THE BIOROBOTICS INSTITUTE

Scuola Superiore Sant'Anna

University of Pisa

Master of Science in Computer Science

Course of Robotics (ROB)

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Robot Sensors

Cecilia Laschi

The BioRobotics Institute

Scuola Superiore Sant'Anna, Pisa

cecilia.laschi@santannapisa.it

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Outline of the lesson

- Definitions of sensor and transducer
- Classification of transducers
- Fundamental properties of sensors
- Position sensors: switches, encoders, potentiometers, Hall-effect sensors
- Distance measurement: triangulation, time of flight
- Proximity sensors: ultrasound and infrared sensors
- Force sensors: strain gauges and force/torque sensors
- Inertial sensors

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Definitions of sensor and transducer

- SENSOR:

  device sensitive to a physical quantity and able to transform it in a measurable and transferable signal
- TRANSDUCER:

  device receiving in input a kind of energy and producing in output energy of a different kind, according to a known relation between input and output, not necessarily for measurement purposes

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First classification:

- Passive sensors:
  - convert directly input energy in output, without external energy sources
- Active sensors:
  - require external energy (excitation) for energy conversion

Classification of transducers

based on the kind of input energy, output energy, or external energy

- Radiant – electromagnetic waves:
  - intensity, frequency, polarization and phase
- Mechanical – external parameter of materials:
  - position, velocity, dimension, compliance, force
- Thermal:
  - temperature, gradient of temperature, heat
- Electrical:
  - voltage, current, resistivity, capacity
- Magnetic:
  - field intensity, flow density, permeability
- Chemical – internal structure of materials:
  - concentrations, crystal structure, aggregation state

Trasformations of energy in a transducer

INPUT ENERGY	➡	*AUSILIARY ENERGY*	➡	*OUTPUT ENERGY*
CHEMICAL		CHEMICAL		CHEMICAL
MAGNETIC		MAGNETIC		MAGNETIC
ELECTRICAL		ELECTRICAL		ELECTRICAL
THERMAL		THERMAL		THERMAL
MECHANICAL		MECHANICAL		MECHANICAL
RADIANT		RADIANT		RADIANT
		NONE		

Trasformations of energy in a transducer

INPUT ENERGY	→	*AUSILIARY ENERGY*	→	*OUTPUT ENERGY*
CHEMICAL		CHEMICAL		CHEMICAL
MAGNETIC		MAGNETIC		MAGNETIC
ELECTRICAL		ELECTRICAL		ELECTRICAL
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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

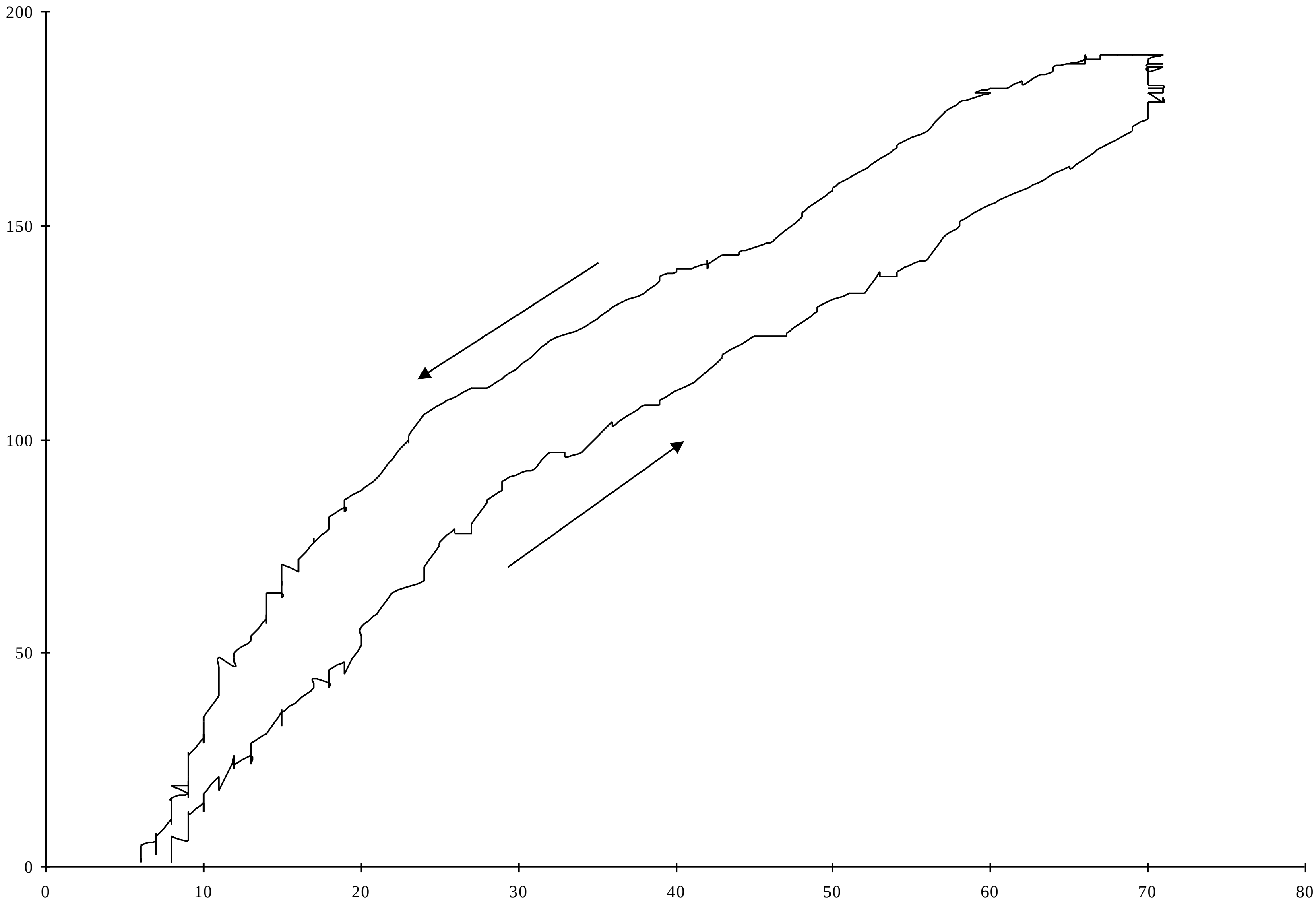
Hysteresis

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 in a tactile sensor



Accuracy

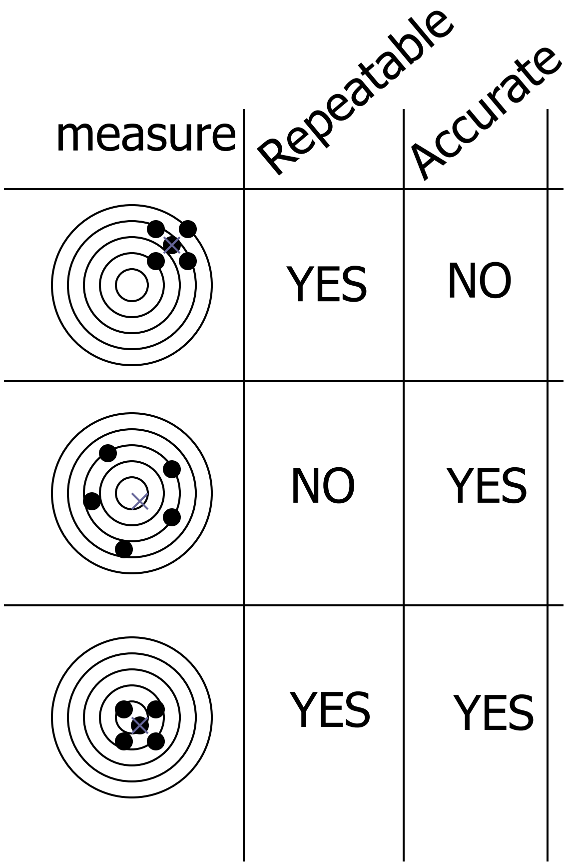
Accuracy represents the maximum error between the actual value and the value measured by the sensor.

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

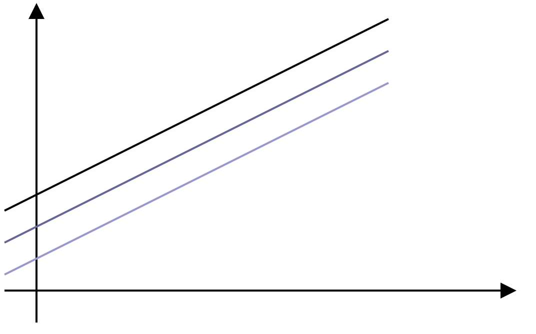
Stability is the capability of the sensor to keep its working characteristics for a given time (short, medium, long).

Other static parameters

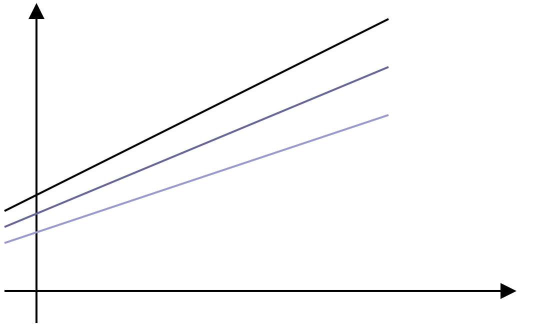
- Response time
- Input range
- Cost, size, weight
- Response in frequency
- Environmental factors
- Maximum/minimum temperature
- Warm-up time
- Presence of smoke, gas, …
- …

Dynamic parameters

- zero drift
  - For instance, due to temperature



- sensitiveness drift



Role of sensors in a robot

- Perception of the **internal state** (proprioception)
- Perception of the **external state** (exteroception)

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. For instance, joint position.

Role of sensors in a robot

- Perception of the **external state**: measurement of variables characterizeing the working environment. For instance, distance, proximity, force.

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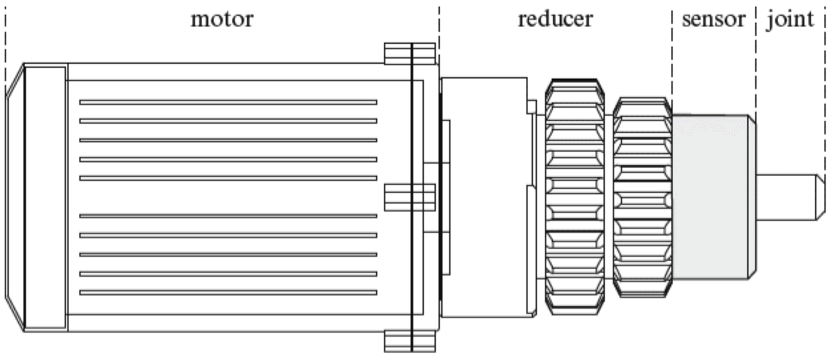
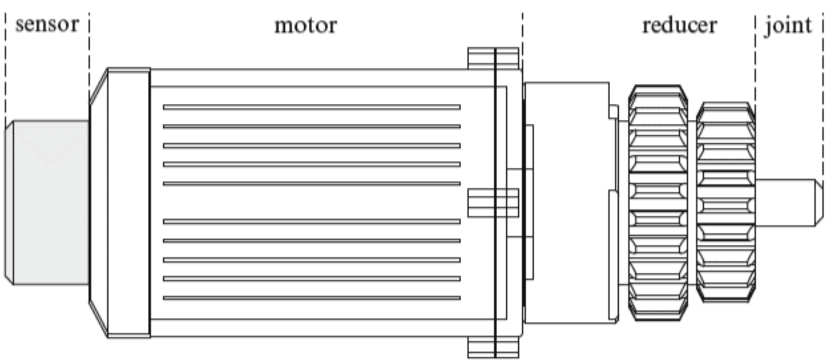
Position sensors

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

Placement of position sensors



Behind reducer



Before reducer

θ: joint angular position

θ_m: motor ngular 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

Switches

- Simplest position sensors
- Provide one datum:

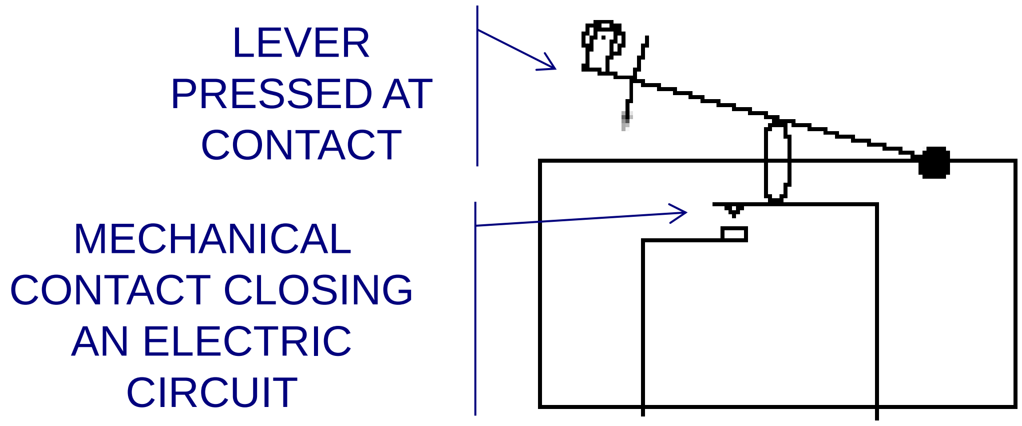
  contact / not contact
- Application as position sensors:
  - collision sensors in mobile robots
  - whiskers
  - end joint sensors for manipulators

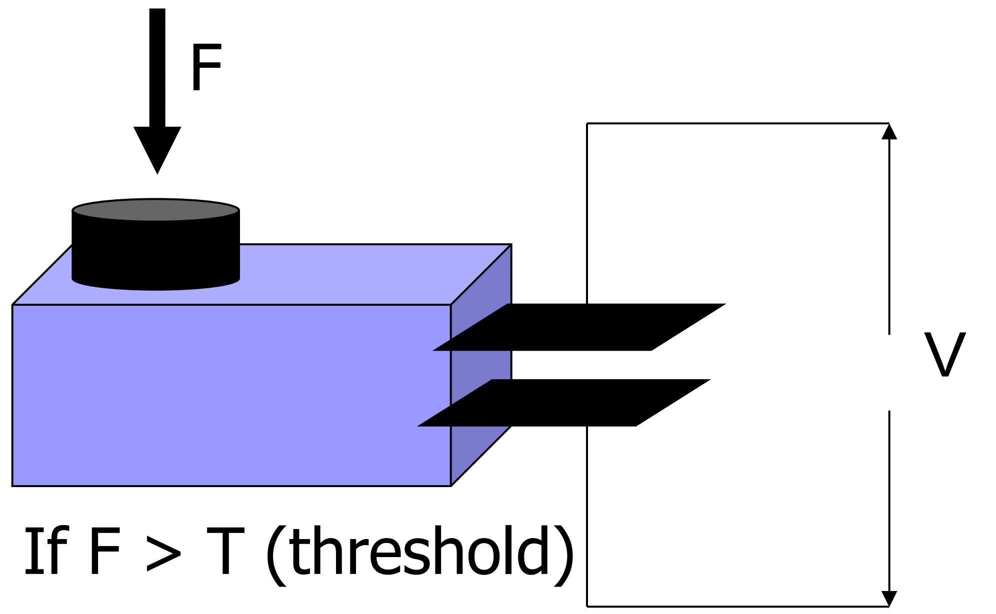
Mechanical switches

- Simplest contact sensors
- Provide one binary datum:

  contact / no contact

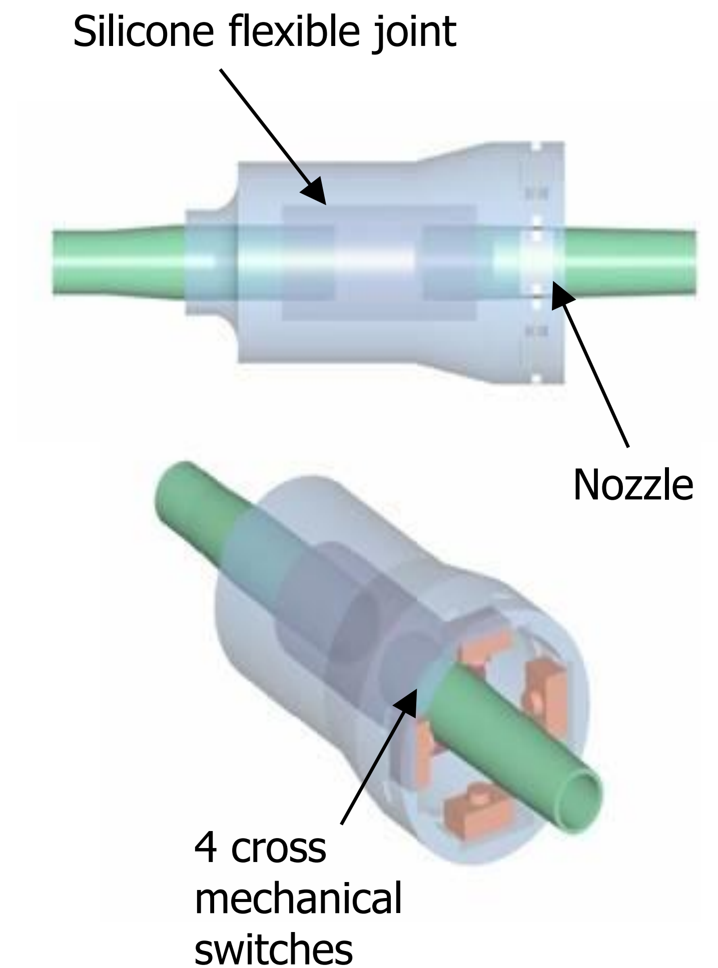
- Applications as tactile sensors:
  - impact sensors on mobile robots
  - whiskers
  - endstop sensors for manipulator joints



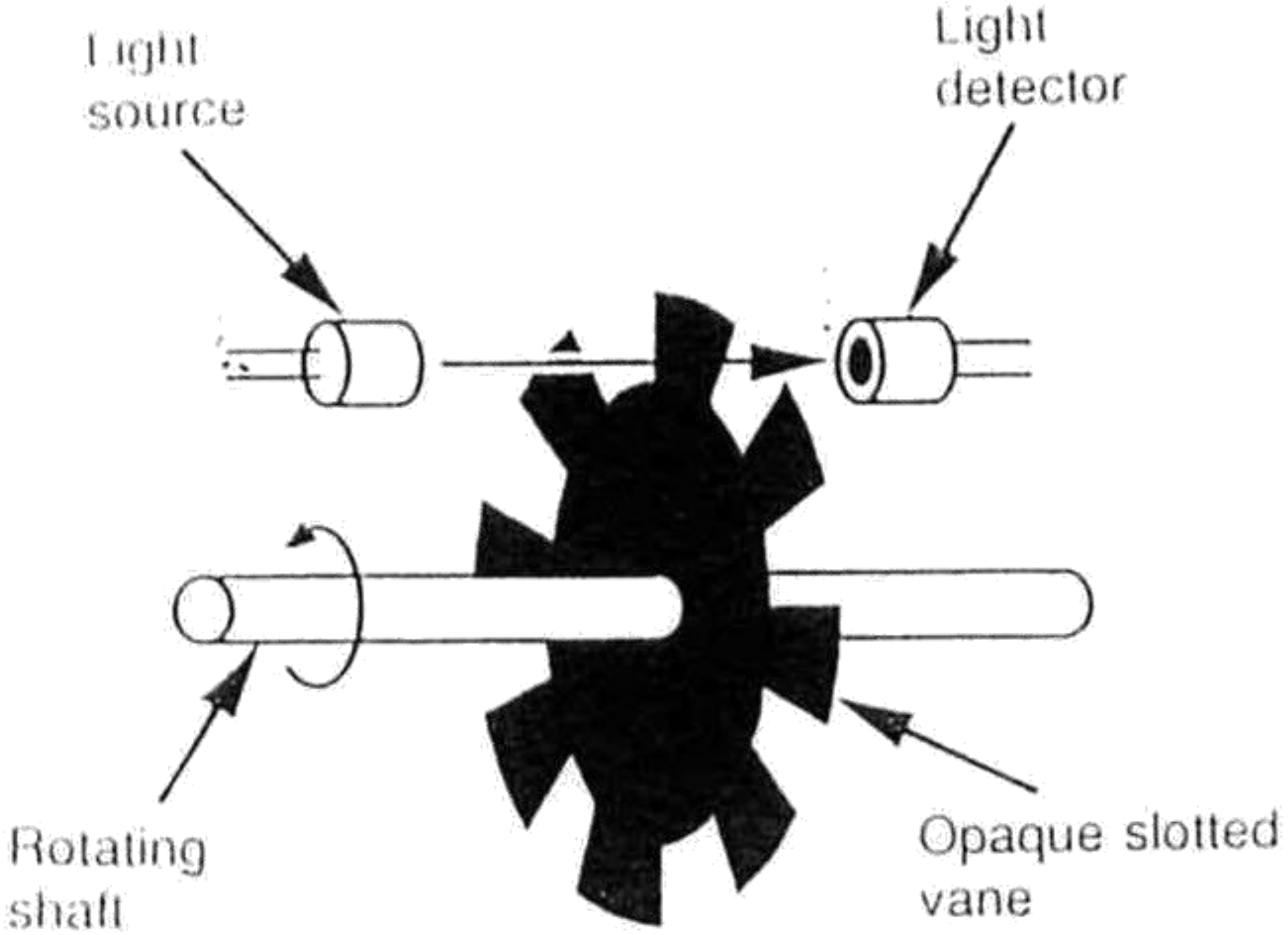


Oral-Joystick: human-machine interface of a feeding assistive device for the severely disabled

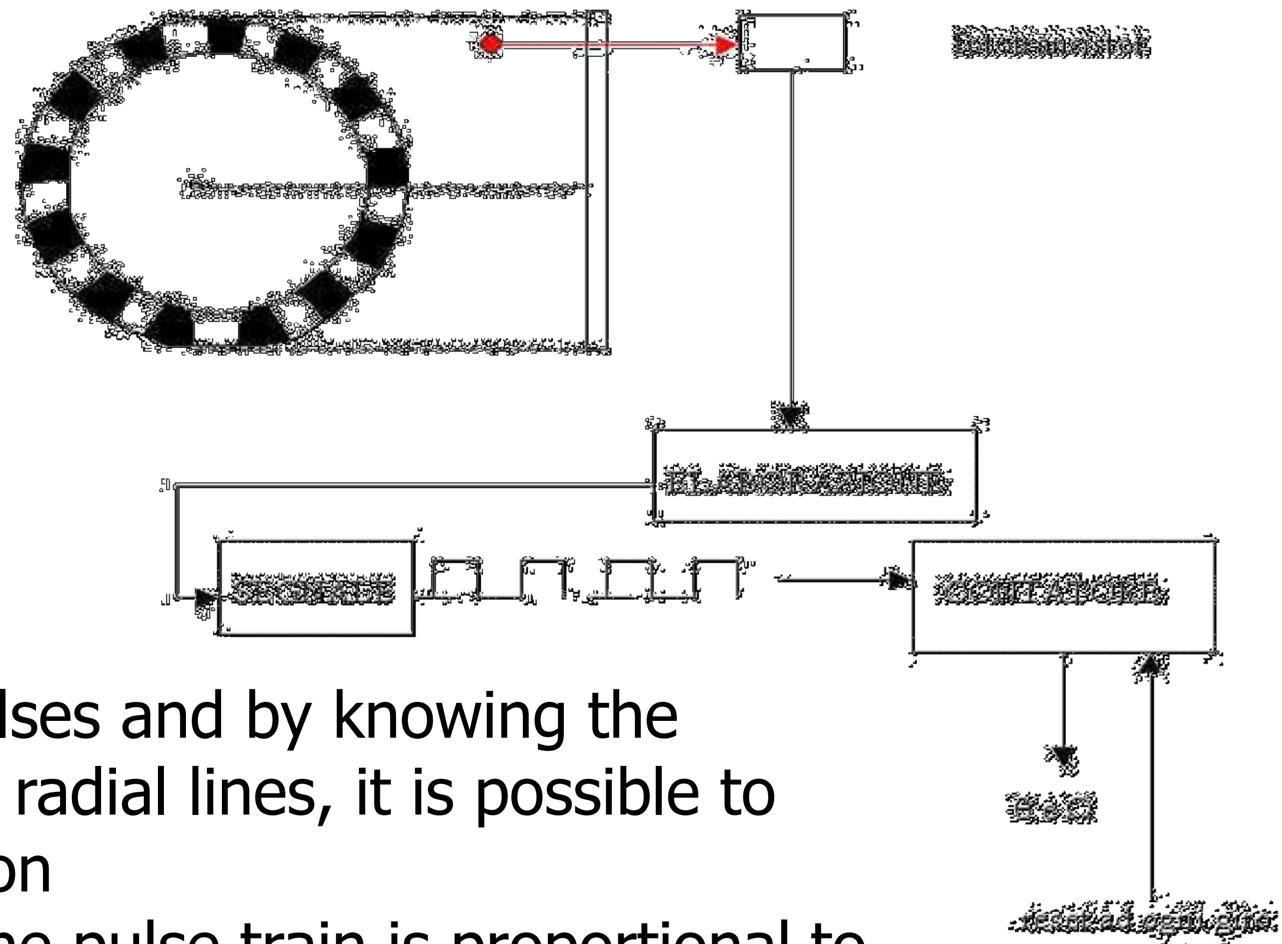
The Oral-Joystick is a straw-like tube for drinking with a nozzle, connected by a *silicone flexible joint*, in contact with four cross mechanical switches. The user can push the switches and activate specific functions of the feeding device, only with simple movements of the mouth.



Optical encoders



Incremental encoder

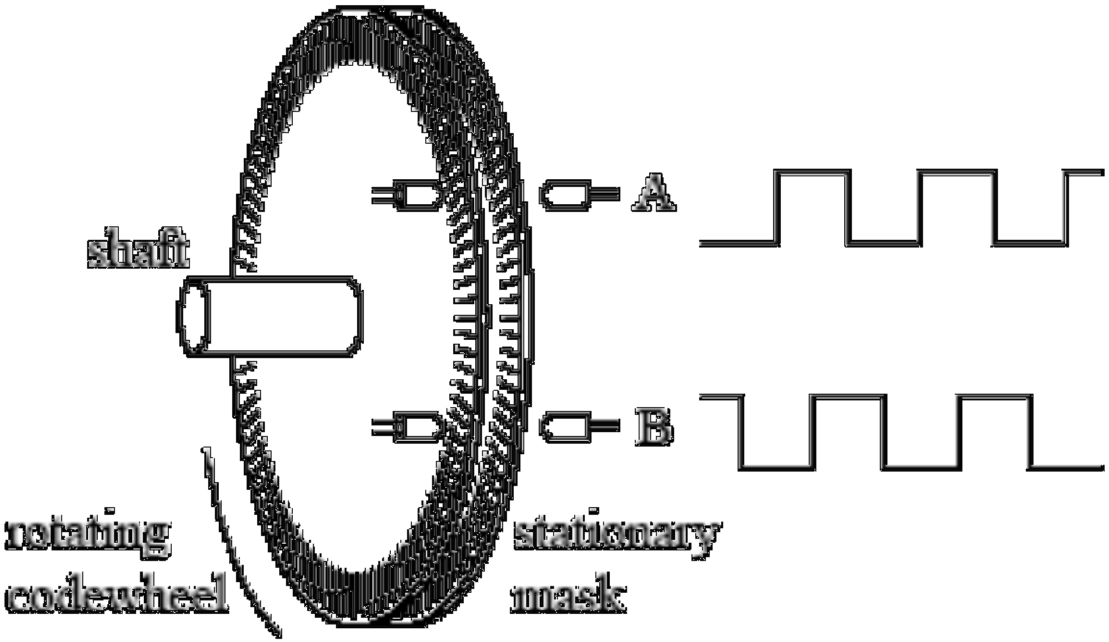


By counting the pulses and by knowing the number of the disk radial lines, it is possible to measure the rotation

The frequency of the pulse train is proportional to angular velocity

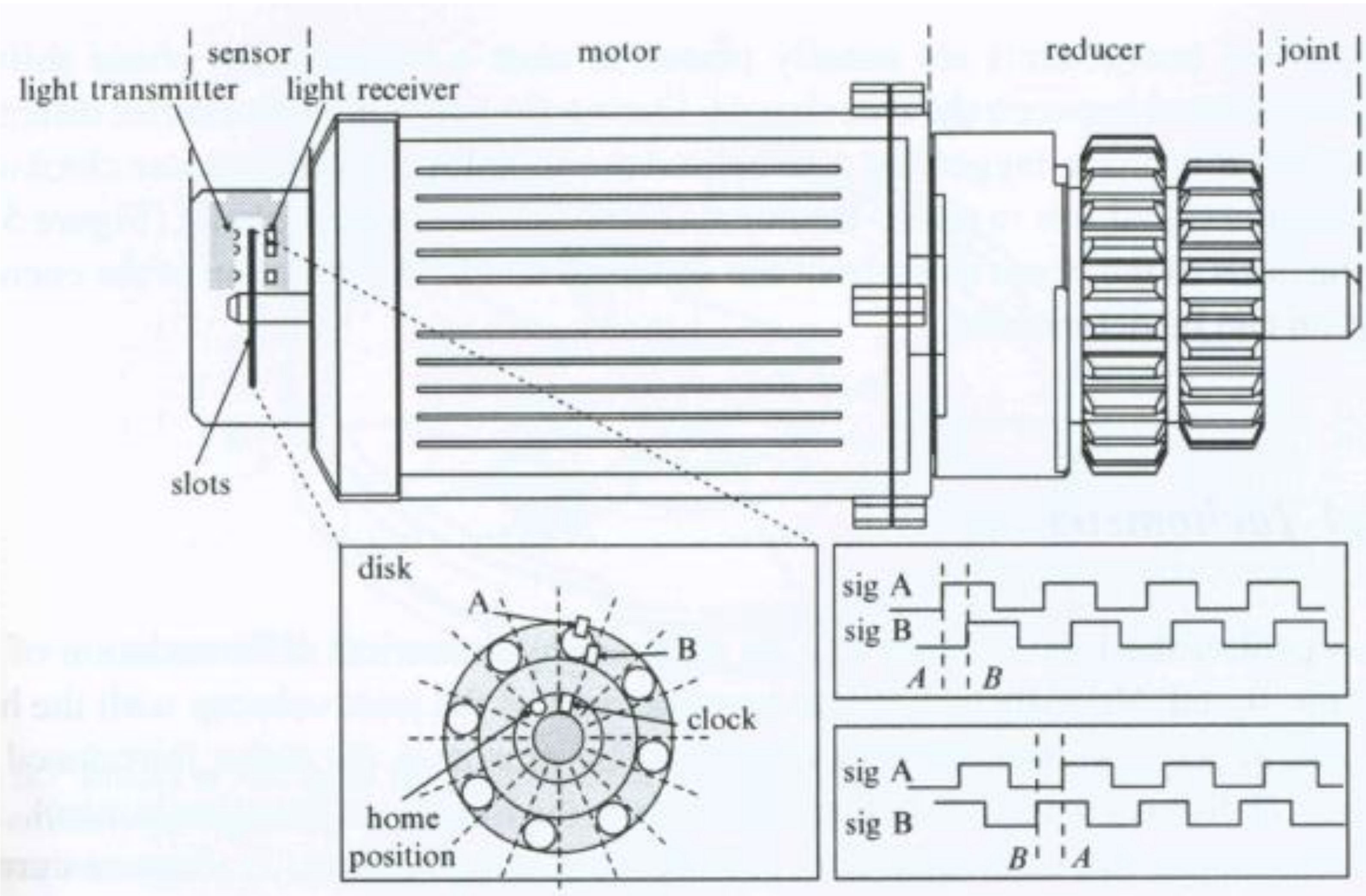
Incremental encoder

- 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

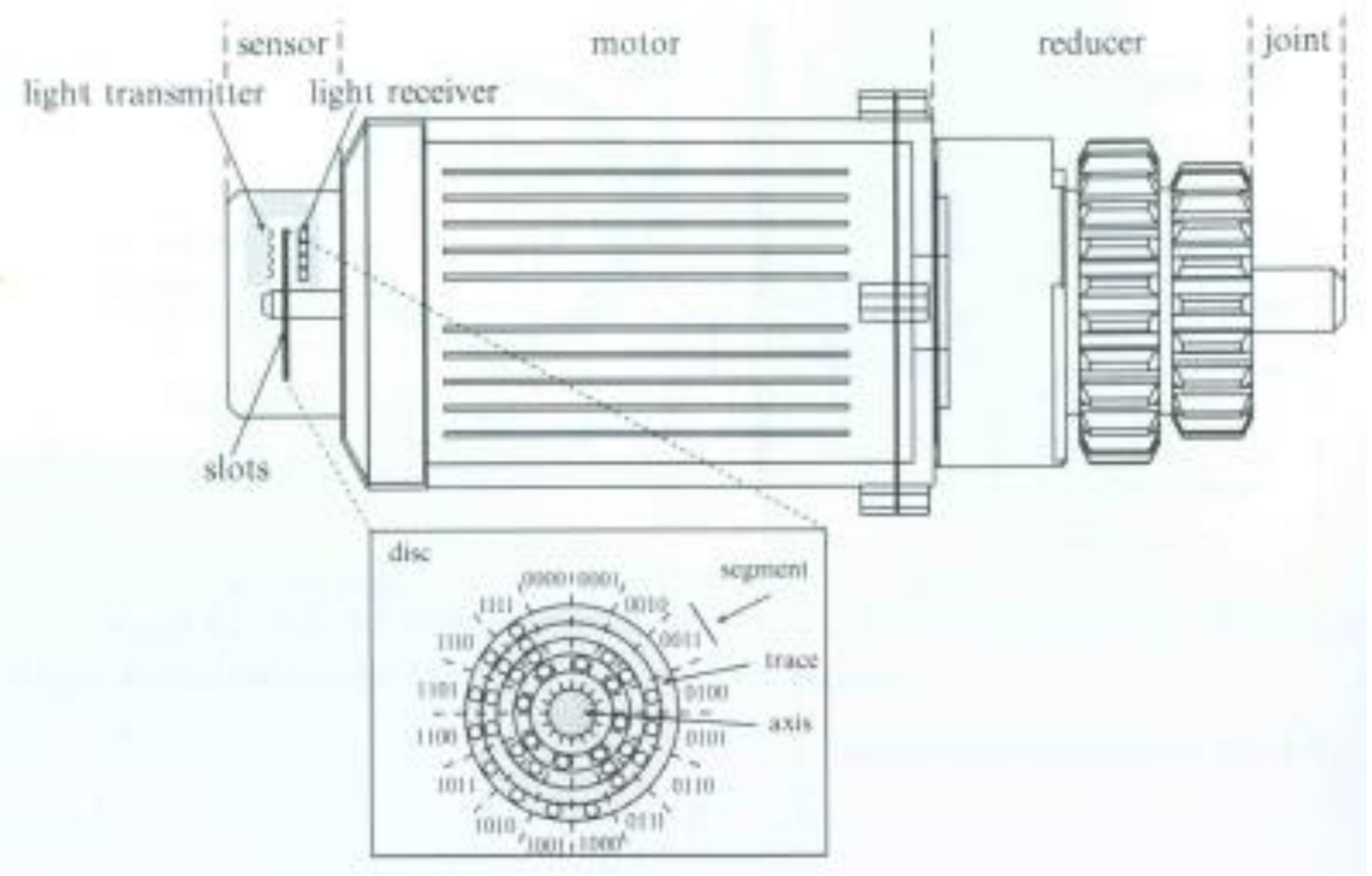


A and B are out of phase of ¼ of cycle
An increase of A with B=0 correspond to a clockwise rotation
An increase of A with B=1 correspond to a counterclockwise rotation

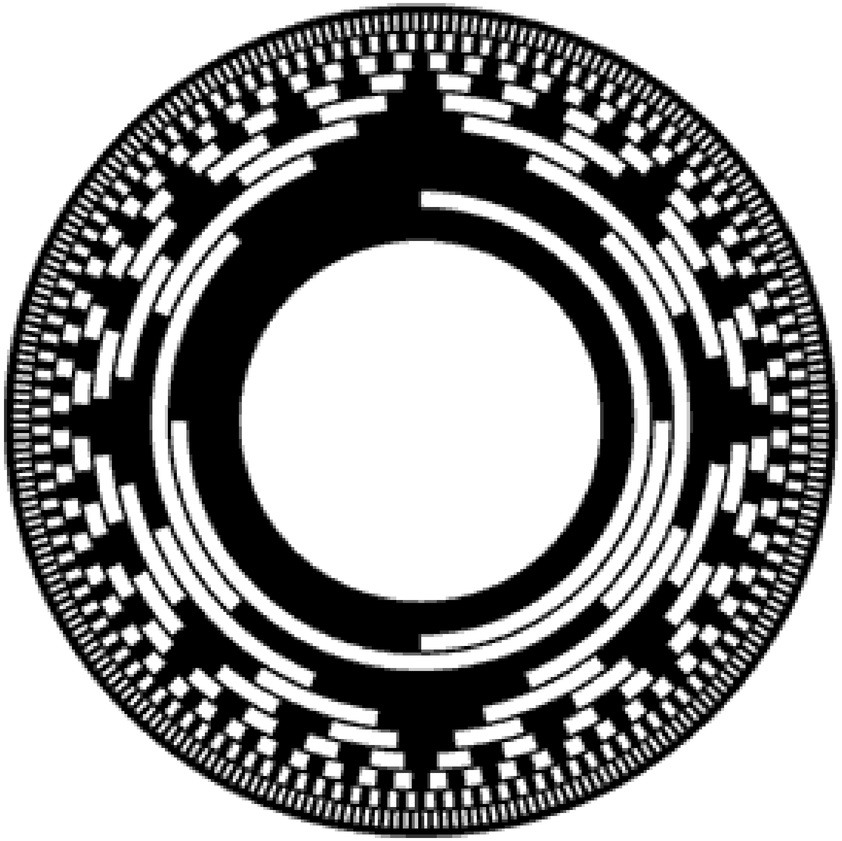
Incremental encoder



Absolute encoder



Absolute encoder



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

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

Absolute encoder

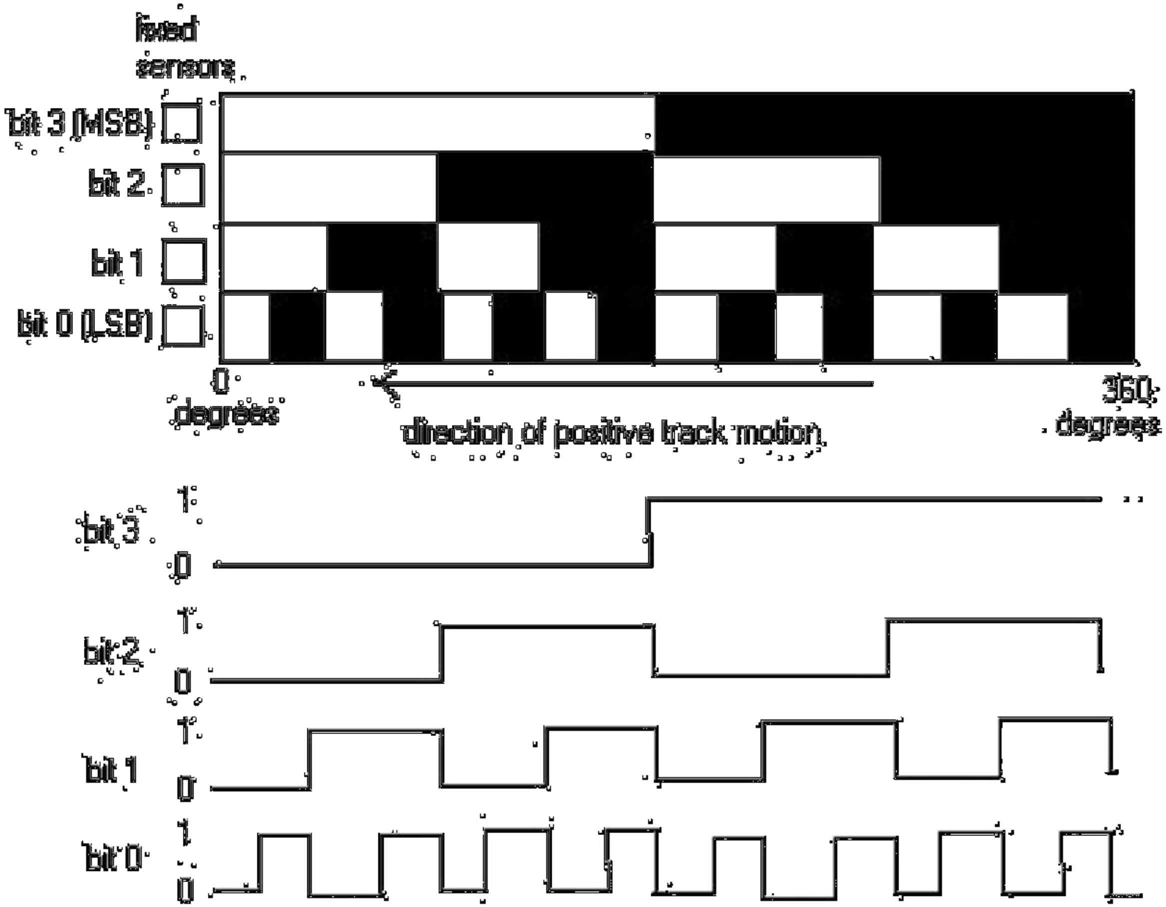


Fig 3 4-Bit binary code absolute encoder disk track patterns

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

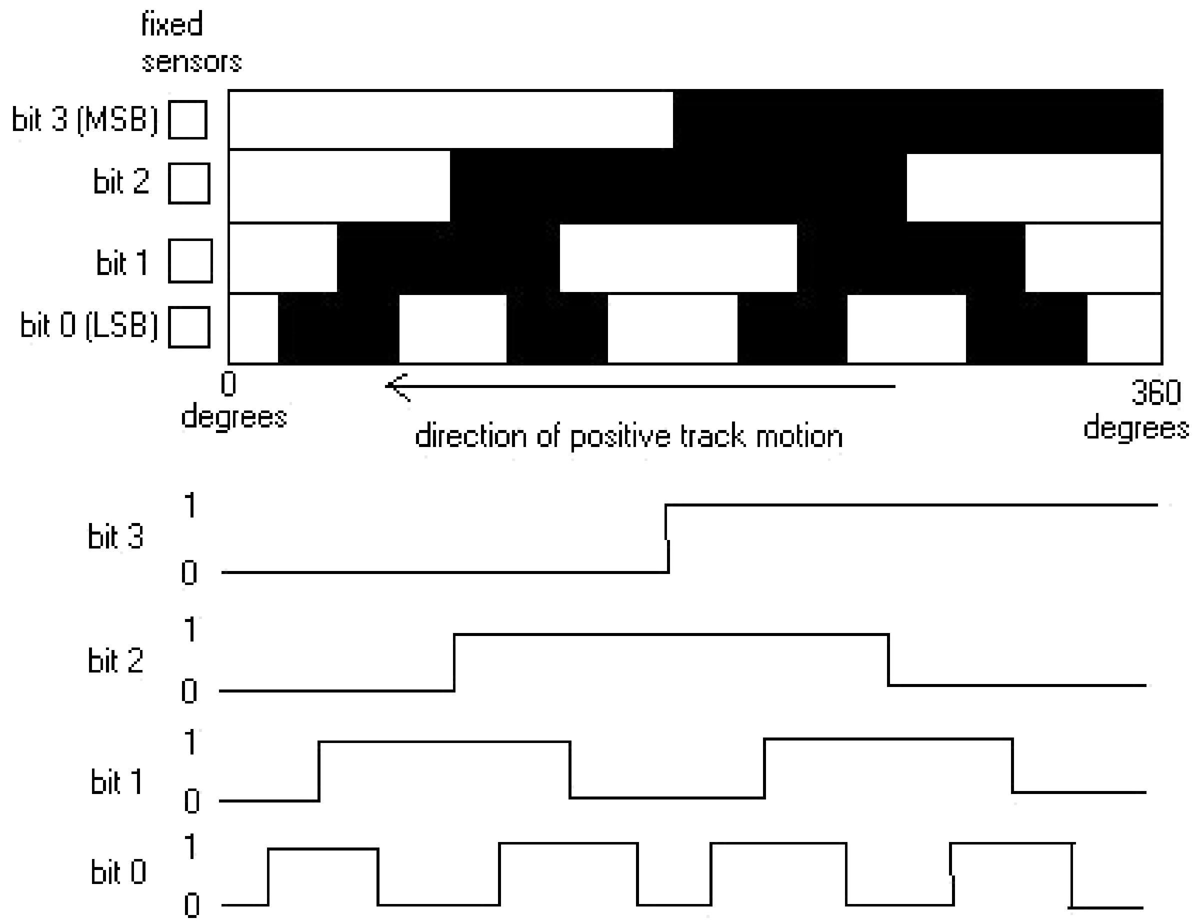
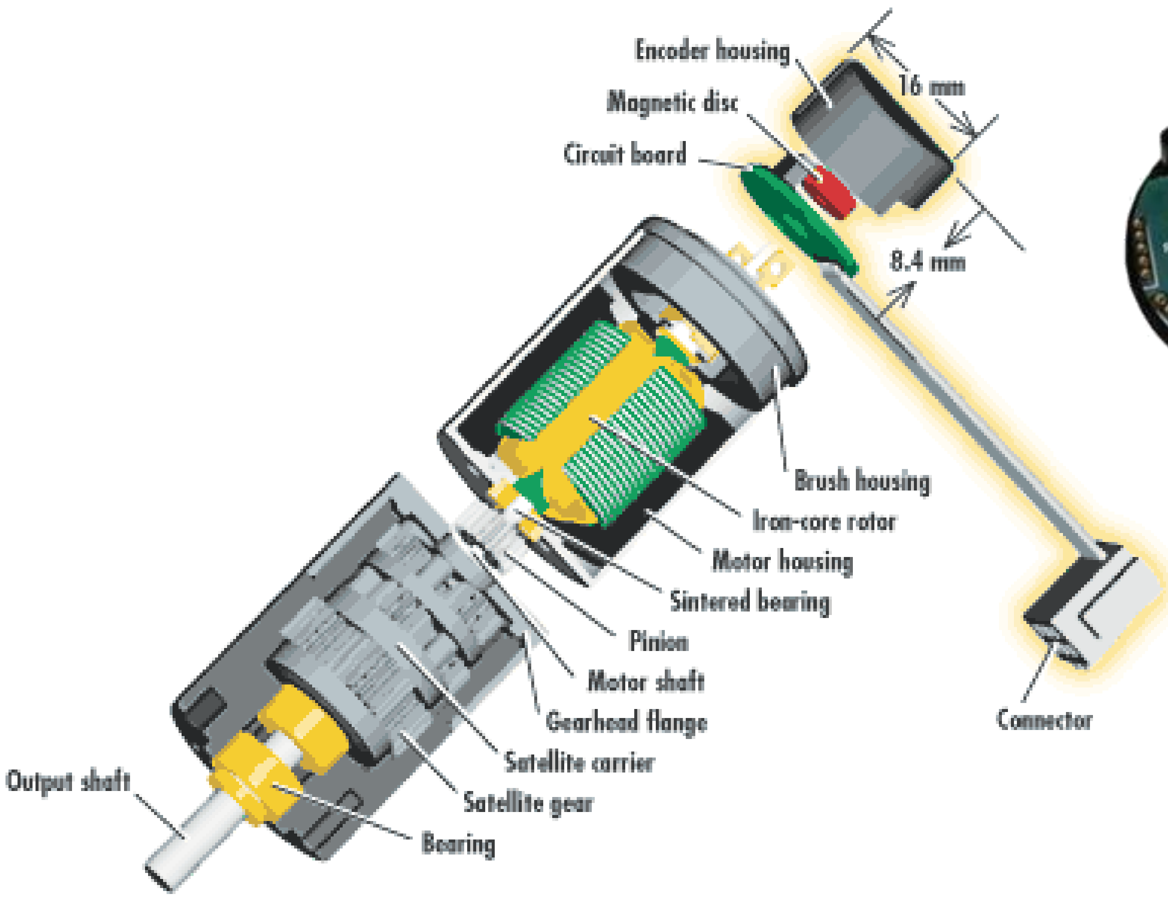
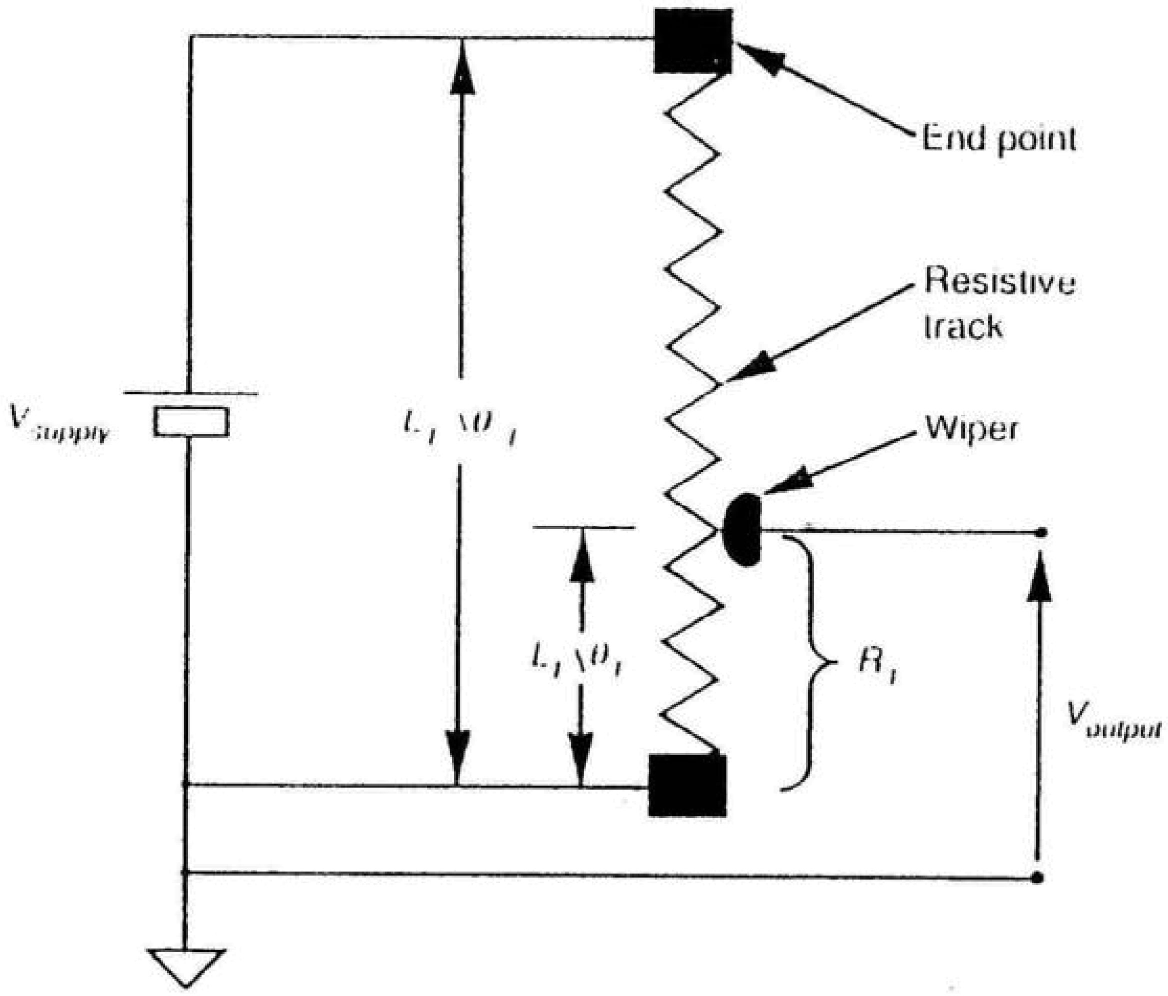


Fig 2. 4-Bit gray code absolute encoder disk track patterns

Encoder


Encoder housing
Magnetic disc
Circuit board
16 mm
8.4 mm
Brush housing
Iron-core rotor
Motor housing
Sintered bearing
Pinion
Motor shaft
Gearhead flange
Satellite carrier
Satellite gear
Bearing
Output shaft
Connector

Potentiometer



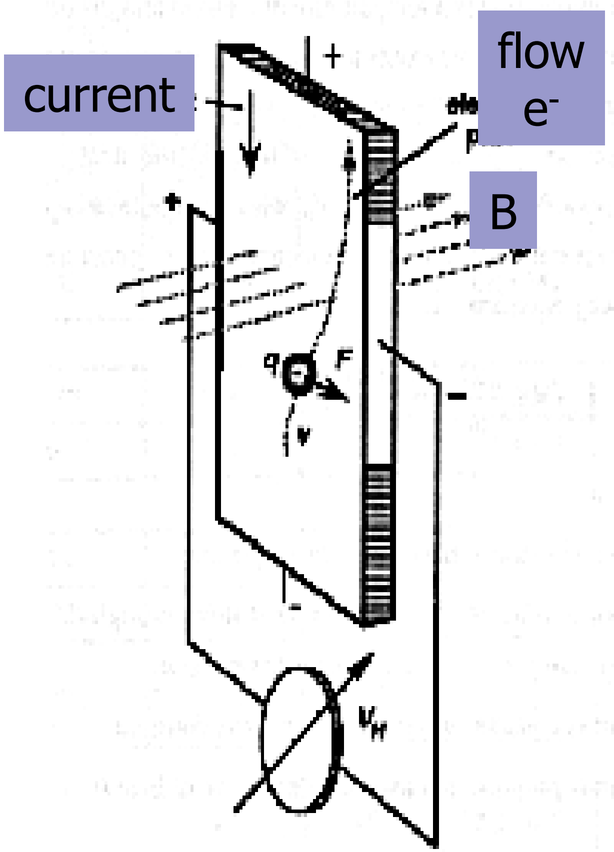
Variable resistor

$L_1 = R_1 L_T / R_T =$

$= V_{output} L_T / V_{supply}$

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.



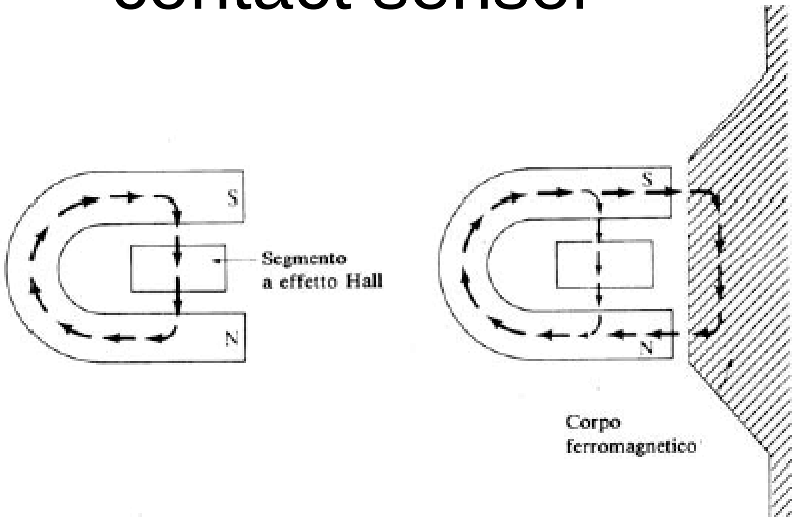
The value of the voltage is proportional to the intensity of the current i and to the intensity of the magnetic field B, while it is inversely proportional to the thickness of the material d:

$$V = R\ i\ B\ /\ d$$

where R = Hall costant or coefficient.

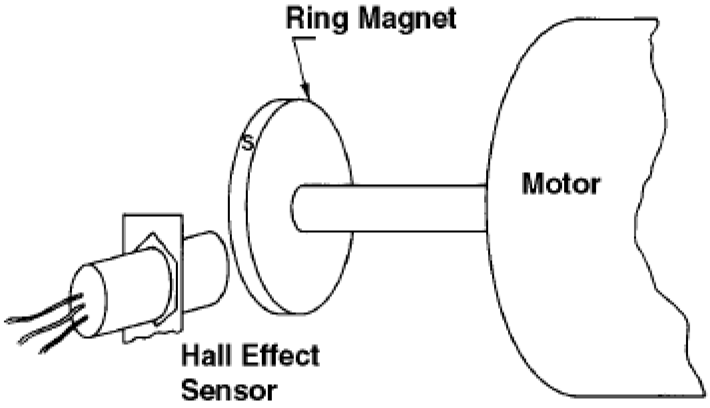
Hall-effect sensors

Hall-effect proximity and contact sensor



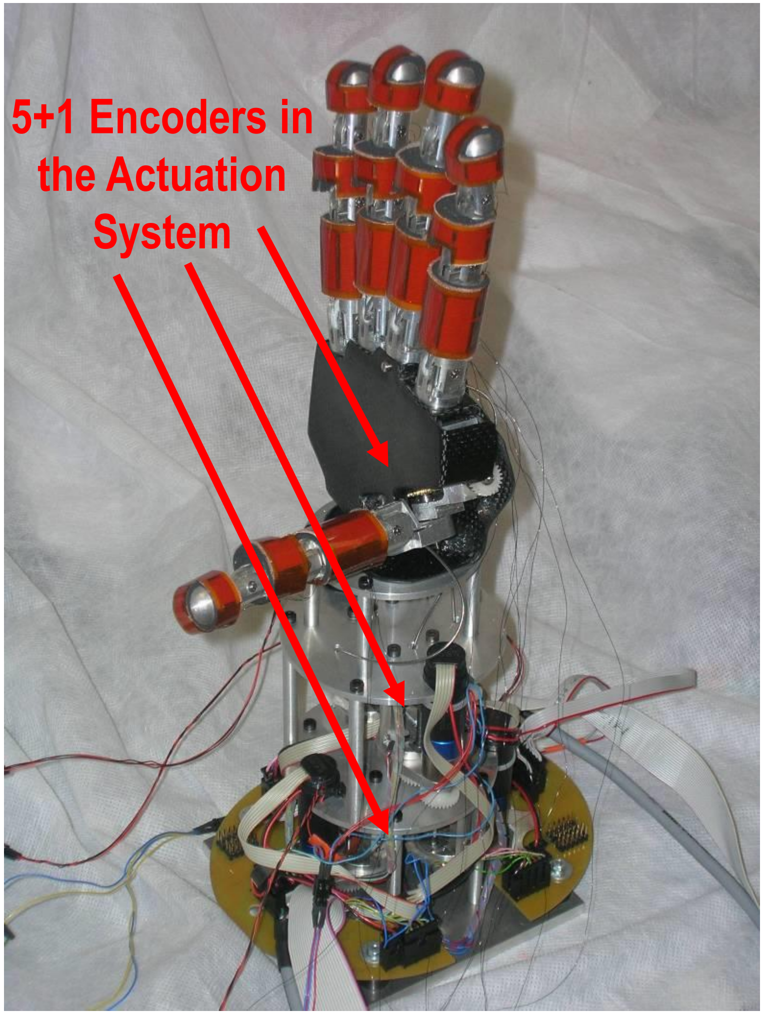
A permanent magnet generates a magnetic field.
The contact with a ferromagnetic object modifies the magnetic field.
The Hall effect allows to measure this variation as a voltage

Hall-effect position sensor



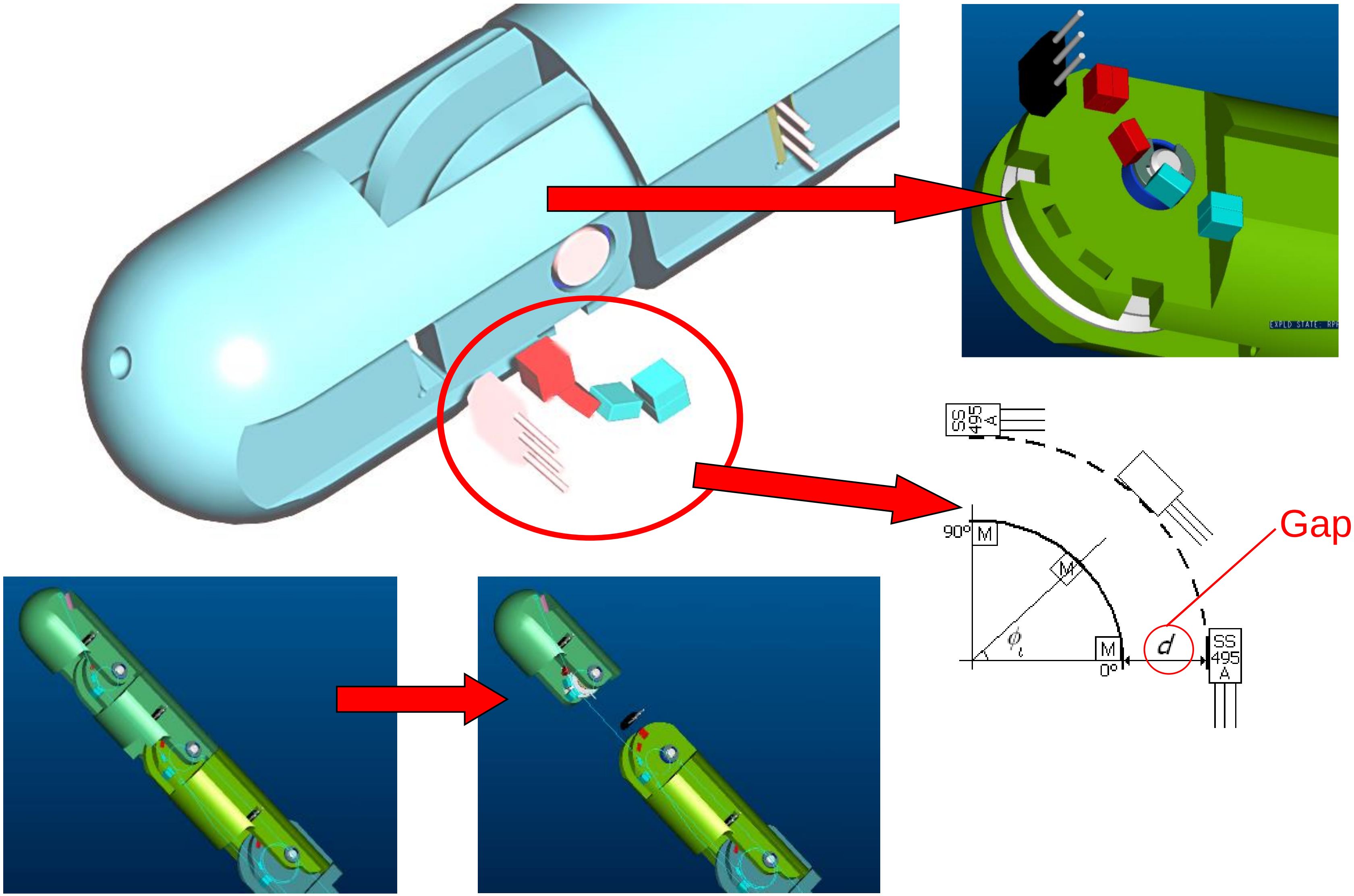
Hall-effect sensors as postion sensors in robotics

Detection of angular joint displacements



15 Embedded Joint Angle Sensors (Hall effect)
(Operational range: 0 – 90 degrees, Resolution: <5 degrees).

Hall-effect joint angle sensors



Example of application of Hall-effect sensors

Sensorized glove for detecting finger position

Esempio di applicazione di sensori a effetto Hall

Guanto sensorizzato per rilevare la

posizione delle dita

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.

Modulo sensore (brevettato)

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

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

RINA

Modulo sensore (brevettato)

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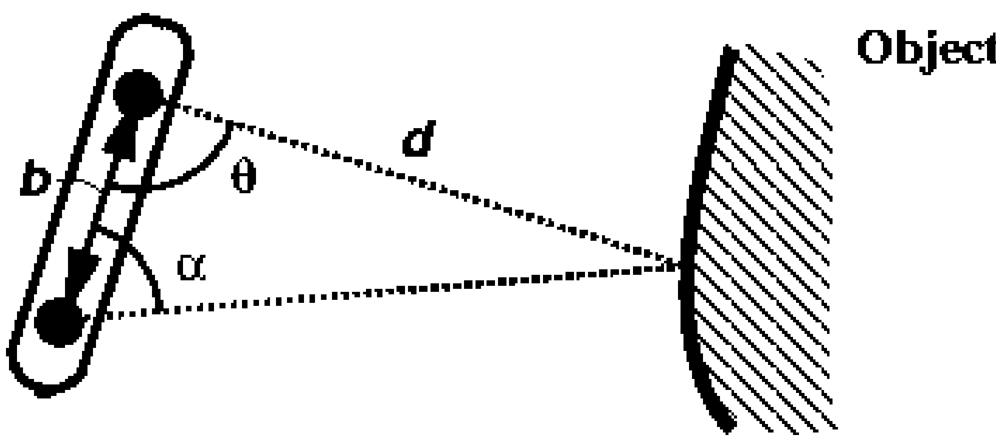
Range/distance sensors

Range is the distance between the sensor and the object detected.
Range sensing is important for object recognition and for robot control.
It is often used together with a vision system to reconstruct the 3D model of a scene.
The physical principle for range sensing is triangulation, that is the detection of an object from two different points of view, at a known relative distance



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

Distance measurement: triangulation

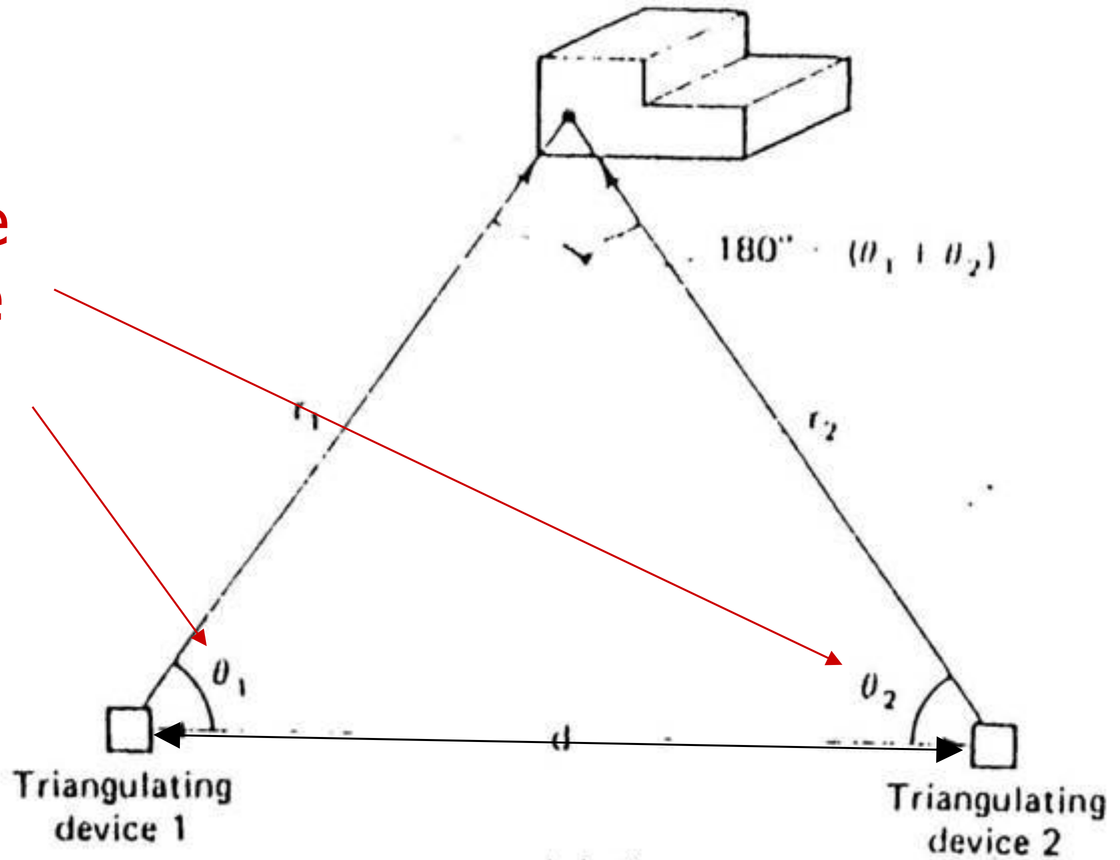
If two imaging devices at a known distance can focus on the same point of an object, then the distance of the object can be measured, by knowing the vergence angles.

PASSIVE TRIANGULATION: uses two imaging devices

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

Passive triangulation

Using the vergence angles

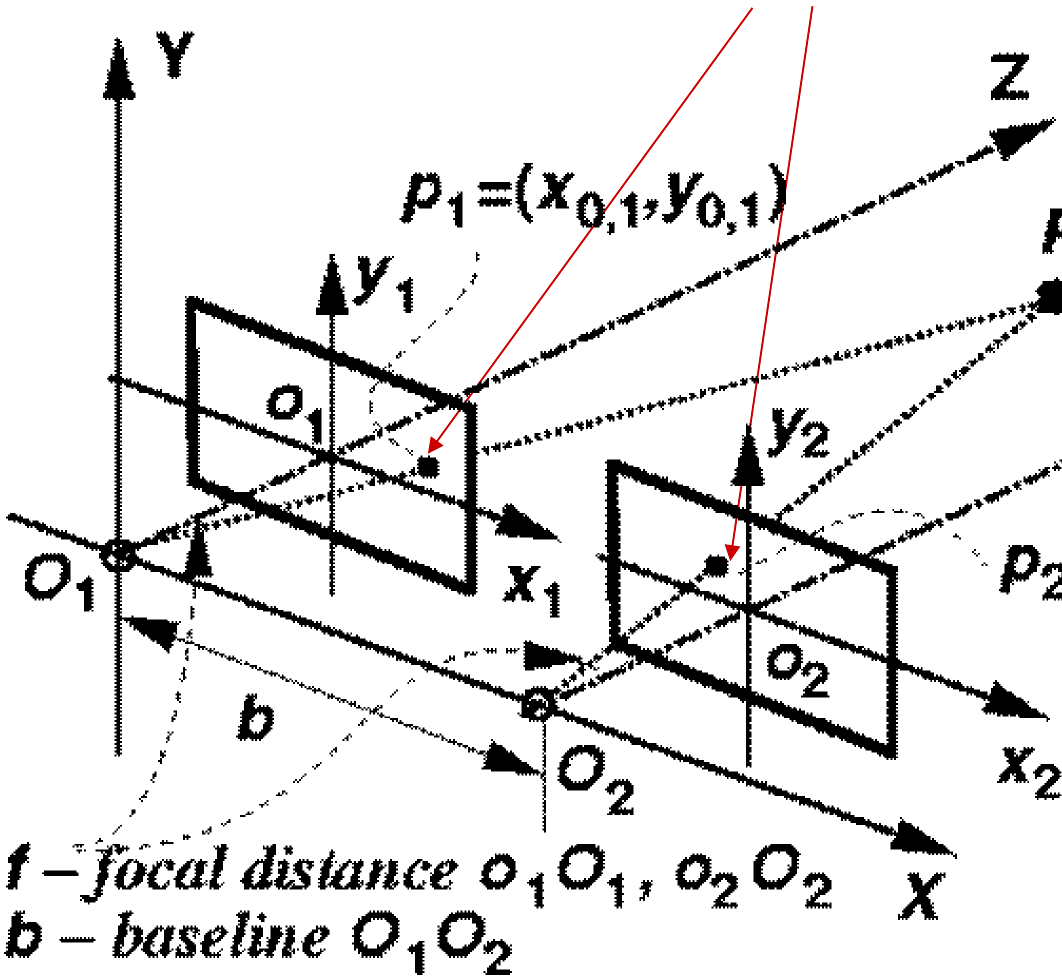


$$r_1 = \frac{d \sin \theta_2}{\sin[180° - (\theta_1 + \theta_2)]}$$

$$r_2 = \frac{d \sin \theta_1}{\sin[180° - (\theta_1 + \theta_2)]}$$

Passive triangulation

Using the projections of the same point in the two images

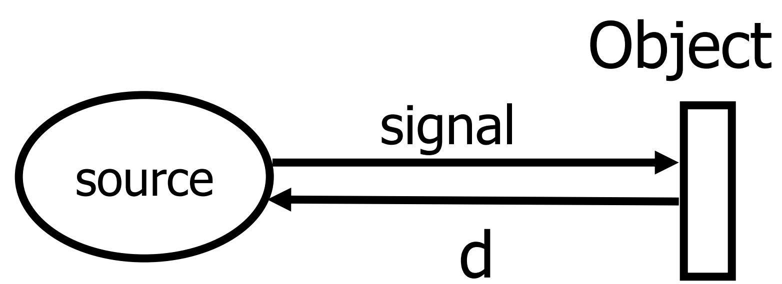


$$Z_0 = \frac{bf}{x_{0,1} - x_{0,2}}$$

Distance measurement: time of flight

The measurement of the distance of an object is given by the measurement of the time needed by a signal to reach the object and to come back

$$d = (v \times t)/2$$



d = object distance

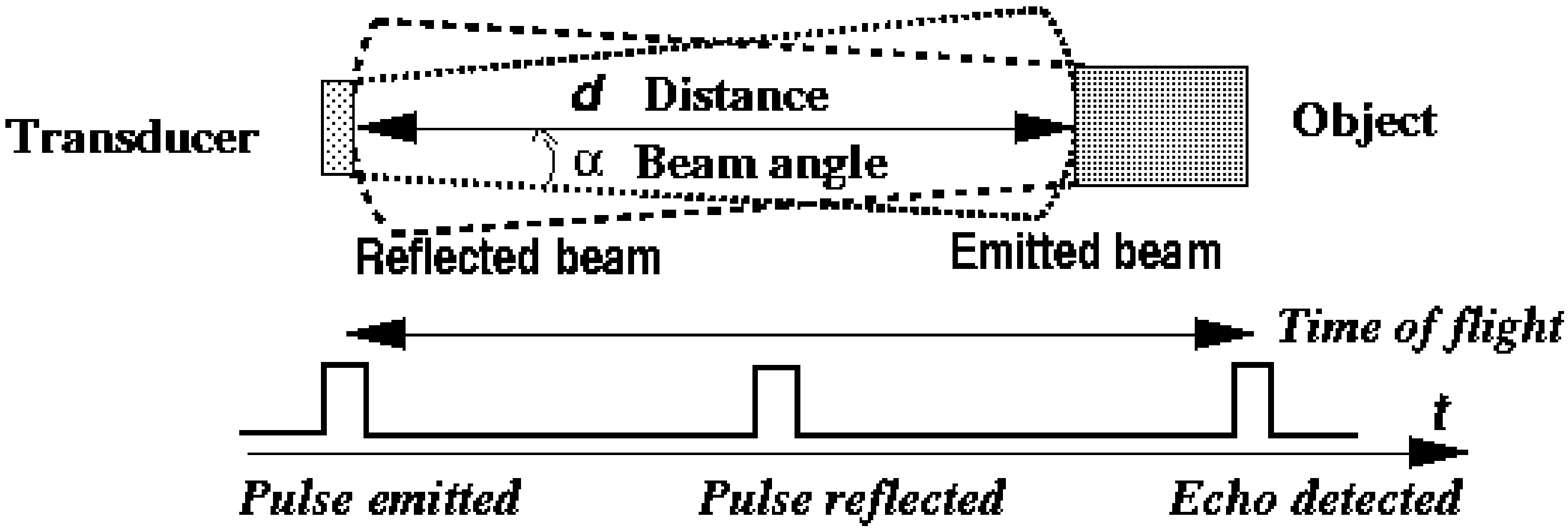
v = signal velocity

t = time needed by the signal to reach the object and to come back

Time of flight measurement:

(example: *radar* and ultrasonic *sonar*) $d = 0.5\, t_e\, v$

where v is the average speed of the signals emitted (air or water) and t_e is the time between the signal emitted and the signal echo received.



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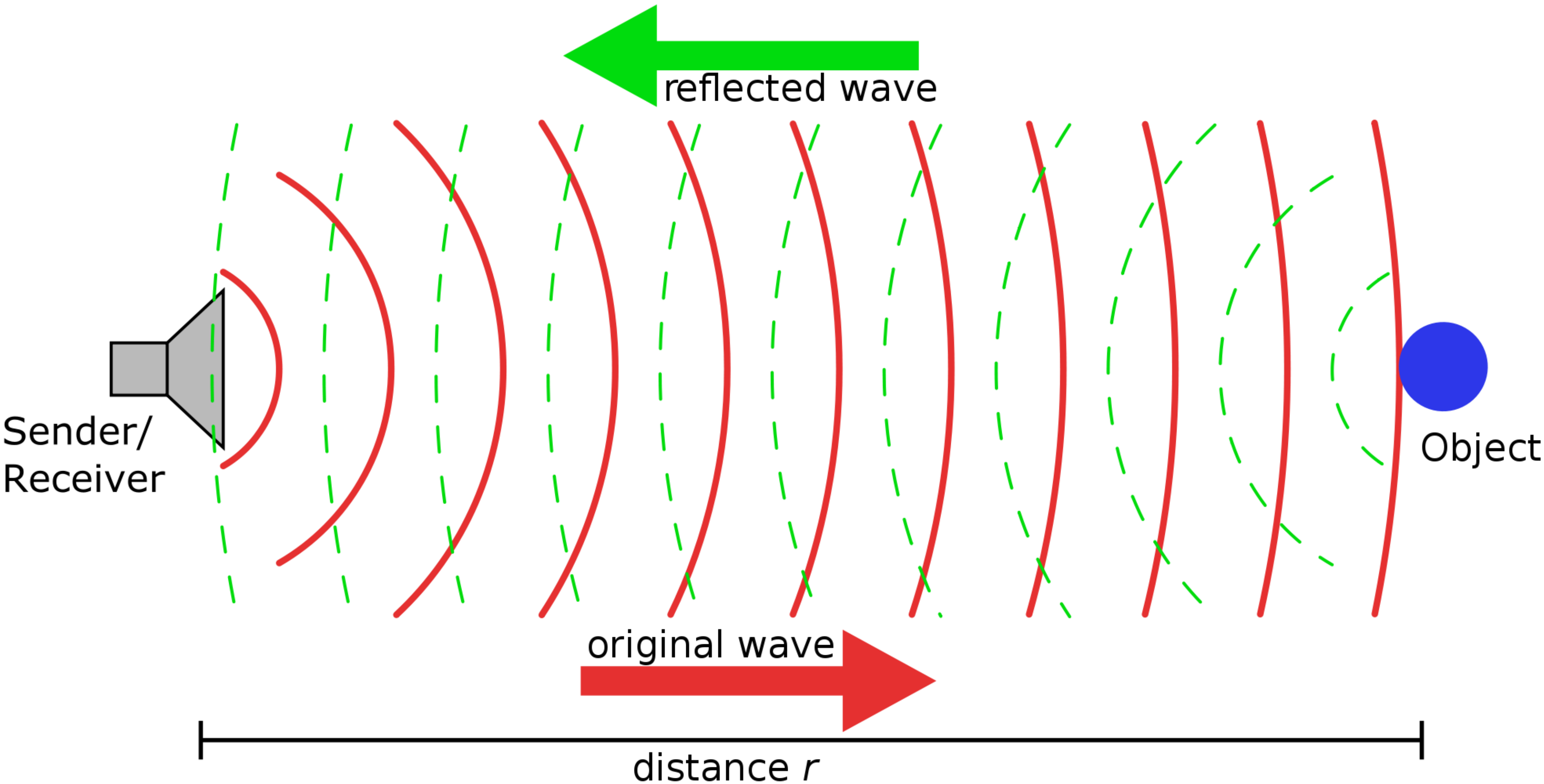
Fu, Gonzalez, Lee, *Robotics*, McGraw-Hill, Cap.6

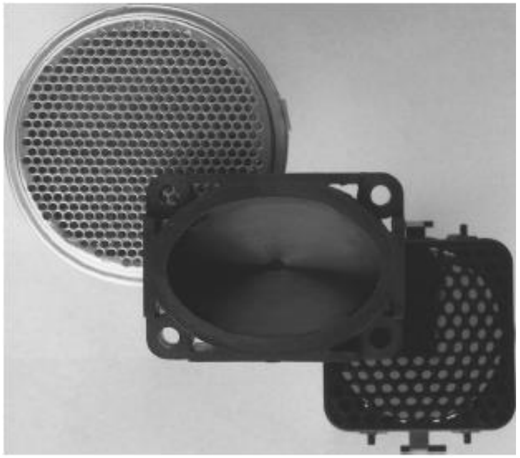
Russel, *Robot Tactile Sensing*, Prentice Hall, Cap.4

Ultrasound sensors



Ultrasound sensors

2 main components:
- ultrasound transducer (working both as emitter and as receiver)
- electronics for computing the distance

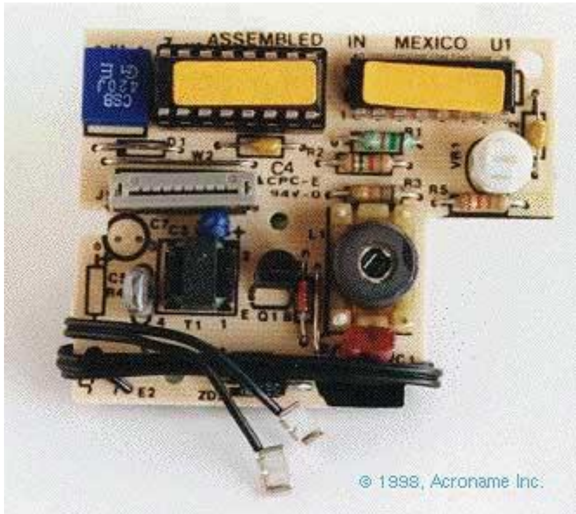


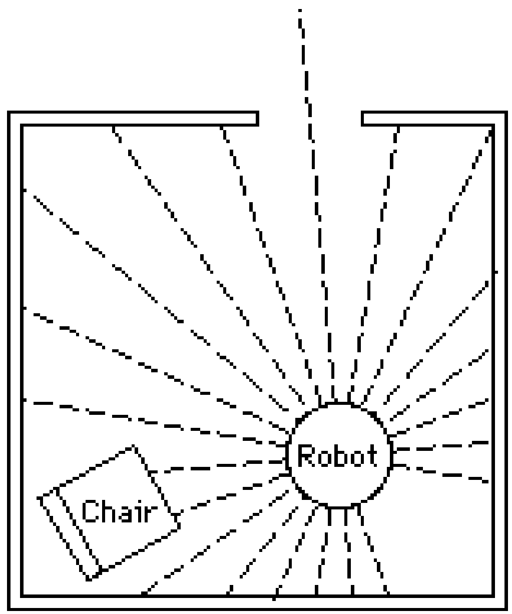
Range: 0.3m to 10.5m
Beam amplitude: 30°
Accuracy: ca. 25mm

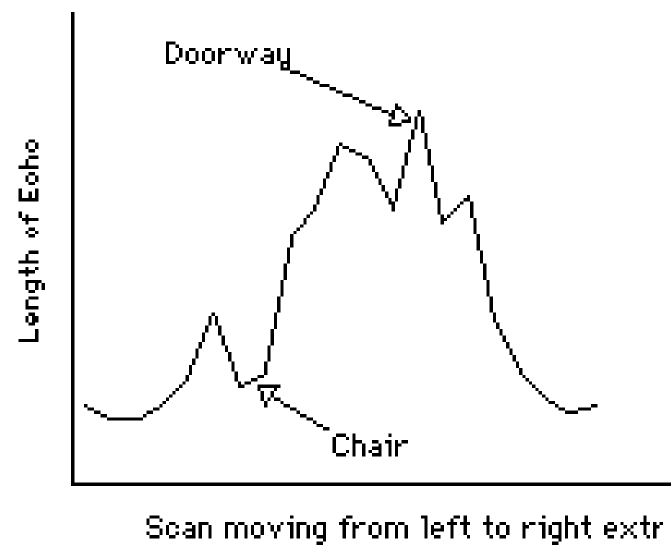
Typical working cycle:
- the electronics controls the transducer to send ultrasounds
- the receiver is disabled ofr a given time, in order to avoid false responses due to residual signal in the transducer
- the received signal is amplified with an increasing gain, to compensate the reduction of intensity with distance
- echos above a given threshold are considered and associated to the distances measured from the time passed from transmission

Examples of application of ultrasound sensors on mobile robots

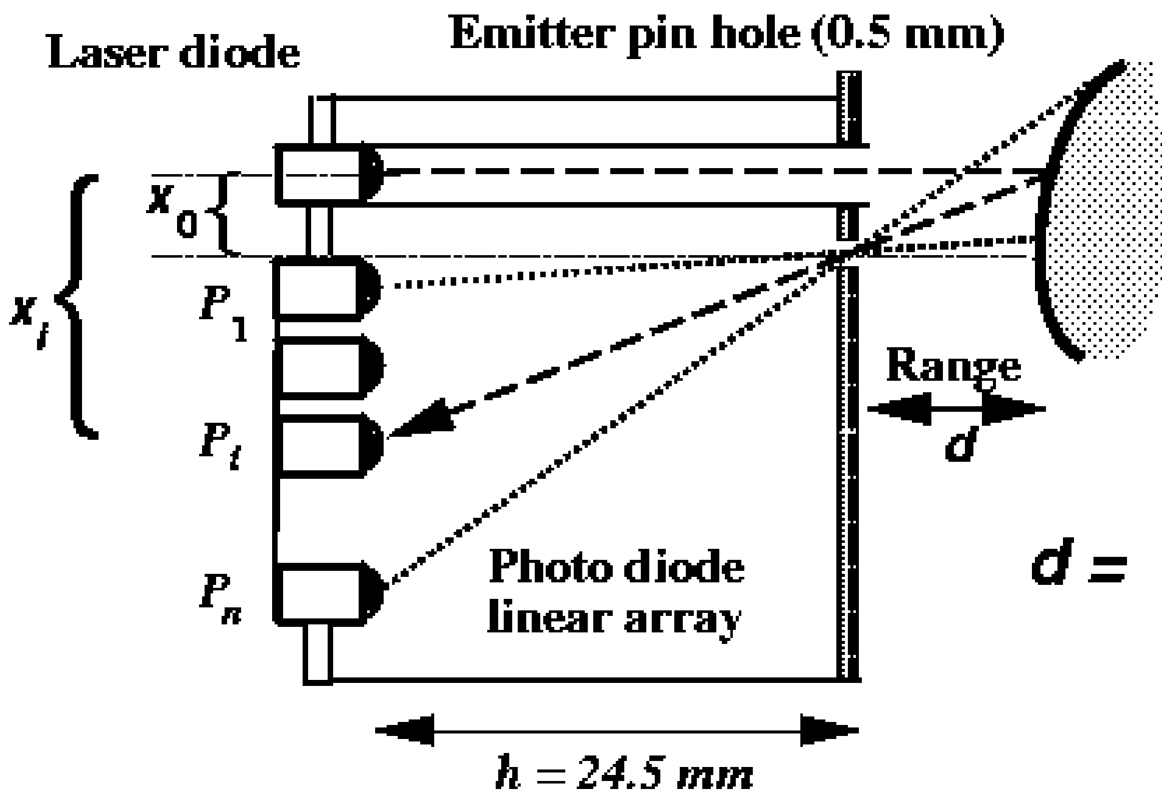
B21 US sensors







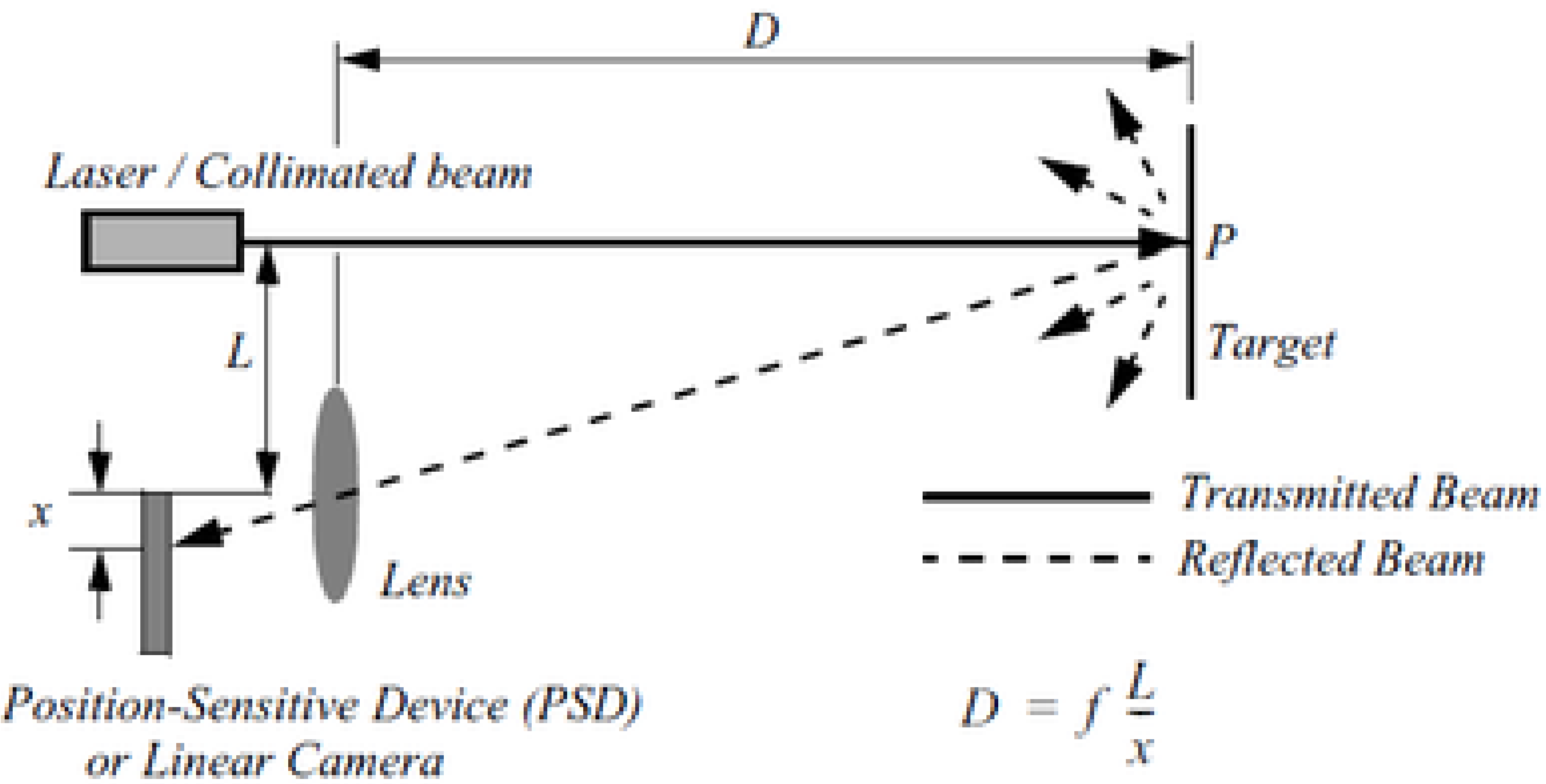
LASER RANGE FINDERS



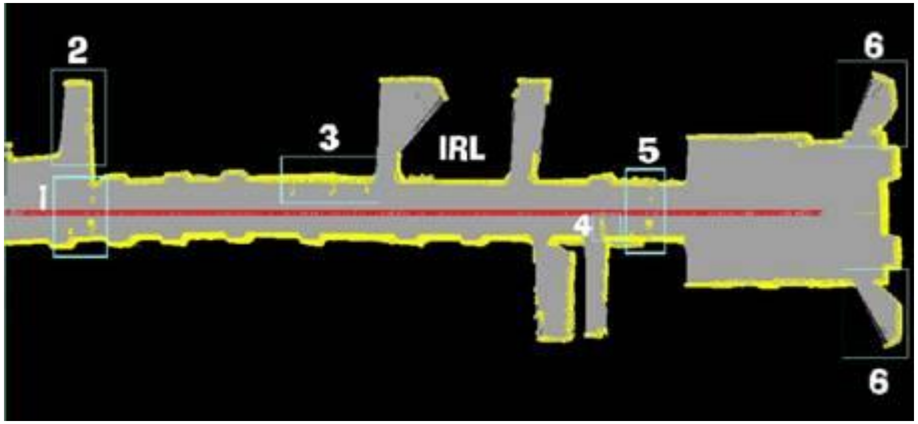
$$d = \frac{hx_0}{x_i - x_0}$$

A simple **pin-hole short-range-finding sensor** uses a laser diode as a light source, and a linear photo-diode array as a detector. The range from a sensor to the object is a function of the position of the maximum detected light along the array.

LASER RANGE FINDERS



B21 LaserFinder LMS 200



Map building using the LMS 200 laser scanner

Technical specification			
	Angular Resolution		1° / 0,5 ° / 0,25°
	Response Time (ms)		13 / 26 / 53
	Resolution (mm)		10
	Systematic Error (mm mode)		+/- 15 mm
	Statistic Error (1 Sigma)		5 mm
	Laser Class		1
	Max. Distance (m)		80
	Data Interface		RS422 / RS232

Proximity sensors

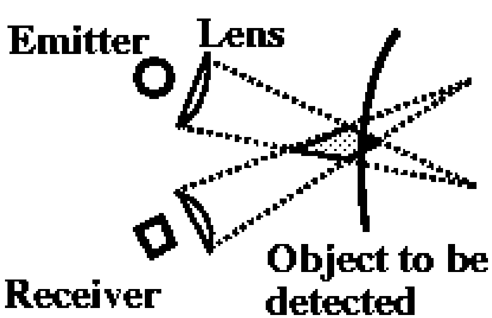
Sensing the presence of an object in a spacial neighborhood

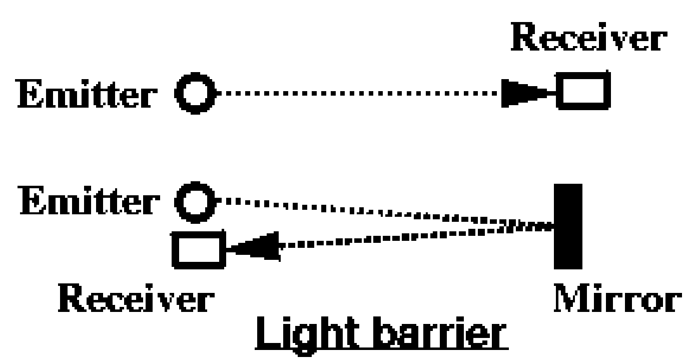
Passive proximity sensors: detect perturbations of the environment, like for instance modifications of the magnetic or the electric field

Active proximity sensors: exploit the variations of an emitted signal, occurring due to the interrupt or the reflection of the signal flight towards the receiver

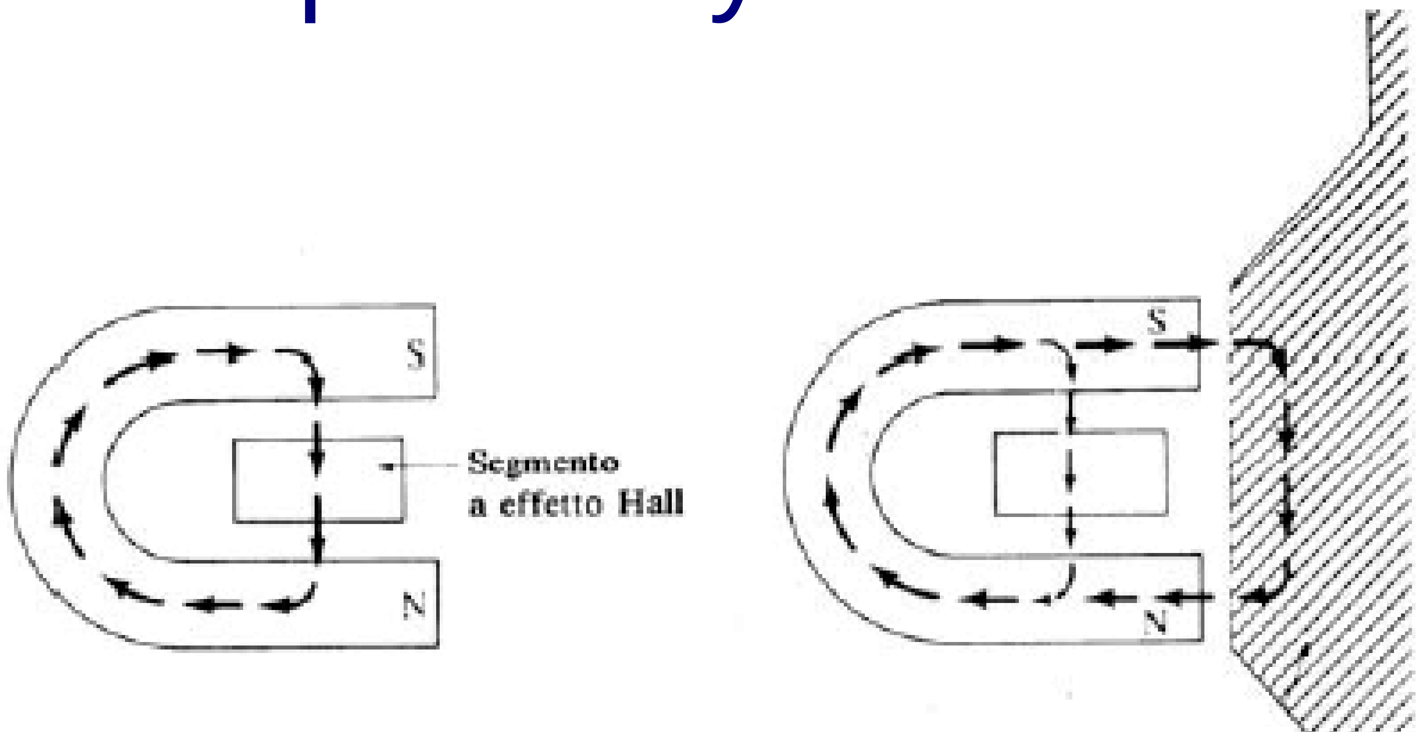
Ex: magnetic passive sensors: Hall-effect sensors

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





Hall-effect proximity 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

Optical sensors

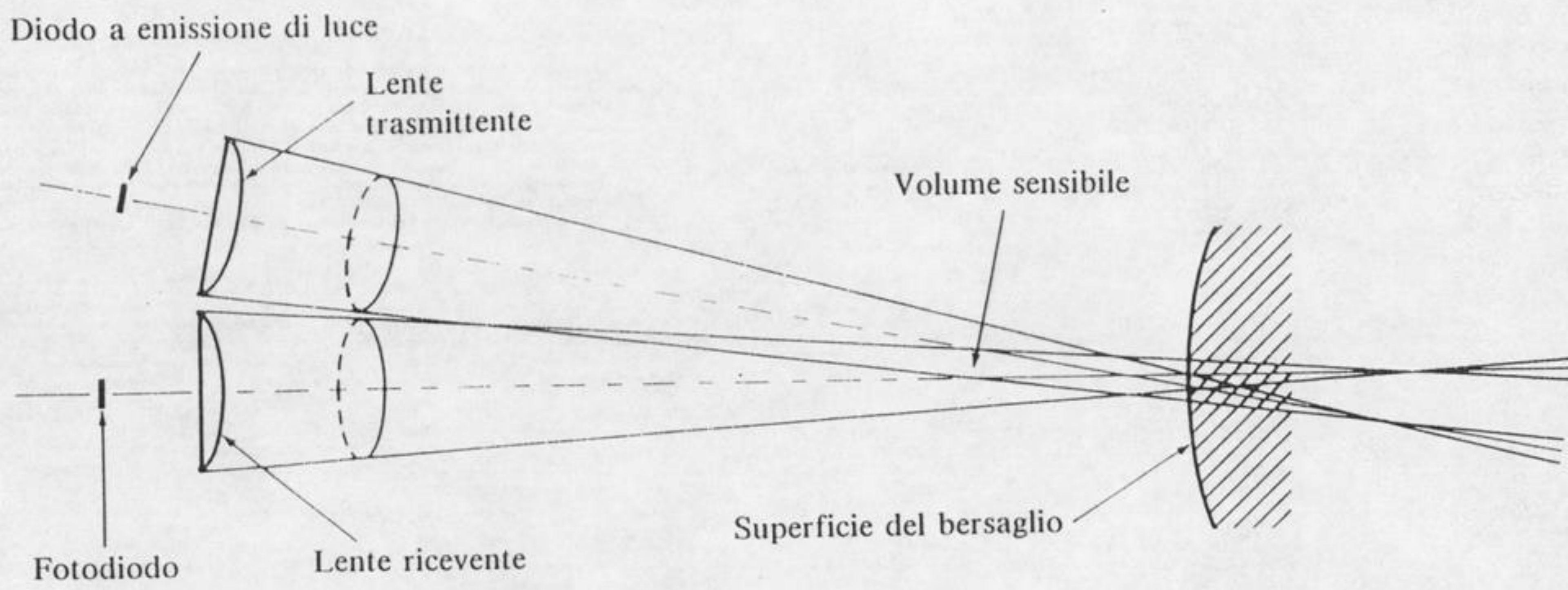


Figura 6.16 Sensore ottico di prossimità. (*Da Rosen e Nitzan* [1977], © *IEEE*).

B21 IR sensors

Sharp GP2D02 IR Distance Measuring Sensor

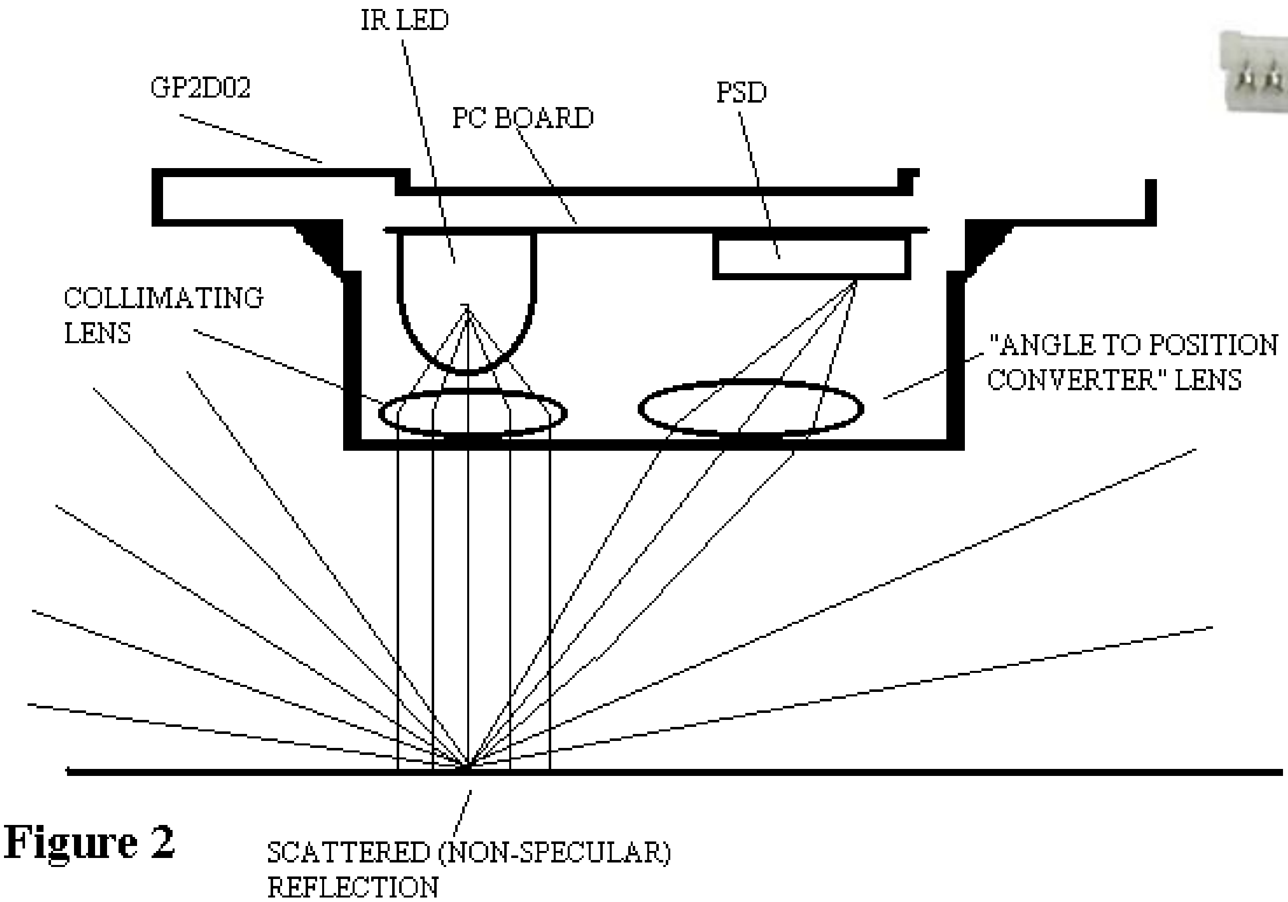


Figure 2

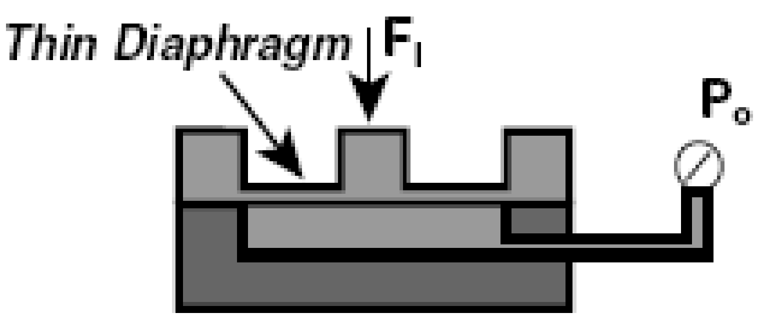
Outline of the lesson

- Definitions of sensor and transducer
- Classification of transducers
- Fundamental properties of sensors
- Position sensors: switches, encoders, potentiometers, Hall-effect sensors
- Distance measurement: triangulation, time of flight
- Proximity sensors: ultrasound and infrared sensors
- Force sensors: strain gauges and force/torque sensors
- Inertial sensors

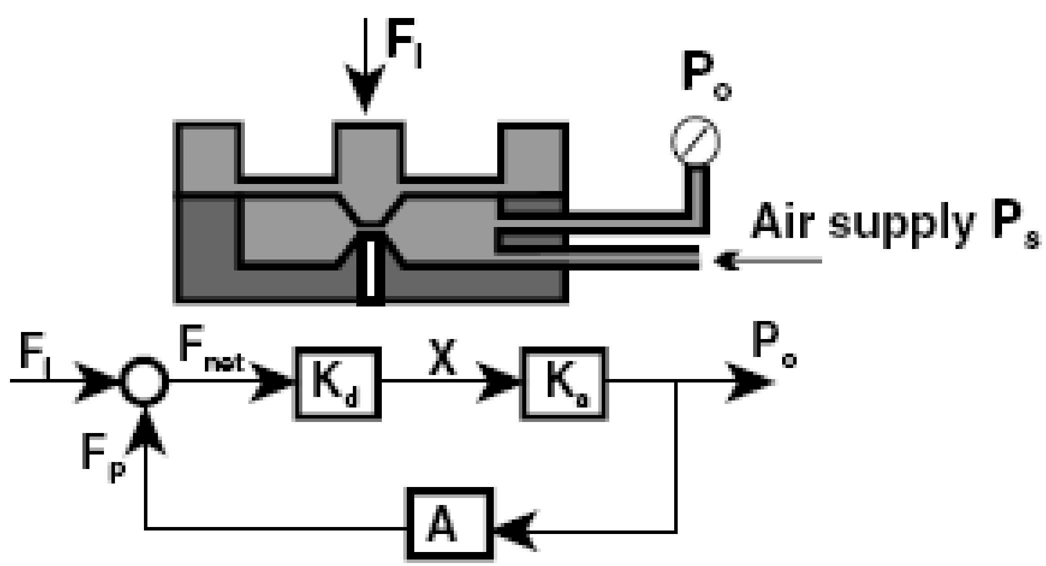
Bibliographical references:
AA.VV., *Handbook of Mechatronics*, CRC Press LLC, 2002, Cap.19

Load cell structures

- Rigid external structure
- Mean for measuring the applied force
- Measuring element



Hydraulic load cell



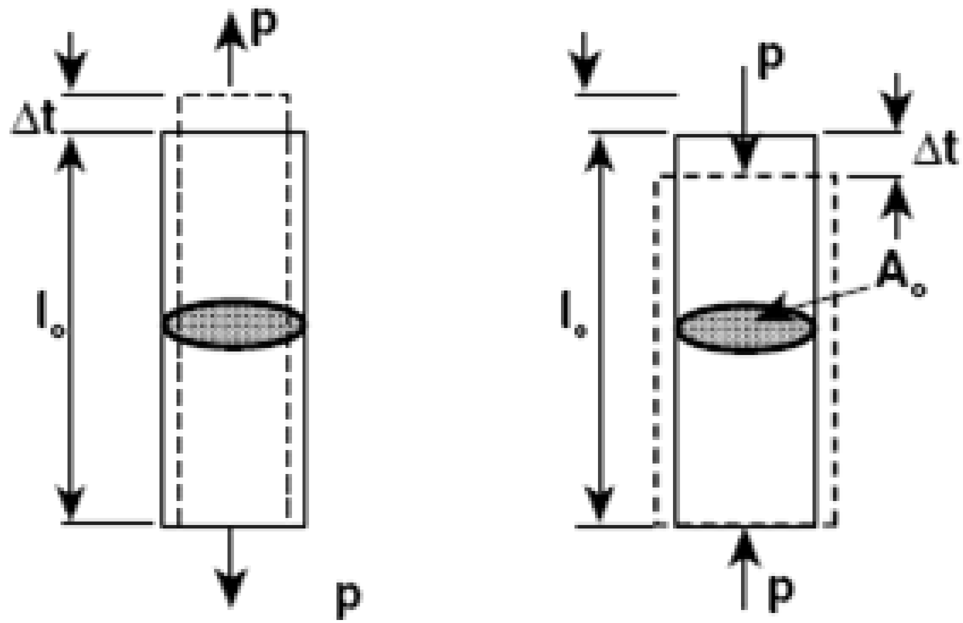
Pneumatic load cell

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

$$\sigma = {p}/{A_0}$$

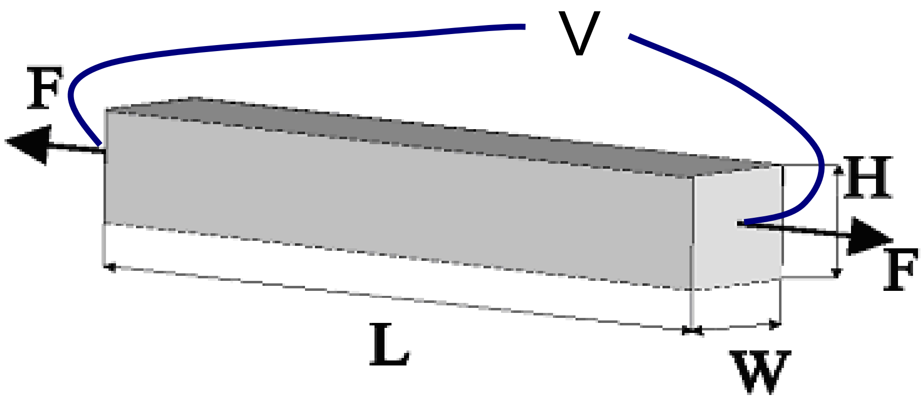
strain

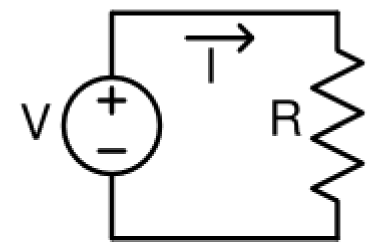
$$\varepsilon = {\Delta l}/{l_0}$$

Poisson's ratio: $\nu = -\frac{\delta A / A_0}{\varepsilon}$ Elasticity module: $E = \frac{\sigma}{\varepsilon}$

Piezoresistive effect

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





V=RI

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

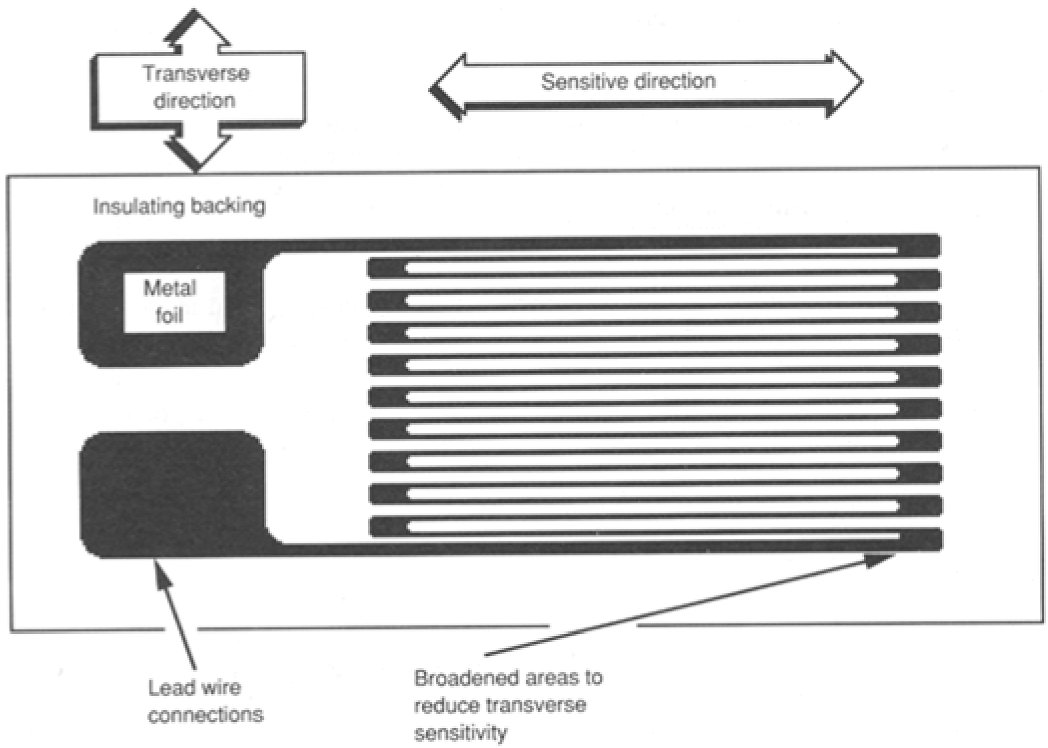
with ρ = resistivity of the material,

L, W, H = dimensions of the block

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

v = Poisson's ratio of the material

Strain gauge

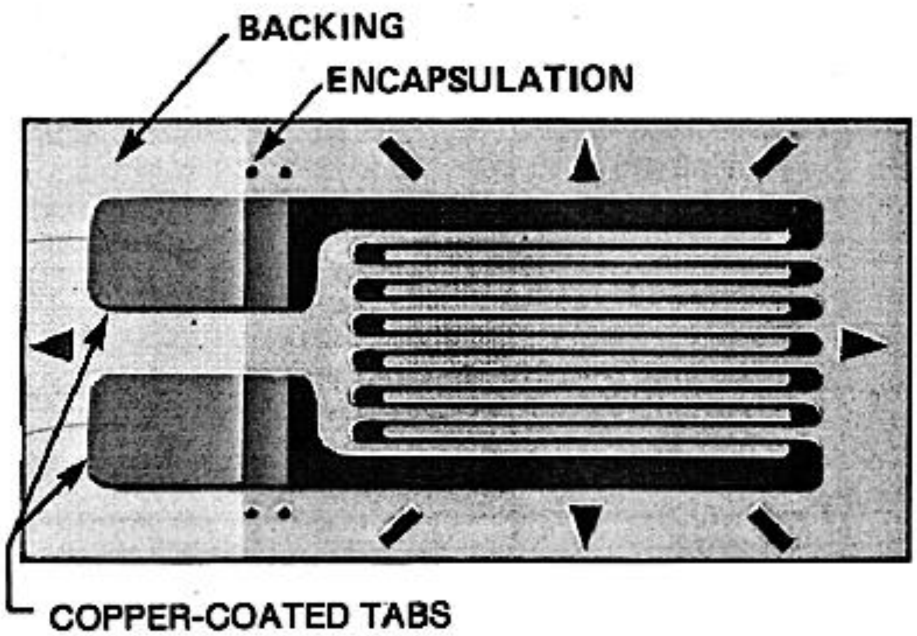


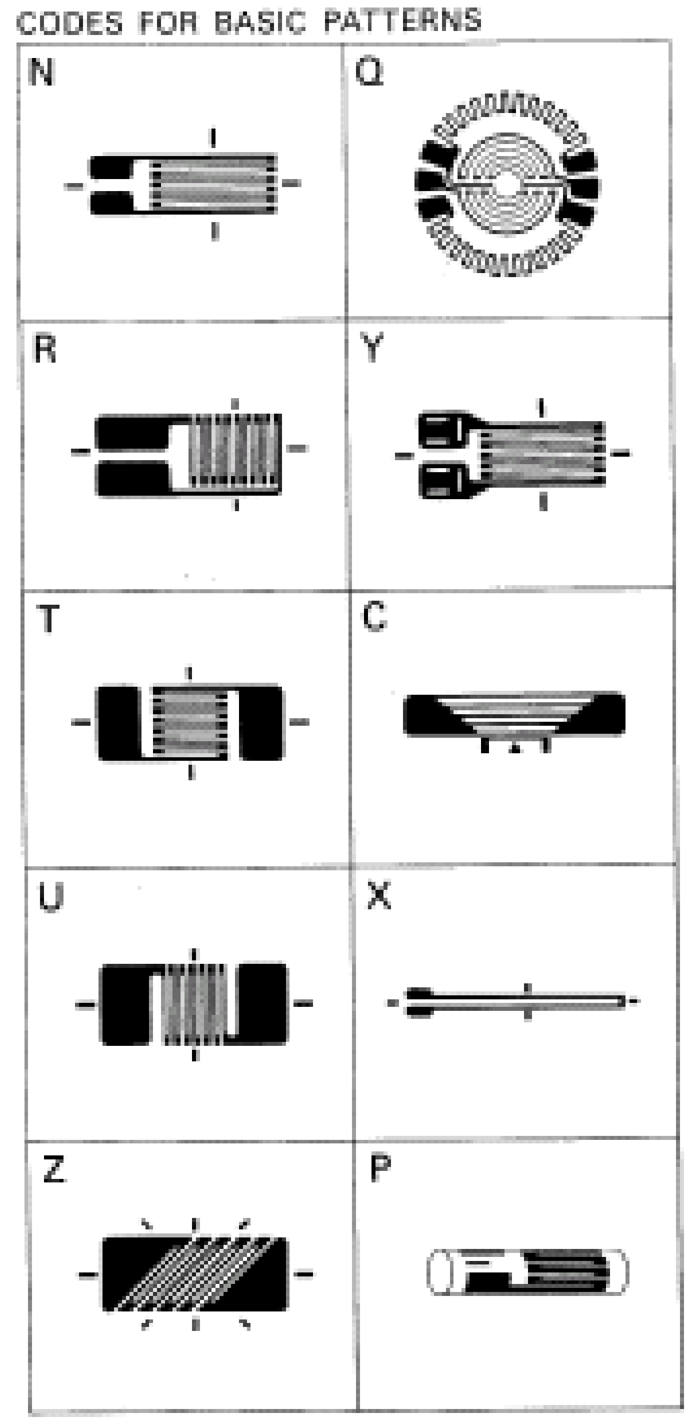
The sensor shape increases sensitivity in one direction

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

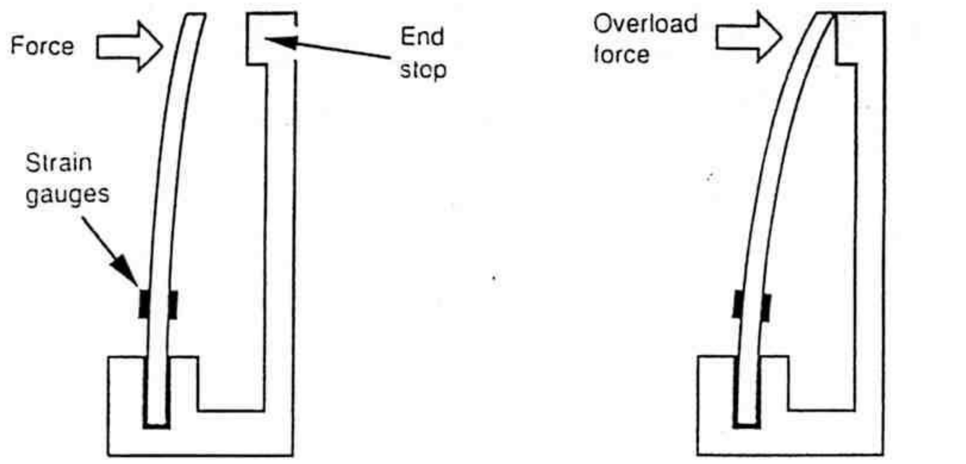
v = Poisson's ratio of the material

Strain gauges

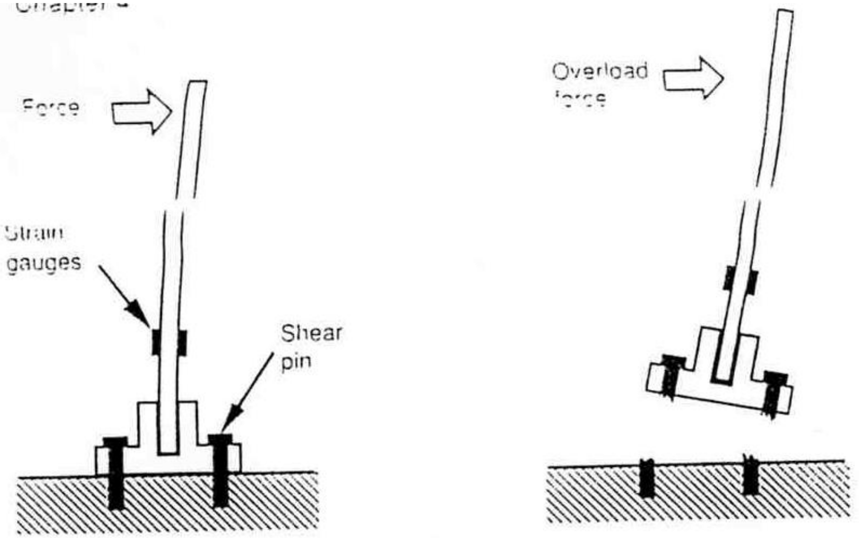




Sensors with strain gauges

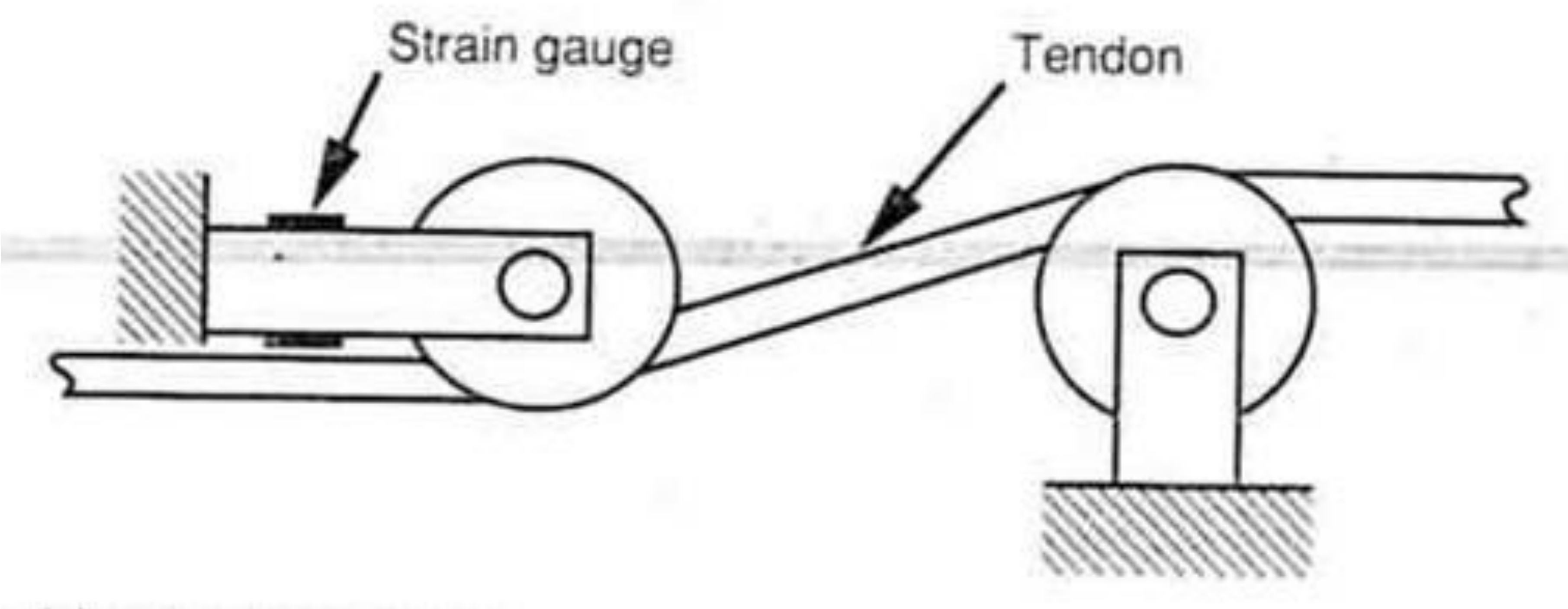


(a) Small applied force (b) Overload force applied

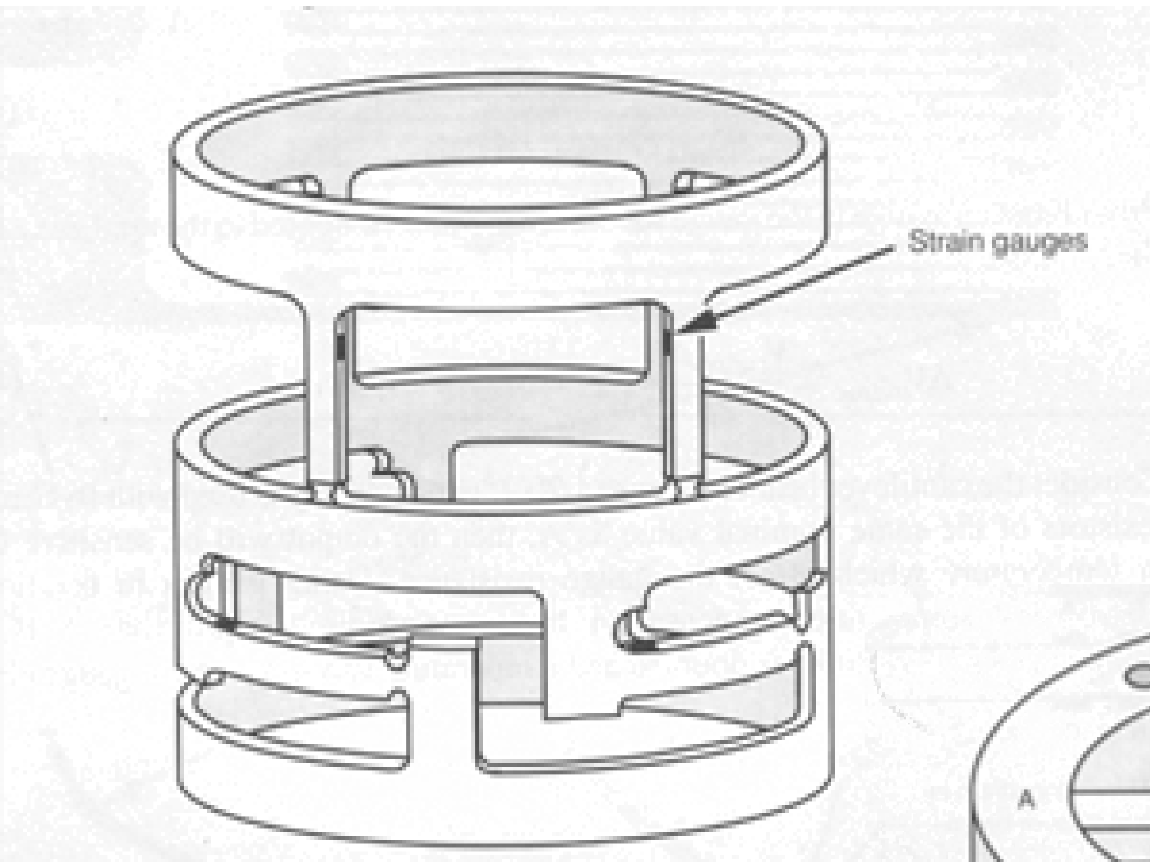


(a) Small applied force (b) Overload force applied

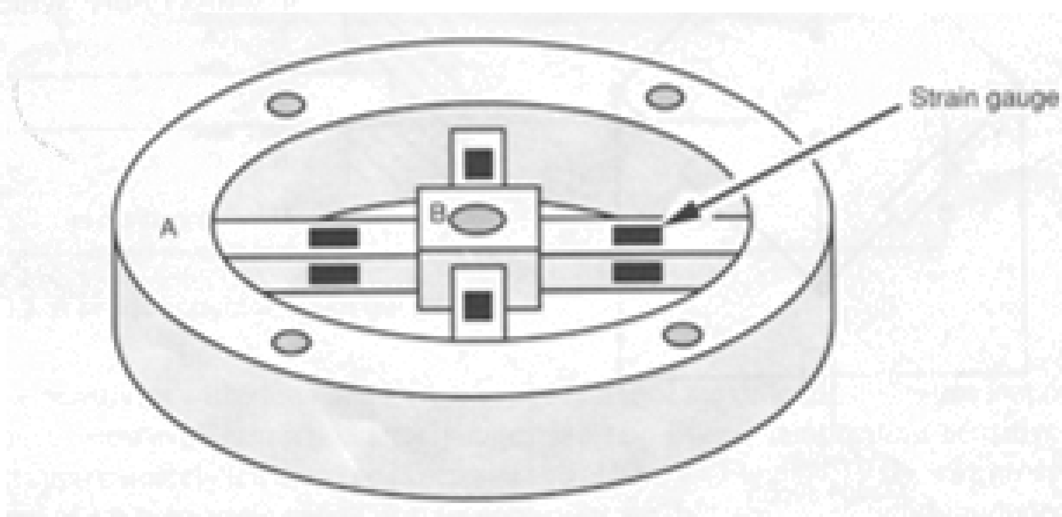
Cable tension sensor



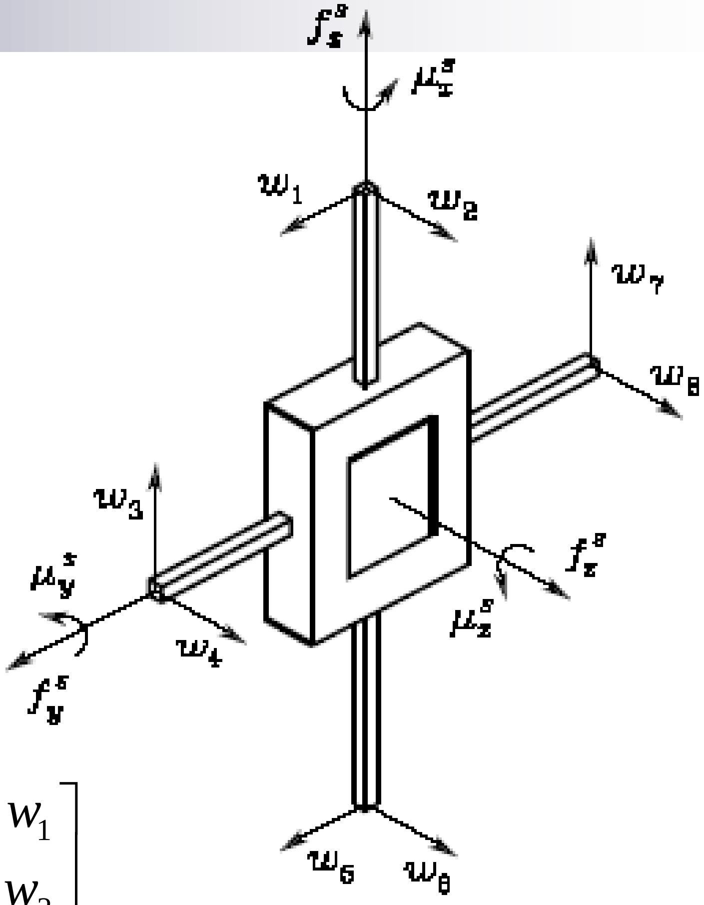
Three-axial force/torque sensors



- 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

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

Example of application of force sensors

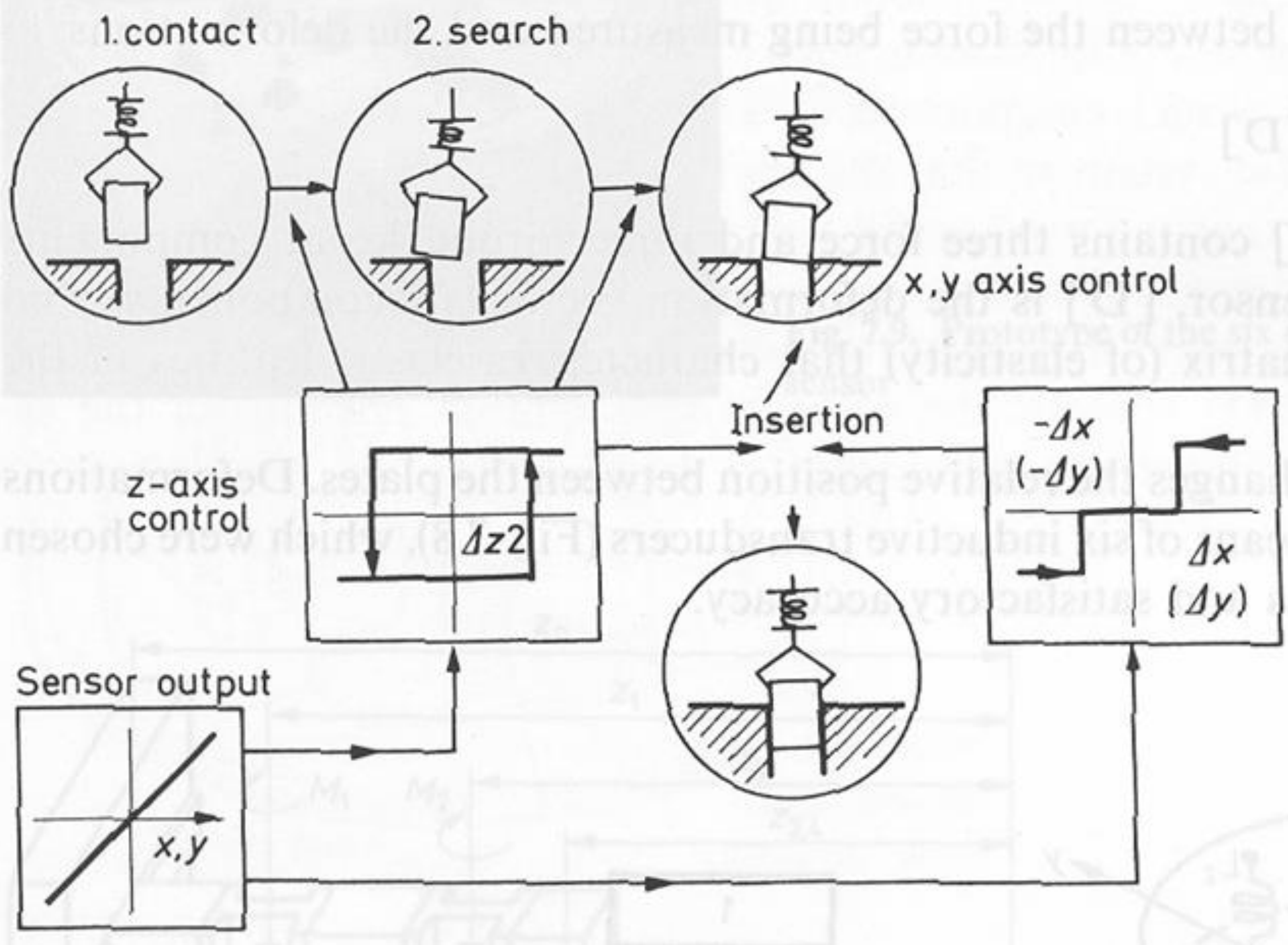
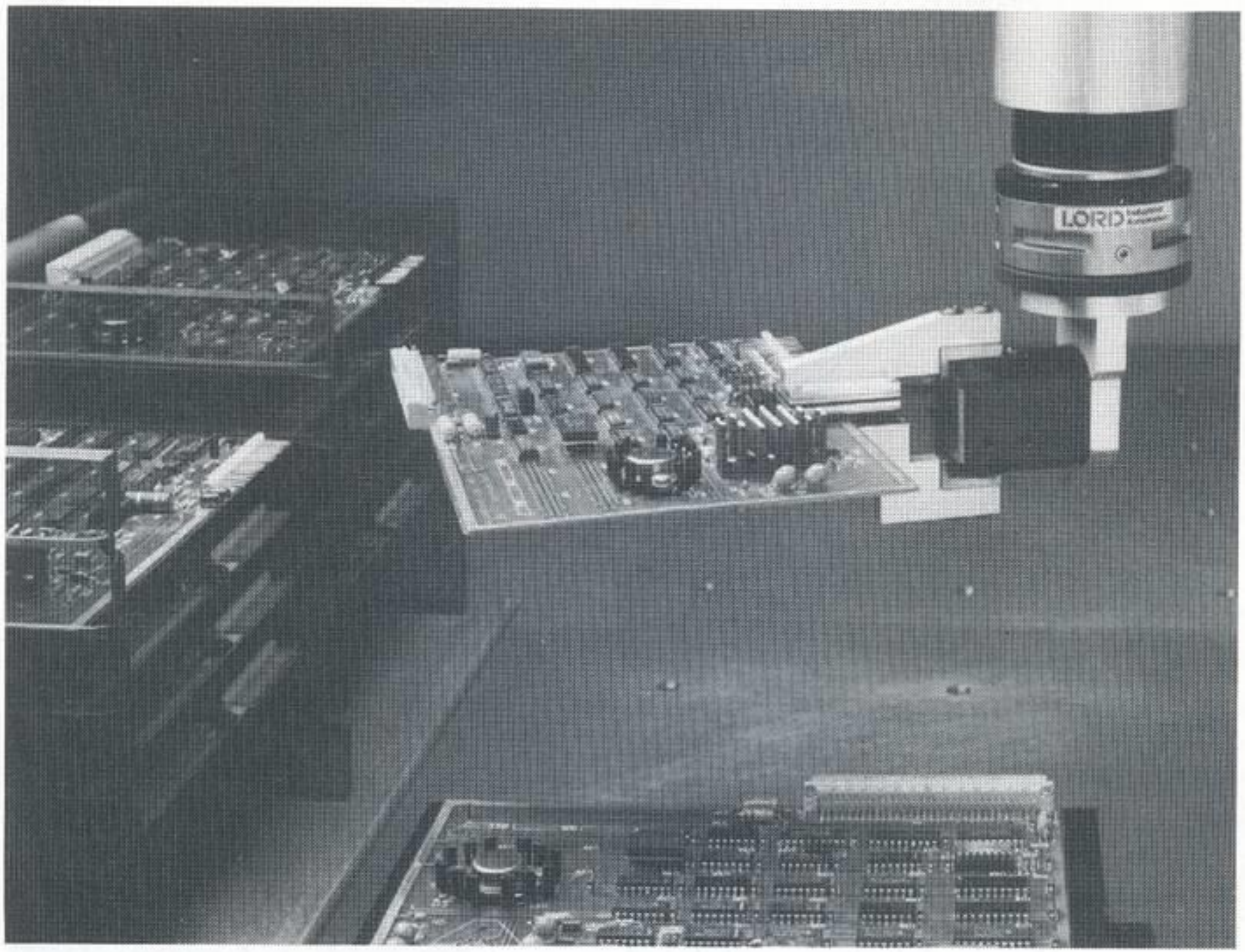


Fig. 7.6. Control algorithm

Example of application of force sensors



Example of sensors of a mobile robotic system

Hall-effect sensors on finger joints

Force/torque sensor on the wrist (with strain gauges)

Encoders on the motors of the arm and of the mobile base

Ultrasound sensors

Switches on the bumper

Potentiometers in the docking system

Outline of the lesson

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- Classification of transducers
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- Position sensors: switches, encoders, potentiometers, Hall-effect sensors
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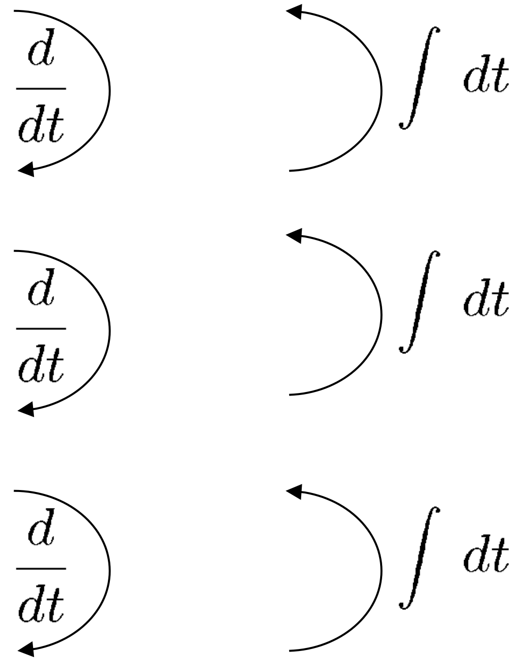
- Inertial sensors

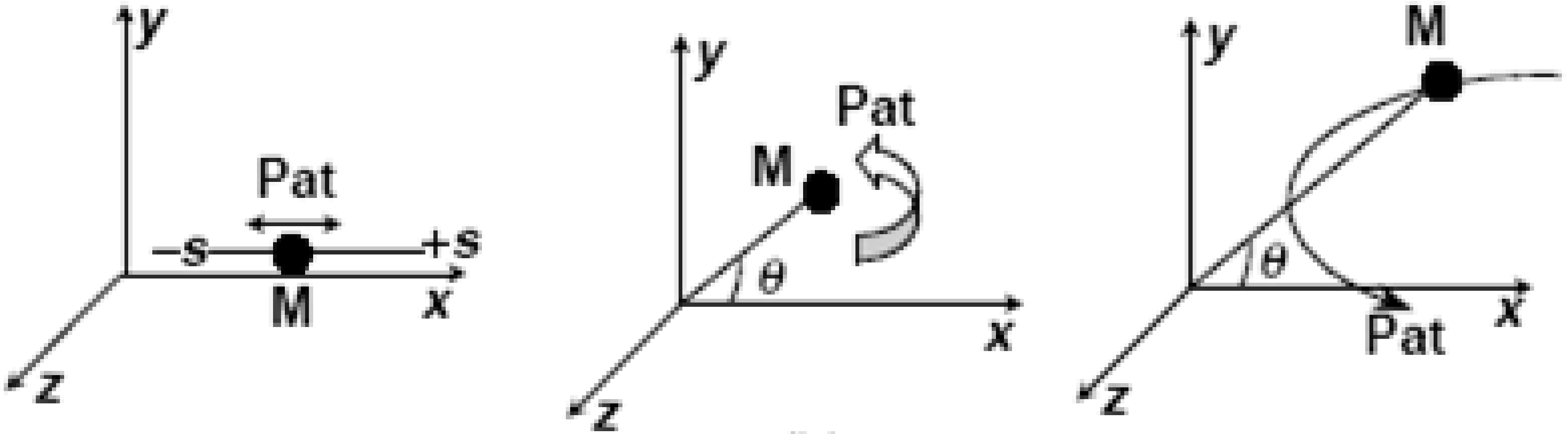
Bibliographical references:
AA.VV., *Handbook of Mechatronics*, CRC Press LLC, 2002, Cap.19

Kinematic quantities

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



Types of motion



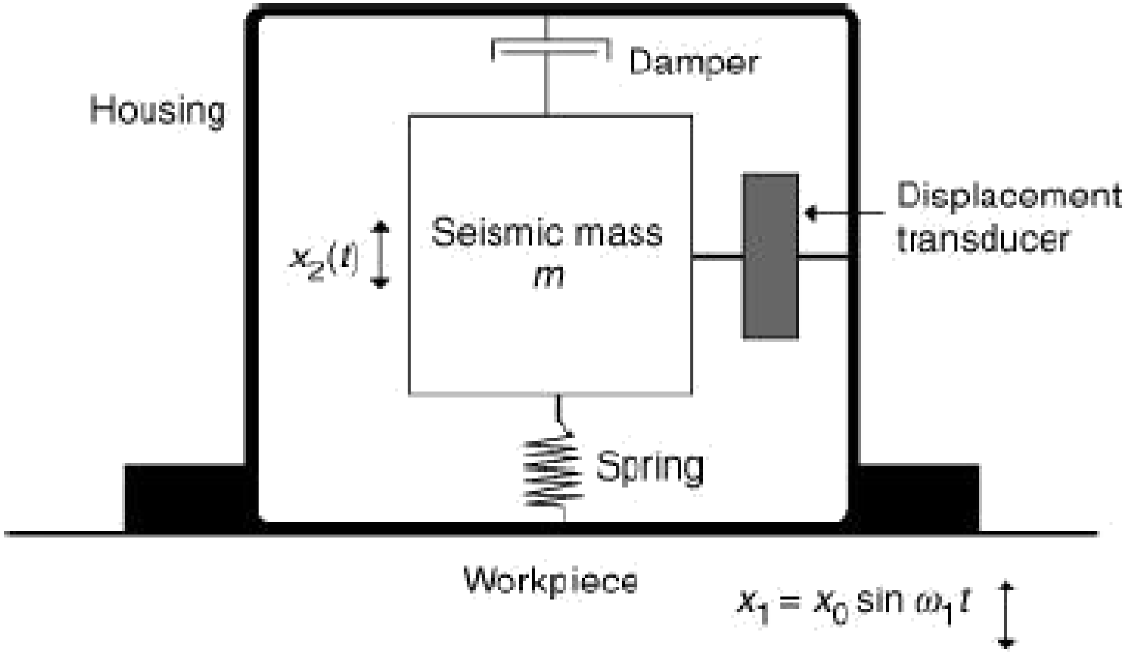
- Linear: $$a = \frac{dv}{dt} = \frac{d(ds/dt)}{dt} = \frac{d^2 s}{dt^2}$$
- Angular: $$\alpha = \frac{d\omega}{dt} = \frac{d(d\theta/dt)}{dt} = \frac{d^2\theta}{dt^2}$$
- Curve: $$\mathbf{a} = \frac{d\mathbf{v}}{dt} = \frac{d^2x}{dt^2}\mathbf{i} + \frac{d^2y}{dt^2}\mathbf{j} + \frac{d^2z}{dt^2}\mathbf{k}$$

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

Typical working principle for accelerometers



$$f(t) = m\frac{d^2x}{dt^2} + c\frac{dx}{dt} + kx$$

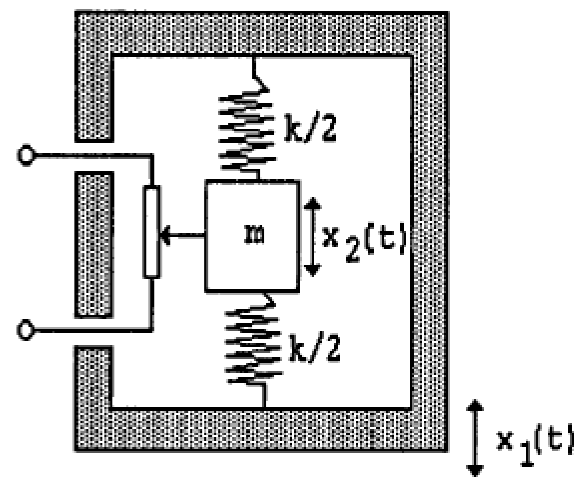
$$m\frac{d^2z}{dt^2} + c\frac{dz}{dt} + kz = mg\cos(\theta) - m\frac{d^2x_1}{dt^2}$$

$$z = x_2 - x_1$$

$$\theta = angle\ with\ respect\ to\ gravity$$

Potentiometer accelerometers

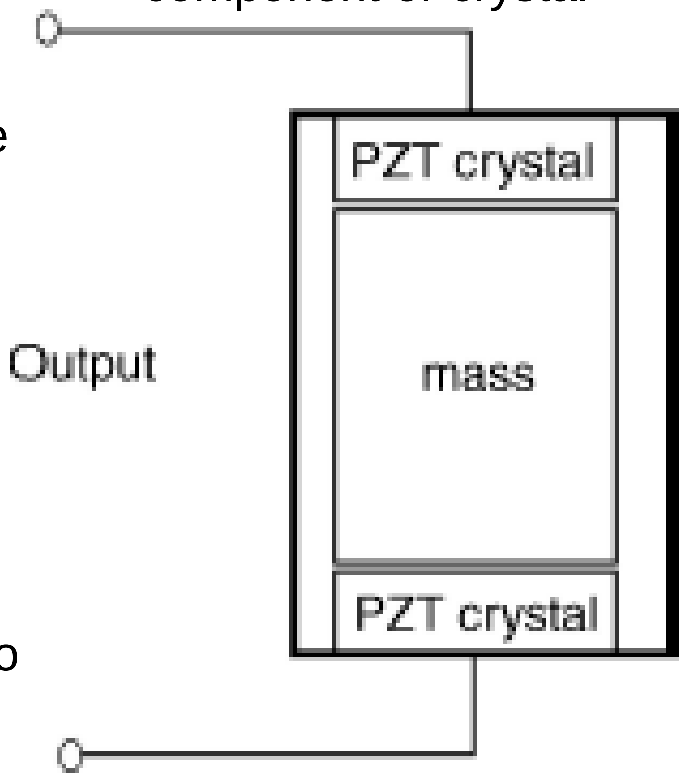
- A potentiometer is used to measure the relative displacement between the seismic mass and the base
  - A viscous fluid continuously interact with the base and the mass to provide damping
  - Low frequency of operation (lower than 100 Hz)
- Dynamic range: ±1*g* to ±50*g* fs.
- Natural frequencies: 12 - 89 Hz,
- Damping ratio ζ: 0.5 - 0.8
- Potentiometer resistence: 1000–10000Ω
  - Corresponding resolution: 0.45–0.25% fs.
- Cross-axial sensibility: <±1%.
- Accuracy: ±1% fs at environmental temperature.
- Dimension: 50mm^3 (<0.1 gr.)



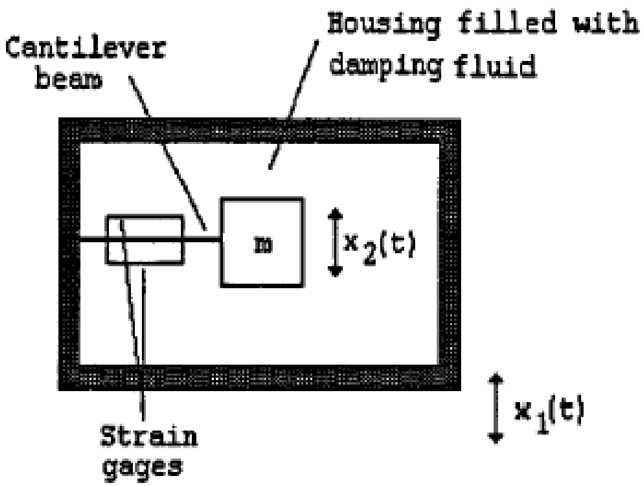
Piezoelectric accelerometers

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

A mass in direct contact with the piezoelectric component or crystal



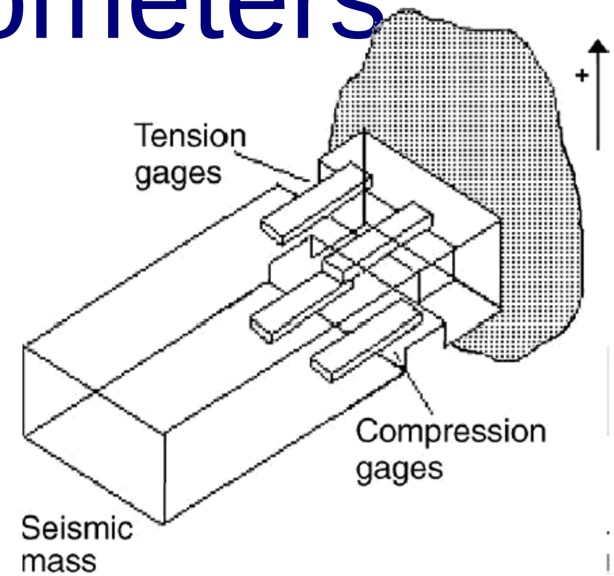
Strain gauge accelerometers



- Electric resistance strain gauges are also 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

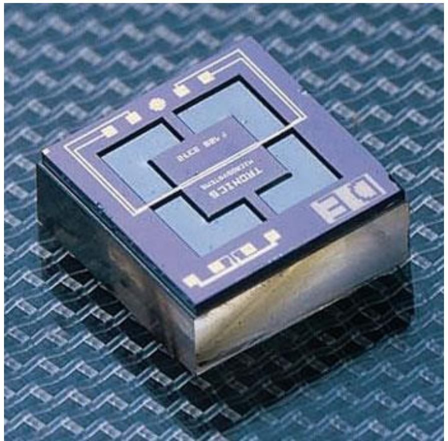
- Piezoresistive accelerometers are essentially semiconductor strain gauges with large gauge factors. The sensitivity of a piezoresistive sensor comes from the elastic response of its structure and resistivity of the material.
- Piezoresistive accelerometers are useful for acquiring vibration information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



pressure changes the resistance by mechanically deforming the sensor

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

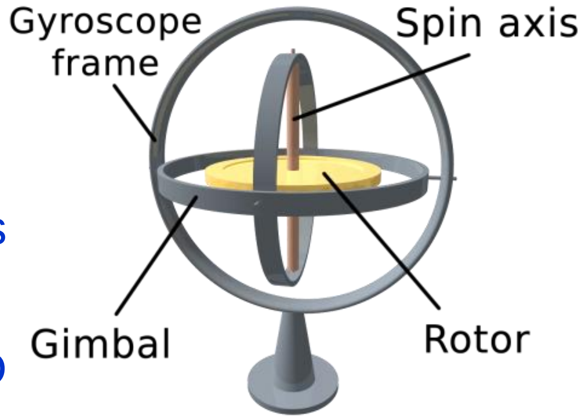


Velocity measurement

- Methods based on a reference
  - Measurements done on the object in motion and on a reference
  - Average speed $v_{avg} = \frac{x_2 - x_1}{t_2 - t_1} = \frac{\Delta x}{\Delta t}$
- Inertial methods
  - Do not require contact with a reference
  - Provide the velocity relative to the initial velocity of the sensor $v(t) = v_i + \int_{t_i}^{t} a(\tau)\, d\tau$

Gyroscopes for measuring angular velocities

Physical rotating device, which tends to keep its rotational axis constant, due to the effect of the angular momentum conservation law,

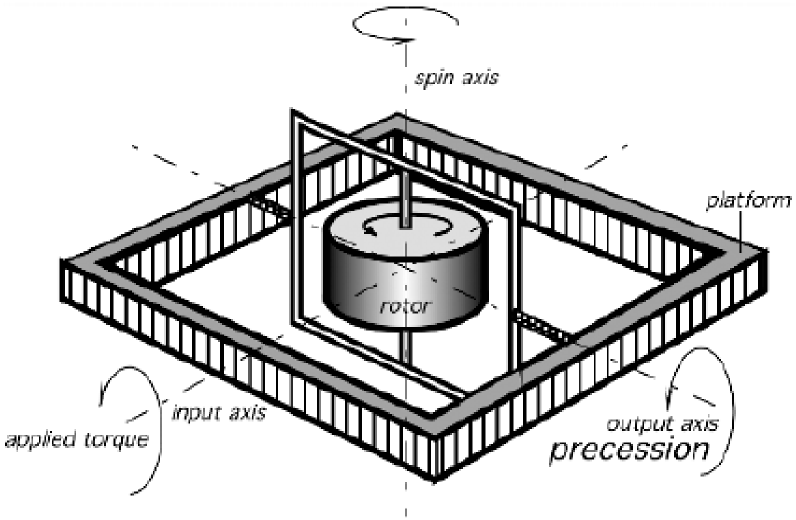


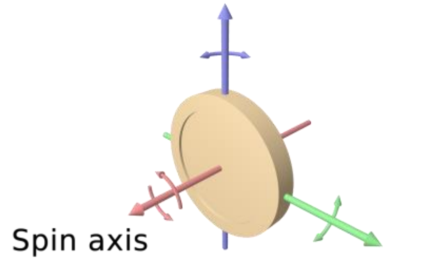
- a gyroscpe is a device composed of:
  - Rotor, with a toroidal shape, rotating around its axis (*Spin axis*)
  - *Gimbal*, which set the rotor free to orient in the 3 3D space directions
  - if the rotor is rotating, its axis tends to keep its orientation, even if the support changes its orientation

(Mechanism invented in 1852 by the physicist Jean Bernard Léon Foucault in the framework of his studies on earth rotation)

Mechanical rotating gyroscope

- A disk (rotor) is free to rotate with respect to one/two spin axes (1/2-DOF gyroscope)
- If a rotation is applied to the gyroscope support around the *input* axis, then the gyroscope tends to rotate around a perpendicular axis (*output* axis)
- The gyroscope generated an aoutput signal which is proportional to the angular velocity on an axis perpendicular to the *spin* axis

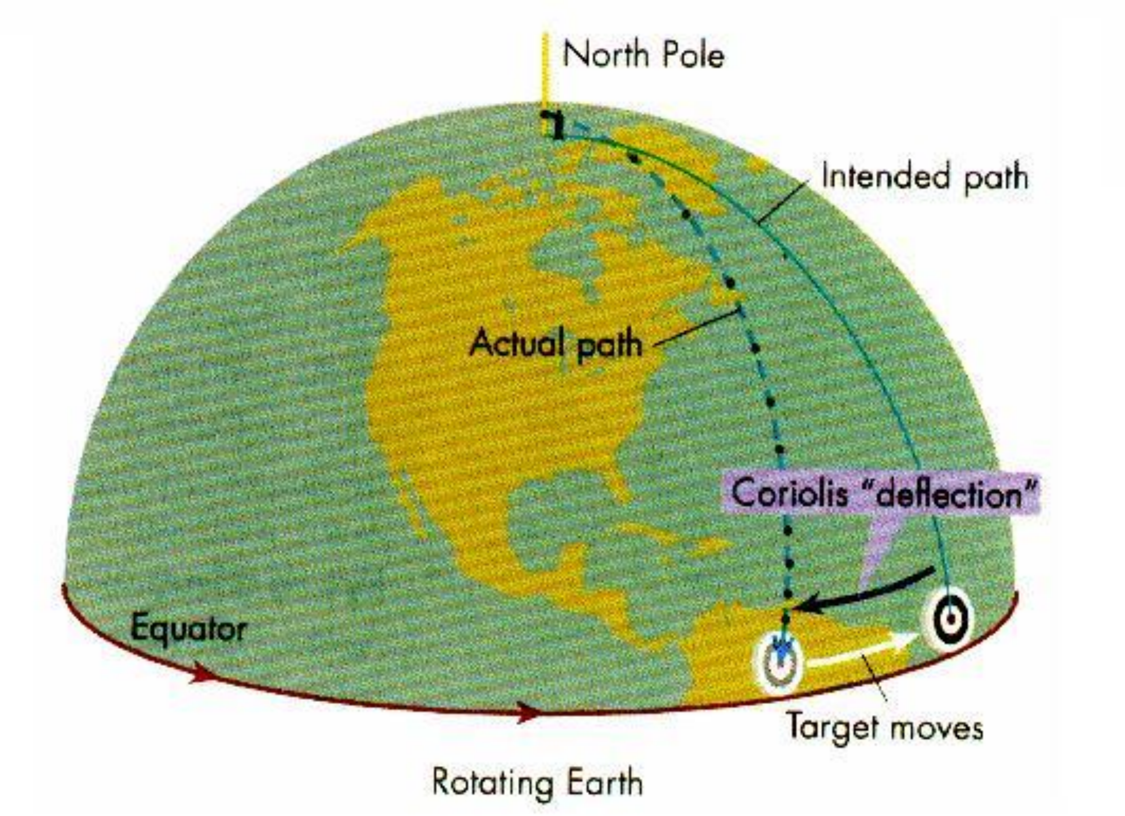




$$T = I\omega\Omega$$

***T* : applied torsion**
***I*: inertia**
***ω*: constant rotor velocity**
***Ω*: angular velocity around the output axis**

Coriolis effect



The mathematical relation expressing the **Coriolis force** is:

$$\vec{F}_C = 2m(\vec{v} \times \vec{\omega})$$

$\vec{F}_C$ is the Coriolis force,
m is the mass,
$\vec{v}$ is the linear velocity,
$\vec{\omega}$ is the angular velocity of the rotation system.

Coriolis-based accelerometers

Vibrating mass gyroscopes

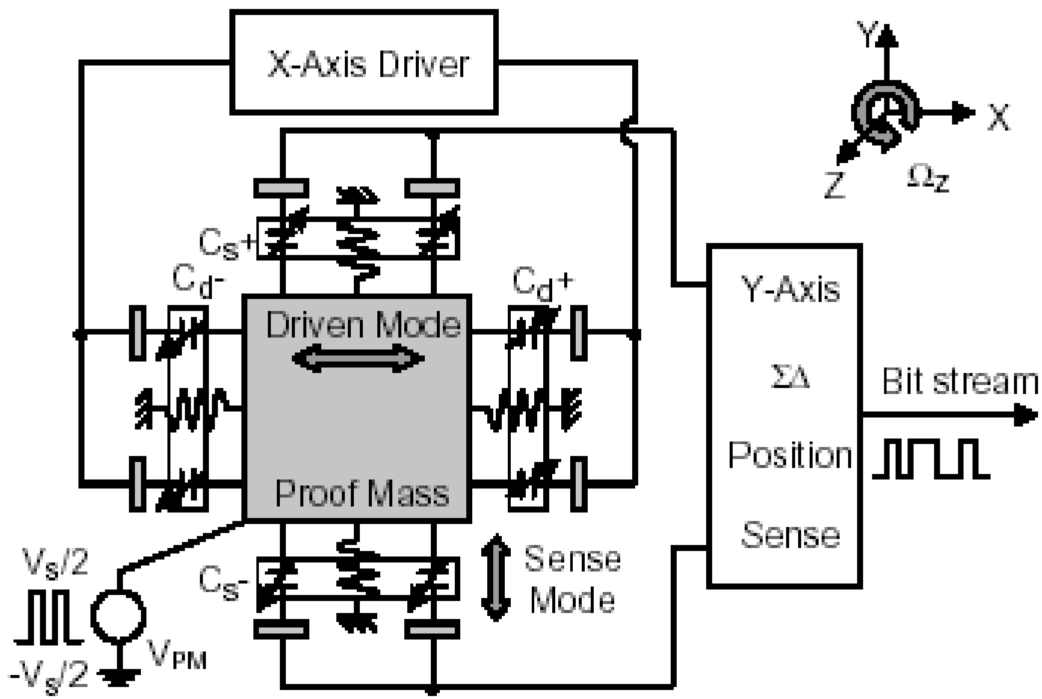
A vibrating element (vibrating resonator) creates an oscillatory linear velocity

If the sensor is rotated about an axis orthogonal to this velocity, a Coriolis acceleration is induced

The vibrating element is subjected to the Coriolis effect that causes secondary vibration orthogonal to the original vibrating direction.

By sensing the secondary vibration, the *rate of turn* can be detected.

The Coriolis force is given by: $\mathbf{F}_C = -2m\left(\boldsymbol{\omega} \times \mathbf{v}\right)$



Gyroscopes based on Coriolis acceleration

The most common design technology for these sensors has generally used a stable quartz resonator with piezoelectric driver circuits.

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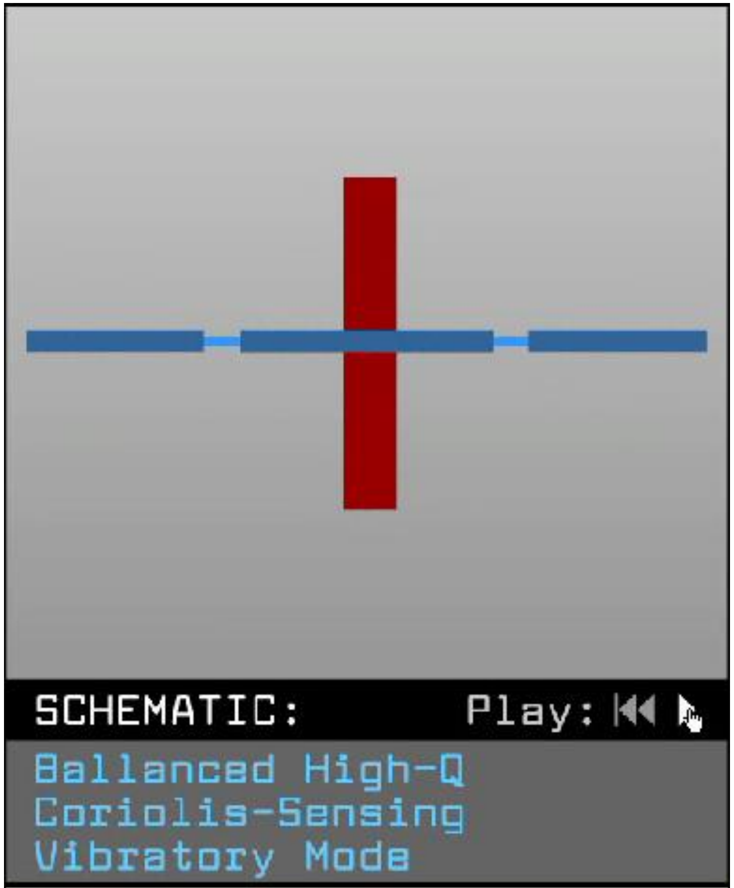

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