University of Pisa
Master of Science in Computer Science
**Course of Robotics (ROB)**
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# Robot Sensors

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http://didawiki.cli.di.unipi.it/doku.php/magistraleinformatica/rob/start

# Robot definition

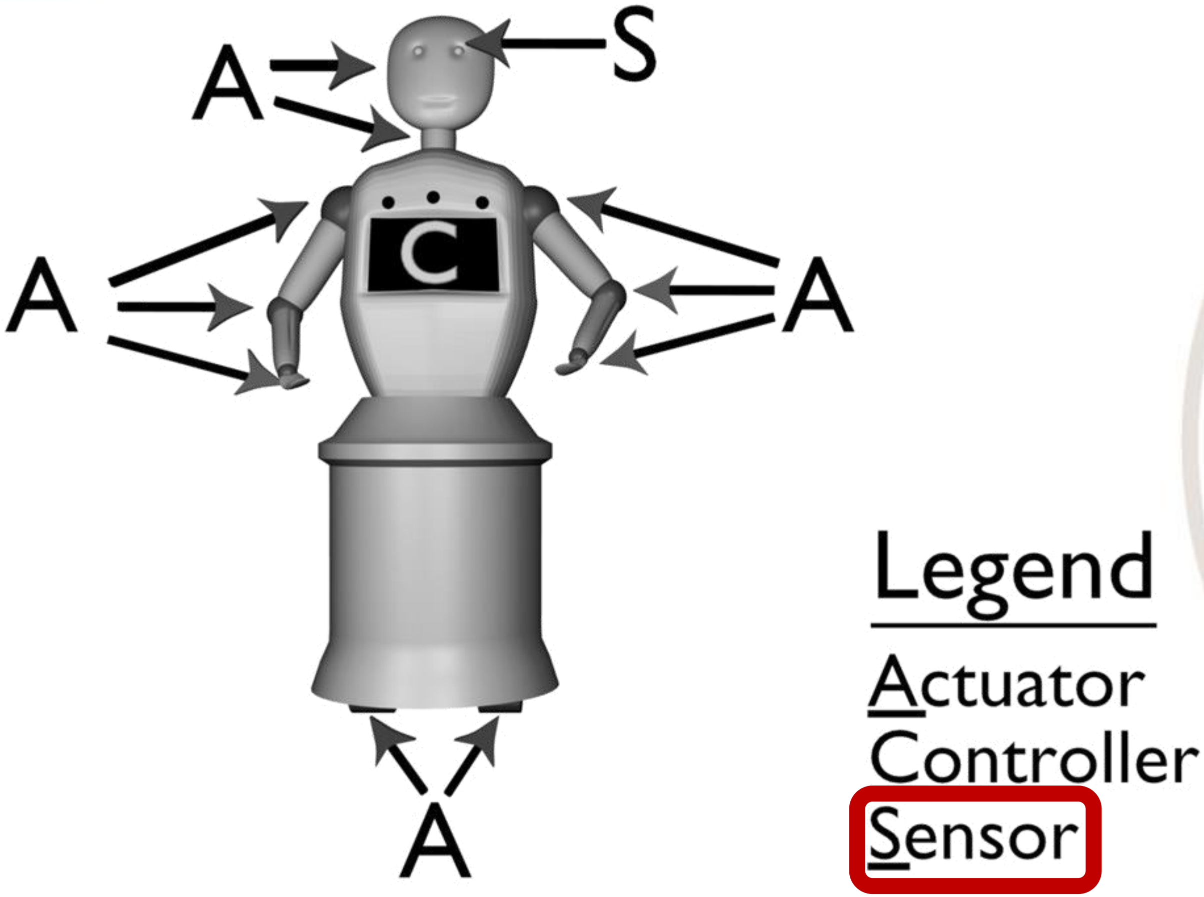
THE BIOROBOTICS INSTITUTE

Scuola Superiore Sant'Anna

A *robot* is an autonomous system
which exists in the physical world,
can sense its environment,
and can act on it to achieve some goals

Maja J Mataric, *The Robotics Primer*, The MIT Press, 2007

# What’s in a robot?
# Robot components




Maja J Mataric, *The Robotics Primer*, The MIT Press, 2007

# Outline of the lesson

- Definitions of sensor and transducer and sensor properties
- Position sensors: switches, encoders, potentiometers, Hall-effect sensors
- Range/Distance sensors: triangulation, ultrasound sensors and laser range finders
- Proximity sensors: Hall-effect and infrared sensors
- Force sensors: strain gauges and force/torque sensors
- Inertial sensors

Bibliographical references:
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# Definitions of sensor and transducer

- TRANSDUCER:

  device transforming a kind of energy in energy of a different kind

  For ex.: pressure-voltage, force-displacement, current-voltage, velocity-voltage

  It can work both as sensor and as actuator

- SENSOR:

  device sensitive to a physical quantity and able to transform it in a measurable and transferable signal (usually, electrical), by using a transducer.

# Fundamental properties of a sensor

- TRANSFER FUNCTION
- CALIBRATION
- LINEARITY
- HYSTERESIS
- ACCURACY
- REPEATABILITY
- RESOLUTION
- SENSITIVENESS
- SENSITIVENESS TO NOISE
- LIFETIME
- STABILITY

# Transfer function

The *transfer function* (or *characteristic function*) is the relation between the quantity to measure (input to the sensor) and the output of the sensor

# Calibration

The *calibration* procedure consists of measuring the output of the sensor for known quantities

*Calibration cycle* means a trial that covers the whole working range of the sensor; the trial is divided in two parts, one with increasing values and the other with decreasing values

# Linearity

If the transfer function of a sensor is represented in a linear plot, *linearity* is a measure of the deviation of the transfer function from a line.

The line can be chosen in two ways:

1) the line between the output of the sensor for the input values corresponding to 0% and 100% of its working range
2) the line that best fits the sensor transfer function, with the minimum squares method

   *Linearity* is measured as the maximum difference, expressed in % of the maximum value of the transfer function, between the transfer function and the reference line

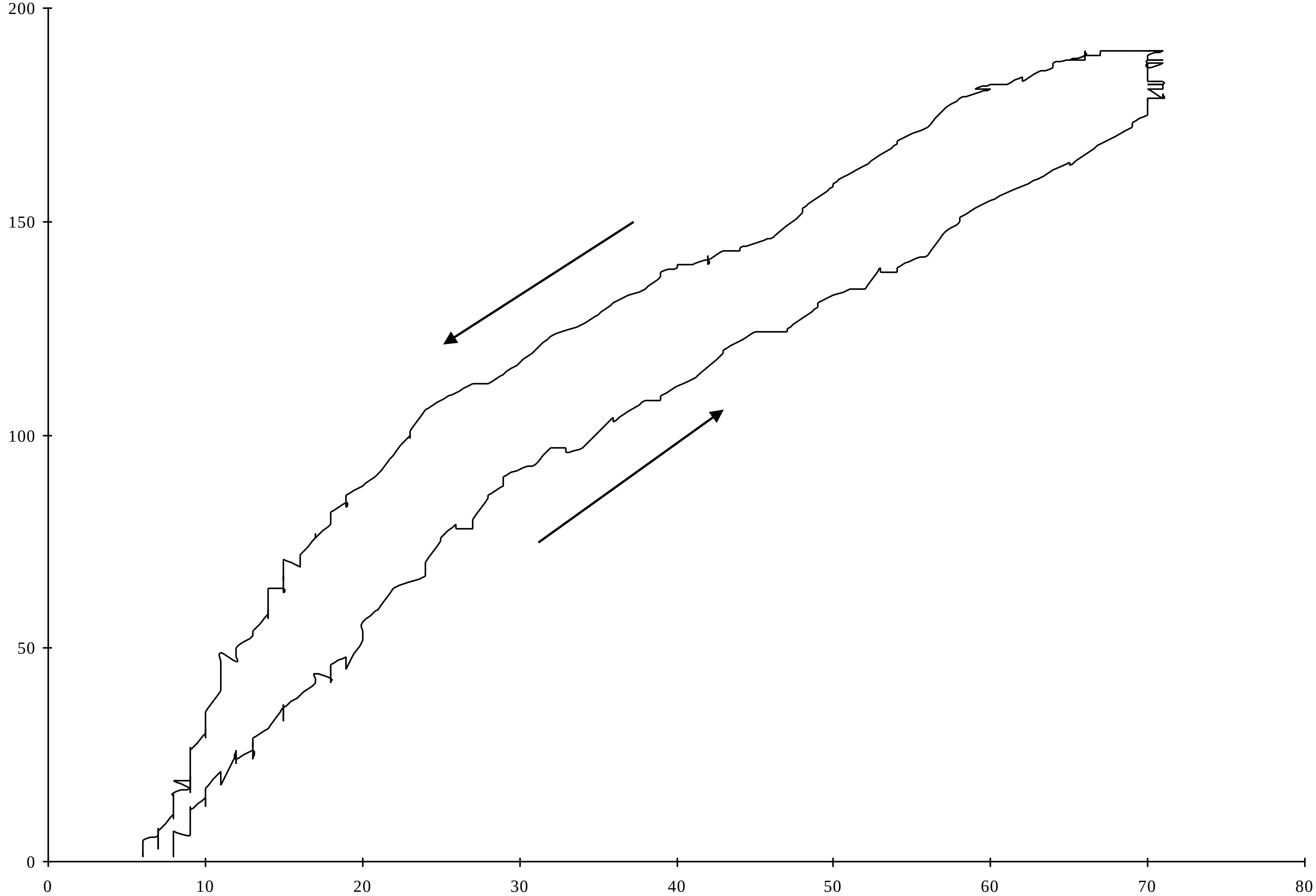
# Hysteresis

If a sensor has *hysteresis*, for a same input value, the output may vary, depending on the fact that the input values are increasing or decreasing.

*Hysteresis* is measured as the maximum difference between the two output curves of the sensor during the calibration cycle.

It is expressed as a % of the maximum value for the transfer function

# Example of hysteresis



# Accuracy

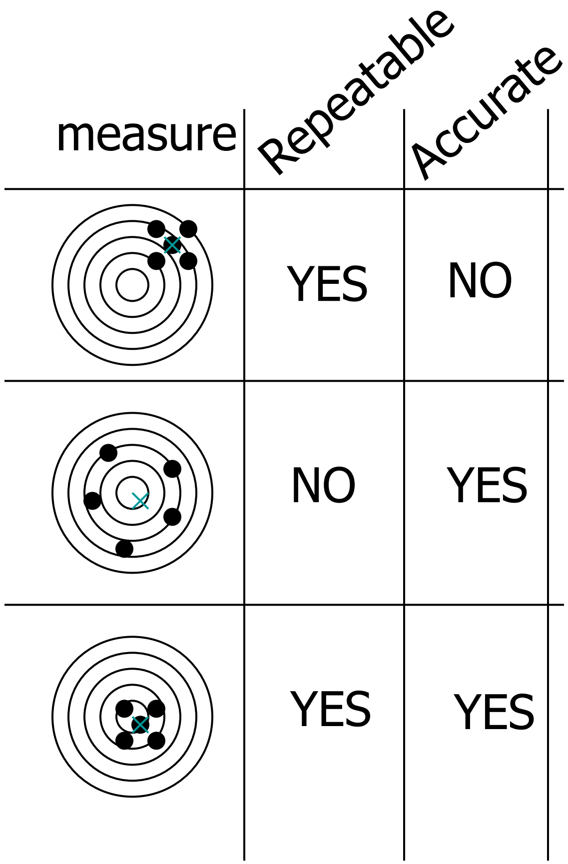
*Accuracy* represents the maximum error between the actual value and the value measured by the sensor.

# Repeatability

When a same input value is applies to a sensor, *repeatability* is a measure of the variability of the output of the sensor.

# Accuracy and Repeatability

- accuracy
  - $100\,(x_m - x_v) / x_v$
  - $x_m$ = average value
  - $x_v$ = actual value
- repeatability
  - dispersion of measures



# Resolution

*Resolution* is the mimimum variation of the input which gives a variation of the output of the sensor.

# Sensitiveness

A small variation of the input causes a corresponding small variation of the output values.

*Sensitiveness* is the ratio between the output variation and the input variation.

# Noise

*Noise* is the amount of signal in the sensor output which is not given by the input.

# Stability

*Stability* is the capability of the sensor to keep its working characteristics for a given time (short, medium, long).

# Role of sensors in a robot

- Perception of the <u>**external state**</u>: measurement of variables characterizing the working environment.

  Ex.: distance, proximity, force.

# Role of sensors in a robot

- Perception of the **internal state**: measurement of variables internal to the system that are used to control the robot.

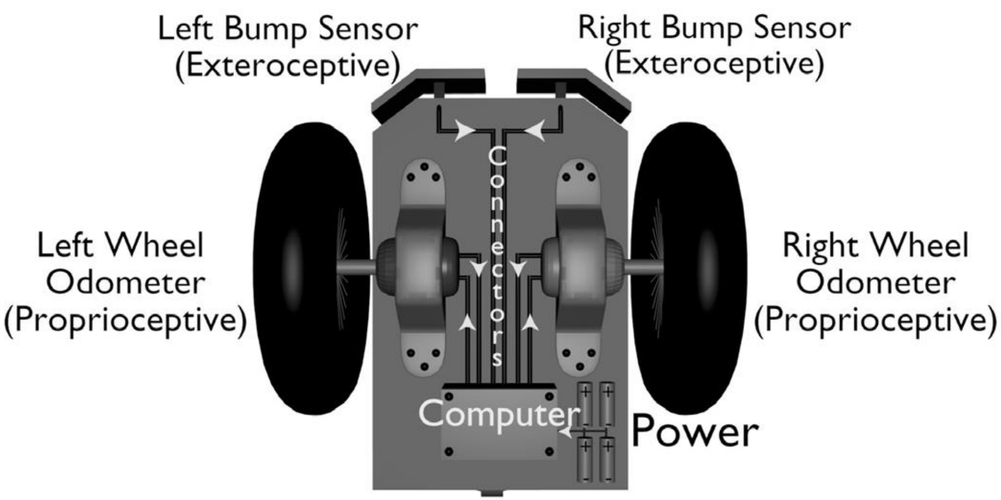
  Ex.: joint position.

# Role of sensors in a robot

- Sensing the **external state (exteroception)**: measurement of variables characterizing the working environment.
- Examples:

| Physical Property | → | Sensing Technology |
|---|---|---|
| Contact | → | bump, switch |
| Distance | → | ultrasound, radar, infra red |
| Light level | → | photocells, cameras |
| Sound level | → | microphones |
| Strain | → | strain gauges |
| Rotation | → | encoders and potentiometers |
| Acceleration | → | accelerometers and gyroscopes |
| Magnetism | → | compasses |
| Smell | → | chemical sensors |
| Temperature | → | thermal, infra red |
| Inclination | → | inclinometers, gyroscopes |
| Pressure | → | pressure gauges |
| Altitude | → | altimeters |

- Sensing the **internal state (proprioception)**: measurement of variables internal to the system that are used to control the robot.
- Examples:
  - Joint position / encoders
  - Battery level



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# Position sensors

- Switches
- Optical encoders
- Potentiometers
- Hall-effect sensors

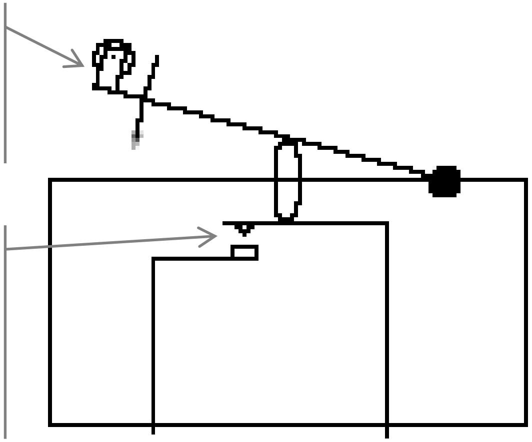
# Mechanical switches

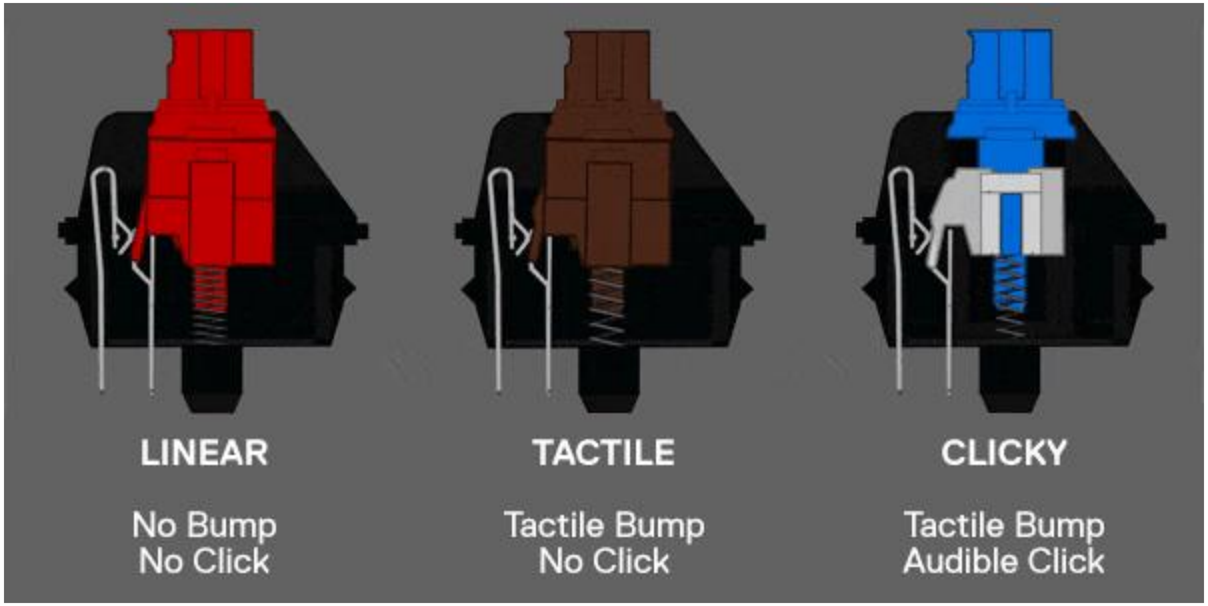
- Simplest contact sensors
- Provide binary data:
  contact / NO contact

ELECTRICAL CIRCUIT

LEVER PRESSED AT CONTACT

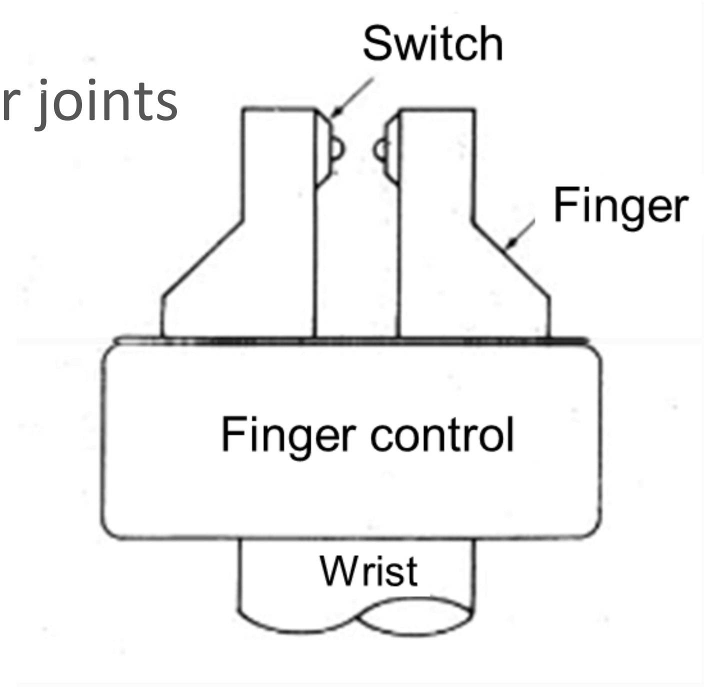
MECHANICAL CONTACT CLOSING AN ELECTRIC CIRCUIT





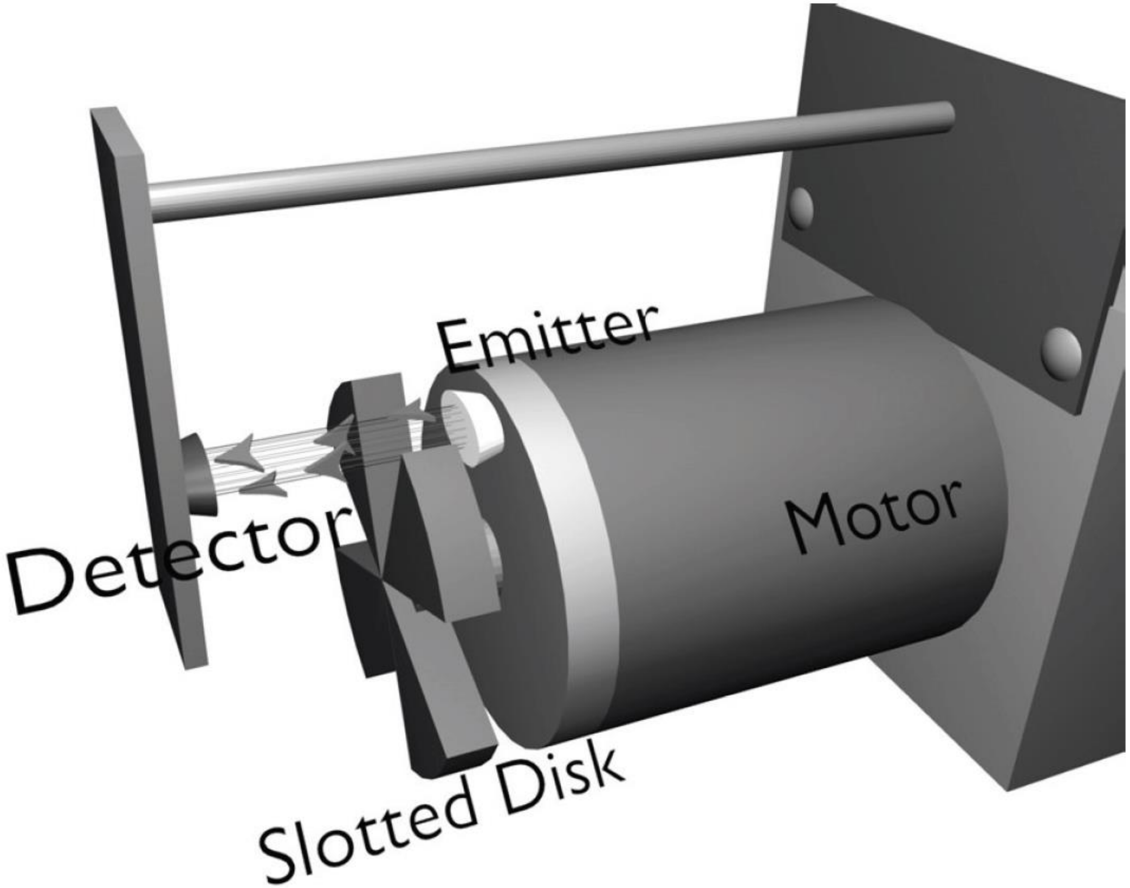
# Mechanical switches

- Applications in robotics:
  - impact sensors on mobile robots
  - contact sensors for grippers
  - endstop sensors for manipulator joints

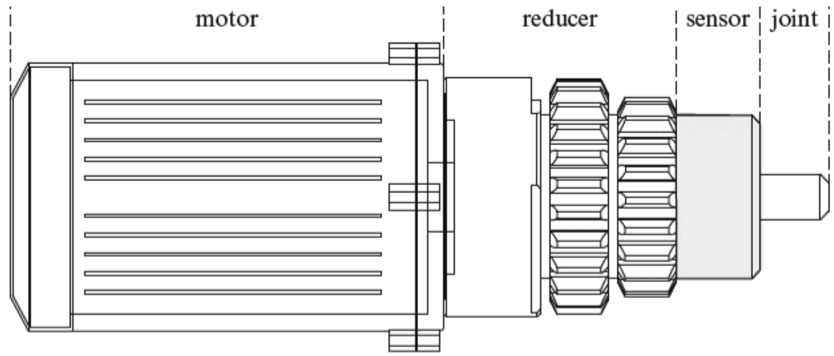


# Optical encoders

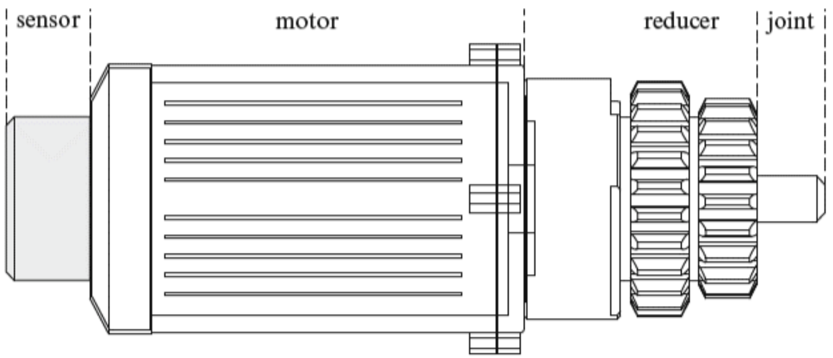
Measurement of angular rotation of a shaft or an axle



# Placement of position sensors




After motor+reducer




Before motor+reducer

θ: joint angular position

$\theta_m$: motor angular position

k: motor reduction ratio

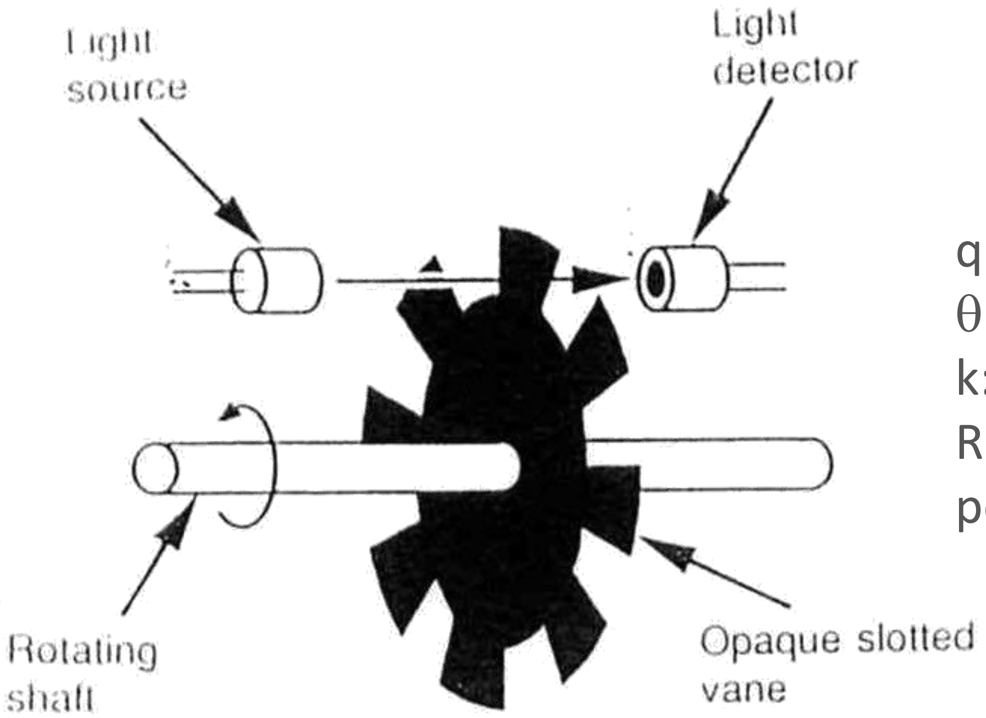
$$\theta = \frac{\theta_m}{k}$$

$$\frac{d\theta}{d\theta_m} = \frac{1}{k} \Rightarrow d\theta = \frac{1}{k} d\theta_m$$

=> The sensor error is reduced of a factor k

# Optical encoders

**Rotation** is measured by counting the **pulses** and by knowing the number of the disk **steps**



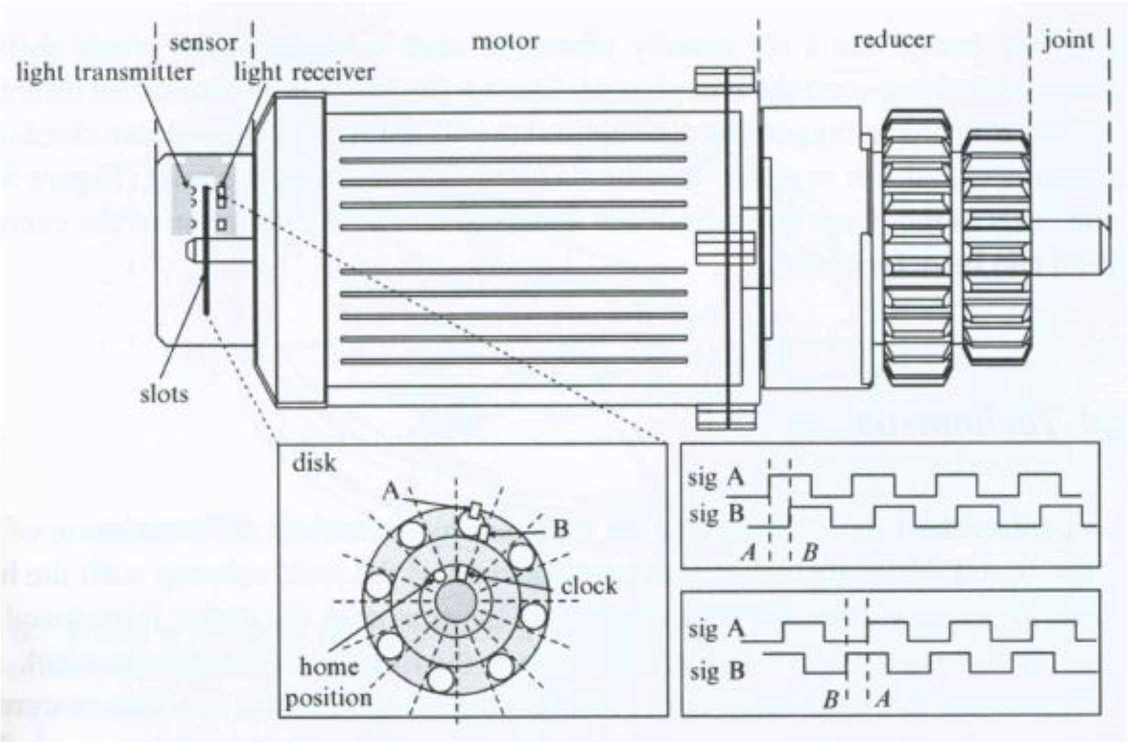

$$q = \frac{\theta \times 360°}{R \times k}$$

q: joint angular position (in degrees)
θ: joint position in encoder steps
k: motor reduction ratio
R: encoder resolution (number of steps per turn)

The **frequency** of the pulse train is proportional to **angular velocity**

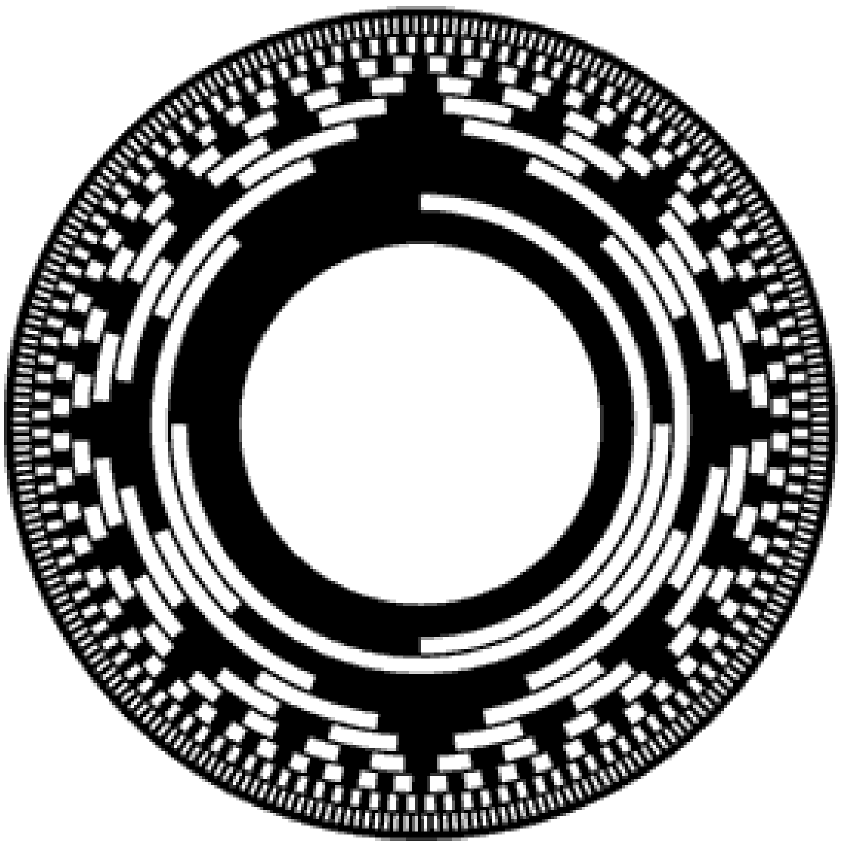
# Incremental encoders

By using 2 photo-switches it is possible to detect the rotation direction, by means of the relation between the phases of their pulse trains




A and B are out of phase of ¼ of cycle
An increase of A with B=0 corresponds to a clockwise rotation
An increase of A with B=1 corresponds to a counterclockwise rotation

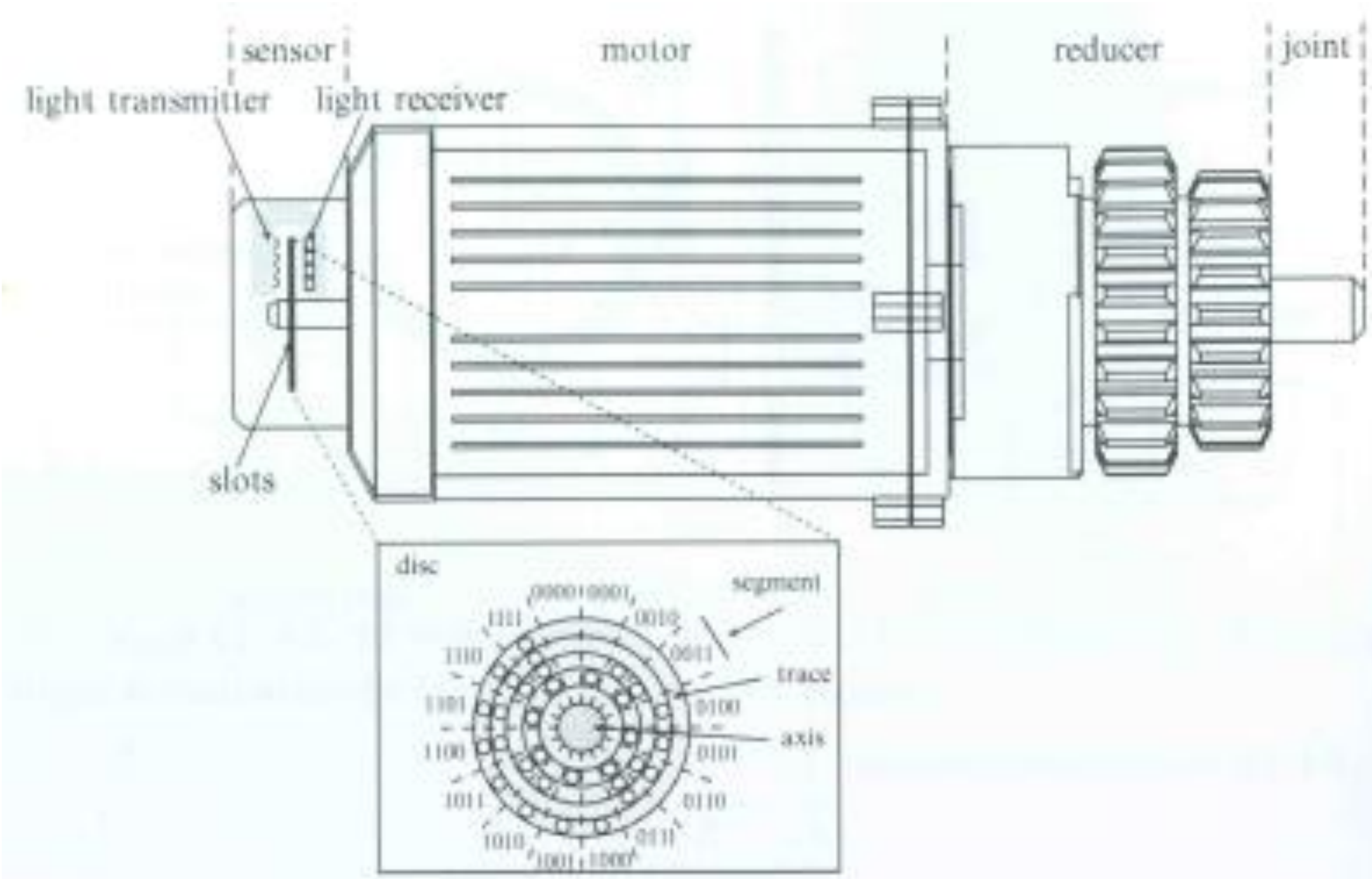
# Absolute encoder



k photo-switches
k code tracks
Binary word of k bits, representing $2^k$ different disk orientations
Angular resolution of $360^\circ/2^k$

- It gives the absolute rotation angle
- Each position is uniquely determined

# Absolute encoder



# Absolute encoder

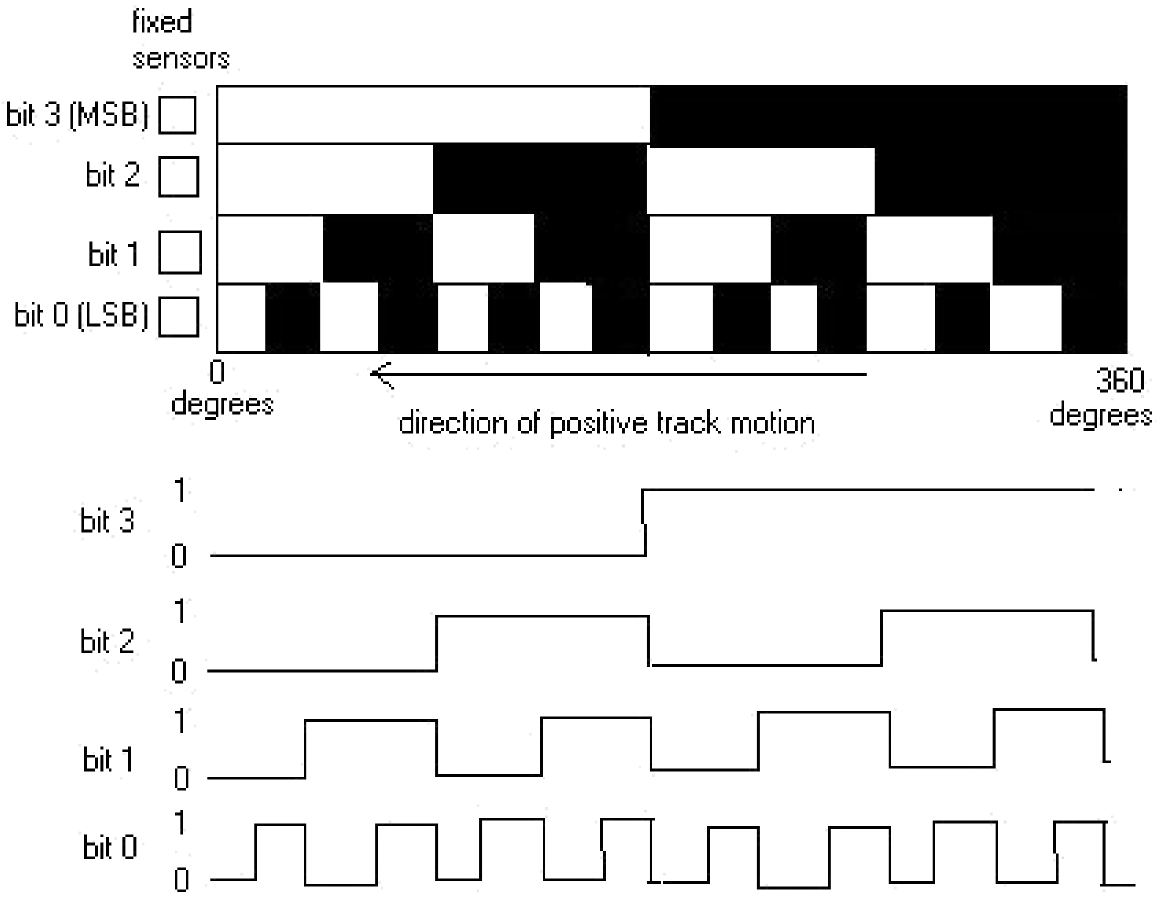



Fig 3 4-Bit binary code absolute encoder disk track patterns

# Absolute encoder - Gray Code

Single transition

| Decimal | Binary | 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 |

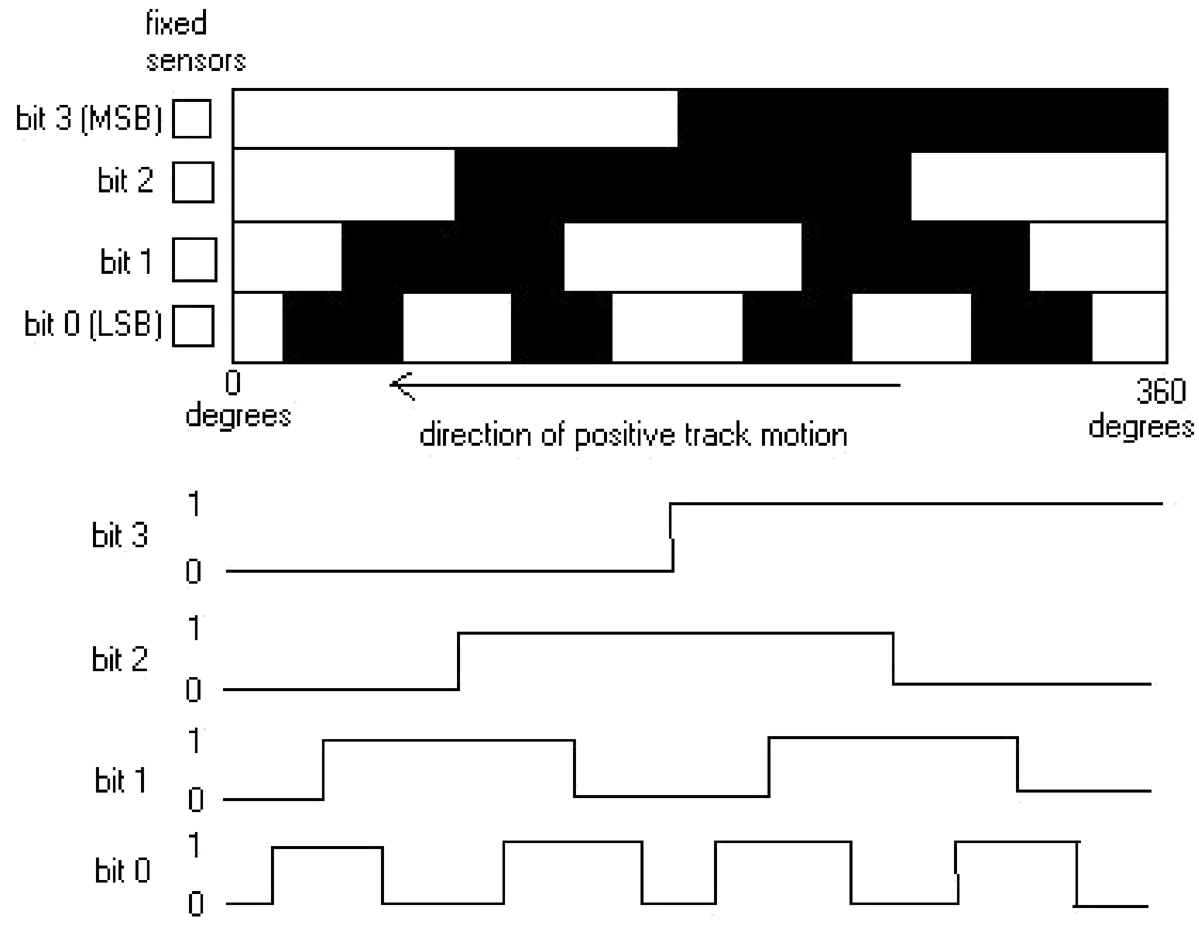
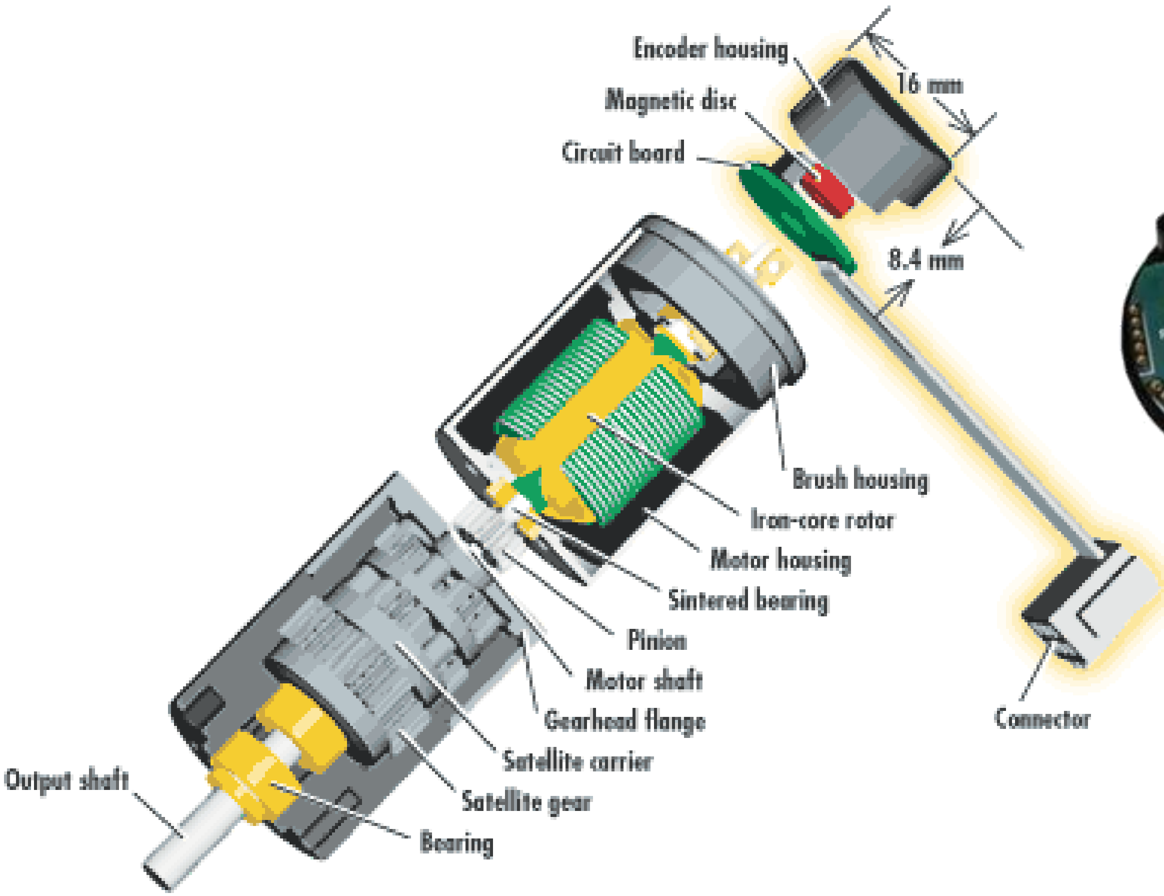
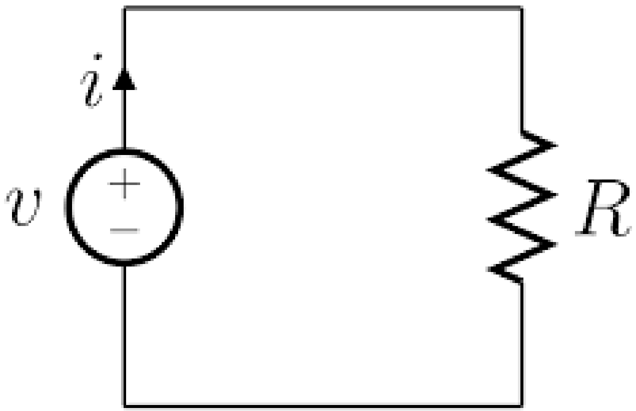



Fig 2. 4-Bit gray code absolute encoder disk track patterns

# Optical encoder in an electric motor




# Ohm's law



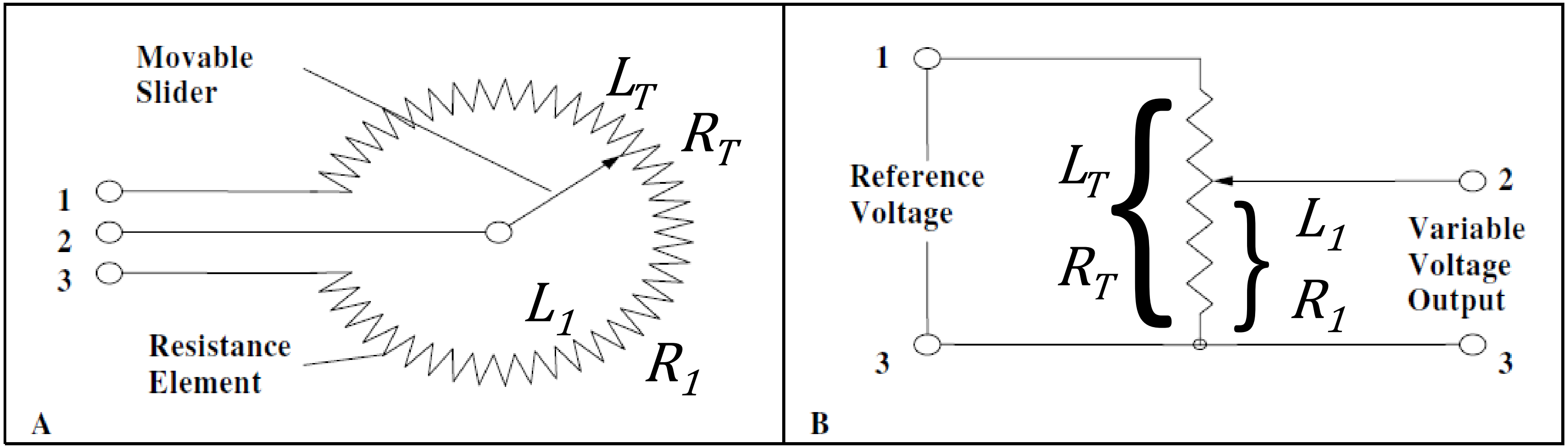

$$v = Ri$$

- $v$: voltage (Volts – V)
- $R$: resistance (Ohms – Ω)
- $i$: current (Amperes – A)

https://www.youtube.com/watch?v=_rSHqvjDksg

# Potentiometers

## Variable resistor




$$\frac{L_1}{R_1} = \frac{L_T}{R_T}$$

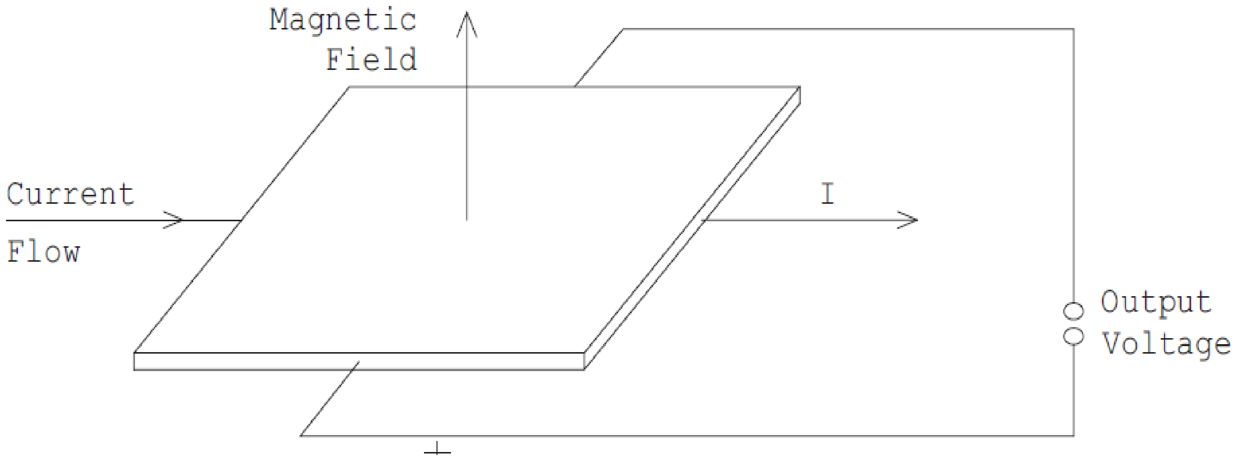
$$\left.\begin{aligned} v_{ref} &= R_T i \\ v_{out} &= R_1 i \end{aligned}\right\} \text{Ohm's law}$$

$$L_1 = L_T \frac{R_1}{R_T} = L_T \frac{v_{out}}{v_{ref}}$$

$v_{out}$ measured between endpoints 2 and 3

# Hall-effect sensors

In a conductor where a current I flows, immersed in a magnetic field of intensity B, a voltage V originates in the direction normal both to the current and to the magnetic field.




$$V_h = \frac{R_h I B}{t}$$

$V_h$ = Hall voltage,
$R_h$ = material-dependent Hall coefficient,
$I$ = current in amps,
$B$ = magnetic flux density (perpendicular to $I$) in Gauss,
$t$ = element thickness in centimeters.

Voltage V is proportional to:

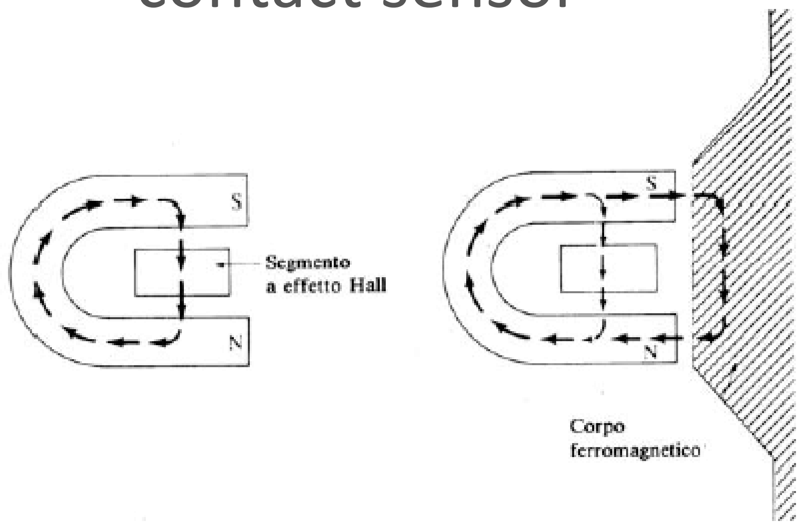
- intensity of the current I
- intensity of the magnetic field B,

while it is inversely proportional to:

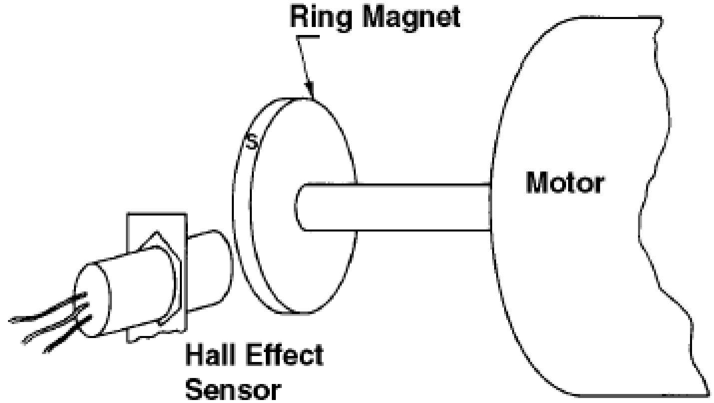
- material thickness t

# Hall-effect sensors

Hall-effect proximity and contact sensor




Hall-effect position sensor

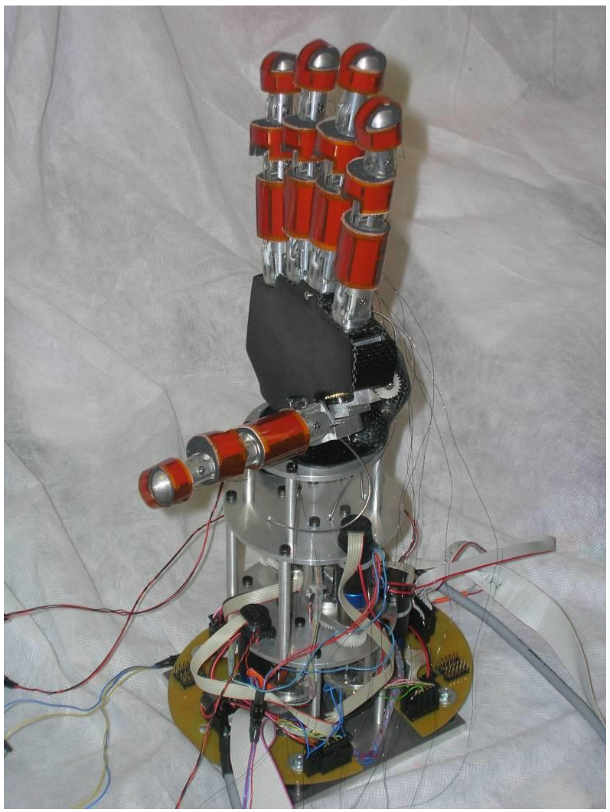


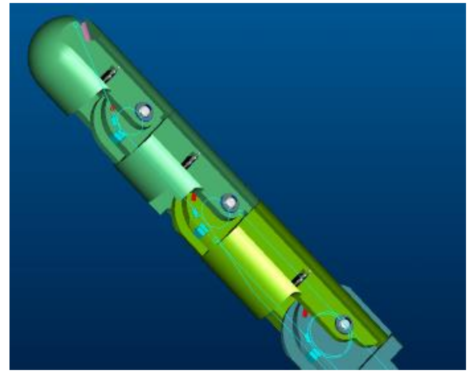

A permanent magnet generates a magnetic field.
The contact with a ferromagnetic object modifies the magnetic field.
The Hall effect measures this variation as a voltage

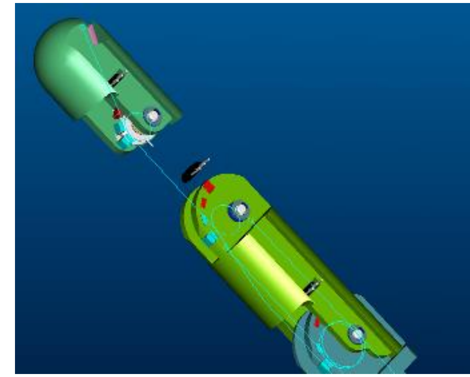
# Hall-effect sensors as position sensors in robotics

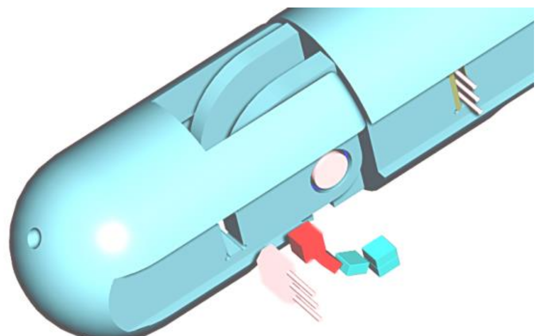
**15 Embedded Joint Angle Sensors (Hall effect)**

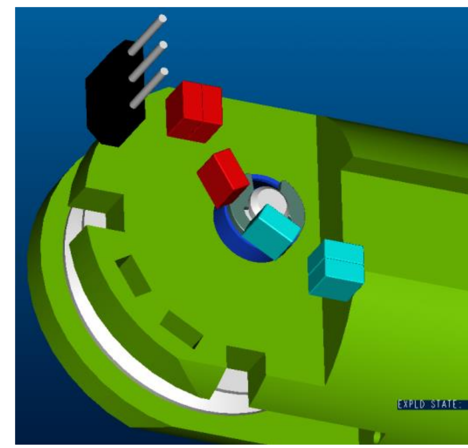
(Operational range: 0 – 90 degrees, Resolution: <5 degrees).

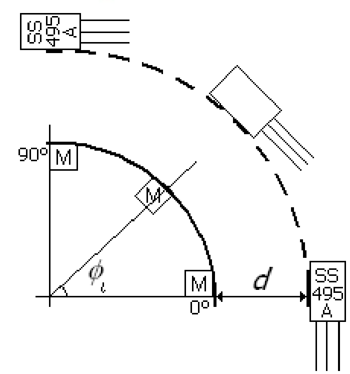












# HUMANGLOVE

## Studia la postura della mano

MOTION LINE

Patent IT/PI1997A000026

*Humanglove* è un guanto sensorizzato a 22 gradi di libertà in grado di rilevare in tempo reale i movimenti della mano durante qualsiasi attività. Può essere utilizzato per applicazioni in Medicina, Neuro-Riabilitazione, Telerobotica e Realtà Virtuale.

*HumanGlove* è compatibile con lo standard di trasmissione dati Bluetooth. In questo modo, dopo averlo indossato è possibile muoversi liberamente, anche in ambienti esterni.

Il guanto è realizzato in materiale elastico e può essere indossato da utenti con mani di taglia diversa. Grazie ad una rapida operazione di calibrazione è possibile adattare le letture dei sensori per un nuovo utente ed i parametri di calibrazione possono essere salvati e riutilizzati successivamente.

Il software mostra i dati in formato numerico, analogico e grafico.

Modulo sensore (brevettato)

### INDOSSABILITÀ

- Il dispositivo offre un elevato comfort grazie all'impiego di tessuti sintetici leggeri ed elastici e all'ingombro molto ridotto dei componenti.
- Il peso complessivo è ca. 290g
- Il sistema può anche lavorare in un ambiente non dedicato (ad es. all'aperto) perchè non necessita di collegamento via cavo.

*HumanGlove* fa uso di ventidue sensori:

- tre sensori di flessione-estensione ed un sensore di abduzione-adduzione per ciascun dito (pollice compreso)
- un sensore di flessione-estensione ed un sensore di abduzione-adduzione per il polso

L'utilizzo di sensori ad effetto Hall garantisce una risposta lineare ed un elevato grado di robustezza e affidabilità.

### CARATTERISTICHE DEL SISTEMA

- Accuratezza dei sensori: 0.1V / 2.5V
- Linearità dei sensori: < 2.0%
- Range dei sensori: > 110°
- Converter: 12 bit A/D
- Alimentazione: 4 batterie AAA
- Trasmissione dati: Bluetooth
- Freq. campionamento: max 100 Hz

La connessione Bluetooth concede all'utente ampia libertà di movimento. La connessione alla periferica avviene attraverso una porta seriale virtuale RS-232 su USB; in questo modo essa può essere collegata a qualsiasi tipo di workstation.

*Humanware* è una società costituita da specialisti in varie discipline, dall'ingegneria meccanica all'informatica ed è una *spin off* della Scuola Superiore Sant'Anna di Pisa.

Humanware

# Example of application of Hall-effect sensors

Sensorized glove for detecting finger movements

Modulo sensore (brevettato)

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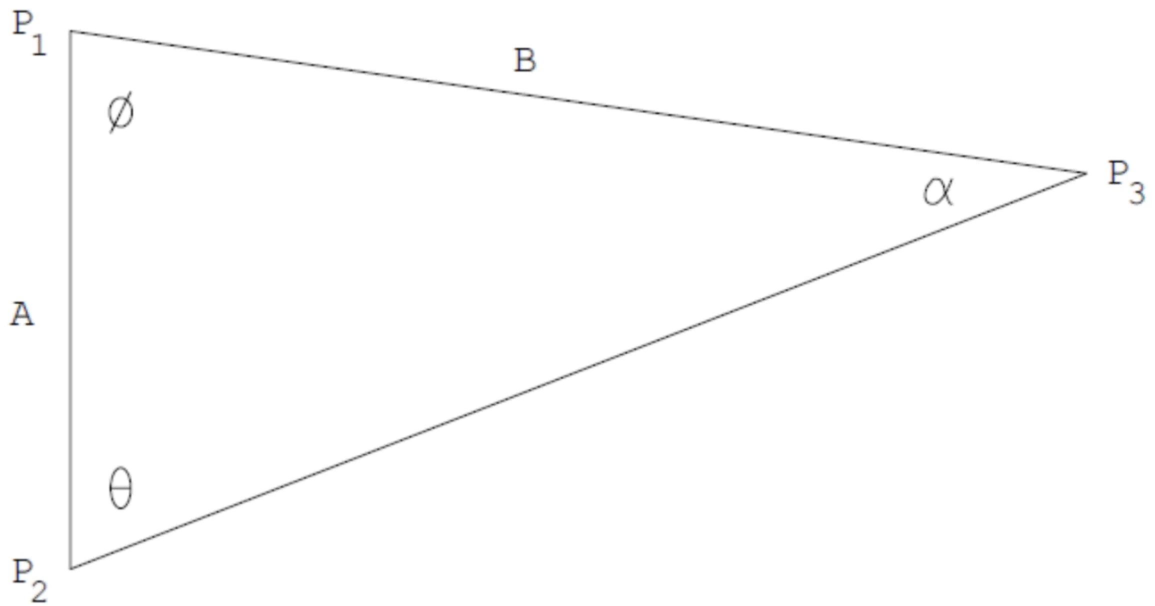
# Distance measurement: triangulation

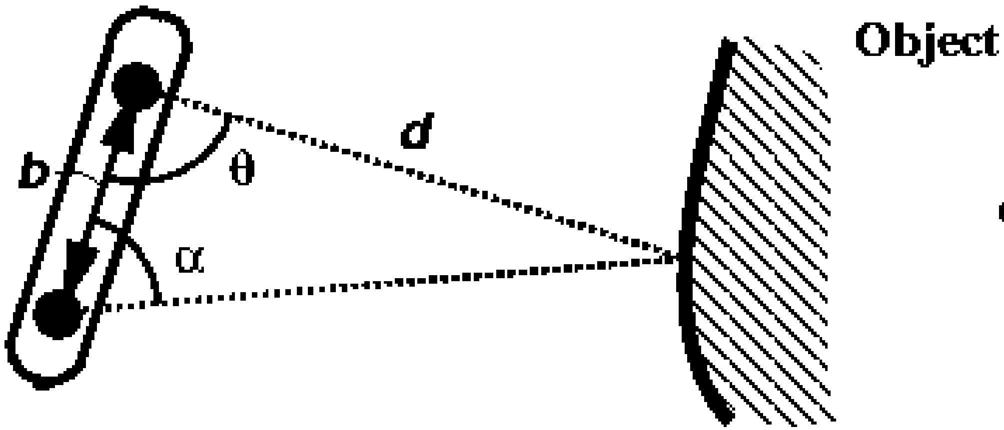
Law of Sines: given the length of a side and two angles of a triangle, it is possible to determine the length of the other sides and the remaining angle.

The basic Law of Sines can be rearranged to represent the length of side B as a function of side A and the angles θ and ϕ



# Range*/distance measurement by triangulation

If two imaging devices at a known distance (b) can focus on the same point of an object, then the range of the object (d) can be measured, by knowing the vergence angles θ and α.



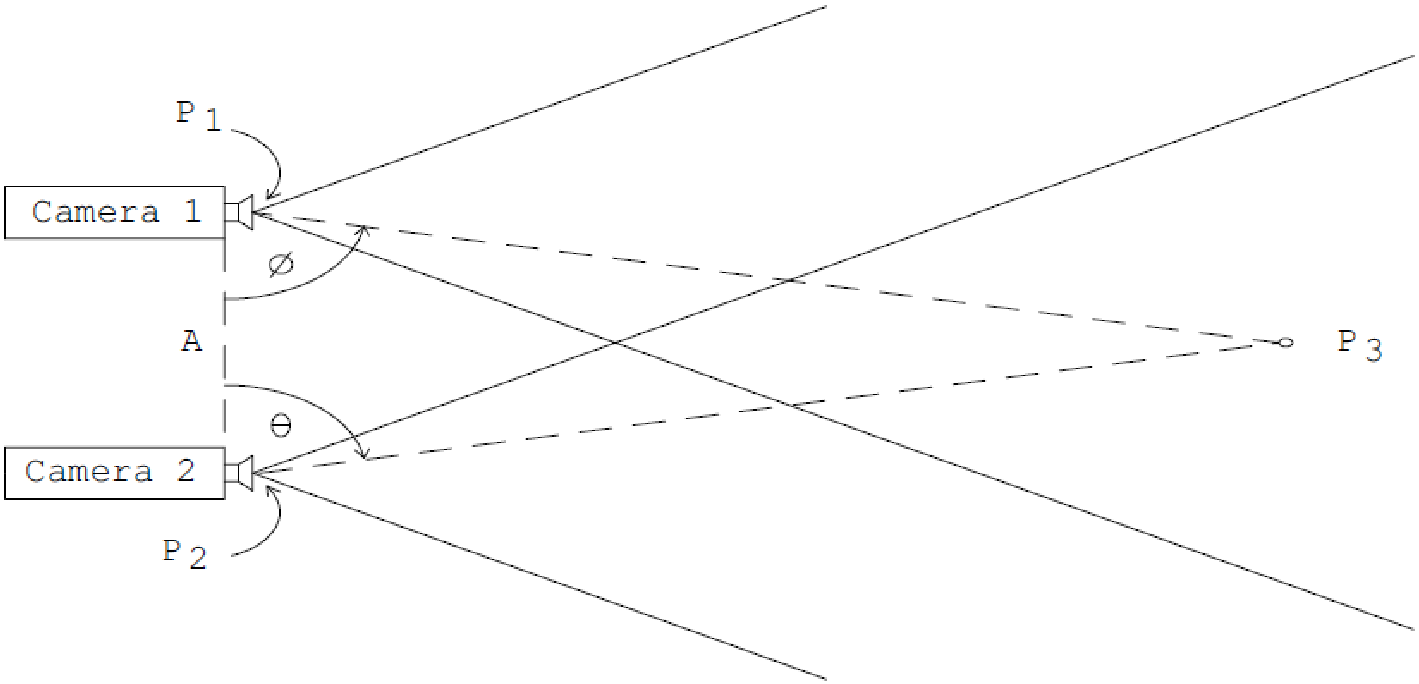

$$d = \frac{b \sin(\alpha)}{\sin(\theta + \alpha)}$$

PASSIVE TRIANGULATION: uses two imaging devices

ACTIVE TRIANGULATION : uses one imaging device and a controlled light source

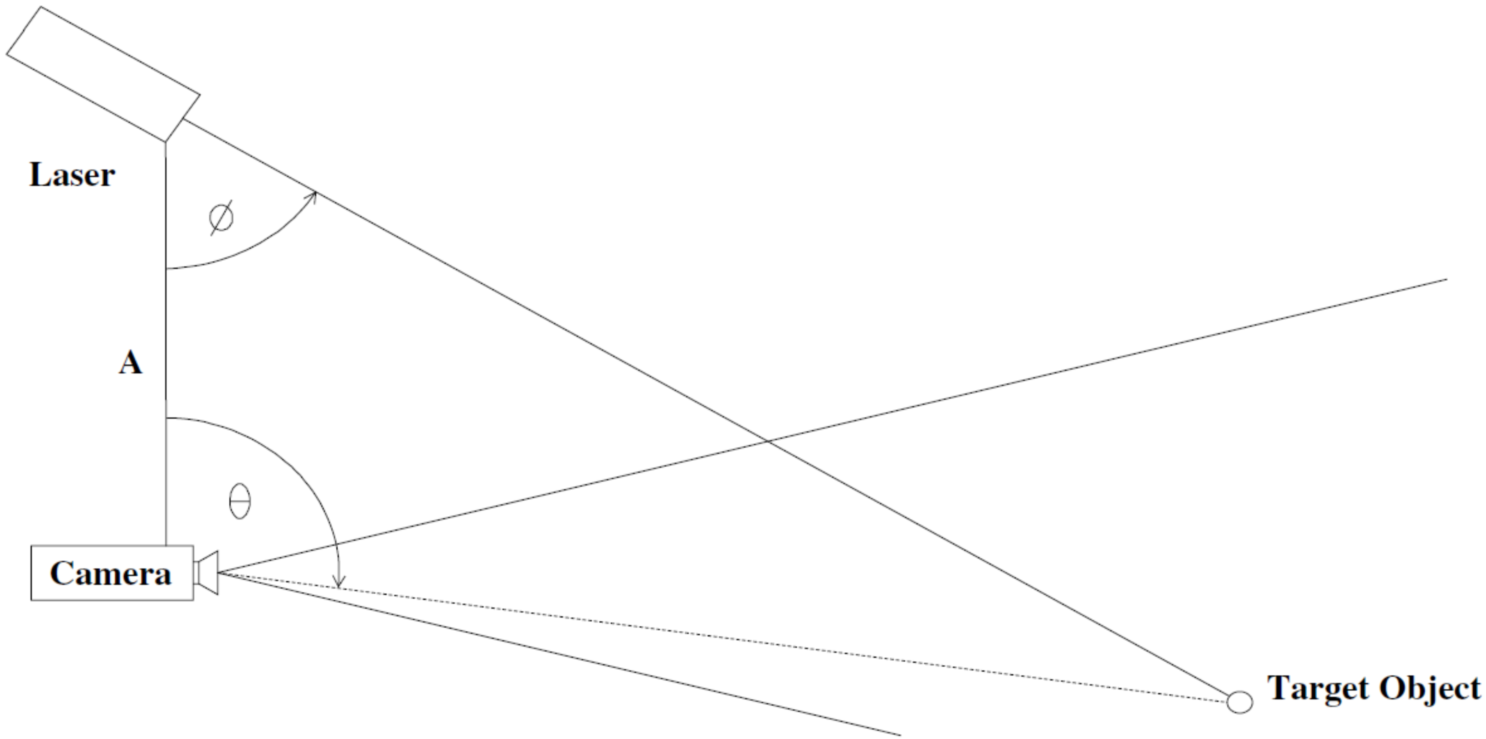
*Range: distance between sensor and object detected

# Passive triangulation




A: known sensor separation baseline

# Active triangulation



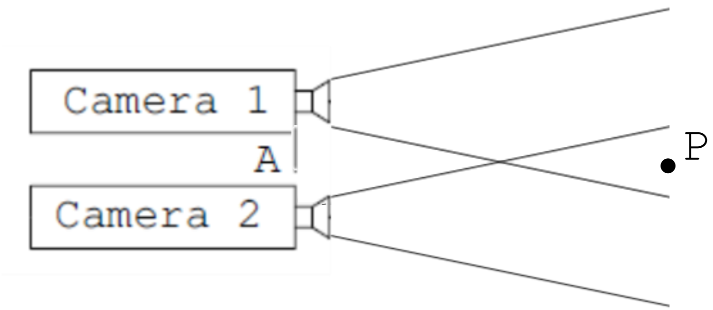

A: known sensor separation baseline

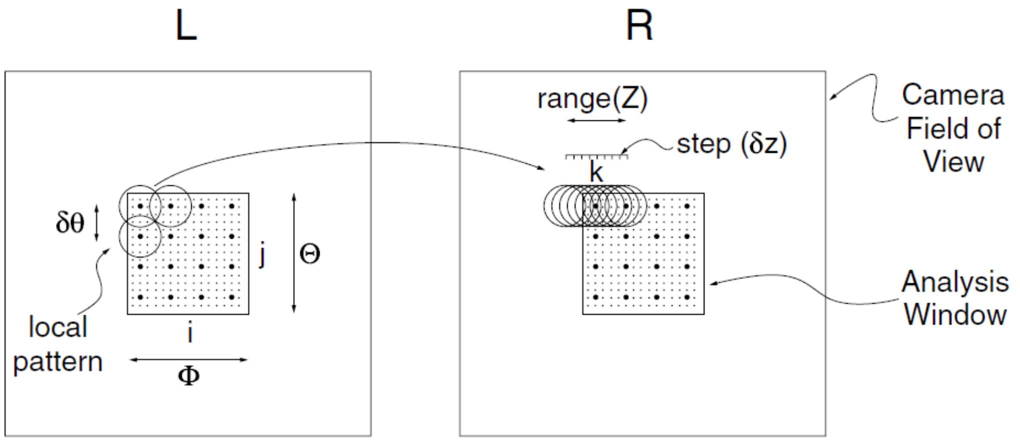
# Stereo vision / stereopsis

When a 3D object is viewed from two locations (on a plane normal to the direction of vision), the image as observed from one position is shifted laterally when viewed from the other.

- This displacement of the image, known as *disparity*, is inversely proportional to the distance to the object.
- The effort to match the two images of the point is called *correspondence*

$$Z = \frac{Af}{P_R - P_L}$$

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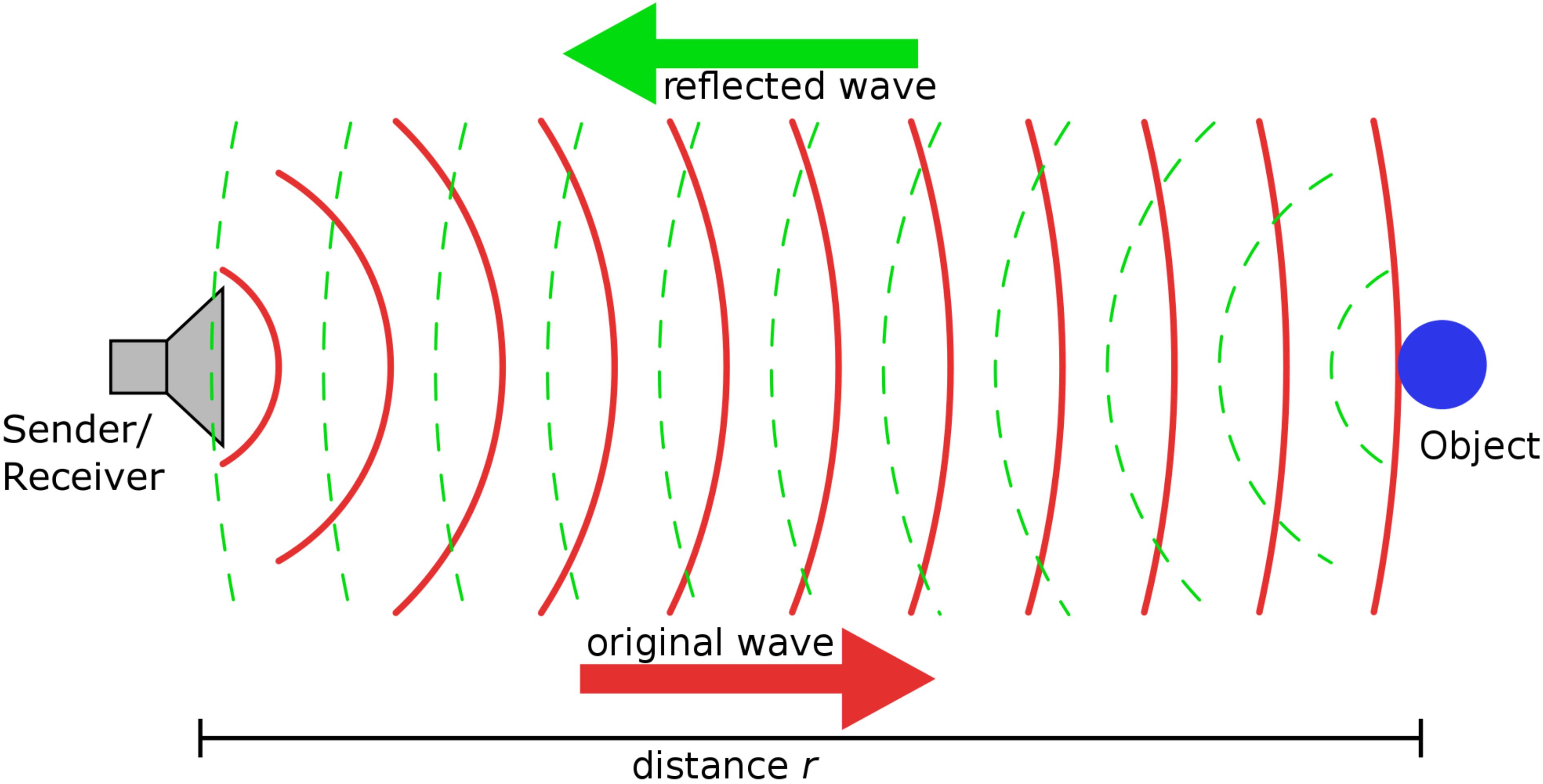
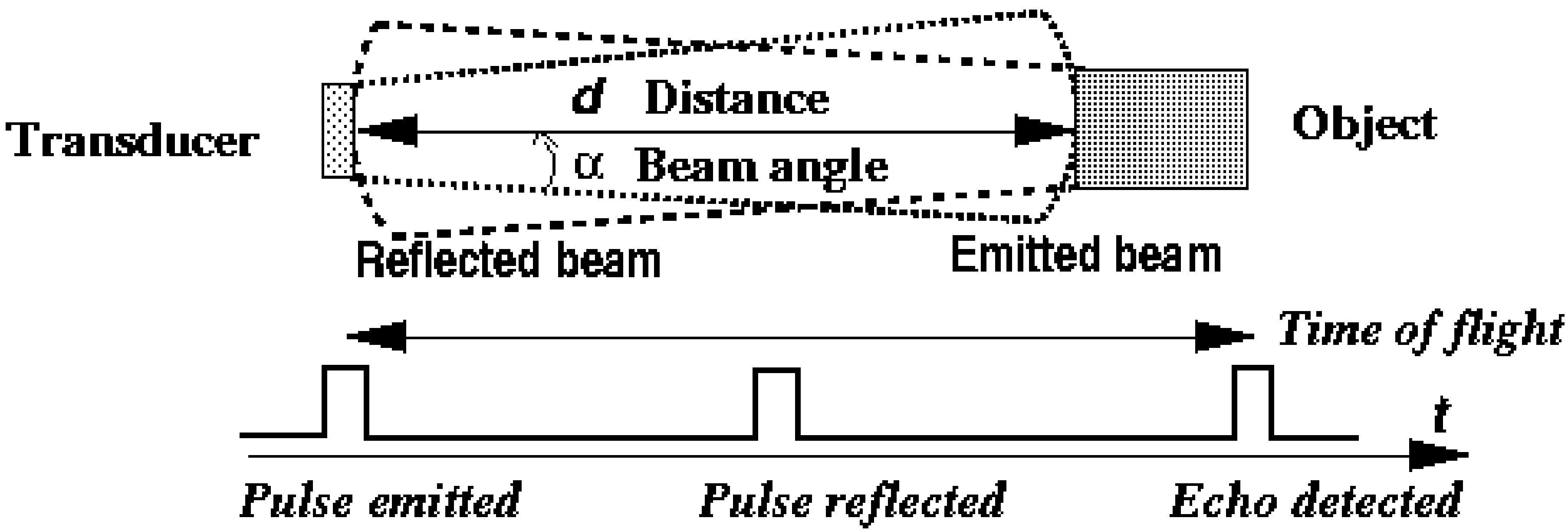
# Time-of-flight distance measurement



# Time-of-flight distance measurement

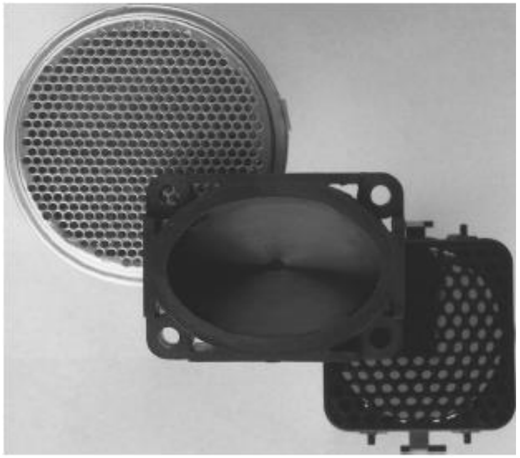
$$d = \frac{t_e v}{2}$$

$v$: average speed of the signals emitted
$t_e$: time between the signal emitted and the signal echo received

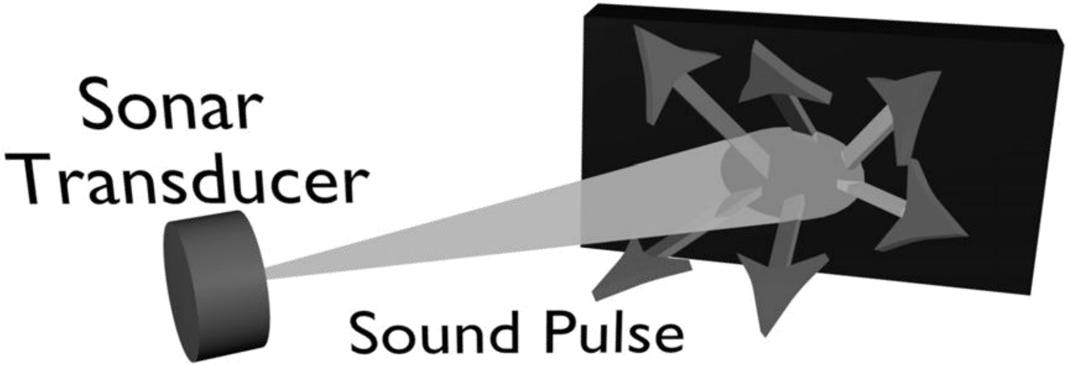


# Ultrasound sensors

Measurement of **range** based on **time of flight**



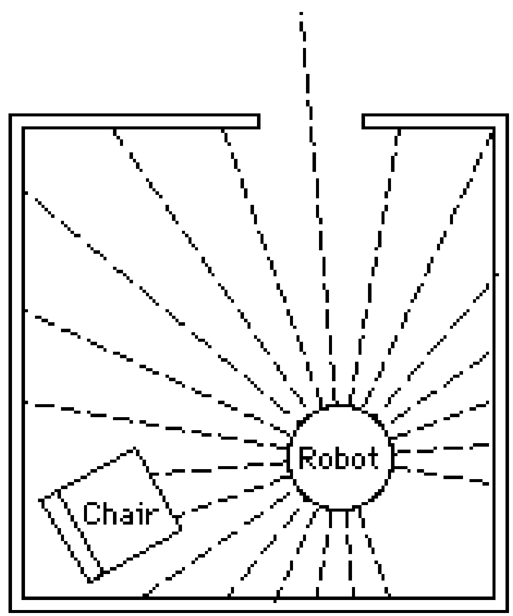
Range: 0.3m to 10.5m
Beam amplitude: 30°
Accuracy: ca. 25mm

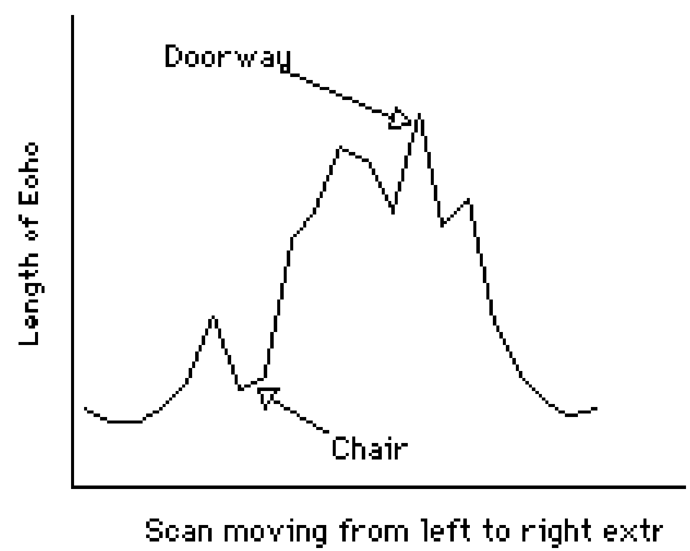



$$d = \frac{t_e v}{2}$$

$v$: sound speed

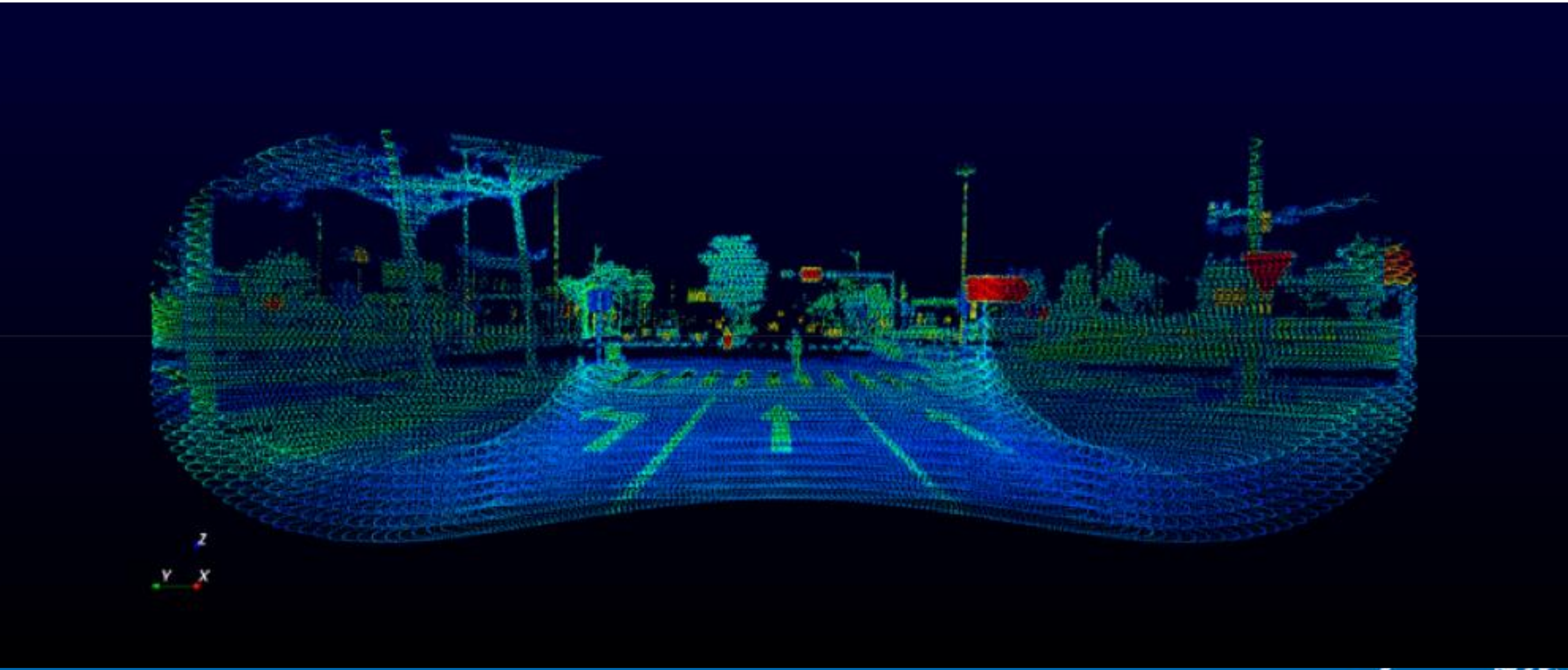
# Examples of application of ultrasound sensors on mobile robots



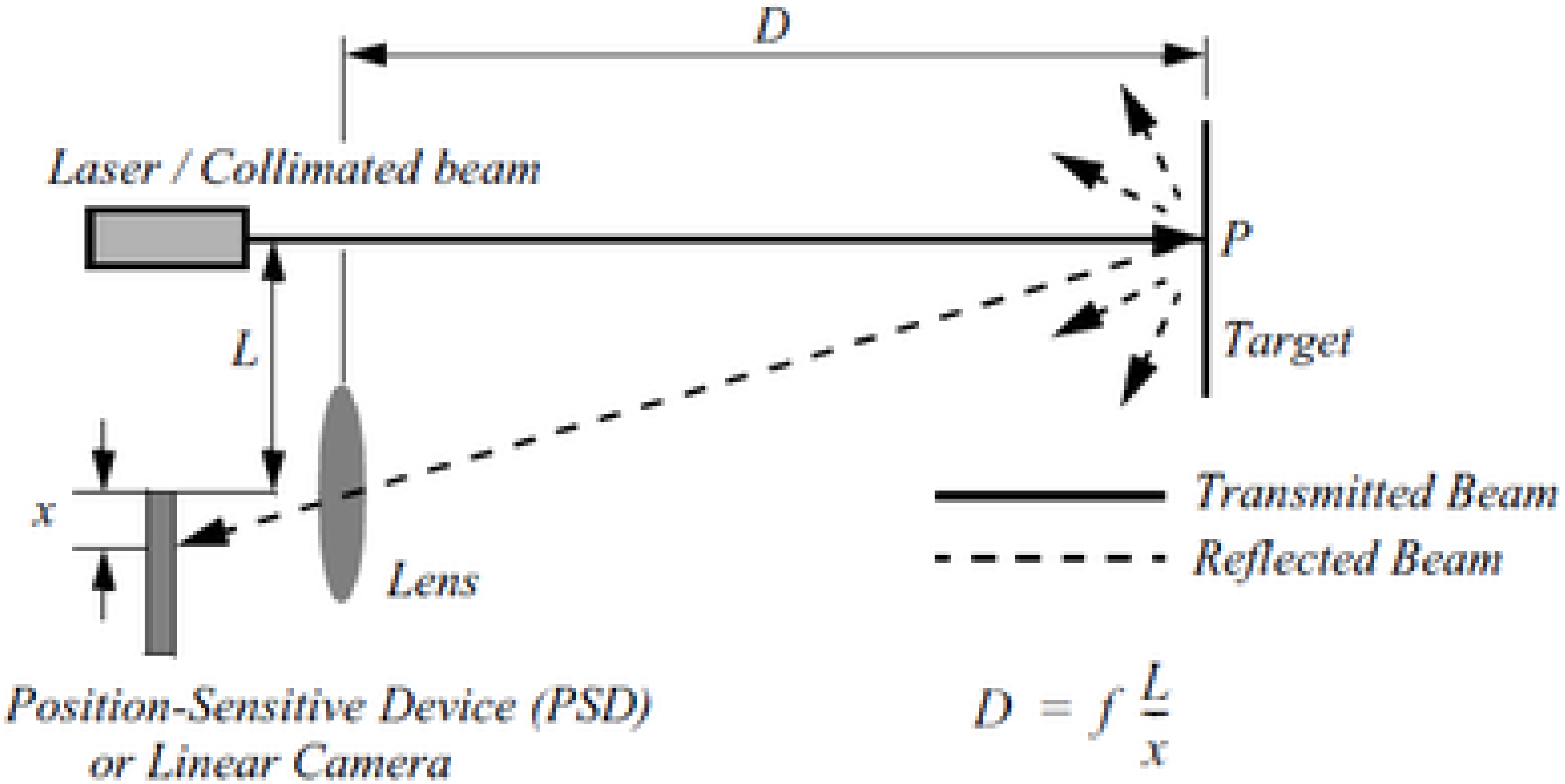
# Laser range finders

Measurement of **range** based on **time of flight**



# Laser range finders

Measurement of **range** based on **triangulation**

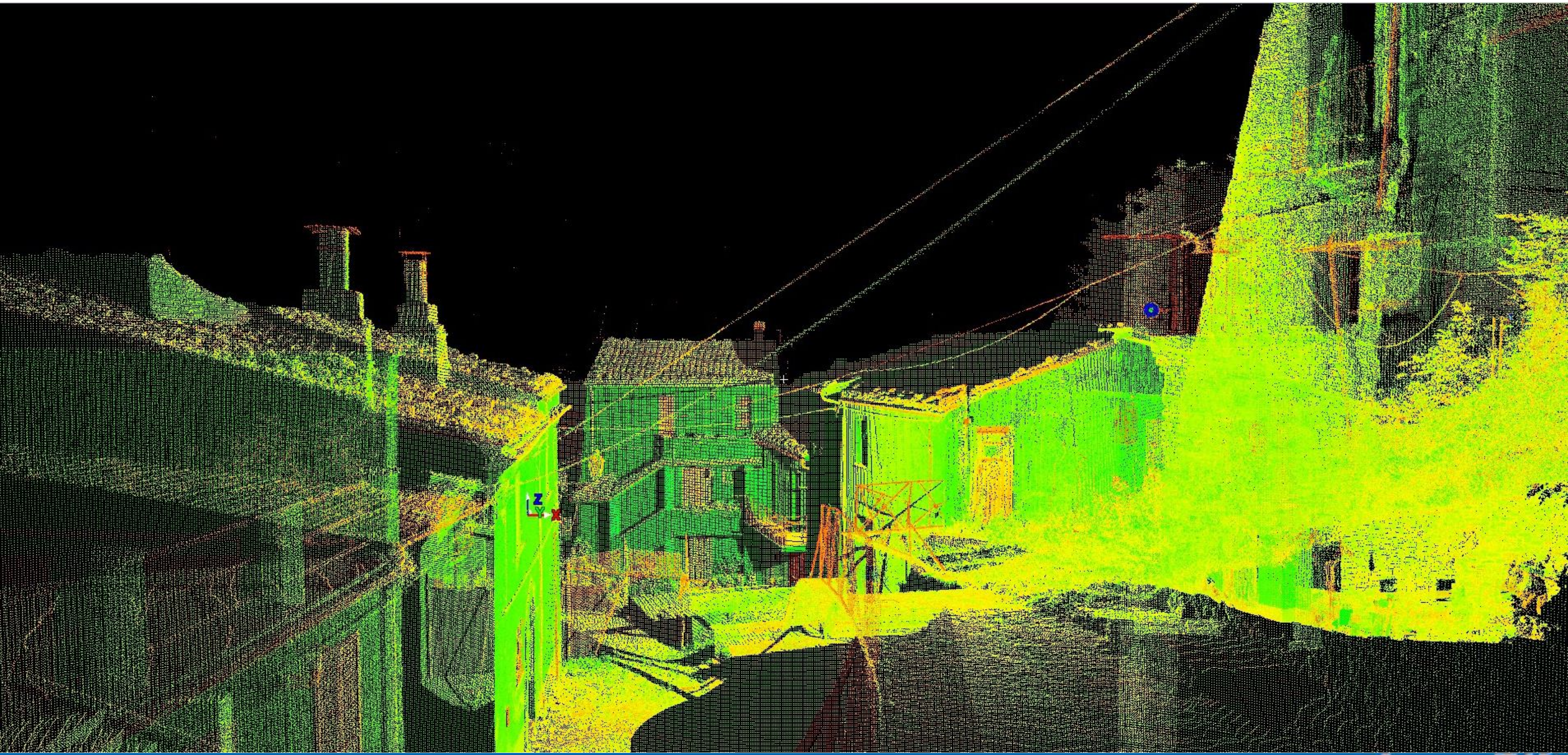



$$D = f\frac{L}{x}$$

https://www.youtube.com/watch?v=EYbhNSUnIdU

# Laser range finders

Measurement of **range** based on **triangulation**



# Outline of the lesson

- Definitions of sensor and transducer and sensor properties
- Position sensors: switches, encoders, potentiometers, Hall-effect sensors
- Range/Distance sensors: triangulation, ultrasound sensors and laser range finders
- **Proximity sensors: Hall-effect and infrared sensors**
- Force sensors: strain gauges and force/torque sensors
- Inertial sensors

Bibliographical references:
AA.VV., *Handbook of Mechatronics*, CRC Press LLC, 2002, Cap.19

# Proximity sensors

Sensing the presence of an object in a **spatial neighborhood** (no measurement of distance)

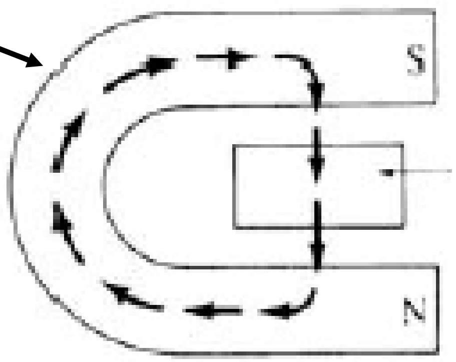
**Passive proximity sensors** detect perturbations of the environment, like for instance modifications of the magnetic or the electric field

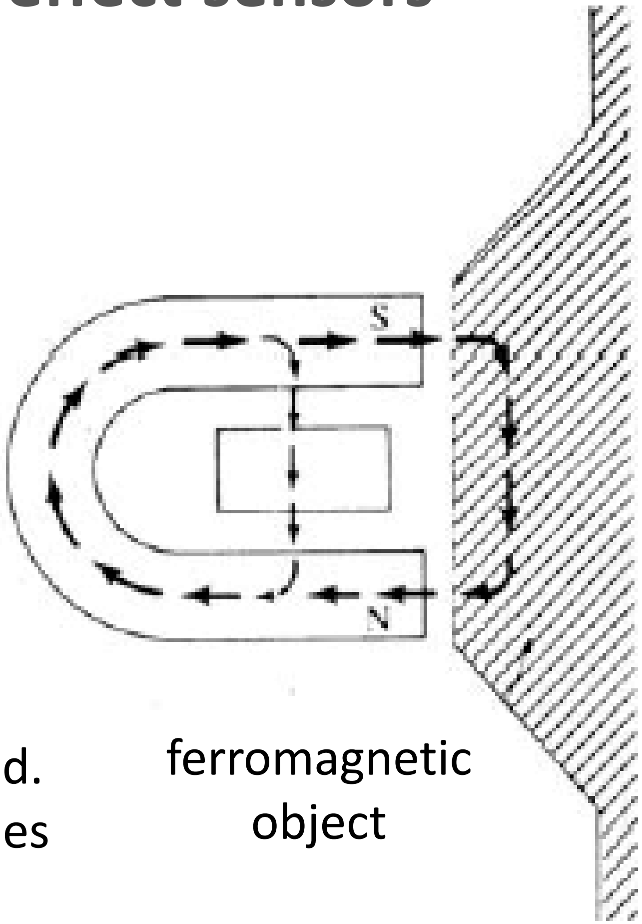
Ex: magnetic passive sensors: Hall-effect sensors

**Active proximity sensors** emit a signal and detect it back, detecting variations or interruptions of the signal received

Ex: active optical sensors: emitter and receiver of light signals

# Passive proximity sensors: Hall-effect sensors



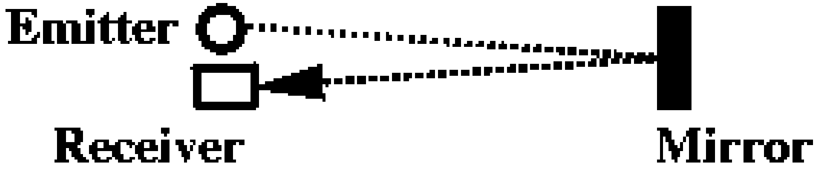




A permanent magnet generates a magnetic field.
The contact with a ferromagnetic object modifies the magnetic field.
The Hall effect allows to measure this variation as a voltage

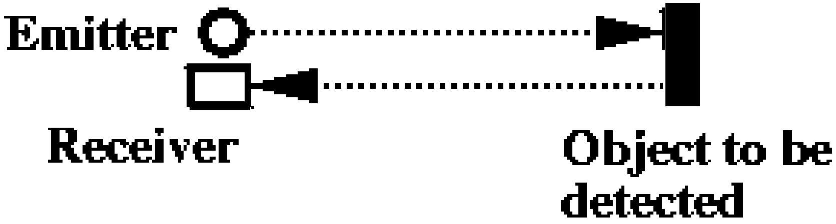
# Active proximity sensors: optical sensors

## Oppose mode

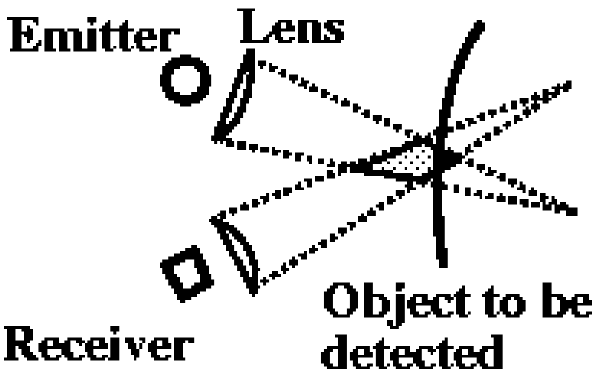

## Retroreflective mode



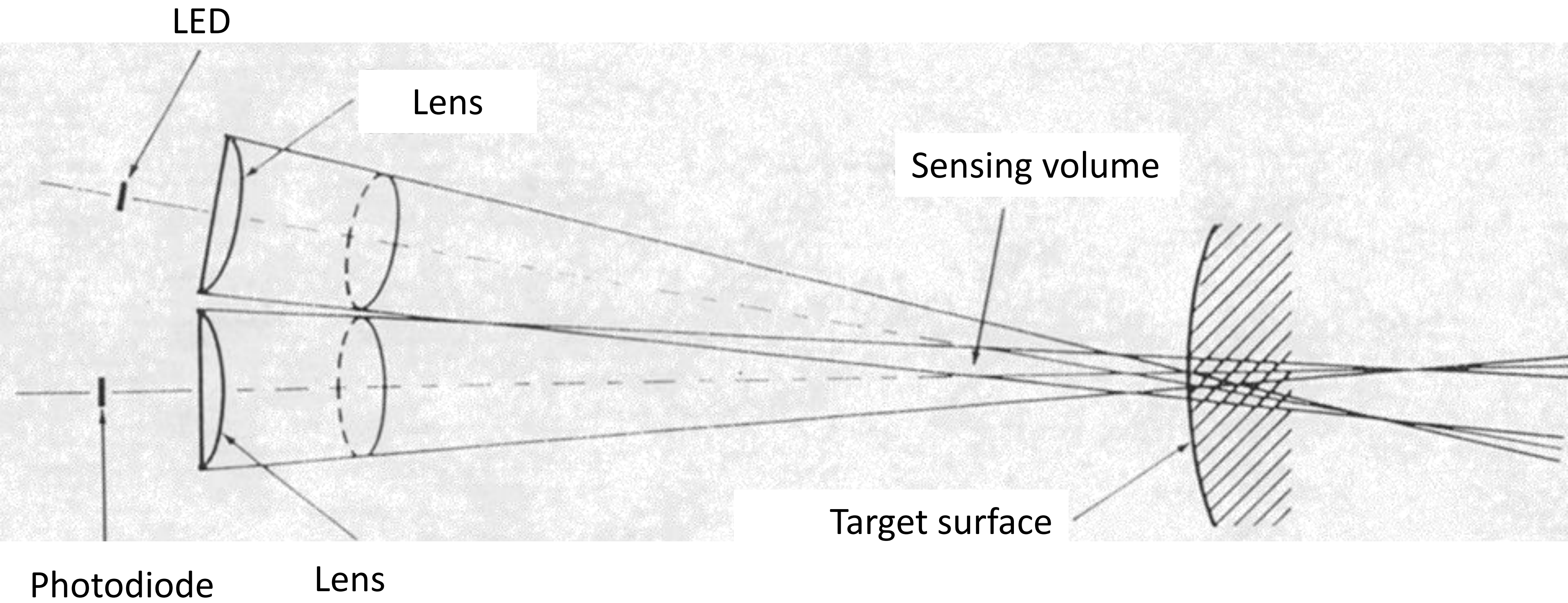

## Diffuse mode



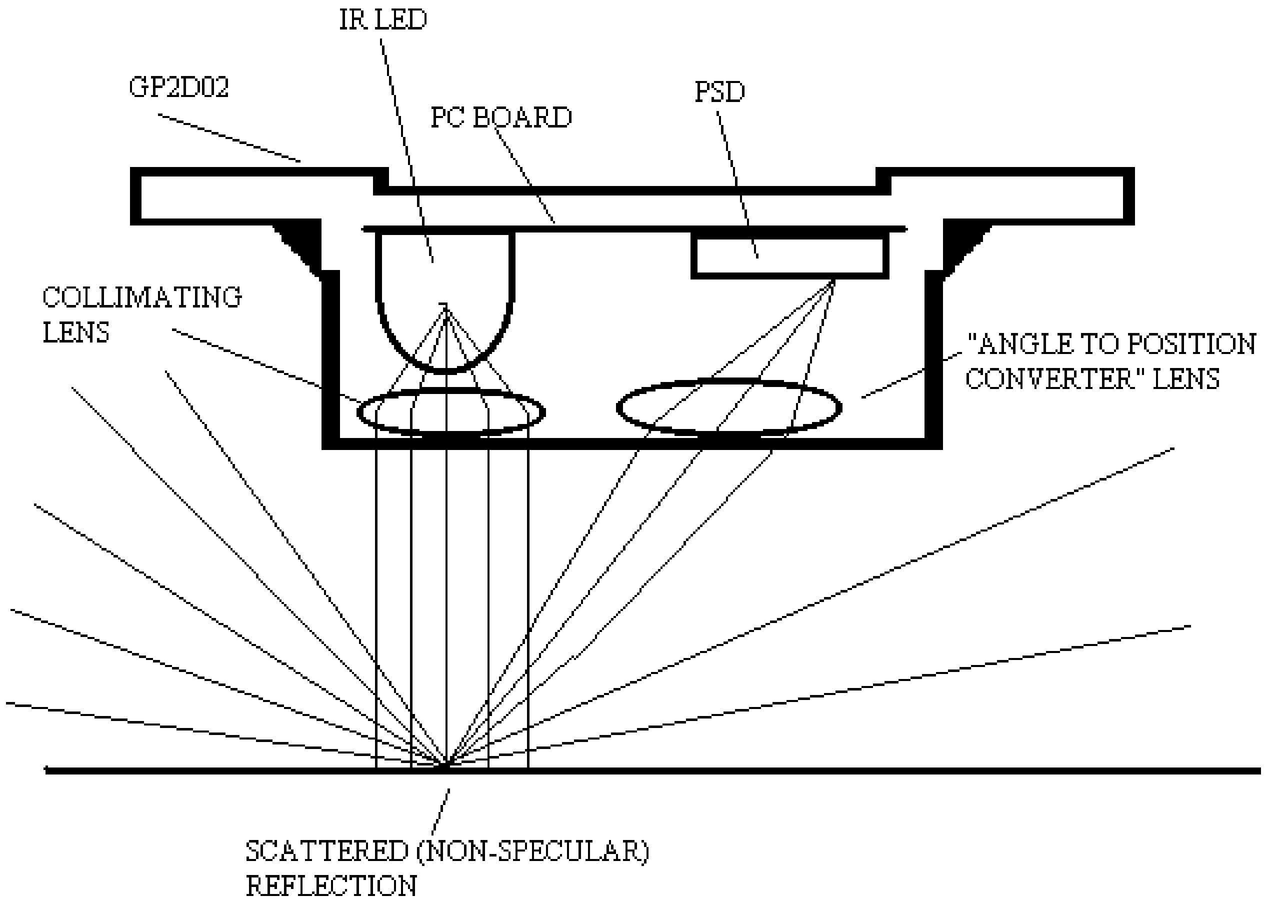

## Convergent mode



# Optical sensors based on infrared light



# Example of application of infrared optical sensor on mobile robots




Sharp GP2D02 IR Distance Measuring Sensor

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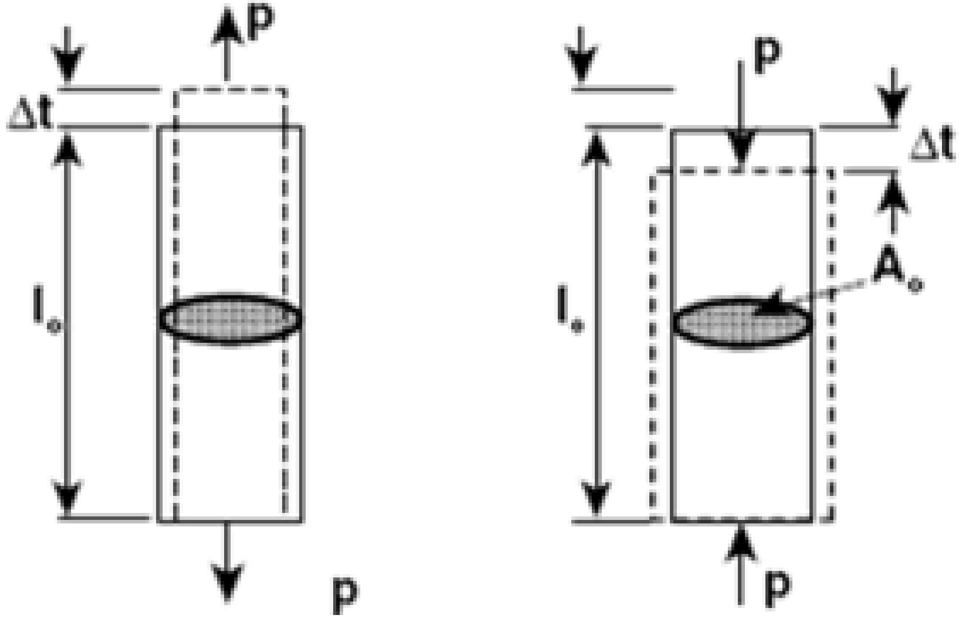
# Piezoresistive effect

Every material changes its electrical resistance with **strain**

# Basics of mechanical behavior of materials

Stress applied to a material causes strain. The material has an elastic behavior until a stress threshold (elastic limit), beyond which the material deformation is plastic




*stress*

$$\sigma = {}^{p}\!/_{A_0}$$

*strain*

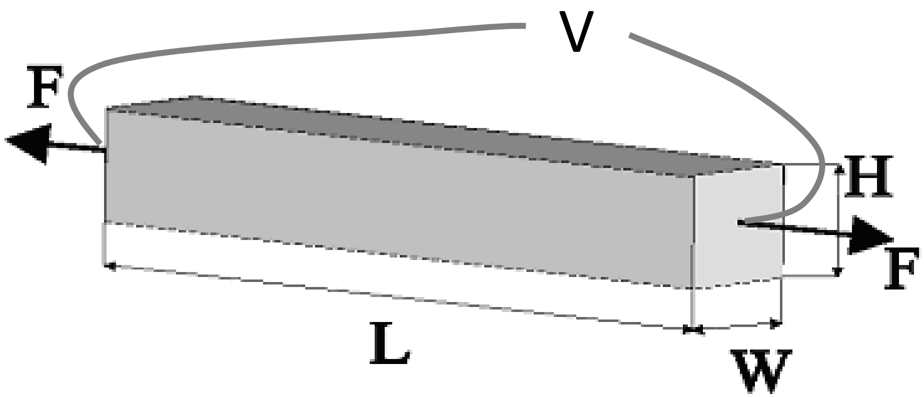
$$\varepsilon = {}^{\Delta l}\!/_{l_0}$$

Poisson's ratio: $\nu = -\dfrac{{}^{\delta A}\!/_{A_0}}{\varepsilon}$

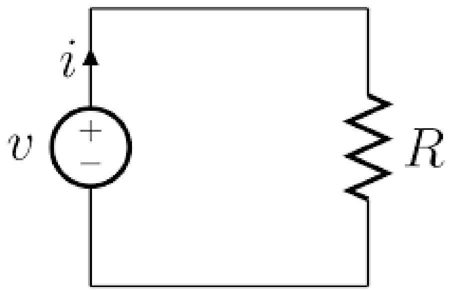
Elasticity module: $E = \dfrac{\sigma}{\varepsilon}$

# Piezoresistive effect

Every material changes its electrical resistance with **strain**




**Ohm's law**




$$v = Ri$$

In a metal block: $R = \rho \dfrac{L}{WH}$

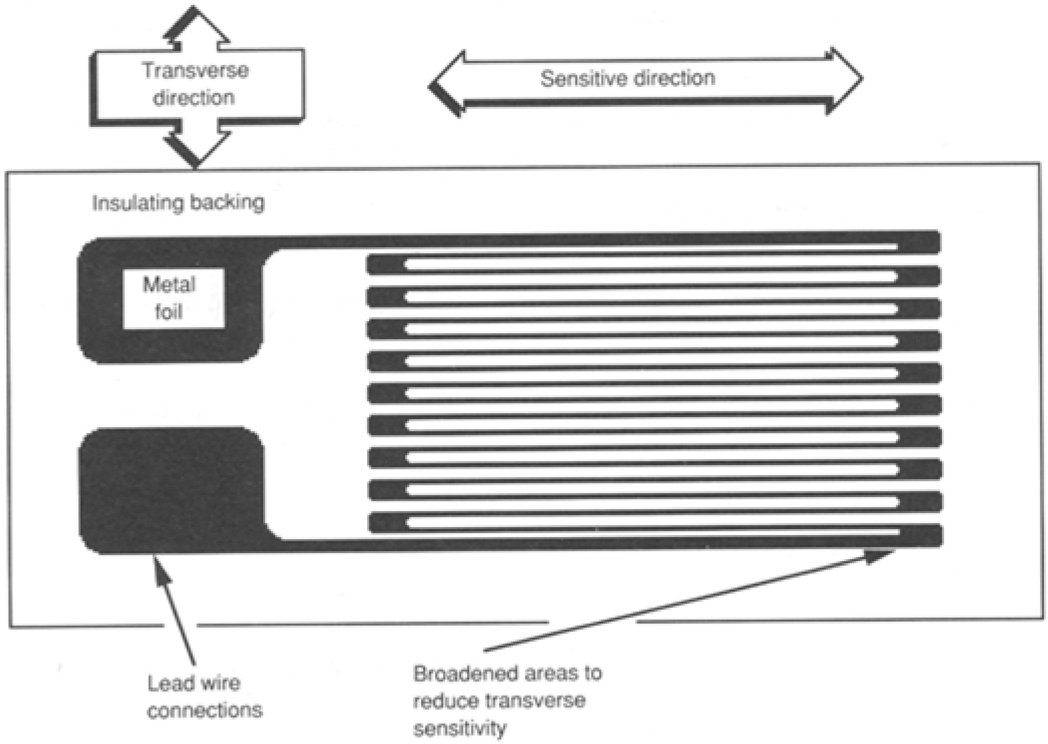
with $\rho$ = resistivity of the material,

*L, W, H* = dimensions of the block

$$\frac{\Delta R}{R} = \varepsilon + 2\nu\varepsilon + \frac{\Delta\rho}{\rho}$$

ν = Poisson's ratio of the material

# Strain gauge

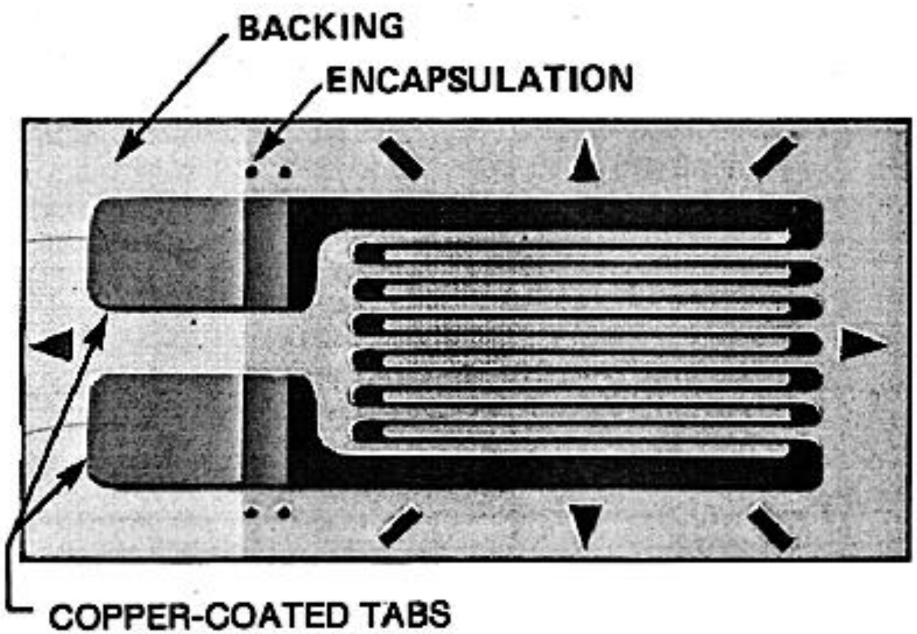


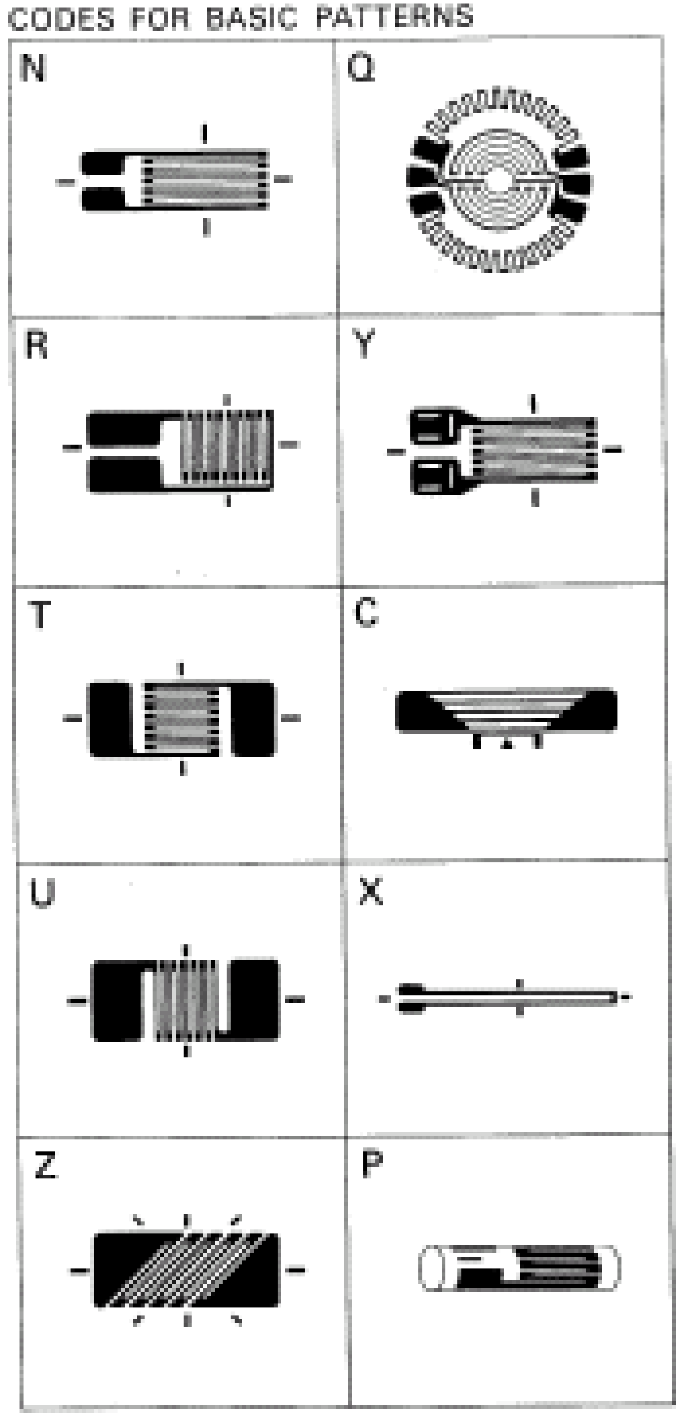

The sensor shape increases sensitivity in one direction

Gauge factor: $$G = \frac{\Delta R / R}{\varepsilon} = 1 + 2\nu + \frac{\Delta \rho / \rho}{\varepsilon}$$

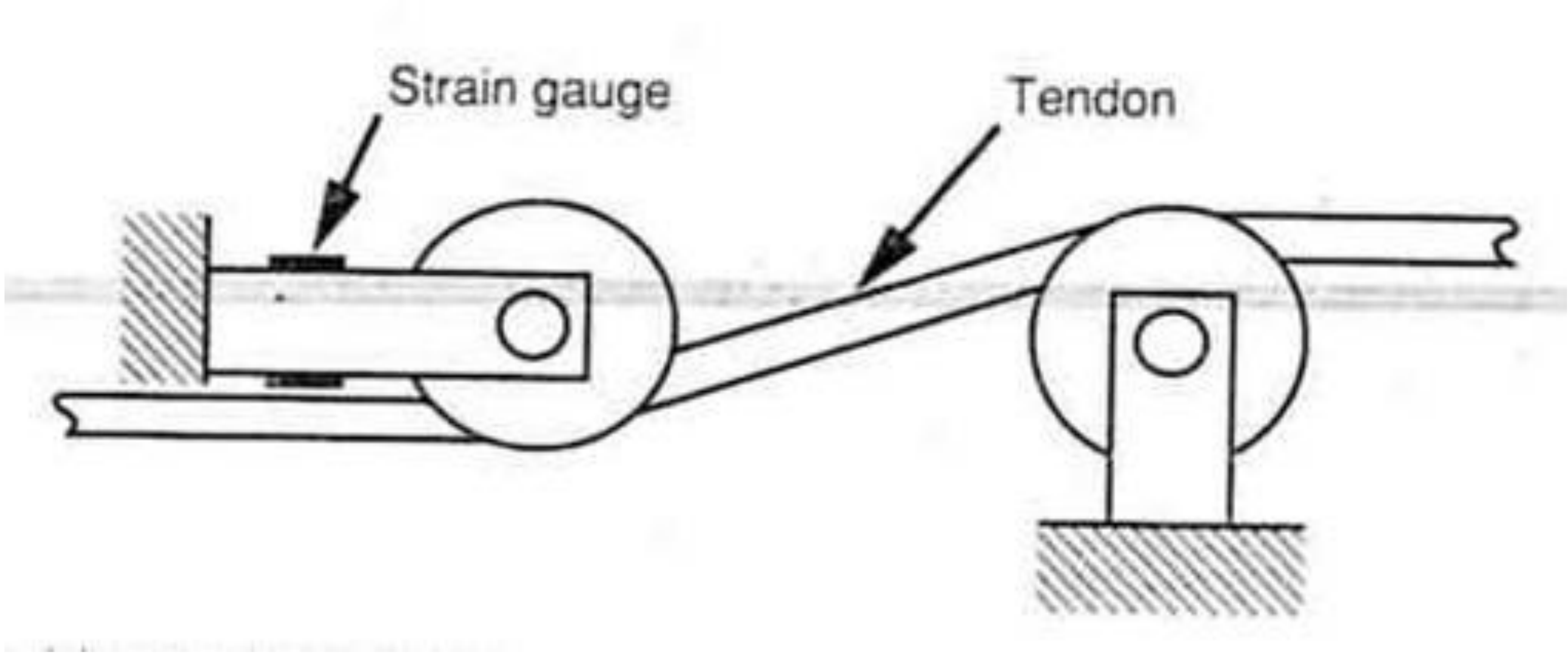
ν = Poisson's ratio of the material

# Strain gauges

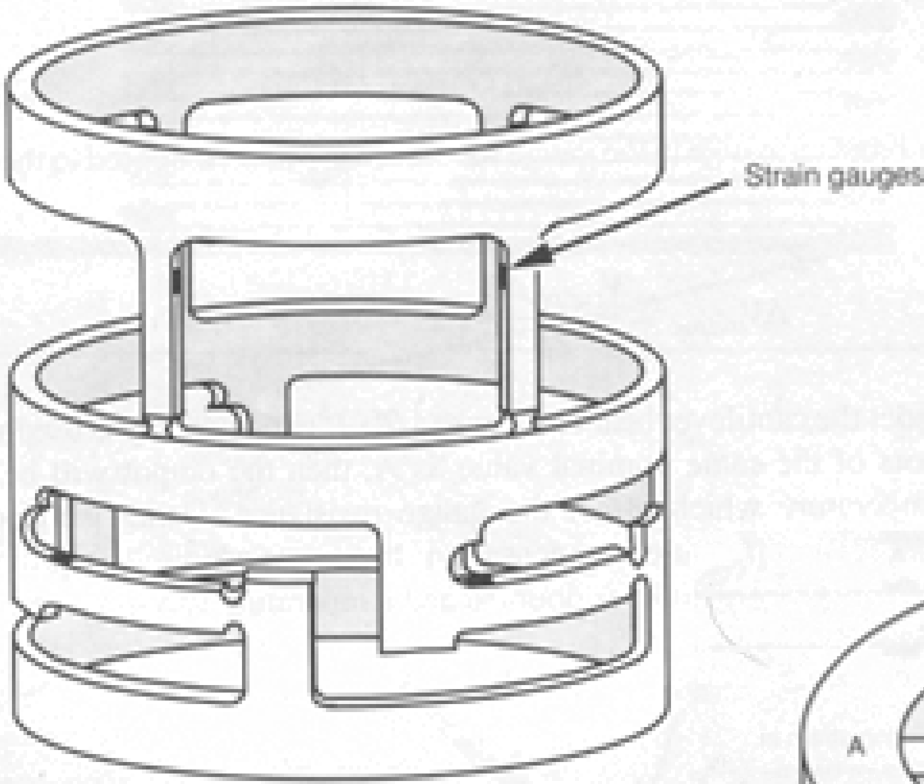


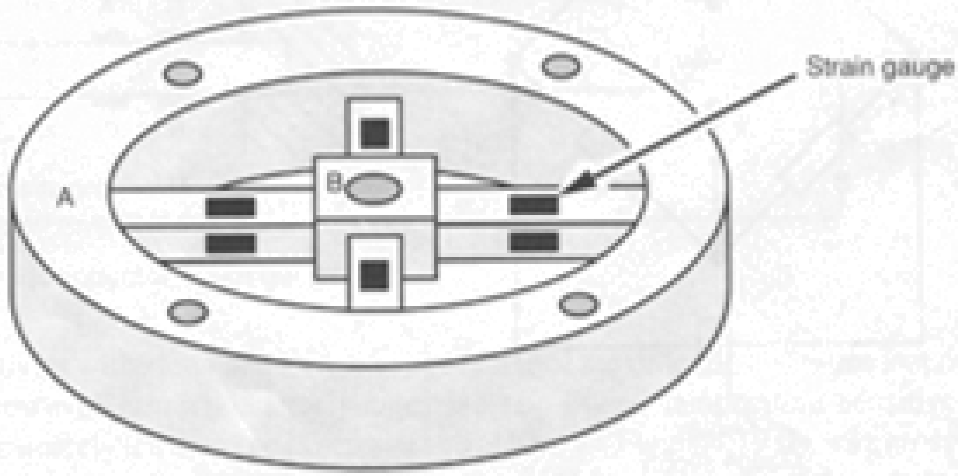
# Cable tension sensors



# Three-axial force/torque sensors

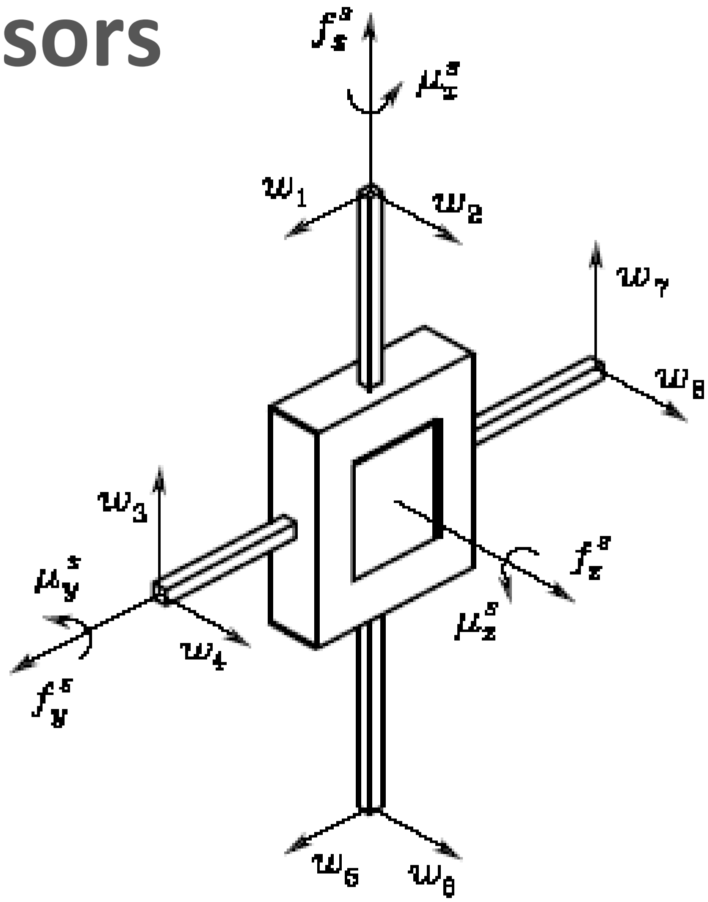



- Mechanical structure with preferred strain directions, along 3 axes
- Strain gauges arranged accordingly



# Three-axial force/torque sensors

- Forces and torques are measured from measures of the resistance variations of the strain gauges, multiplied by a coefficient array, typical for each sensor
- The coefficient array is built by a calibration procedure in which known forces are applied




$$\begin{bmatrix} f_x^s \\ f_y^s \\ f_z^s \\ \mu_x^s \\ \mu_y^s \\ \mu_z^s \end{bmatrix} = \begin{bmatrix} 0 & 0 & c_{13} & 0 & 0 & 0 & c_{17} & 0 \\ c_{21} & 0 & 0 & 0 & c_{25} & 0 & 0 & 0 \\ 0 & c_{32} & 0 & c_{34} & 0 & c_{36} & 0 & c_{38} \\ 0 & 0 & 0 & c_{44} & 0 & 0 & 0 & c_{48} \\ 0 & c_{52} & 0 & 0 & 0 & c_{56} & 0 & 0 \\ c_{61} & 0 & c_{63} & 0 & c_{65} & 0 & c_{67} & 0 \end{bmatrix} \begin{bmatrix} w_1 \\ w_2 \\ w_3 \\ w_4 \\ w_5 \\ w_6 \\ w_7 \\ w_8 \end{bmatrix}$$

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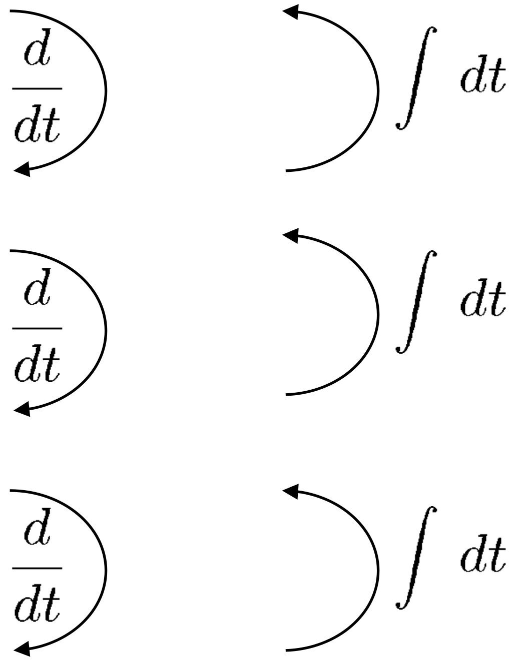
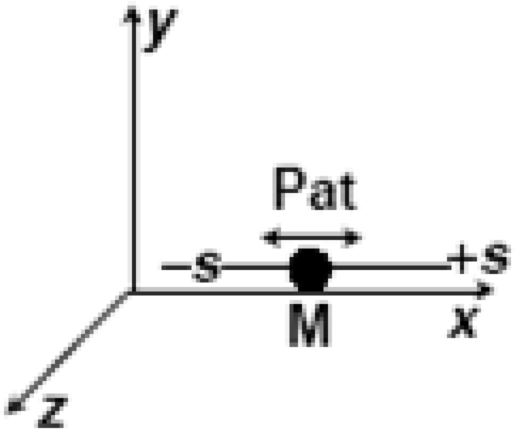
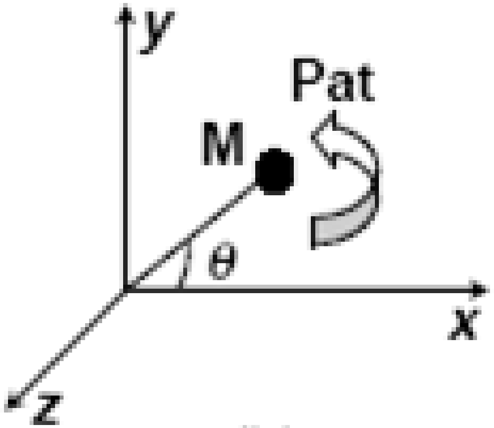
# Kinematic quantities

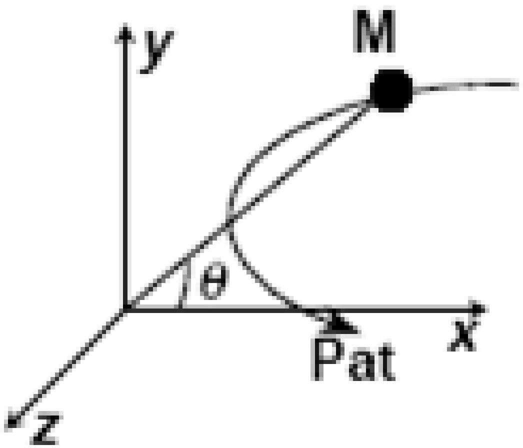
- Position
  - x(t); θ(t)
- Velocity
  - v(t); ω(t)
- Acceleration
  - a(t); α(t)
- Jerk
  - …



# Types of motion




- Linear: $$a = \frac{dv}{dt} = \frac{d(ds/dt)}{dt} = \frac{d^2s}{dt^2}$$
- Angular: $$\alpha = \frac{d\omega}{dt} = \frac{d(d\theta/dt)}{dt} = \frac{d^2\theta}{dt^2}$$
- Curve: $$\mathbf{a} = \frac{d\mathbf{v}}{dt} = \frac{d^2x}{dt^2}\mathbf{i} + \frac{d^2y}{dt^2}\mathbf{j} + \frac{d^2z}{dt^2}\mathbf{k}$$

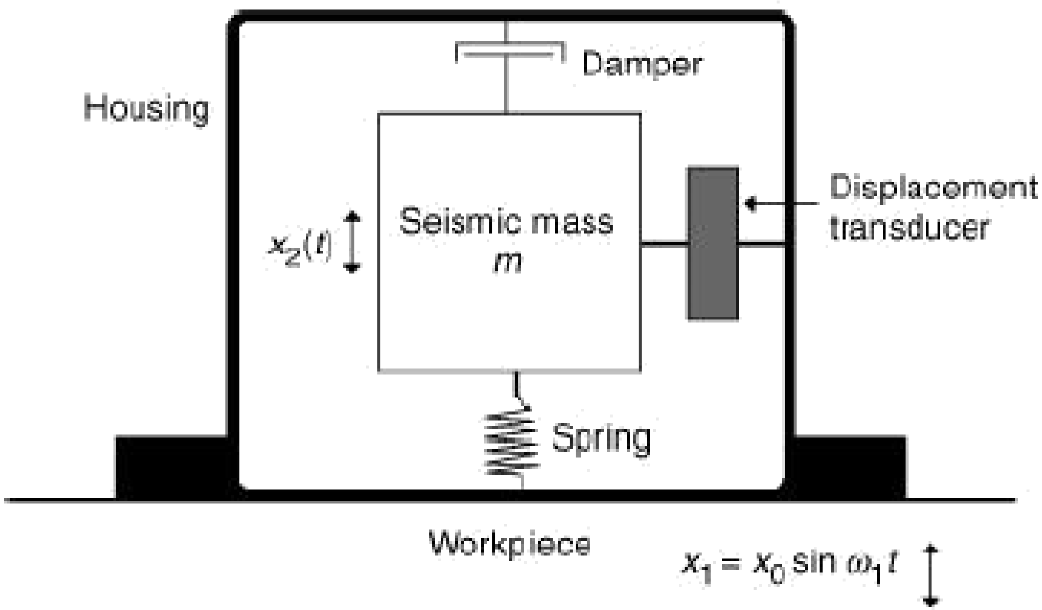
# Acceleration measure

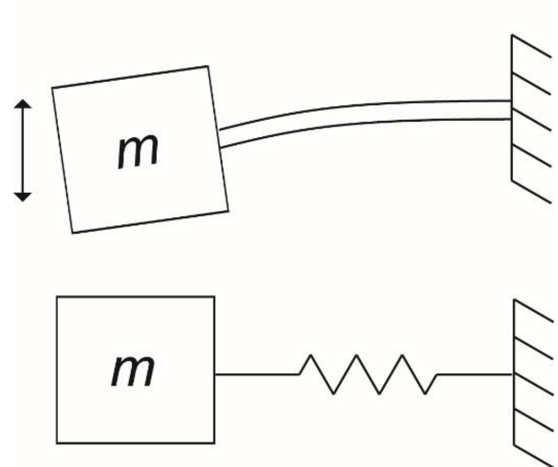
- DIRECT: through accelerometers
- INDIRECT: by deriving velocity

- In linear or angular motion, direct measurement is preferable
- In curve motion, acceleration is measured with indirect methods

# Working principle of accelerometers

- Accelerometers measure the acceleration of a *proof mass* moving inside a rigid frame or suspended by a compliant structure
- Measuring the displacement of the proof mass allows estimating the acceleration



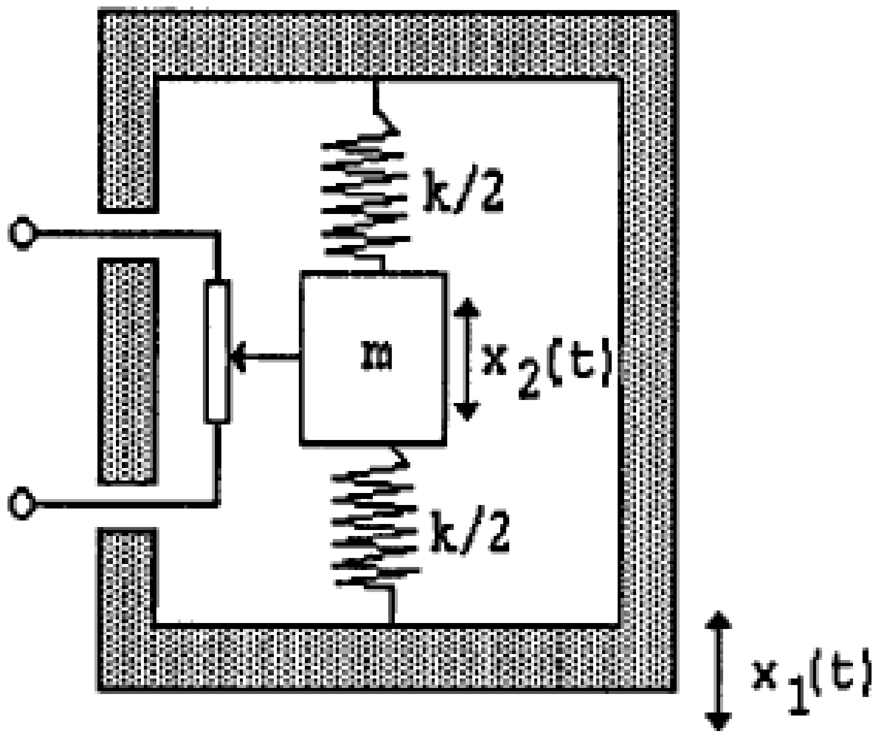



# Potentiometer accelerometers

A potentiometer is used to measure the relative displacement between the seismic mass and the base

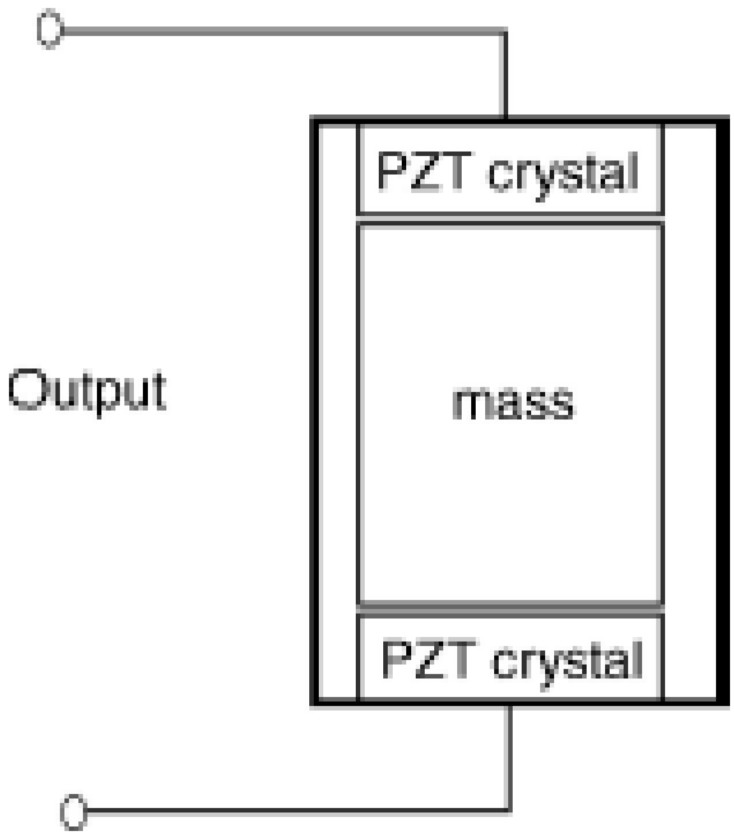
A viscous fluid continuously interact with the base and the mass to provide damping

- Dynamic range: $\pm 1g$ to $\pm 50g$ fs.
- Natural frequencies: 12 - 89 Hz,
- Damping ratio ζ: 0.5 - 0.8
- Potentiometer resistence: 1000–10000Ω
  - Corresponding resolution: 0.45–0.25% fs.
- Cross-axial sensibility: $< \pm 1\%$.
- Accuracy: $\pm 1\%$ fs at environmental temperature.
- Dimension: 50mm$^3$ (<0.1 gr.)



# Piezoelectric accelerometers

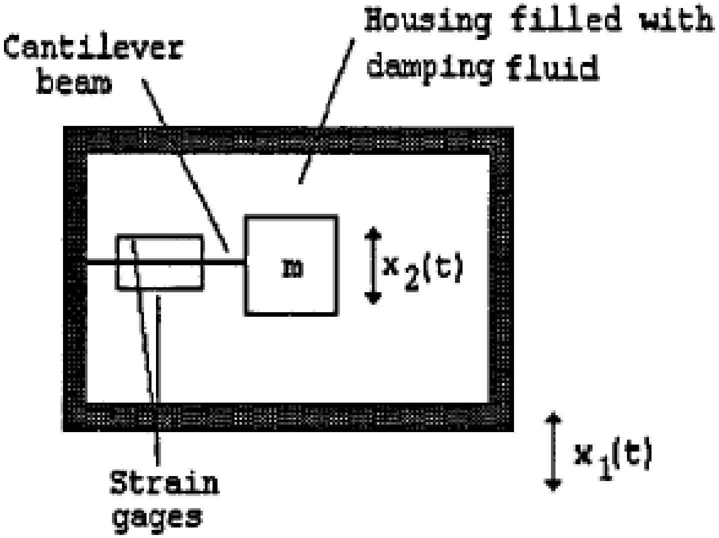
## A mass in direct contact with the piezoelectric component or crystal




When a varying motion is applied to the accelerometer, the crystal experiences a varying force excitation ($F = ma$), causing a proportional electric charge q to be developed across it.

- They are basically motion transducers with large output signals and comparatively small sizes
- widely used for general-purpose acceleration, shock, and vibration measurements, useful for high-frequency applications
- These accelerometers
- available in a wide range of specifications: as small as 3 x 3 mm in dimension with about 0.5 g in mass, including cables
- excellent temperature ranges and some of them are designed to survive the intensive radiation environment of nuclear reactors
- piezoelectric accelerometers tend to have larger cross-axis sensitivity than other types, about 2–4%.

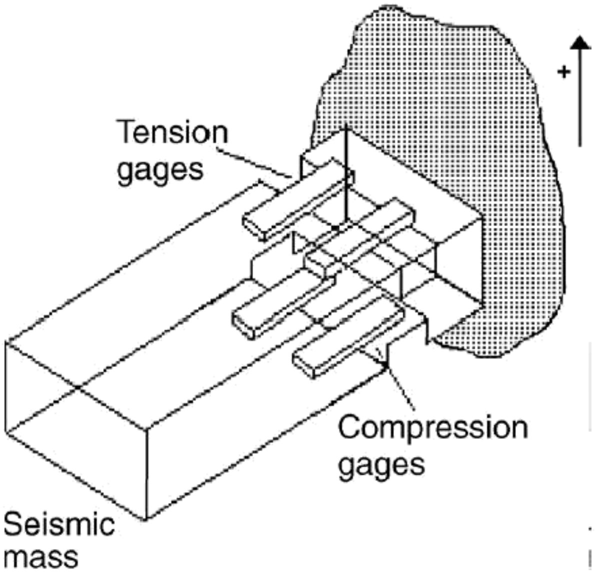
# Strain gauge accelerometers




- Electric resistance strain gauges are used for displacement sensing of the seismic mass
  - the seismic mass is mounted on a cantilever beam rather than on springs.
- Resistance strain gages are bonded on each side of the beam to sense the strain in the beam resulting from the vibrational displacement of the mass.
- Damping for the system is provided by a viscous liquid filling the housing.
- The output of the strain gages is connected to an appropriate bridge circuit.
- The natural frequency of such a system is about 300 Hz.
  - The low natural frequency is due to the need for a sufficiently large cantilever beam to accommodate the mounting of the strain gages.

# Piezoresistive accelerometers

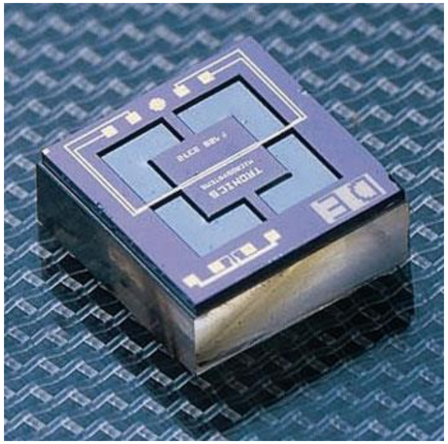
- Piezoresistive accelerometers are essentially semiconductor strain gauges with large gauge factors. The sensitivity of a piezoresistive sensor comes from the elastic response of its structure and resistivity of the material.
- Piezoresistive accelerometers are useful for acquiring vibration information at low frequencies. They are suitable to measure shocks well above 100,000g.




Characteristics

- Frequency: Less than 1Hz-20kHz
- Limited temperature range: Calibration
- Light weight: Less than 1 to 10g
- AC/DC response
- Less than .01g to 200,000g

pressure changes the resistance by mechanically deforming the sensor



Nintendo