Instrumentation & Measurement

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Position-Displacement Measurement

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Position-Displacement Measurement

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Chapter 27-28

Position-Displacement Measurement

- Topics
  - Mechanical Switches
  - Proximity sensors and describe their properties and applications.
  - Photoelectric Switches
  - Photoelectric distance measurement
  - Translational and Rotational displacement measurement
  - Encoders
  - Accelerometer

Mechanical Switches

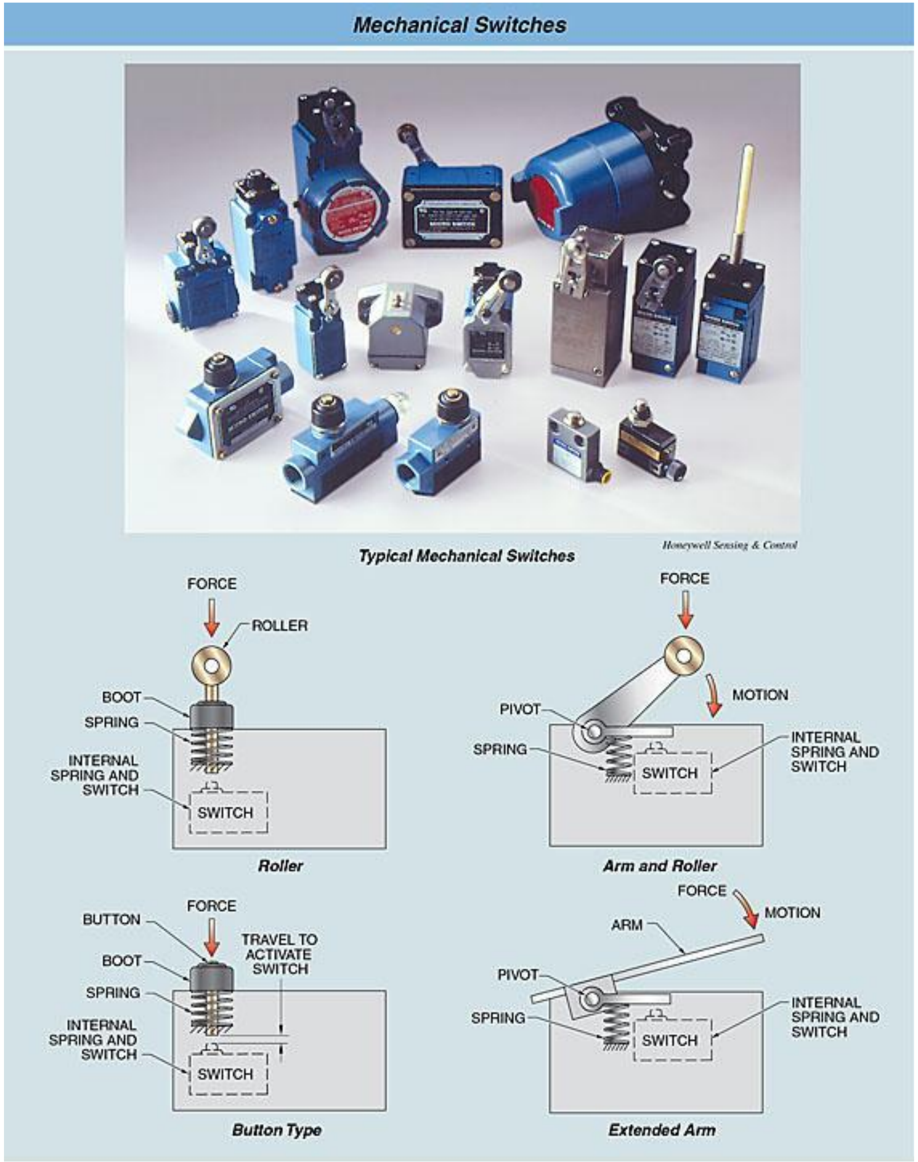
A mechanical switch is a switch that requires physical contact with an object to actuate a switch mechanism.

Mechanical switches are widely used in industry because the trip points can be set very accurately. However, the switches can become damaged and fail if the switches are exposed to outdoor weather or corrosive service conditions. This failure is commonly due to corrosion of the moving parts, especially if the switch is not frequently actuated.

The switch-actuating mechanism typically is spring loaded so that the switch returns to its original position when no longer in contact with the object.

The switches come with NO and NC contacts.

The position mechanical switch are also referred to as **limit switches**.



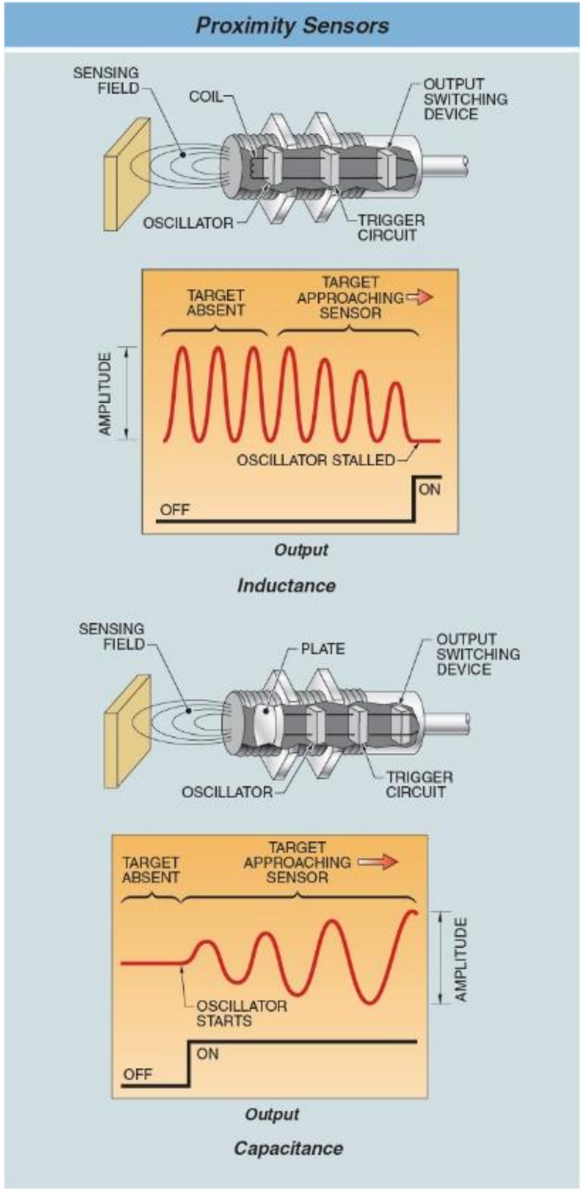
Proximity Sensors

Types:

- Inductive
- Capacitive
- Magnetic
- Ultrasonic

Inductive proximity sensors can detect metal object.

The capacitive sensor can detect other types of material like glass , plastic , fluid,

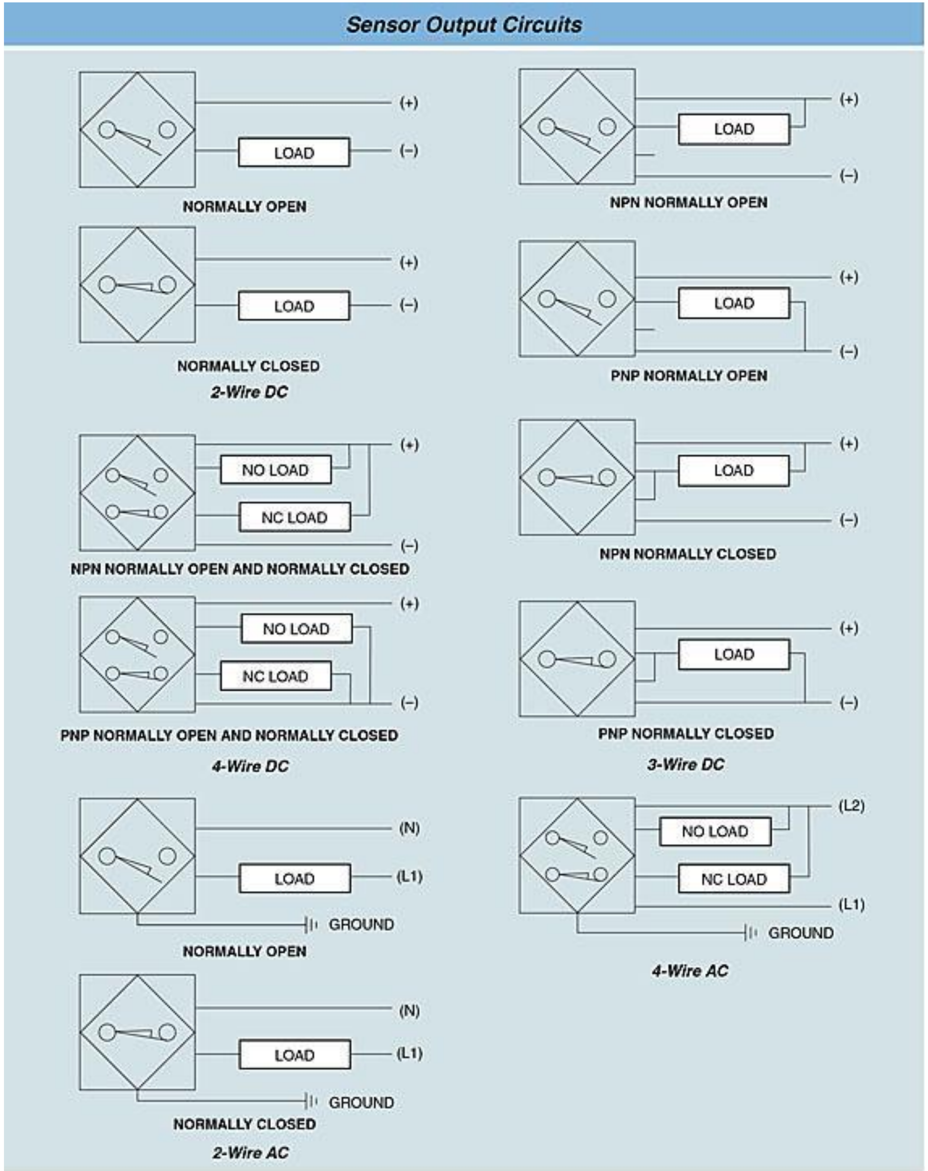


Proximity Sensors outputs

They have transistor type output.

They come with NO or NC and PNP and NPN output.

They can come as 2, 3 , 4 wire sensors.



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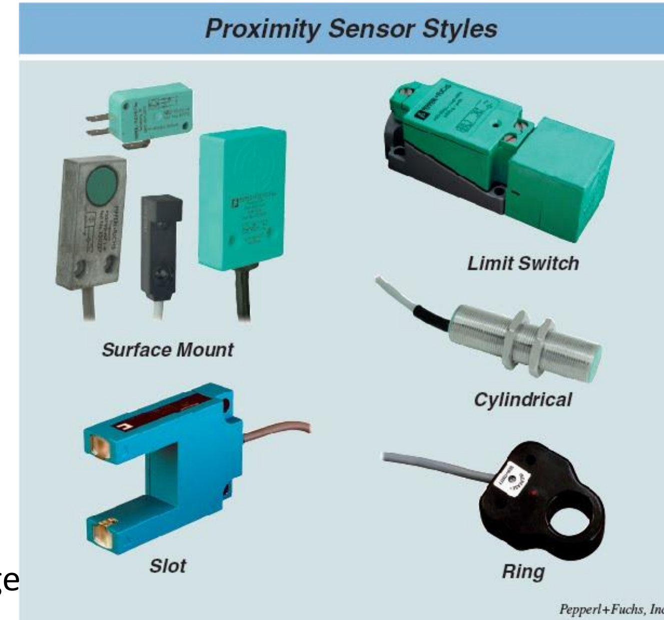
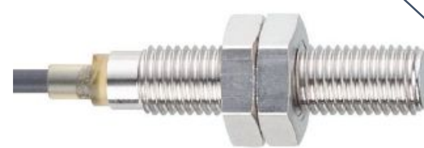
Inductive and Capacitive Sensor Forms

- They can come with different shape make them suitable for different application.
- Cylindrical Housing comes as M8, M12 M20 M30.
- M8 means the diameter of cylinder is 8 mm
- They come with cable or with connector.



Sensitivity Range



Shielded
with cable

Unshielded
with cable

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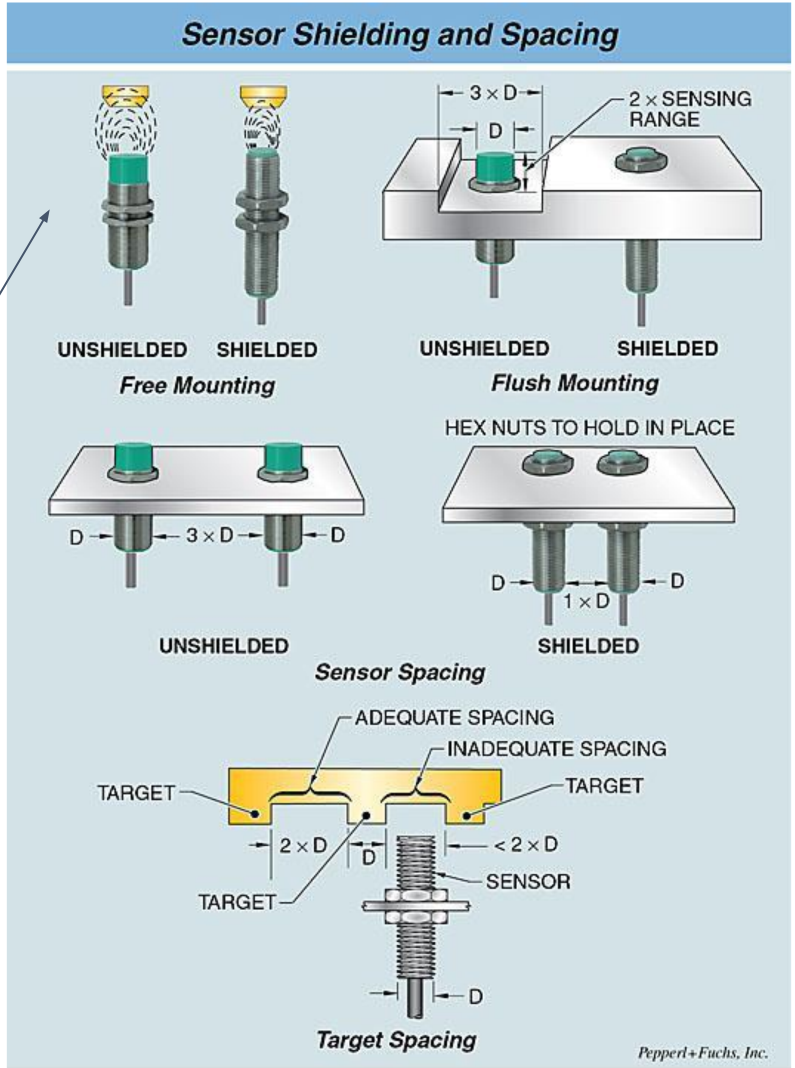
Inductive and Capacitive Shielded and unshielded

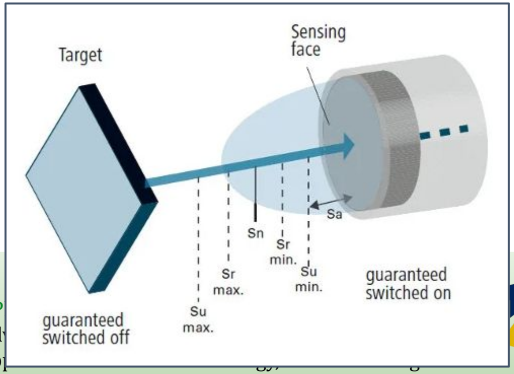
- The unenclosed end of the sensor contains the inductance coil or the capacitance plate. Although the basic design focuses the detection field axially from the end of the sensor, there is some lateral field generated. If non-flush type of sensor is flush mounted in a metal plate, the metal around the end of the sensor is sensed by the lateral field and continuously activates the sensor. This prevents the sensor from sensing the target object.
- Shielded and unshielded sensors have different mounting requirements. Sensor spacing and target spacing must also be taken into account when installing sensor systems.
- The shielded sensor is also referred to as flush and unshielded as non-flush mountable.



Sensing Distance

The international standard EN 60947-5-2 defines the sensing distance as follows:

the sensing distance is the distance at which a standard target moving toward the sensing face of a proximity switch causes a signal change.



- Larger sensor diameter, higher sensing distance
- With same diameter, shielded sensor has lower sening distance compare to unshielded.
- For inductive proxies the sensing distance is affected by target material type. For example sensing distance could be different for Iron and aluminum

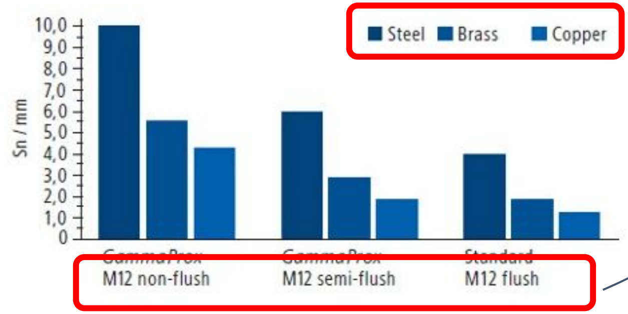


Photo source: [Functionality and technology of inductive sensors | Baumer international]

Actuation and Hysteresis

Proximity sensors can be actuated by laterally or axially moving targets.

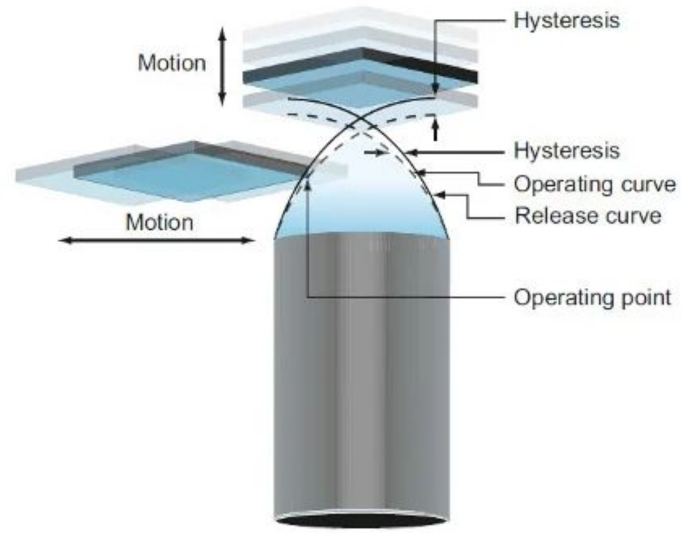
The sensor have hysteresis property.

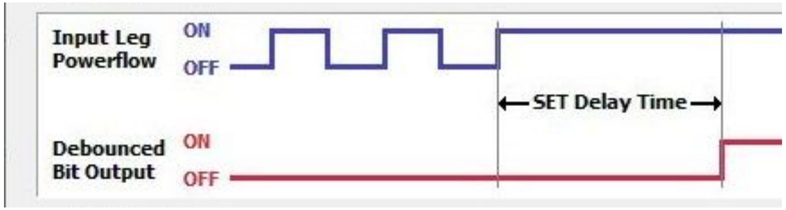
The point the sensors turns ON and OFF are not the same.

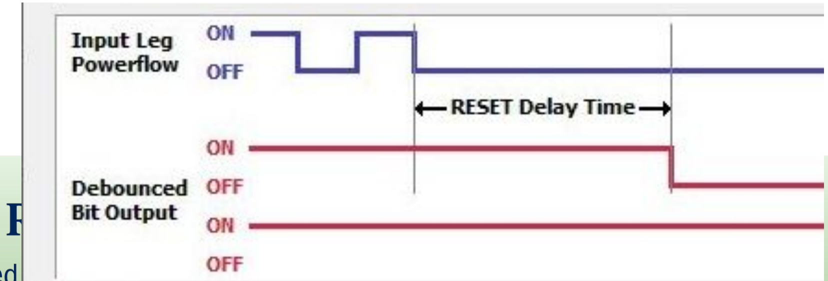
The hysteresis property can be useful when there is vibration in system.

Generally to cancel the signal chattering a delay timer can be used in the controller to cancel the vibration and chattering effect.

This timer referred to as delay time or debounce timer also.







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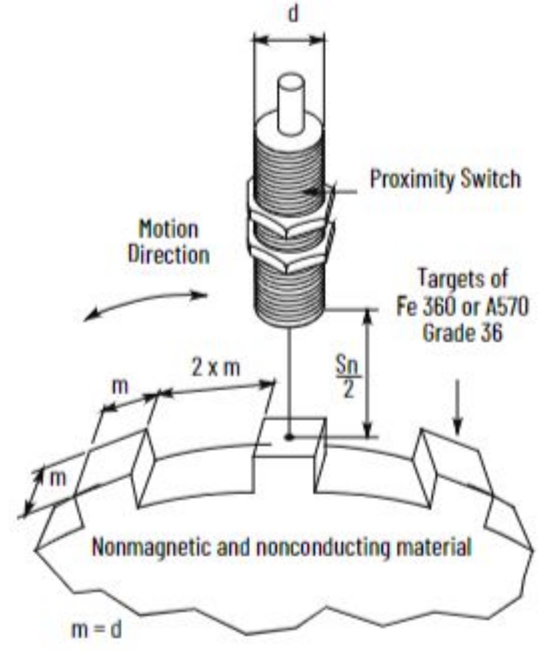
Switching Frequency

EN 60947-5-2 standards:

The switching frequency is the highest possible number of switchings per second.



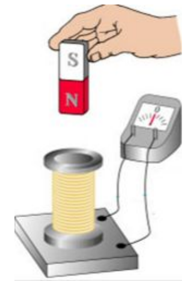
Inductive and Capacitive Proximity sensors property

- They have limited sensing distance range.
- The target object is not going to be physically in contact with sensor.
- The Capacitive are sensitive to dirt and dust

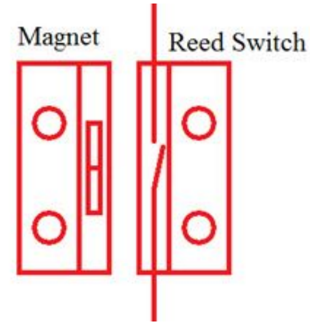
Magnetic Proximity Sensors

Types of magnetic proximity sensors:

1) **Variable Reluctance** sensors made of permanent magnet and a pick-up coil.

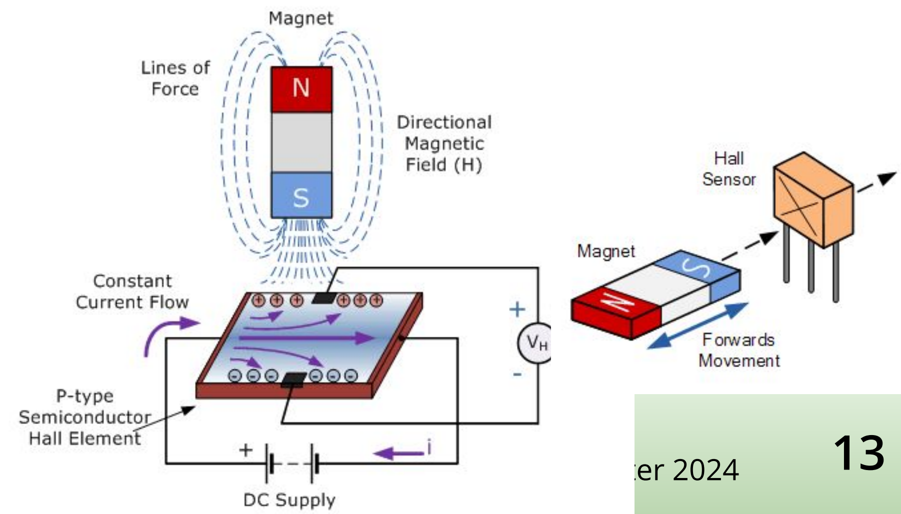


2) **Reed Switch**



3) **Hall effect:** A plate as front is connected to a voltage and carrying a constant current. When a magnetic field is applied to it, a force (Lorentz Force) will be applied to electrons and push them to th
One side with excess of electron (negative potential) and anothe
lack of electron (Positive potential). Then Exist of voltage means
of magnetic field.

The main difference with variable reluctance is that it can detect
stationary object, in variable reluctance the object with zero spe
not be detected. in fact arriving an object can be detected but n
presence.



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Magnetic Proximity Sensors Applications

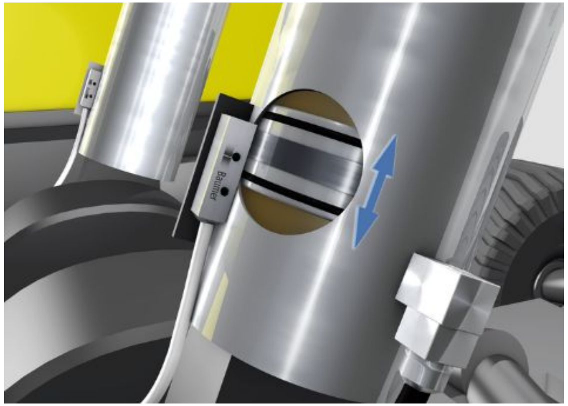
- Stroke limitation in cylinders.

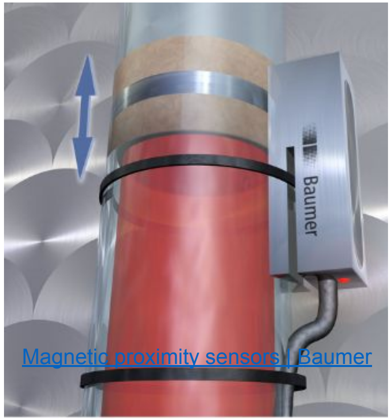
The piston-carried permanent magnet is detected from the outside of the cylinder wall

- Liquid level detection using a float carried magnet.

Non-invasive monitoring through tank wall without direct media contact and contamination by the sensor

- Detecting Door open close





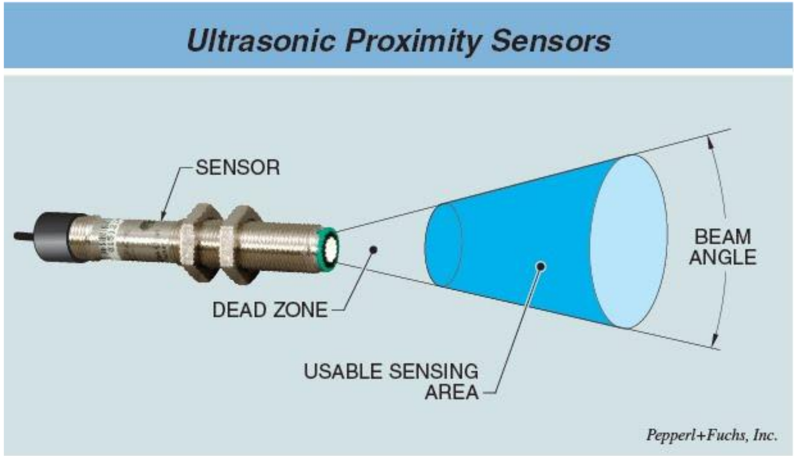
Magnetic proximity sensors | Baumer

Ultrasonic proximity sensors

An ultrasonic proximity sensor is a proximity sensor that uses a pulse of sound waves to detect the presence of an object. Sound waves travel toward the target and are reflected toward the sensor. Frequencies range from 65 kHz to 400 kHz, depending on the type of sensor used. The elapsed time between the pulse generation and the detection of the reflection is related to the distance to the target. The ultrasound beam diverges as it leaves the sensor.

Ultrasonic sensors have a dead zone close to the sensor where a target cannot be detected.

Sound is a mechanical wave therefore functionality depends on medium also. For example there might be different functionality in clear air dusty air like grain silo



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Photoelectric sensors

A photoelectric sensor is a proximity sensor that uses visible light and infrared radiation sources to detect target objects.

The sources can be pulsed, which increases the range and life of the source and makes the sensor less susceptible to interference by external light sources.

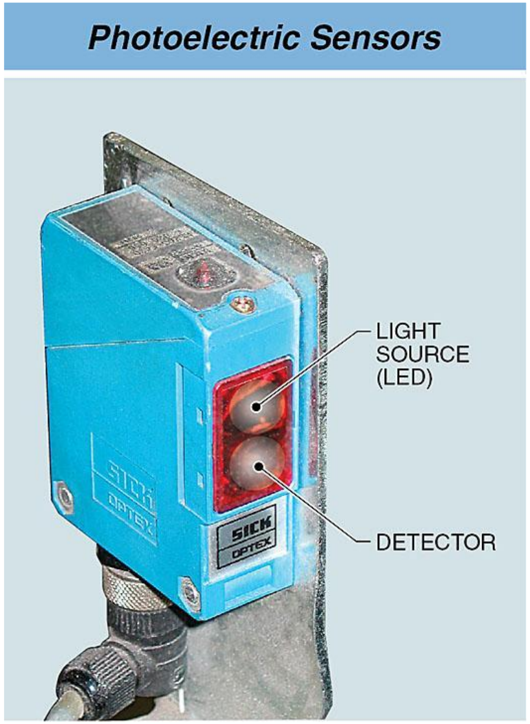
The housings can be cylindrical for the smaller sizes and rectangular for the larger sizes.

The three common types of photoelectric detection are

- diffused
- retro-reflective
- through-beam detection.

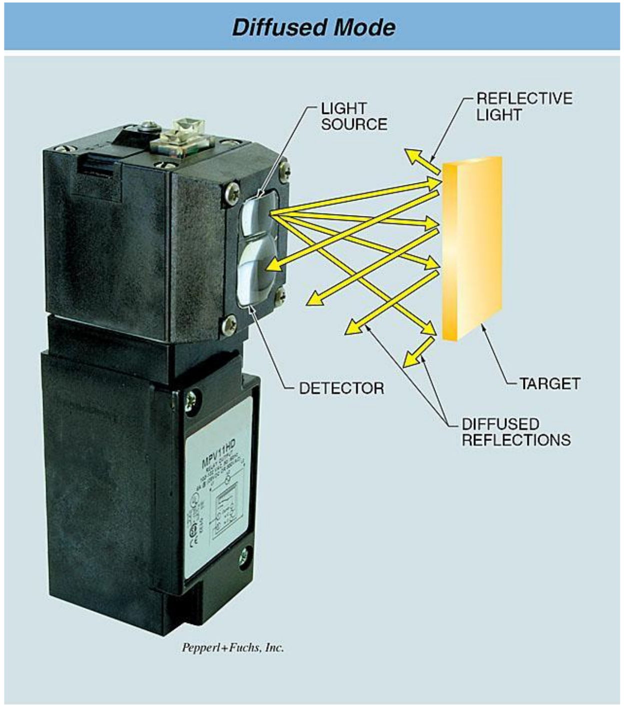
They come with

- NO or NC outputs
- PNP or NPN outputs



Photoelectric sensors - Diffused

- A diffuse type photoelectric sensor directs its source against a target object and detects a reflection from the target object. The reflection is diffused and is thus not very strong.
- An infrared light source is much stronger than a visible light source and is thus better suited to this type of sensor.
- The color, finish, and size of the target object have a significant impact on whether this photoelectric mode is suitable for an application.
- Shiny targets reflect more light, but only at a specific angle. Therefore the sensor must be aimed directly at the target.



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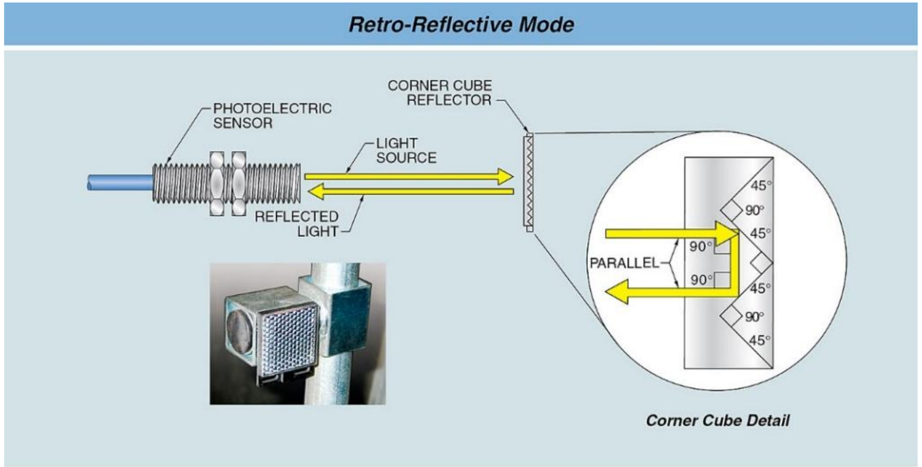
Photoelectric sensors - Retro-reflective sensors

A special corner cube reflector is typically used to reflect the light beam back to the detector. The corner cube reflector has a triangular grooved surface that returns the light beam on a parallel axis.

Cross conveyor for example

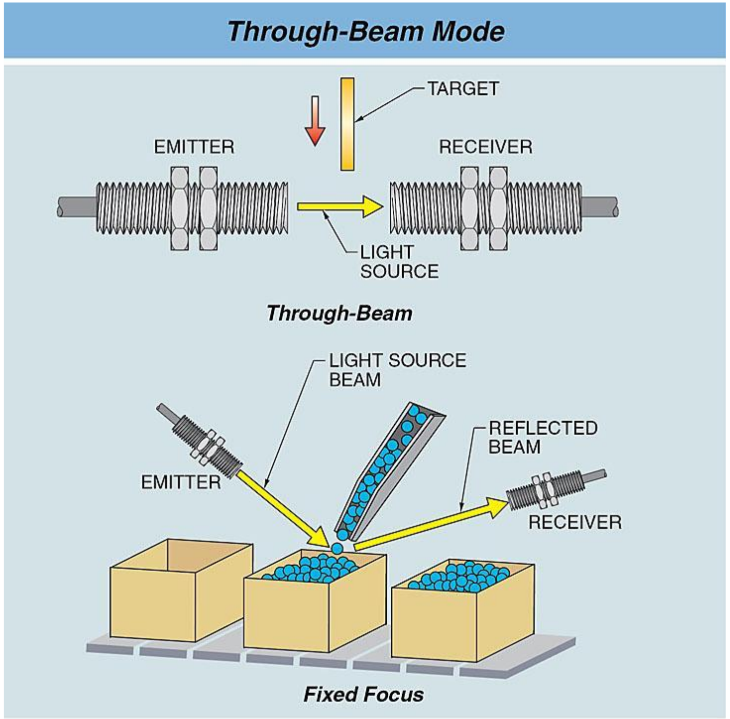


Photoelectric sensors - Through-beam sensors

The sensor is made of emitter and receiver.

The through-beam mode of sensing provides the greatest range. Compare to the other two, the light should travel one way.

Because of the tightly focused source, the through-beam mode is less susceptible to atmospheric contamination.



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Distance Measurement

- Light sensors and ultrasonic sensors are used to measure distances.
- They send a beam and measure time for reflection. The speed of light or sound is known by having the time, the distance can be measured.
- By measuring the distance the speed and acceleration of a moving object can be calculated.

Application of Position switches

- By a position switch it can be detected an on object is at a pacific point.
- They can be used for counting parts, stroke and so on.
- The counting can be used for measuring flow example in paddle wheel.

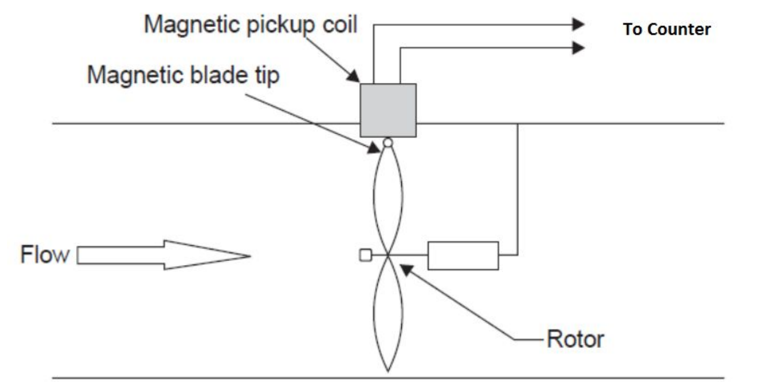

Fig. A simple Turbine Flow meter

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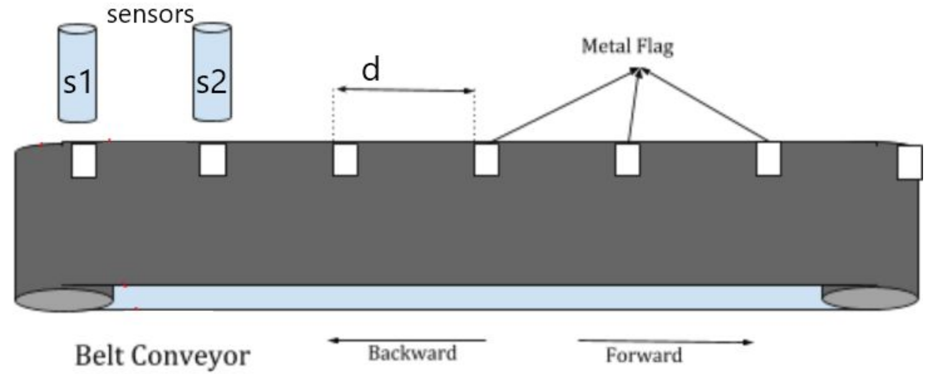
Application of Position switches

- They can be used to measure speed and acceleration for translational motion
- The can be used to detect motion direction



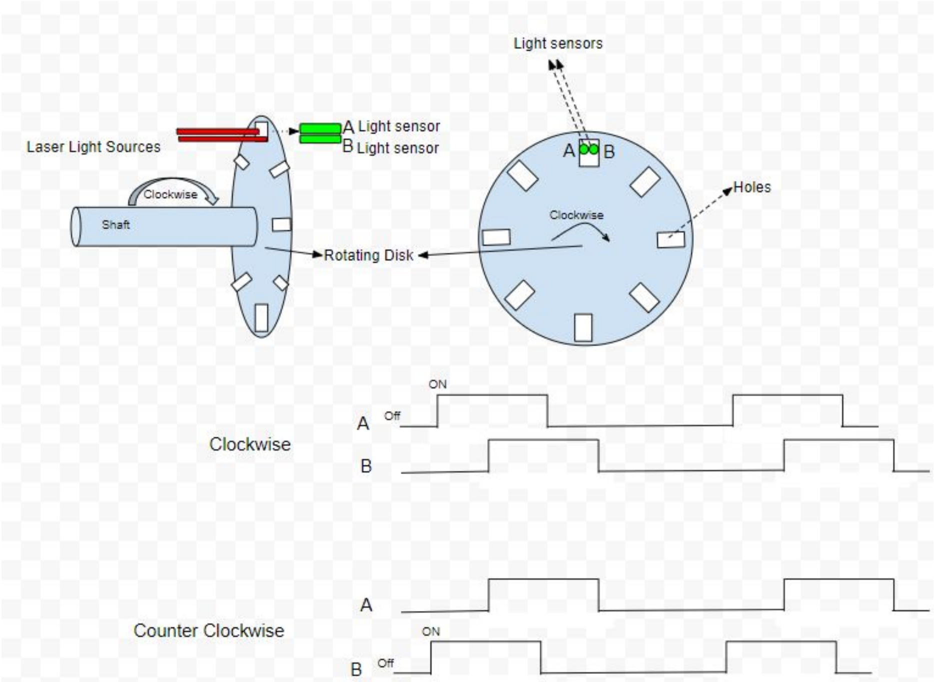
$$Forward = latch(S1) AND \ (Edge\, of\ S2)$$
$$Reverse = latch(S2) AND \ (Edge\, of\ S1)$$
$$V = \frac{d}{\Delta t}$$
$$a = \frac{\Delta V}{\Delta(\Delta t)}$$

Application of Position switches

- They can also be used to measure speed and acceleration for rotational motion
- The can be used to detect motion direction

$$Clockwise = (A) AND \ (Edge\, of\, B)$$
$$Counter\, Clockwise = \ (B) AND \ (Edge\, of\, A)$$
$$angular\, displacement\, \Theta = \ count\, of\, A \ \times \ \angle two\, holes$$
$$anglular\, velocity\ \omega = \frac{\Delta\Theta}{\Delta t}$$
$$anglular\, acceleration\ \alpha = \frac{\Delta\omega}{\Delta t}$$

Let's assume every time the sensor turns on when it sees a hole



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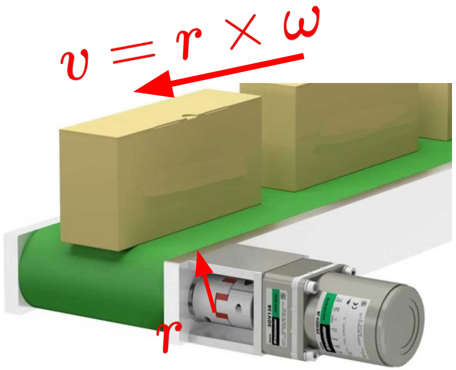
An Incremental Encoder

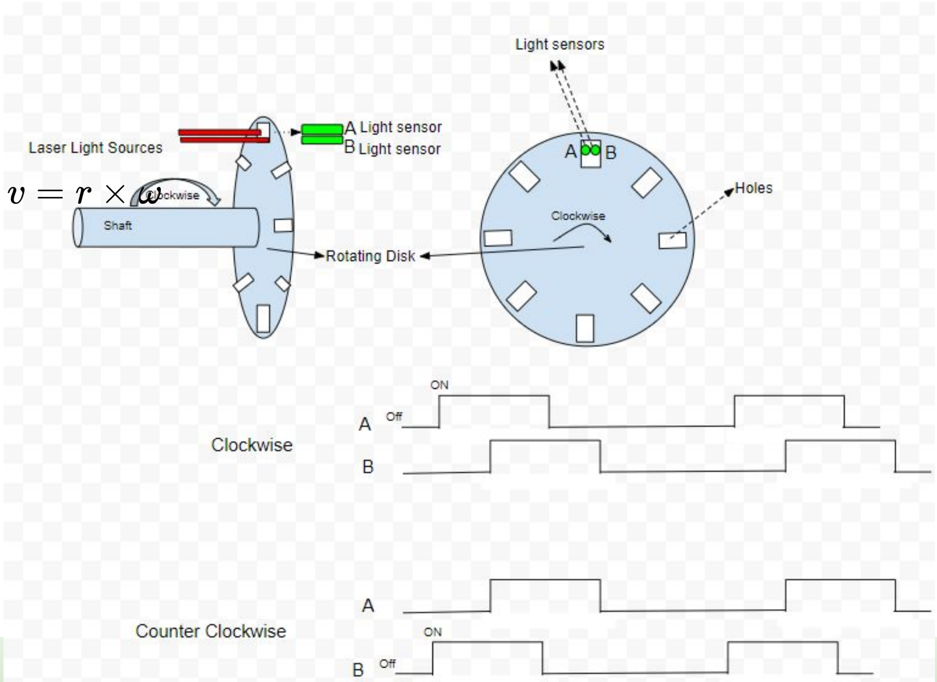
- This is the base for incremental encoder

$$Clockwise = (A) AND\ (Edge\,of\,B)$$
$$Counter\,Clockwise = \ (B) AND\ (Edge\,of\,A)$$
$$angular\,displacement\,\Theta = \ count\,of\,A\ \times\ \angle two\,holes$$
$$anglular\,velocity\ \omega = \frac{\Delta\Theta}{\Delta t}$$
$$anglular\,acceleration\ \alpha = \frac{\Delta\omega}{\Delta t}$$

Linear velocity $v = \ r\ \times\ \omega$

Linear $acceleration\ a = \ r\ \times\ \alpha$





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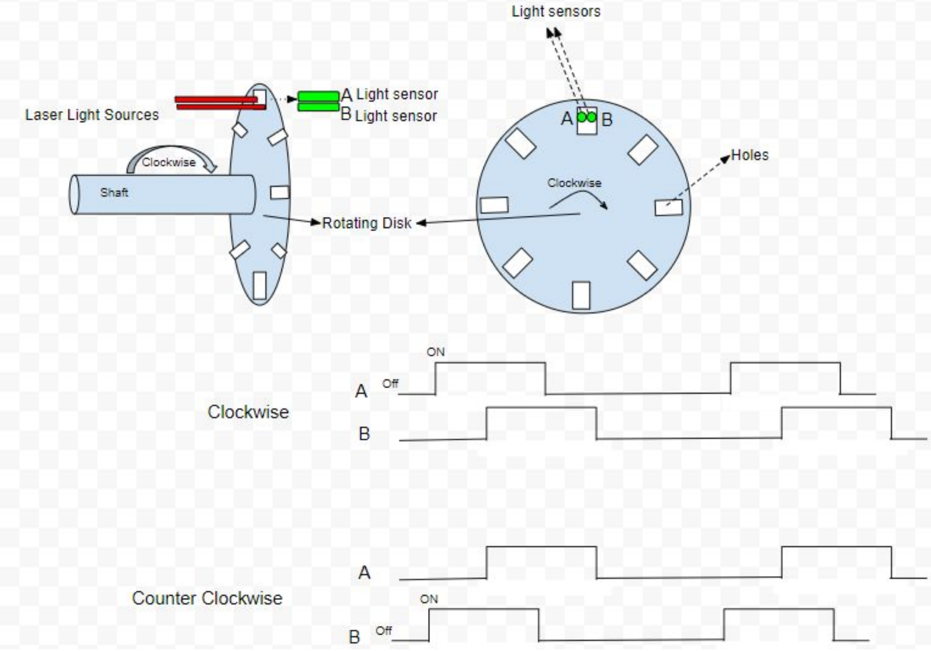
Encoders Outputs

Encoders can come with below outputs:

- Incremental with Pulses of A, B, C, in this case a high speed counter is needed to count the pulses. The rollover number depends on how many bits is used for counting and it should be taken into account.
- Analog output 4-20 mA
- Digital output of position or steps via network like ethernet-IP /Profinet/ IO-link/…
- Gray Code or BCD number
- Incremental Encoder pulse outputs are very prone to the noises, the Encoder with digital outputs are better alternative



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Pulse Counting / Roll over

- The number of pulses per revolution multiply the number of revolution per second could be a large number. For example if an encoder designed to send 1000 pulses per revolution and the shaft is rotating 30 time per second, then the encoder sends out 30 000 pulses per second. (30 kHz).
- To count high number of pulses a fast input and fast processor should be used. The inputs are usually known as fast input and the counter is known as High speed counters which attach to the controller.
- This also means that counting the number of shaft revolution per second will be dependent on maximum pulses can be sent out from encoder and maximum number of pulses which can be coined by encoders.

- To count 30 000 pulses per second two bytes needed. The largest number can be stored in two bytes is 2^16-1= 65535 . When counting reach to this number then next count will be 0. This is called roll over.
- Let's assume you have controller and you are reading high speed counter value every 100 ms.

First reading : 50000

second reading : 60000

$$\frac{60000-50000}{1000} = 10 \; rev \; per \; 100 \; ms$$

Third reading : 4465

$$\frac{4465-50000}{1000}$$

In second time roll over should be taken in account for calculation

BCD - Binary Coded Decimal

- In BCD number coding each digit of integer number is coded with 4 bits. Example in front.

Properties:

- easy for human interpretation and conversion
- It takes more space for coding numbers. For example the BCD code for 15 is 0001 0101 which news 8 bits where as the binary code for 15 is 1111 which needs just 4 bits
- The BCD used for digital display
- Computations by cpu are done in binary

Decimal	Binary
0	0000
1	0001
2	0010
3	0011
4	0100
5	0101
6	0110
7	0111
8	1000
9	1001

Integer: 6 5 0 1

BCD: 0110 0101 0000 0001

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Encoders

- Rotary Encoders
  - Incremental Encoders
  - Absolute Encoders
    - Single turn example 0-359 °
    - Multiturn 0-359 ° plus number of revolution
- Linear Encoders

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Absolute Encoder

picture from Chapter 20 Morris

A disk with specific pattern of holes is in front of the light sensors. Depends on which sensor detecting holes or not , we could know what is angle of the plate.

Property of the absolute encoder is that after power cycle shows the same value as position. the new position can be read accordingly even If during the power shutdown the shaft is rotated . In an incremental encoder the current position could be lost if provision is not taken to save the current count.

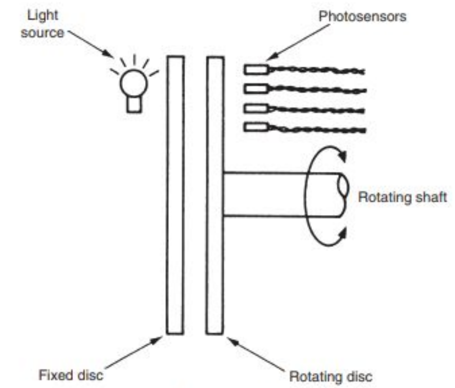

Figure 20.5
Coded-disk shaft encoder.

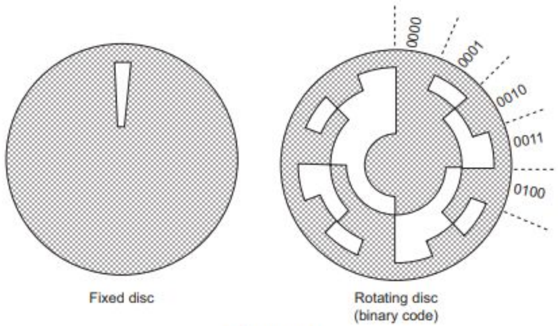

Figure 20.6
Window arrangement for coded-disk shaft encoder.

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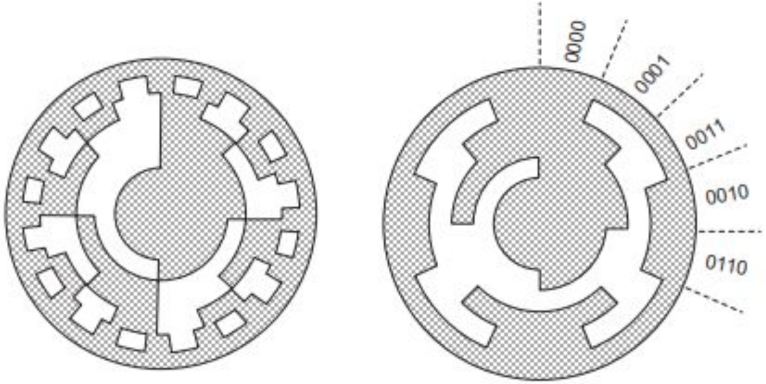
Gray Code

Gray code is another type of output for encoders.

In this type of coding, from one number to the succeeding number, just one bit changes.

In binary code more than one bit might change from one integer to the next compare to Gray code which just one bit changes. Therefore the probability of signal corruption and misinterpretation will be higher.



Binary code with anti-ambiguity track

Gray code

Figure 20.7
Modified window arrangements for the rotating disk.

Table 20.1: The gray code.

Decimal number	Binary code	Gray code
0	0000	0000
1	0001	0001
2	0010	0011
3	0011	0010
4	0100	0110
5	0101	0111
6	0110	0101
7	0111	0100
8	1000	1100
9	1001	1101
10	1010	1111
11	1011	1110
12	1100	1010
13	1101	1011
14	1110	1001
15	1111	1000

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Encoder Resolution

Incremental encoder resolution is defined as number of Pulses Per Revolution (PPR).

It could range from 10 , … 1024,...

For single turn absolute encoder the resolution is defined as steps per revolution or number of bits.

For multiturn absolute encoder it is based on the steps per revolution and number of revolutions or also bits assigned per one revolution and for the number of the revolutions

For linear can come with unit of measurement

Incremental

Measuring/setting range	
Resolution	1...10000; (parameterisable; Factory setting: 1024) resolution
Accuracy / deviations	
Accuracy [°]	0.1

https://www.ifm.com/ca/en/product/RO3100

Absolute - Single-turn

Outputs	
Code	binary
Measuring/setting range	
Resolution	8192 steps; 13 bit

https://www.ifm.com/ca/en/product/RN7012

Absolute - Multi-turn

Measuring/setting range	
Resolution	65536 steps; 32768 revolutions; 31 bit
Accuracy / deviations	
Accuracy [°]	0.1

https://www.ifm.com/ca/en/product/RMB300

OUTPUT	STROKE LENGTH	RESOLUTION
PROFINET	25...6350 mm (1...250 in.)	0.5 µm
EtherNet/IP™	25...6350 mm (1...250 in.)	1 µm
SSI	25...6350 mm (1...250 in.)	0.1 µm
POWERLINK	25...6350 mm (1...250 in.)	0.5 µm
EtherCAT®	25...6350 mm (1...250 in.)	0.5 µm
Analog	25...6350 mm (1...250 in.)	16 bit

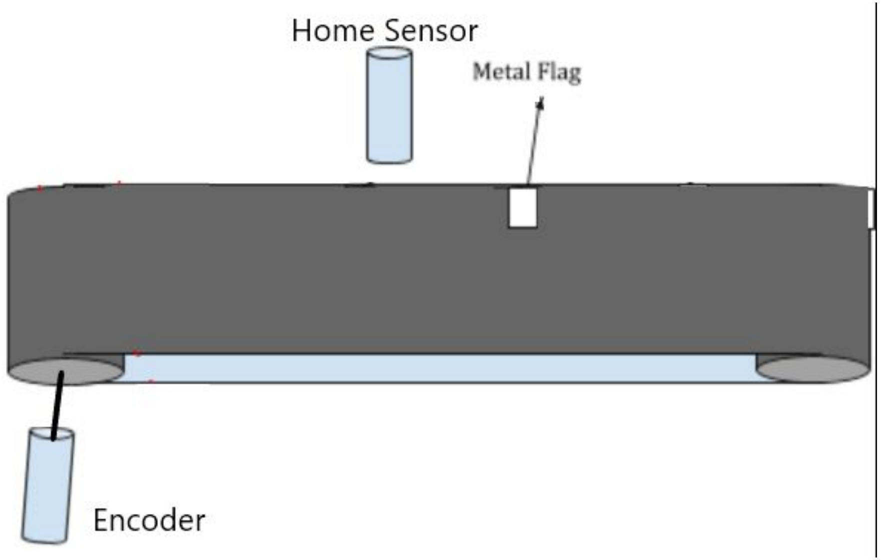
https://www.temposonics.com/Products/IndustrialPositionSensors/R-SeriesVPositionSensors/R-SeriesVRP5

Home Sensor

In encoder applications a position is defined as home position. This will play role as reference position for any other position calculation.

The home position (position zero) can be attained by an extra position switch sensor. Every time the home sensor turns on the counter can be reseted to 0.

One property of of having home sensor is that if an error happs during pulse counting or position calculation , it will be reseted in home position and will not affect further position calculations.



Encoder Installation

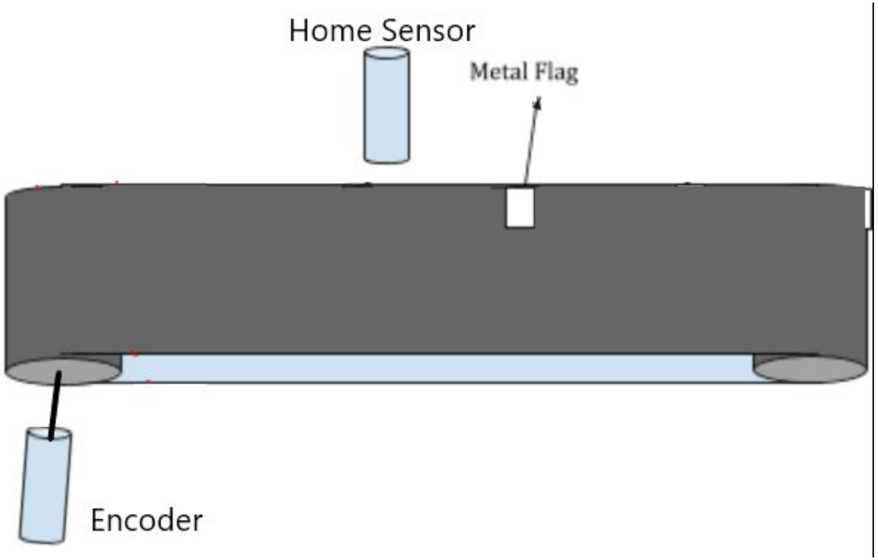
Connecting to motor shaft

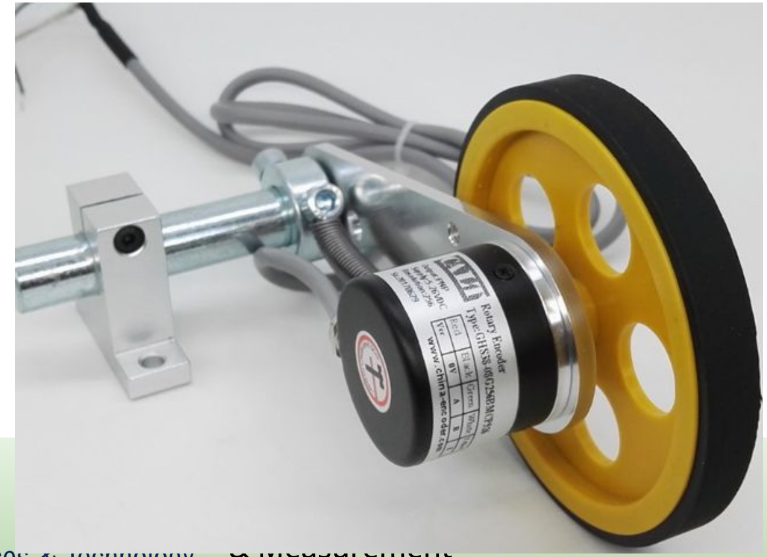
Using encoder wheel as below

Depends on application, when encoder is connected to shaft belt slippage will be missed and create error in position.

Also when the belt is worn off , the encoder will not sense it.

The encoder wheel provide measurement directly from displacement



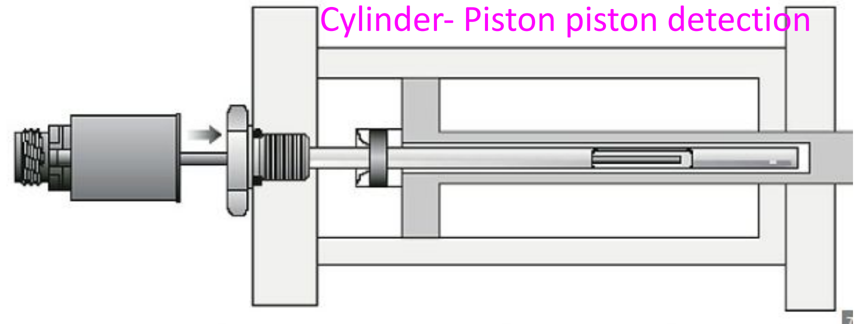


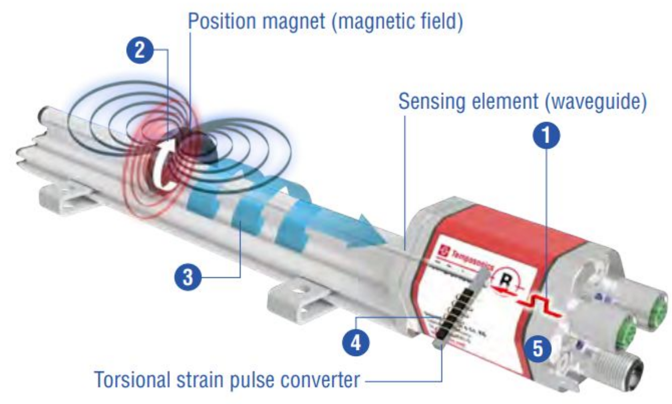
Linear Encoder

The type presented in front is based on magnetoresistive.

An electromagnetic wave is generated in head of sensor and it will be conducted through the sensor body length. When it hits the magnet ring , it will bounce back.

Travel time is measure by sensor head and then distance of magnet ring from head is calculated.





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Example

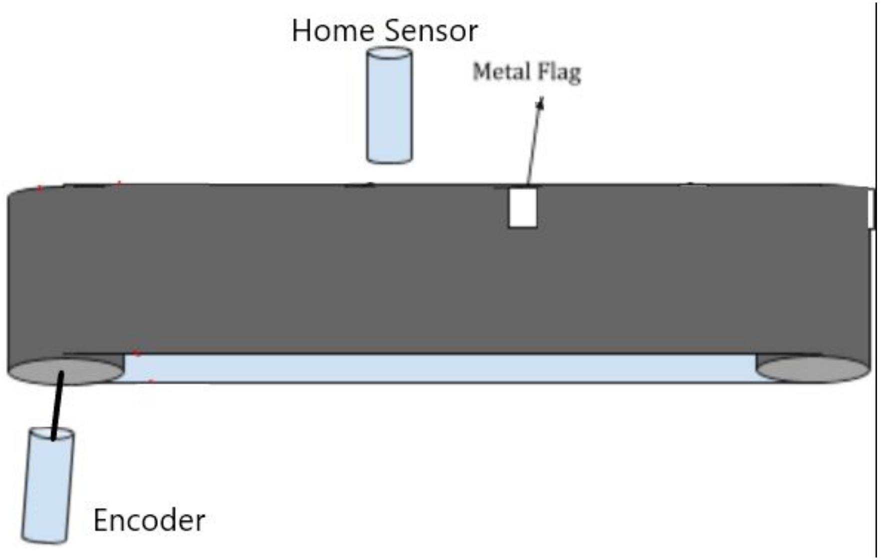
An incremental encoder is connected to the shaft of a motor. The roller diameter is 5 inch. The encoder output is 1024 PPR and the output is connected to a high speed counter with a shielded cable.

The metal piece turns the home sensor on. At the rising edge of Home sensor the counter is reset to zero. After 10 second the counter value is 1960

1- What is the roller shaft RPM?

2- How much the metal flag is displaced?

3- what was the average speed of conveyor belt?



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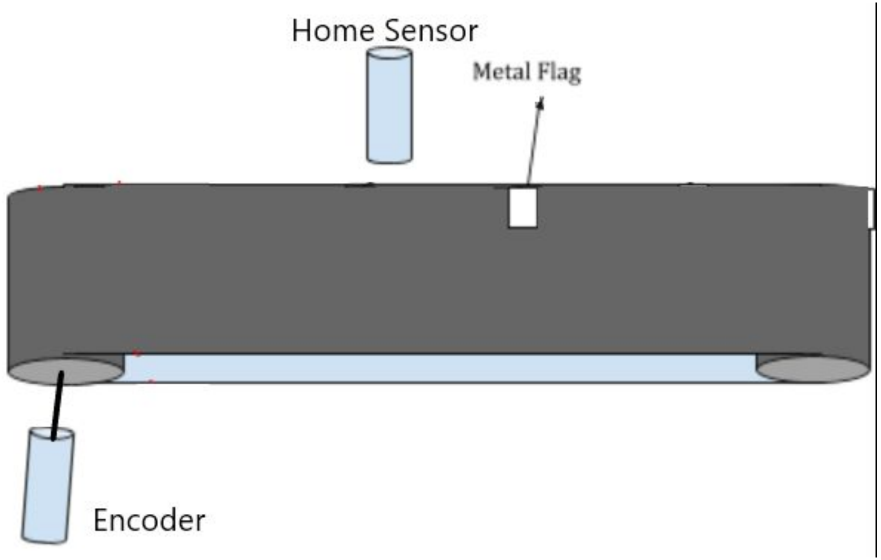

$$\text{revolutions} = \frac{1960}{1024} = 1.914$$

$$\text{revolution per minute (RPM)} = \frac{1.91}{10} \times 60 = 11.5$$

$$\text{roller circumference C} = 2\pi r = 2\pi \times 5 = 10\pi$$

$$\text{Linear displacement} = 1.91 \times 10\,\pi \approx 60\,inch$$

$$Belt\ Speed\ \frac{60\,inch}{10} \approx 6\,ips = 30\,fpm$$

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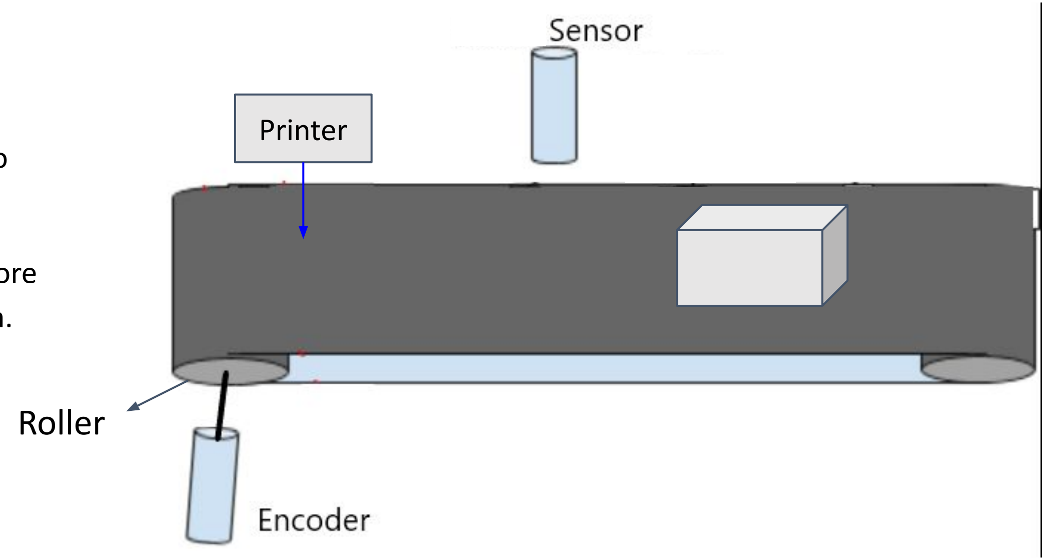
Example

A conveyor is used in packaging machine. There is a printer to print the expiry date on the package.

The tolerance for expiry date misplacement is ±1 mm, therefore the accepted tolerance for encoder measurement is ±0.1 mm.

The conveyor roller diameter is 15 cm. what should be the resolution of the encoder?



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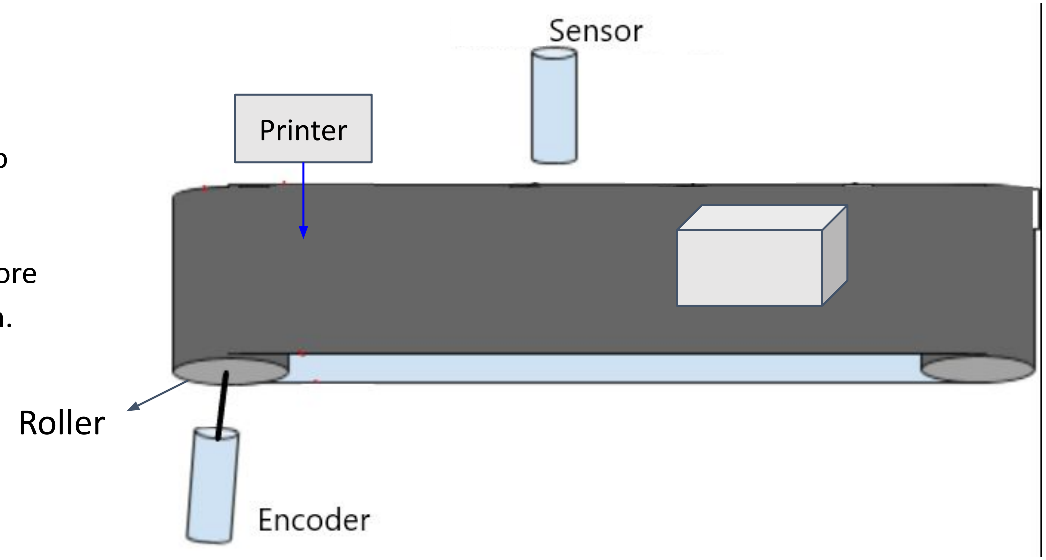

$$Encoder\,error = \pm 1\,\text{count}$$

$$Encoder\,error = \pm 1\,\text{count} \times 0.1\,mm = \pm 0.1\,mm$$

$$\text{roller circumference C}=2\pi r = 2\pi \times 150 = 300\pi\,mm$$

$$\frac{300\,\pi}{0.1} = 9424\,PPR \implies \text{encoder resolution 10000}$$

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Accelerometers & Inertial Navigation

Geometrically

$$a = \frac{d^2x}{dt^2}$$

$$v = \frac{dx}{dt}$$

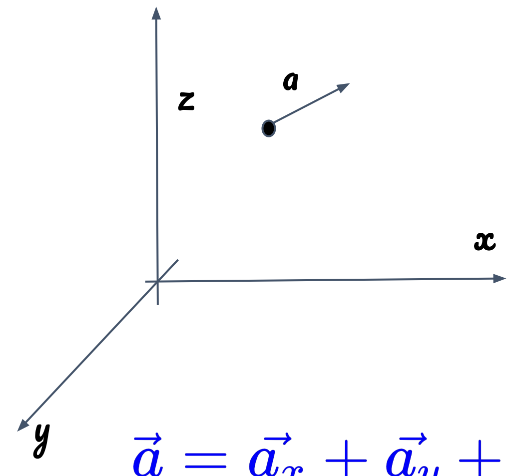
x displacement

Dynamically

$F = ma$ F $\leftarrow Force$ $m \leftarrow mass$

$$\Rightarrow v = \int_0^t \frac{d^2x}{dt^2}\,dt = \int_0^t \frac{F}{m}\,dt$$

$$\Rightarrow x = \int_0^t \left(\int_0^t \frac{d^2x}{dt^2}\,dt^2\right)dt = \int_0^t \left(\int_0^t \frac{F}{m}\,dt\right)dt$$



$$\vec{a} = \vec{a_x} + \vec{a_y} + \vec{a_z}$$

Three accelerometers along three axis can provide the acc of the object.

By Having the ACC the speed and displacement of the object can be calculated without contacting anywhere else, this is inertial navigation.

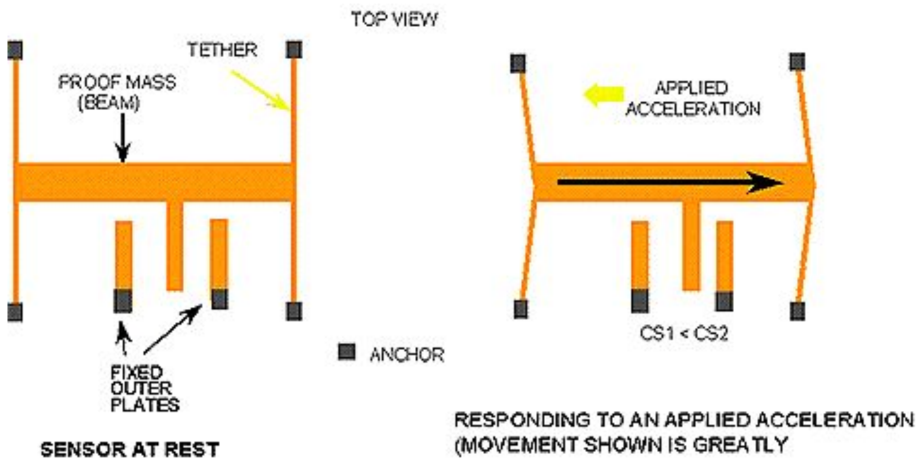
Accelerometers

The ADXL accelerometer

www.analog.com

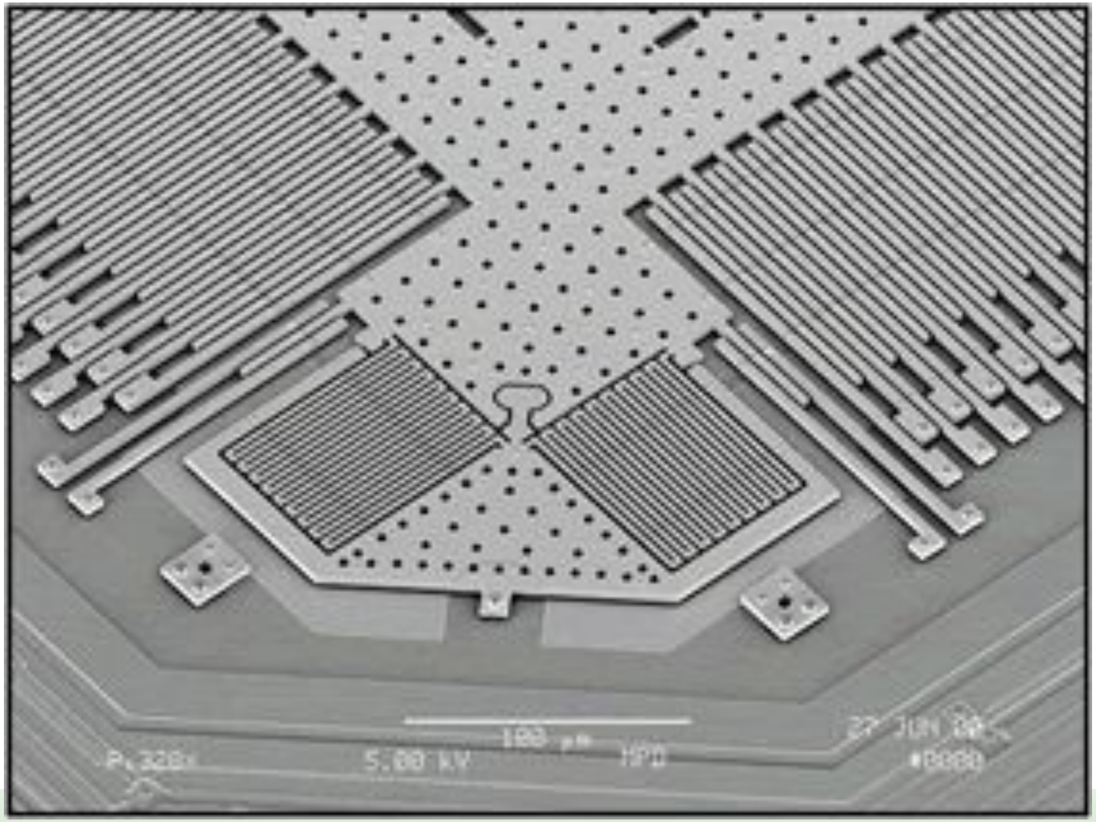
S. D. Senturia: Microsystem Design, page497-525 describes accelerometers and the ADXL

[ADXL in Analog Devices]



Micro Electro Mechanical Systems (MEMS) Fabrication

Two dimensional ADXL under microscope



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IMSAS, Prof. Walter Lang

Cell Phone Sensors