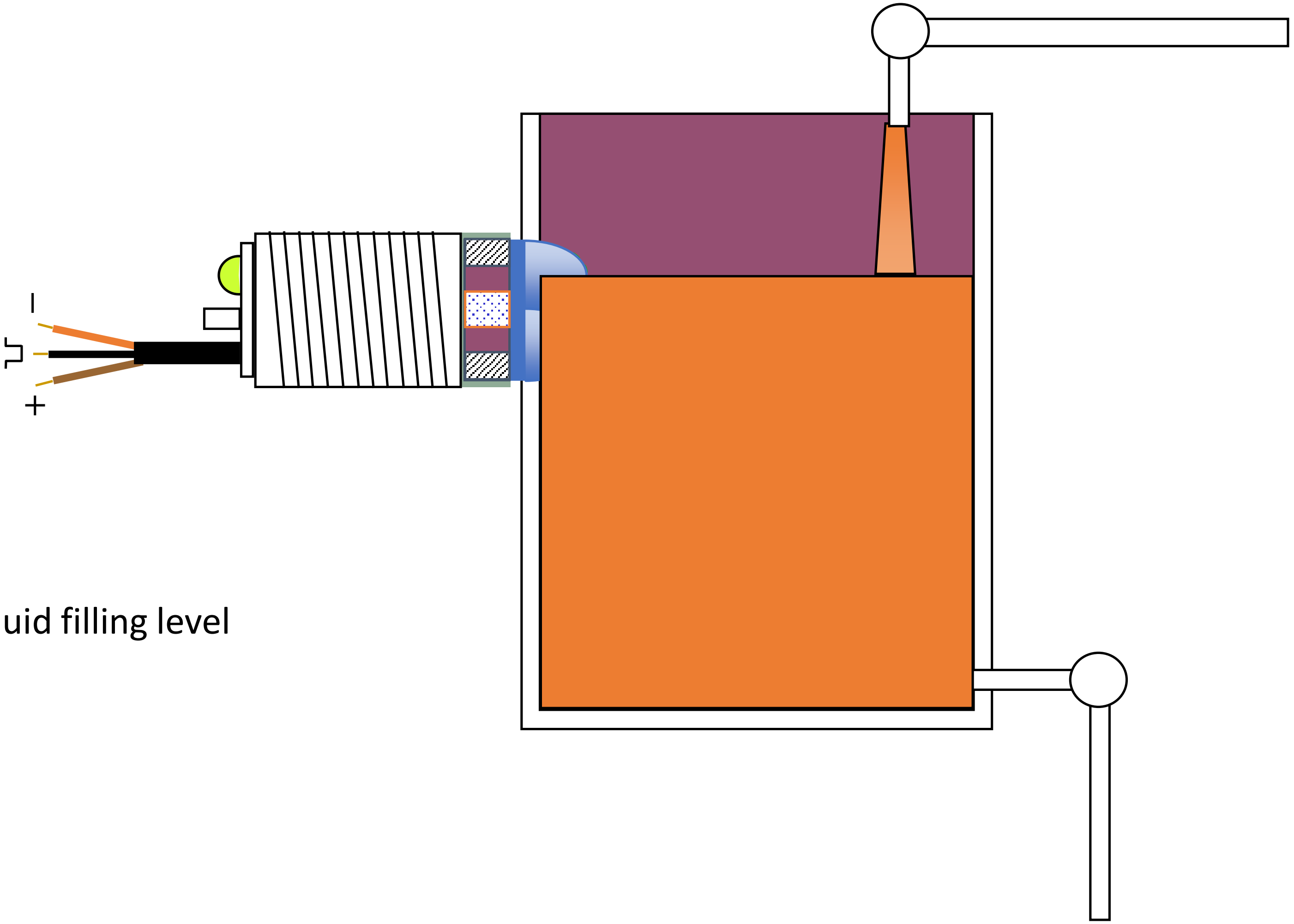
- ***Typical applications* of capacitive proximity sensors in control systems:**
- Liquid level detection
- Bulk material level control
- Process control



Sensor is adjusted so that it does not 'see' the wall of the vessel.



As the level rises the fluid affects the sensor field.



To detect liquid filling level

Photoelectric Sensors

- A *photoelectric sensor* is a semiconductor component that reacts to light or emits light. The light may be either in visible range or the invisible infrared range.

- Infrared sensors may be active or passive. The active sensors send out an infrared beam and respond to the reflection of the beam against a target.

Photoelectric Sensors

- The distinct *advantage* of photoelectric sensors over inductive or capacitive sensors is their *increased range*.

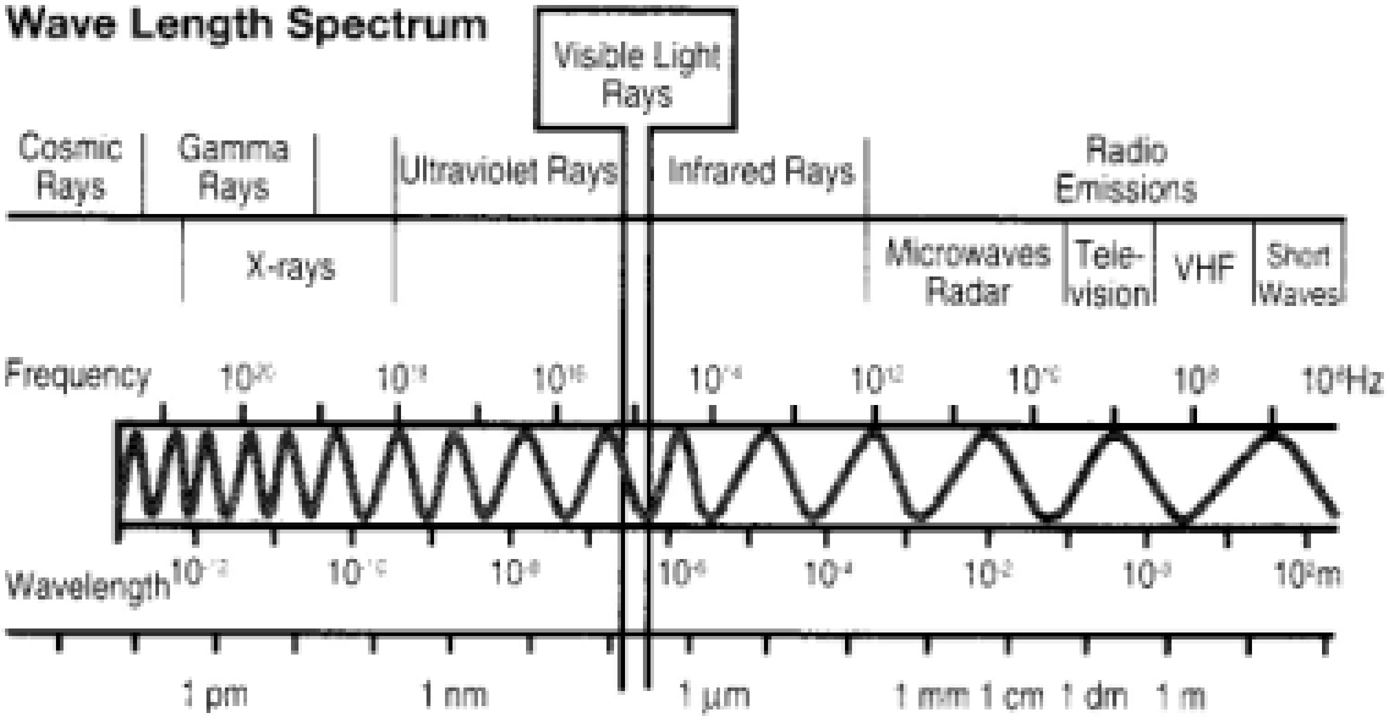
- Dirt, oil mist and other environmental factors will hinder operation of photoelectric sensors during manufacturing process.

Photoelectric Sensors

- There are three modes of detection used by photoelectric sensors:
  - Through-beam detection method
  - Reflex/retro-reflective detection method
  - Proximity/Diffuse reflective detection method

Photoelectric Sensors

- The light source used for each of the three modes comes from an LED.
- LEDs emit a visible colored light (red, green, yellow) or invisible (infrared) light.



Photoelectric Sensors

- Visible LEDs are used for in retro-reflective applications, they provide easy reflector alignment to the sensor.

- Light intensity of infrared LEDs is greater than the visible ones. They are better suited for through-beam and diffused style sensors.

Photoelectric Sensors

- Switching the LED off and on at a predetermined frequency (modulating), increases the light intensity and lifetime of the LED while reducing the average power consumed.

- The pulsed LED provides a stronger signal when compared to a continuously illuminated LED, therefore, a larger sensing range can be obtained.

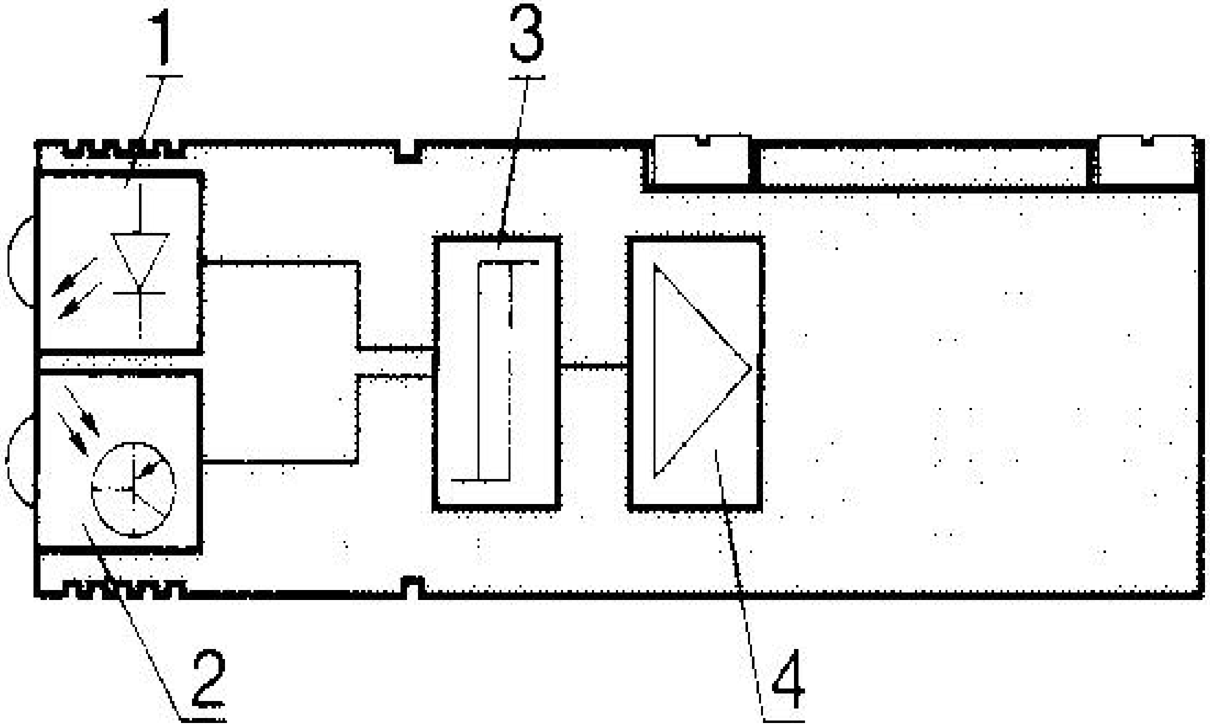
Photoelectric Sensors

- Another key advantage to modulating the sensor is to provide protection against external light interference.
- The receiving circuit, typically phototransistor based, is modulated at the same frequency as the emitter's.

Photoelectric Sensors

Photoelectric sensors are comprised of the following components :

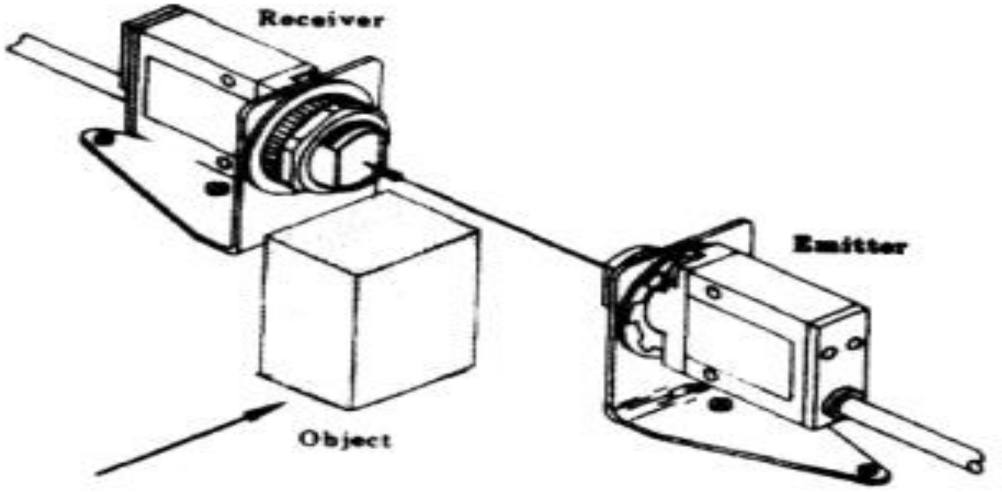
1. Light Source (LED)
2. Receiver (phototransistor)
3. Signal Converter
4. Amplifier



Photoelectric Sensors

- The generated light pulses that are received by the phototransistor are converted into electrical signals.
- These signals are analyzed in order to determine if they are the result of the actual transmitted light.
- Upon verification, the output of the sensor is switched accordingly.
- With the appropriate conditioning, light or dark sensing is achieved.

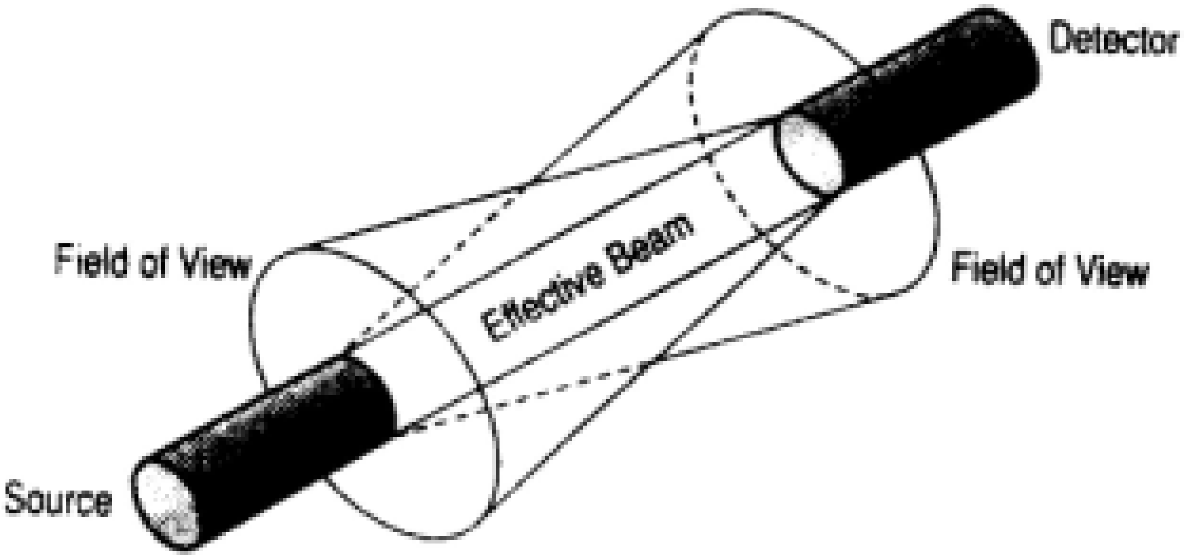
Photoelectric Sensors
Through-beam detection method



- Sensor have separate source and detector elements aligned opposite each other, with the beam of light crossing the path that an object must cross.
- When an object passes between the source and detector, the beam is broken, signaling detection of the object.

Photoelectric Sensors
Through-beam detection method

- The effective beam area is that of column of light travels straight between the lenses.



Photoelectric Sensors
Through-beam detection method

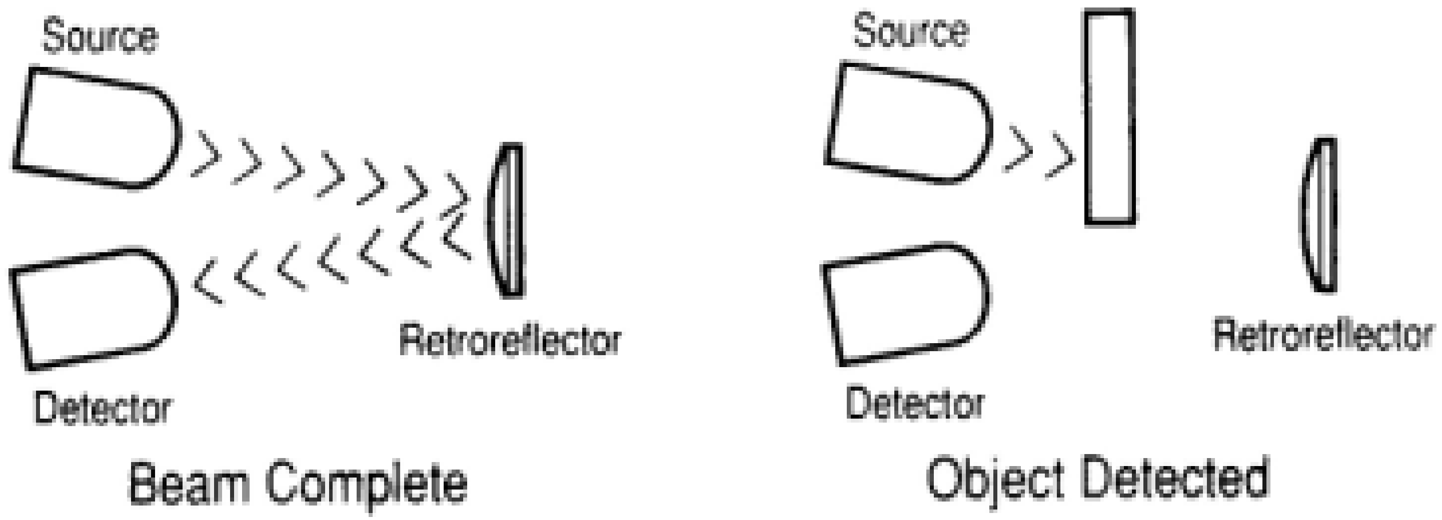
- Light from the source is transmitted directly to the photo-detector , through-beam sensors offer the following benefits:
  - Longest sensing range
  - Highest possible signal strength
  - Greatest light/dark contrast ratio

Photoelectric Sensors
Through-beam detection method

- Through-beam detection generally provides the longest range of the three operating modes and provides high power at a shorter range to penetrate steam, dirt, or other contaminants between the source and detector.
- The limitation of through-beam sensors are as follows:
  - They require wiring of the two components across the detection zone.
  - It may be difficult to align the source and the detector if the distance between the sensor and the detector is relatively far.
  - If the object to be detected is smaller than the effective beam diameter, an aperture over the lens may be required.

Reflex/Retro-reflective detection method

- Reflex photoelectric controls position the source and detection parallel to each other on the same side of the target.
- The light is directed to a retro-reflector and returns to the detector. The switching and output occur when an object breaks the beam.



Reflex/Retro-reflective detection method

- Since the light travels in two directions (hence twice the distance), reflex controls will not sense as far as through-beam sensors. However, reflex controls offer a powerful sensing system that is easy to mount and does not require that electrical wire to be run on both sides of the sensing areas.

- The main limitation of these sensors is that a shiny surface on the target object can trigger false detection. Hence the object to be detected must be less reflective than the retro-reflector.

- The reflex method is widely used because it is flexible and easy to install and provides the best cost-performance ratio of the three methods.

Proximity/Diffuse reflective detection method

- The proximity detection method requires that the source and detector are installed on the same side of the object to be detected and aimed at a point in front of the sensor.

Beam Not Complete

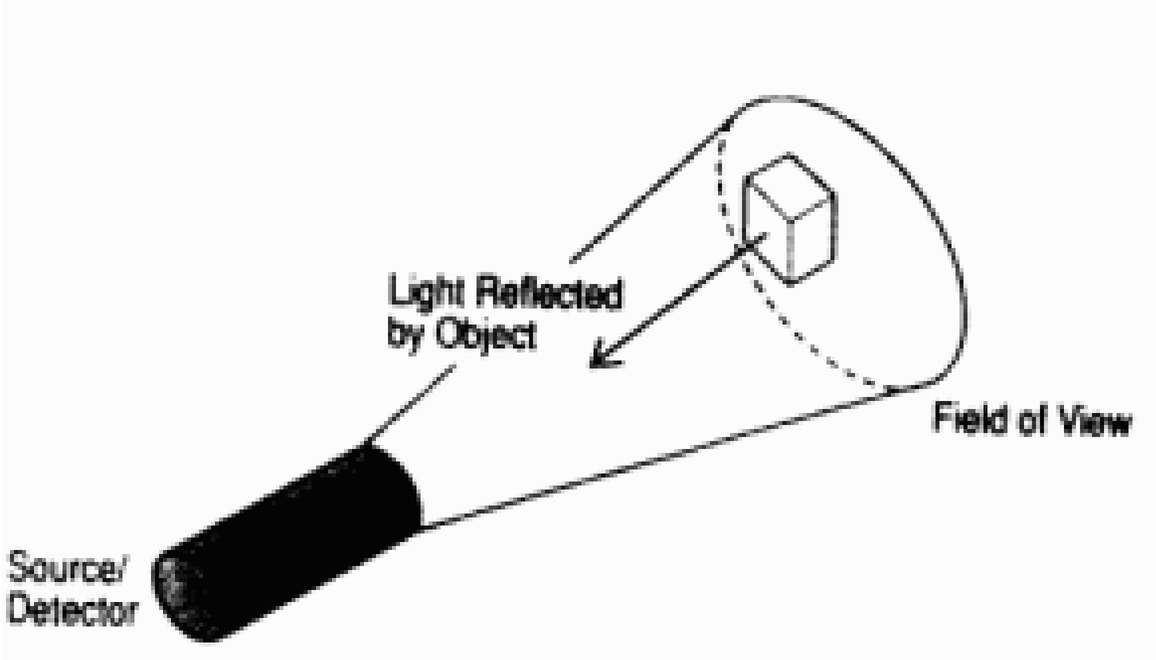
Object Detected

Proximity/Diffuse reflective detection method

- When an object passes in front of the source and detector, light from the source is reflected from the object’s surface back to the detector, and the object is detected.
- Each sensor type has a specific operating range. In general, through-beam sensors offer the greatest range, followed by reflex sensors, then by proximity sensors.
- The maximum range for through-beam sensors is of primary importance. At any distance less than the maximum range, the sensor has more than enough power to detect an object.

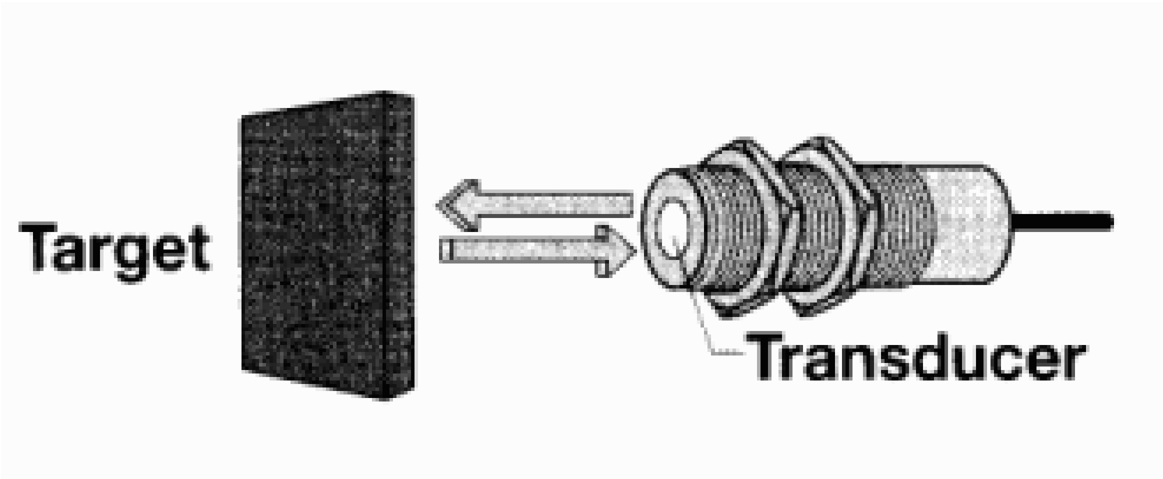
Proximity/Diffuse reflective detection method

- The optimum range for the proximity and reflex sensors is more than significant than the maximum range. The optimum range is the range at which the sensor has the most power available to detect objects.

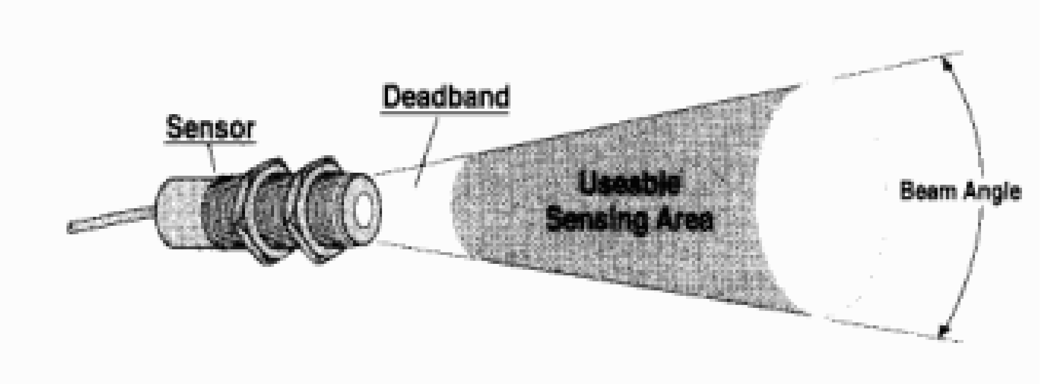


Ultrasonic Sensors

- *Ultrasonic sensors* are used in non-contact material monitoring applications including web loop control, level control, positioning, flow monitoring and conveyor transfer.
- Ultrasonic sensors use the propagation time of sound pulse to calculate the distance of a target. Sound pulses are emitted and received by a diaphragm in the face of the transducer as illustrated in the diagram below.



Terminology of Ultrasonic Sensor

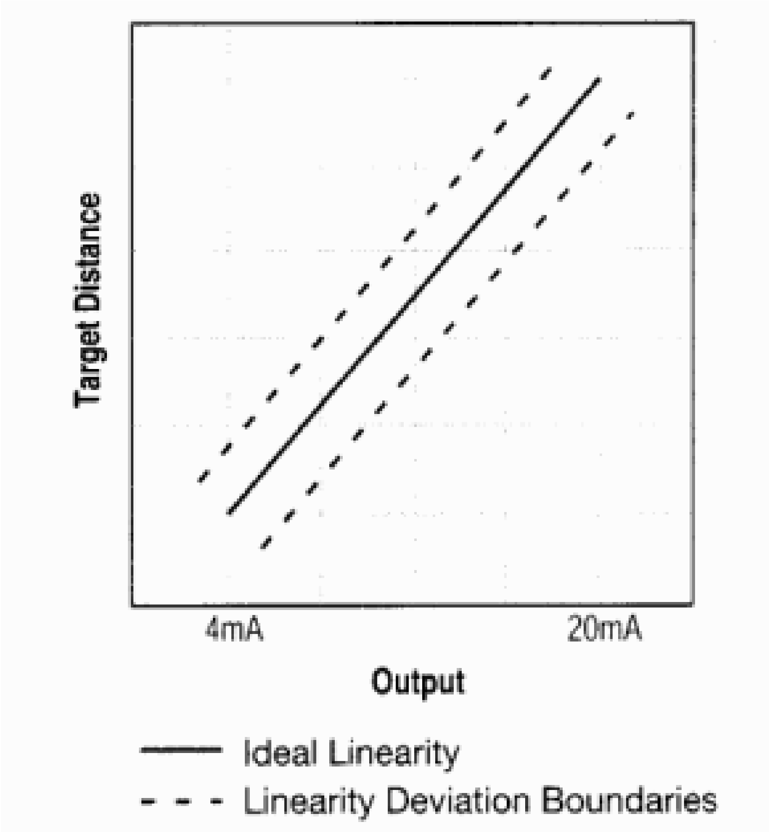


Beam Angle: The beam angle is the angle formed by sound waves as they emanate from an ultrasonic sensor. The beam angle defines the usable area in which target detection is possible.

Deadband: The deadband is the unusable region that defines the minimum distance for target detection. The unusable region occurs because a transducer must be pulsed in order to produce a sound wave, and the oscillations from the shocked must stop before the transducer can register its echo pulse.

Terminology of Ultrasonic Sensor

- *Linearity:* If the “perfect” analog ultrasonic sensor could be produced, its output, from beginning-to-end of the span limits, would appear in graphical form as a perfect straight line. Linearity defines the tolerances within which the sensor’s output may vary from the “perfect” line during “real life” target monitoring. Linearity specifications are always given as a percentage.



Terminology of Ultrasonic Sensor

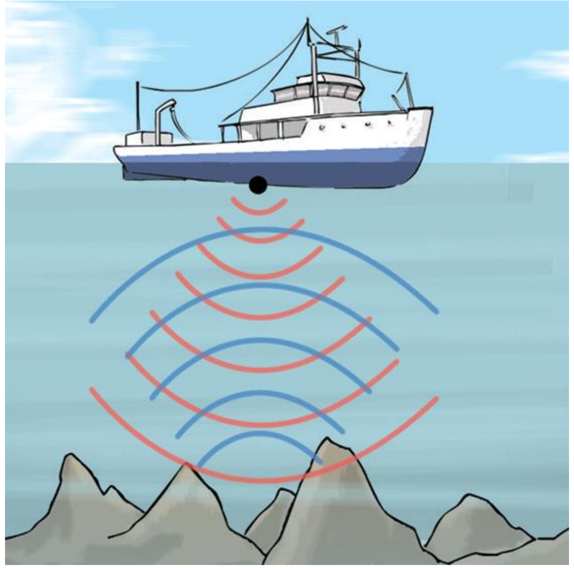
- *Resolution:* Resolution is the smallest target movement an ultrasonic sensor can identify and evaluate. For example, if an ultrasonic sensor has a resolution of 10mm, the sensor output remains unchanged until the target moves more than 10mm.
- *Repeatability:* Repeatability is the ability of a sensor to consistently detect a target at the same point. Repeatability is expressed as a percentage of sensing range and is frequently affected by environmental conditions.

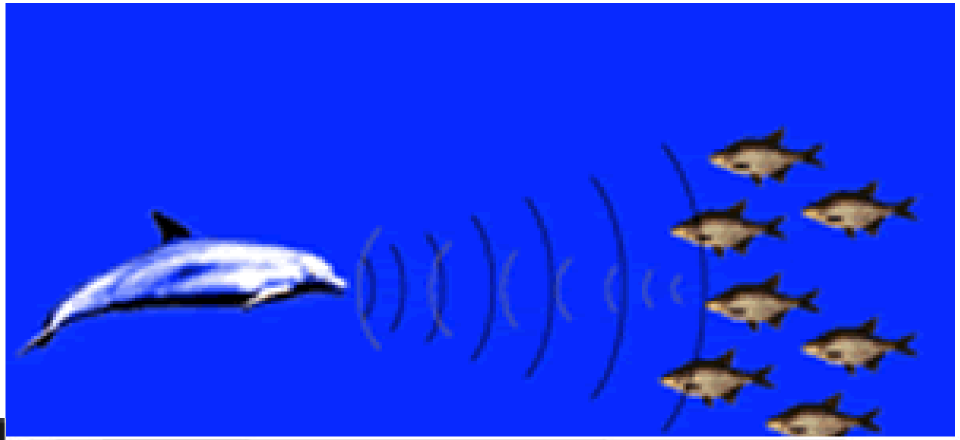
Terminology of Ultrasonic Sensor Target

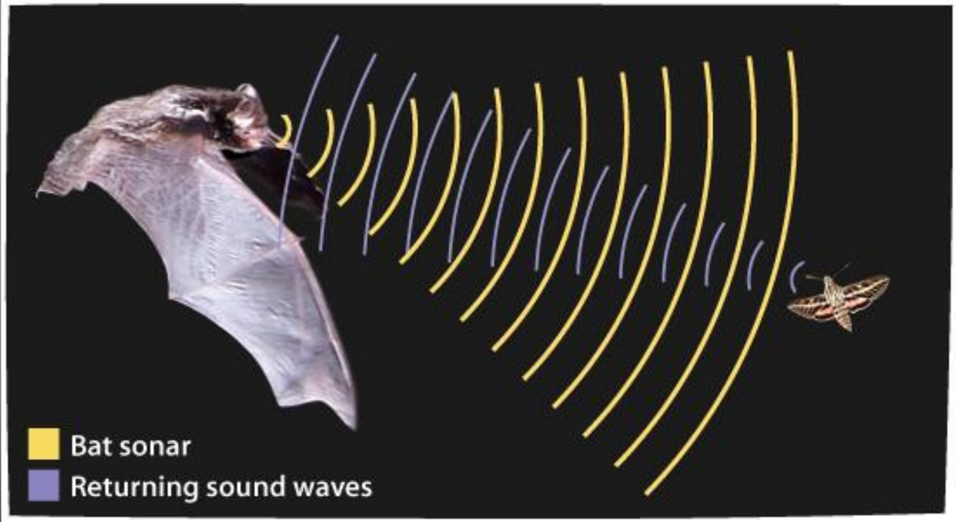
- ***Good Targets:*** Ultrasonic sensors function best in the detection and monitoring of objects with a relatively high density. Solid, liquid or granular media make ideal targets due to their high acoustic reflectivity. Unlike photoelectric sensors, target color and dusty atmospheric conditions do not affect ultrasonic sensors.
- ***Poor Targets:*** Porous targets such as felt, cloth or foam rubber have very high sound absorption properties, and subsequently make poor candidates for ultrasonic detection. In addition, liquid targets, typically excellent for ultrasonic detection, may become undetectable if bubbles or foam cover the surface.
- ***Unstable Targets:*** Standard ultrasonic sensors can generate erroneous output signal when monitoring turbulent or unstable targets.

Applications

- Ultrasound imaging
- SONAR
- echolocation







Ultrasound uses in medicine

- prenatal examinations
- diagnosing ophthalmological conditions
- applications in physiotherapy
- blood flow with Doppler ultrasound

https://www.youtube.com/watch?v=OBV7i9zRAto
https://www.youtube.com/watch?v=rkcQbrraouk

SONAR/Echolocation

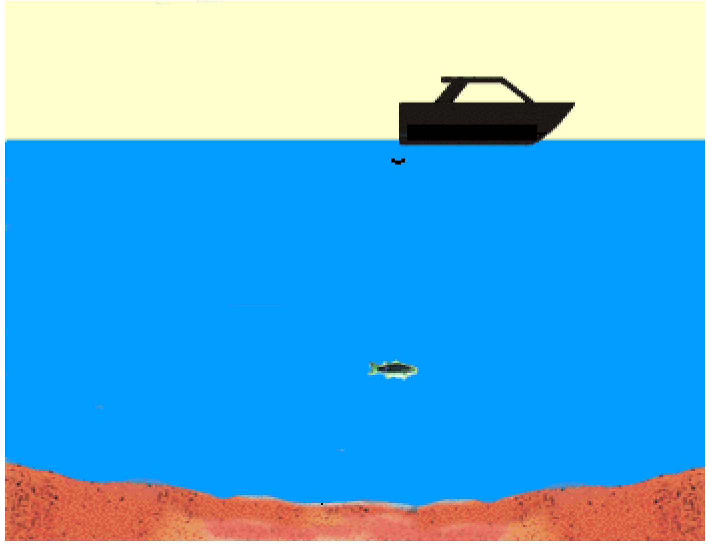
Determining the distance to an object by timing how long it takes for the sound pulse to travel out and bounce back again

- SONAR – used by ships to map ocean floor or find submarines (or as “fish finders” recreationally)
- Echolocation – used by dolphins, bats, etc. to find obstacles and food
- https://www.youtube.com/watch?v=KF_46xNw5V0

SONAR

The speed of sound in fresh water is 1.5×10^3 m/s. Ultrasound sent from a boat on a fresh water lake strikes a school of fish and is received back at the surface after a total elapsed time of 100 ms. How far are the fish from the boat?

a) 1.5×10^5 m
b) 7.5×10^4 m
c) 150 m
d) 75 m



Piezoelectric Sensors

Actual Operation of Piezoelectric Materials

- Consider operation with the ‘direct piezoelectric effect’
- If a material is strained, a charge will build up on opposite faces of the crystal:
- You can think of a piezoelectric crystal like a ‘capacitor’ that generates charge on the upper and lower surfaces when you strain it
- Piezoelectric ceramics tend to be very good insulators (i.e. poor conductors), so the charge will tend to remain on the upper and lower surfaces.
- There will be some finite amount of electric leakage of charge from one surface to another.
- More importantly, if we try to do work with the developed potential (+V), buy connecting it to a load, current will flow to do the work. Therefore, the accumulated charge will drain, and the developed potential will drop.

Operational Limits of Piezoelectric Materials

- During normal operation, a piezoelectric material is either strained (to create an electric potential) or is subjected to an electric potential (to create a strain).
- Care must be taken to operate the material within the parameters specified by the manufacturer other wise the following could occur:
  - Electrical depolarization: if a piezoelectric material is subjected to extreme electric fields (or voltages) which will cause it to lose (or significantly degrade) its piezoelectric effects.
  - Mechanical depolarization: if a material is excessively strained to the point where the crystal domains are significantly disturbed.
  - Thermal depolarization can occur if a material subjected to temperatures beyond the ‘Curie point’ of the material. A safe operational temperature is about half the Curie point temp

Governing Equations of Piezoelectric Effect

- The direct effect of piezoelectricity can be described by the
- general equation:
- Governing Equations of Piezoelectric Effect
- *D = dT + εE*

$$\begin{bmatrix} D_1 \\ D_2 \\ D_3 \end{bmatrix} = \begin{bmatrix} d_{11} & d_{12} & d_{13} & d_{14} & d_{15} & d_{16} \\ d_{21} & d_{22} & d_{23} & d_{24} & d_{25} & d_{26} \\ d_{31} & d_{32} & d_{33} & d_{34} & d_{35} & d_{36} \end{bmatrix} \begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \\ T_5 \\ T_6 \end{bmatrix} + \begin{bmatrix} \varepsilon_{11} & \varepsilon_{12} & \varepsilon_{13} \\ \varepsilon_{21} & \varepsilon_{22} & \varepsilon_{23} \\ \varepsilon_{31} & \varepsilon_{32} & \varepsilon_{33} \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \\ E_3 \end{bmatrix}$$

- Where: D - Electrical Polarization (C/m2)
- T - Stress Vector (N/m2)
- d - Piezoelectric Coefficient Matrix
- ε - Electrical Permitivity Matrix (F/m) (*Note: this is NOT strain*)
- E - Electric Field Vector (V/m)

Governing Equations of Piezoelectric Effect

- The direct effect of piezoelectricity can be simplified down to the following equation, in the absence of an external electric field (i.e. E=0).

$$D = dT$$

$$\begin{bmatrix} D_1 \\ D_2 \\ D_3 \end{bmatrix} = \begin{bmatrix} d_{11} & d_{12} & d_{13} & d_{14} & d_{15} & d_{16} \\ d_{21} & d_{22} & d_{23} & d_{24} & d_{25} & d_{26} \\ d_{31} & d_{32} & d_{33} & d_{34} & d_{35} & d_{36} \end{bmatrix} \begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \\ T_5 \\ T_6 \end{bmatrix}$$

Governing Equations of Piezoelectric Effect

- The inverse effect of piezoelectricity can be described by the general equation:

$$s = ST + dE$$

$$\begin{bmatrix} s_1 \\ s_2 \\ s_3 \\ s_4 \\ s_5 \\ s_6 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} & S_{13} & S_{14} & S_{15} & S_{16} \\ S_{21} & S_{22} & S_{23} & S_{24} & S_{25} & S_{26} \\ S_{31} & S_{32} & S_{33} & S_{34} & S_{35} & S_{36} \\ S_{41} & S_{42} & S_{43} & S_{44} & S_{45} & S_{46} \\ S_{51} & S_{52} & S_{53} & S_{54} & S_{55} & S_{56} \\ S_{61} & S_{62} & S_{63} & S_{64} & S_{65} & S_{66} \end{bmatrix} \begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \\ T_5 \\ T_6 \end{bmatrix} + \begin{pmatrix} d_{11} & d_{21} & d_{31} \\ d_{12} & d_{22} & d_{32} \\ d_{13} & d_{23} & d_{33} \\ d_{14} & d_{24} & d_{34} \\ d_{15} & d_{25} & d_{35} \\ d_{16} & d_{26} & d_{36} \end{pmatrix} \begin{bmatrix} E_1 \\ E_2 \\ E_3 \end{bmatrix}$$

- Where: s - Strain Vector
- S - Compliance Matrix
- T - Stress Vector (N/m2)
- d - Piezoelectric Coefficient Matrix
- E - Electric Field Vector (V/m)

Governing Equations of Piezoelectric Effect

- The inverse effect of piezoelectricity can be simplified to the following expression, if there is no additional mechanical stress present (i.e. T=0). Where strain is related the electric field by:

$$s = dE$$

$$\begin{bmatrix} s_1 \\ s_2 \\ s_3 \\ s_4 \\ s_5 \\ s_6 \end{bmatrix} = \begin{pmatrix} d_{11} & d_{21} & d_{31} \\ d_{12} & d_{22} & d_{32} \\ d_{13} & d_{23} & d_{33} \\ d_{14} & d_{24} & d_{34} \\ d_{15} & d_{25} & d_{35} \\ d_{16} & d_{26} & d_{36} \end{pmatrix} \begin{bmatrix} E_1 \\ E_2 \\ E_3 \end{bmatrix}$$

Governing Equations of Piezoelectric Effect

The units of the piezoelectric constant, d_{ij}, are the units of electric displacement over the unit of the stress. Therefore:

$$[d_{ij}] = \frac{[D]}{[T]} = \frac{[\varepsilon][E]}{[T]} = \frac{\frac{F}{m}\frac{V}{m}}{\frac{N}{m^2}} = \frac{Coulomb}{N}$$

Recall that:

$$V = Et$$

Where: V - Voltage
E - Electric Field
t - distance of interest through E

Therefore the piezoelectric constant is a good way to measure the intensity of the piezoelectric effect, since we can think of it in terms of Coulombs generated, per Newton applied.