Sensors for Robots

An overview

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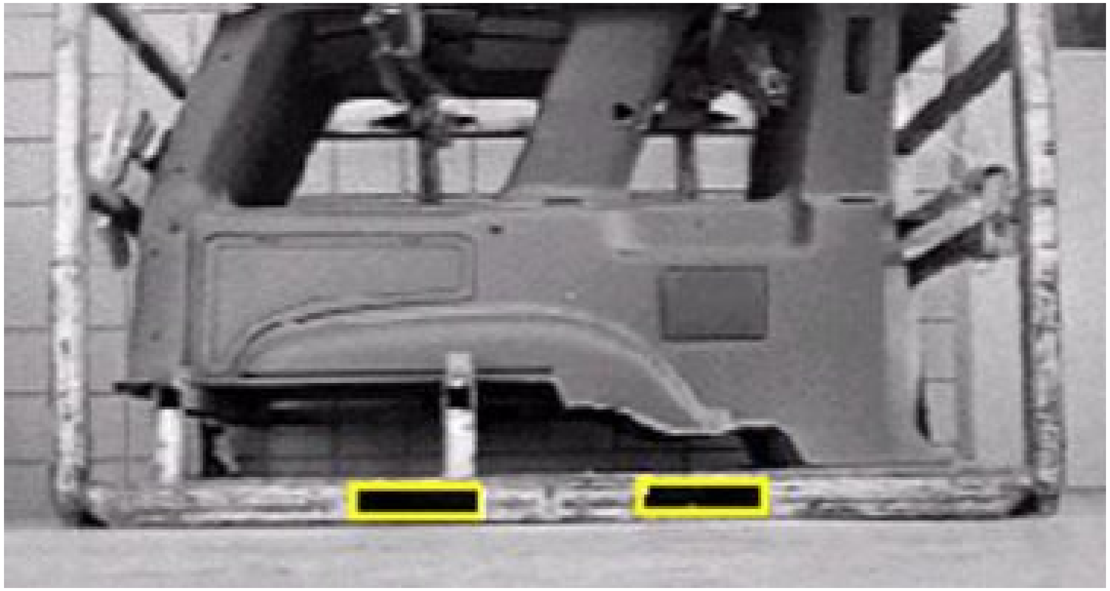
Courtesy to several authors of presentations on the web.

Lecture outline

Note: students graduated from the bachelor KyR studied sensors in the course Sensors and Measurement. This subject was not specialized to robotics.

- Motivation, why robots need sensors?
- Robotic sensor classification.
- Proprioception in humans.
- Various sensors overview.

Where are the forkholes?



Autonomous forklift for material handling

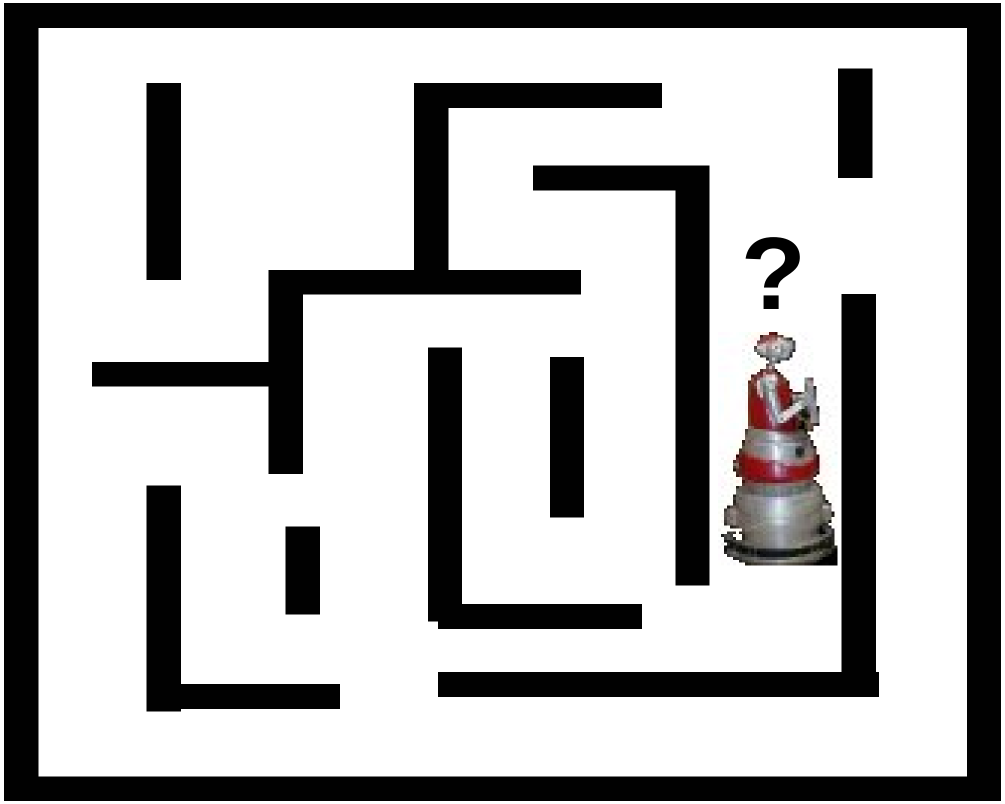
Will robot hit anything?

Obstacle detection

Where is the cropline?

Autonomous harvesting

Where am I ?



Localization in the environment

Robot sensors, generally

- Sensor constitute robot's window to the environment.
- A robot needs sensing to be an active participant in the environment.
- Each sensor is based on a transduction principle, i.e. a conversion of energy from one form to another.
- Sensors measure a physical quantity, they do not provide state.

Classification of sensors

- **Proprioceptive** ("sense of self", internal state).
  - Measures values internally to the system (robot), e.g. battery level, wheel position, joint angle, etc.
- **Exteroceptive** (external state).
  - Observations of robot environment, objects in it.

- **Active** (emits energy, e.g. radar) vs.
- **Passive** (passively receives energy, e.g., camera).

General sensor classification

General classification (typical use)	Sensor Sensor System	PC or EC	A or P
Tactile sensors (detection of physical contact or closeness; security switches)	Contact switches, bumpers	EC	P
	Optical barriers	EC	A
	Noncontact proximity sensors	EC	A
Wheel/motor sensors (wheel/motor speed and position)	Brush encoders	PC	P
	Potentiometers	PC	P
	Synchros, resolvers	PC	A
	Optical encoders	PC	A
	Magnetic encoders	PC	A
	Inductive encoders	PC	A
	Capacitive encoders	PC	A
Heading sensors (orientation of the robot in relation to a fixed reference frame)	Compass	EC	P
	Gyroscopes	PC	P
	Inclinometers	EC	A/P

A, active; P, passive; P/A, passive/active; PC, proprioceptive; EC, exteroceptive.

General sensor classification 2

General classification (typical use)	Sensor Sensor System	PC or EC	A or P
Ground-based beacons (localization in a fixed reference frame)	GPS Active optical or RF beacons Active ultrasonic beacons Reflective beacons	EC EC EC EC	A A A A
Active ranging (reflectivity, time-of-flight, and geometric triangulation)	Reflectivity sensors Ultrasonic sensor Laser rangefinder Optical triangulation (1D) Structured light (2D)	EC EC EC EC EC	A A A A A
Motion/speed sensors (speed relative to fixed or moving objects)	Doppler radar Doppler sound	EC EC	A A
Vision-based sensors (visual ranging, whole-image analysis, segmentation, object recognition)	CCD/CMOS camera(s) Visual ranging packages Object tracking packages	EC	P

Characterizing sensor performance

- Measurement in real world environment is error prone.
- Basic sensor response ratings:
  - **Dynamic range:** Ratio between lower and upper limits, usually in decibels.
  - **Range:** Difference between min and max.
  - **Resolution:** Minimum difference between two values.
  - **Linearity:** Variation of output signal as function of the input signal.
  - **Bandwidth or frequency:** The speed with which a sensor can provide a stream of readings.

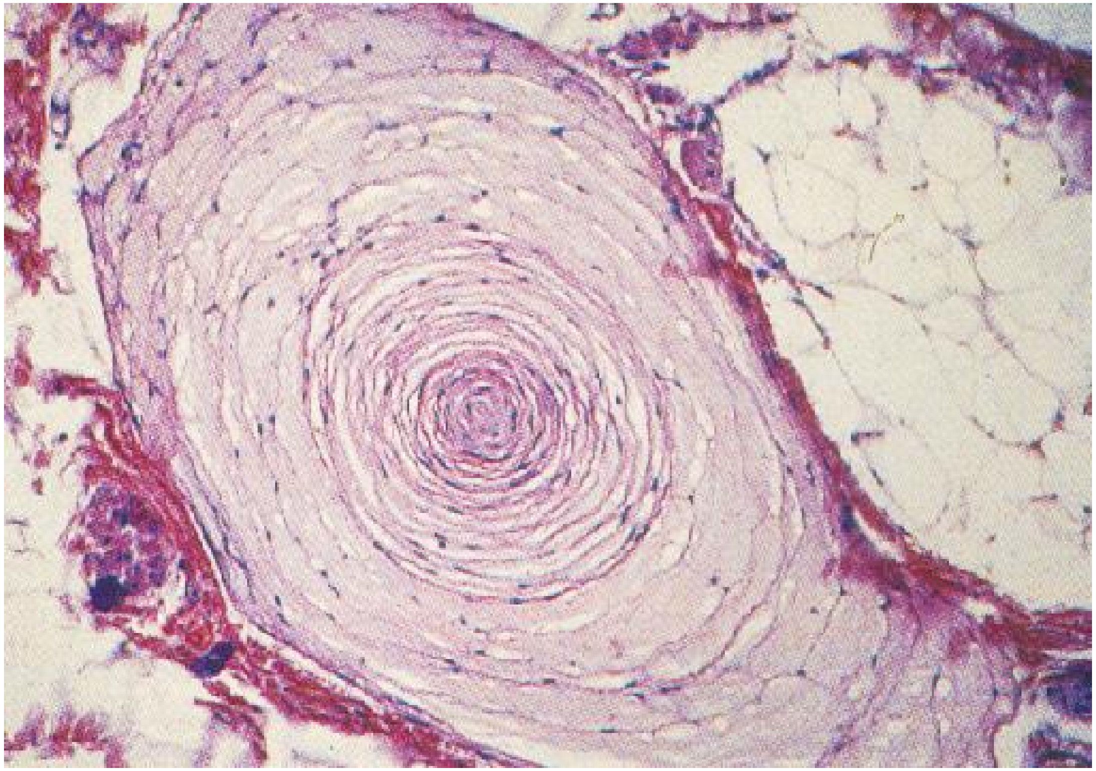
In Situ sensor performance

Characteristics that are especially relevant for real world environments

- **Sensitivity**: Ratio of output change to input change.
- **Cross-Sensitivity**: Sensitivity to environmental parameters that are orthogonal to the target parameters.
- **Error/Accuracy**: Difference between the sensor's output and the true value.
- **Systematic/Deterministic Error**: Caused by factors that can be modeled (in theory), e.g., calibration of a laser sensor.
- **Random Error**: e.g., hue instability of camera, black level noise of camera.
- **Reproducibility**: Reproducibility of sensor results.

Proprioception: detecting human's own movements

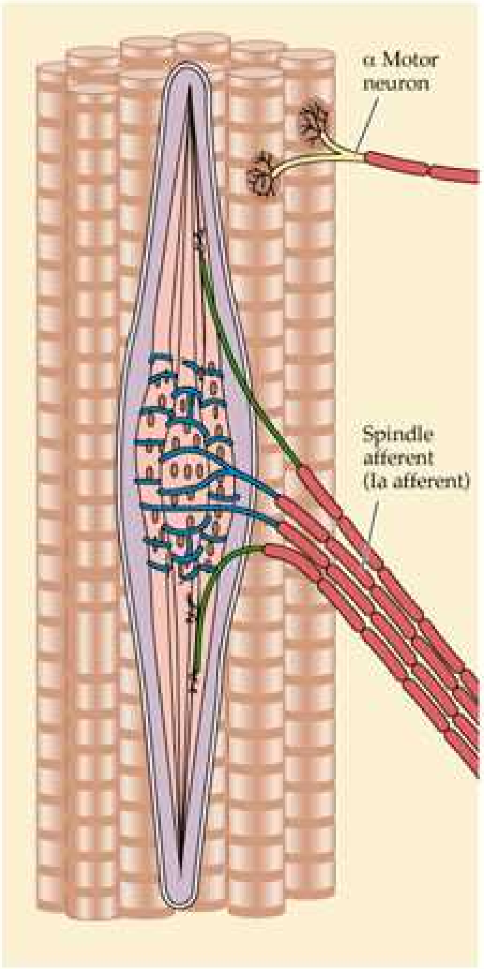
- To control our limbs, we need feedback on where they are.
- Muscle spindles *(svalové vřeténko)*.
- Pressure sensors in skin.

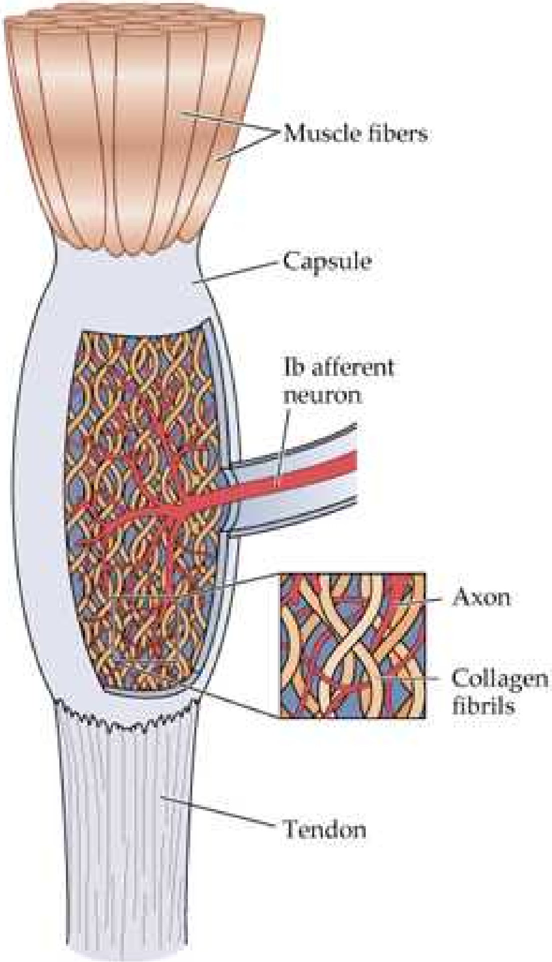


Pacinian corpuscle – transient pressure response

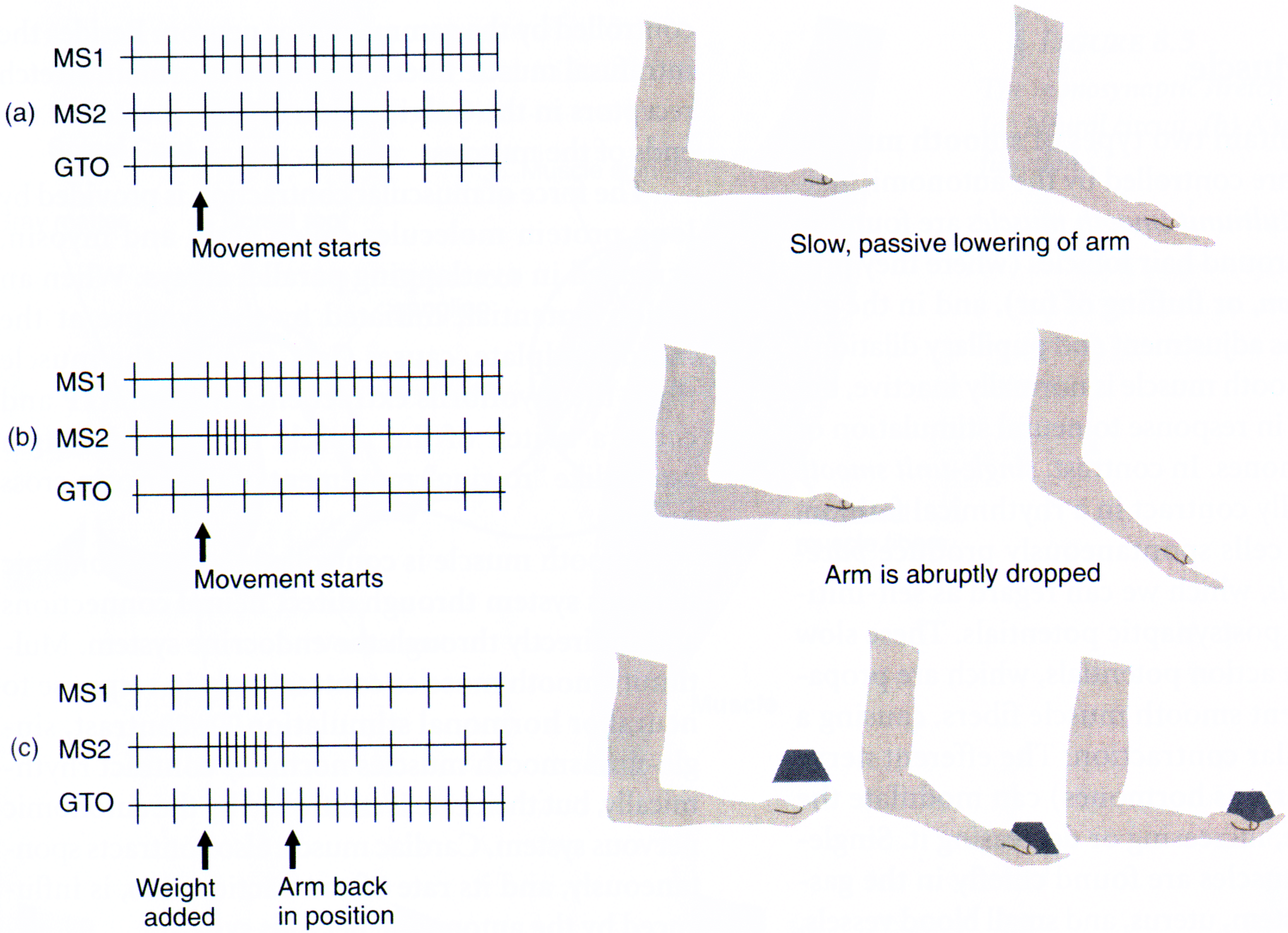
Sensors, feedback in muscles

- To control our limbs we need feedback.
- Muscle spindles
  - where: length
  - how fast: rate of stretch
- Golgi tendon organ
  - how hard: force



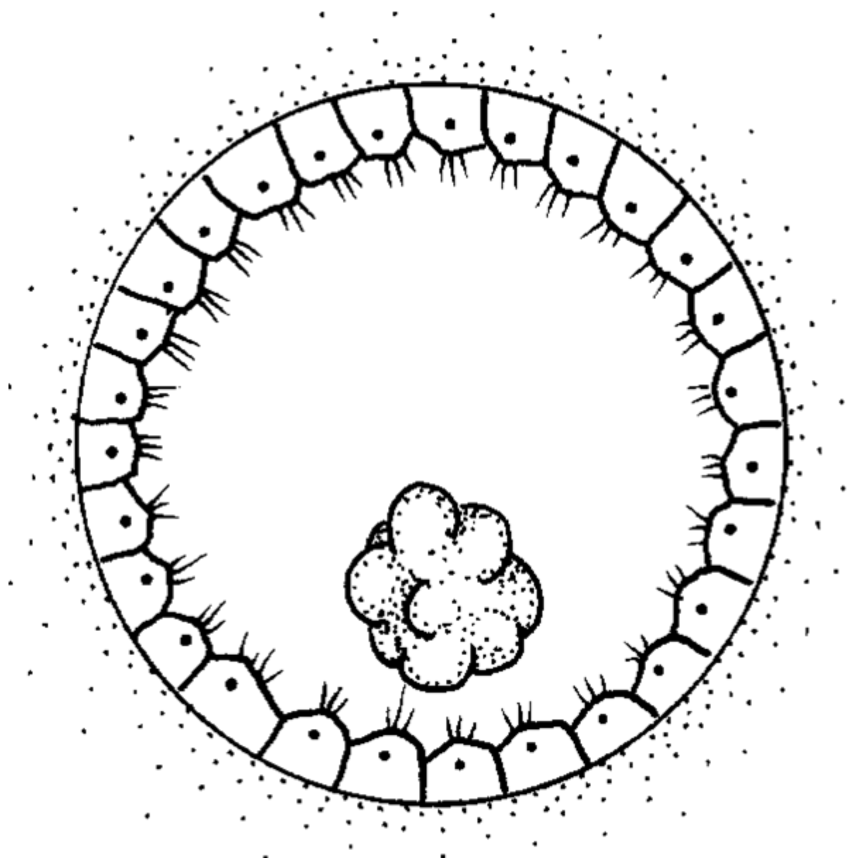


Neuron firing, example



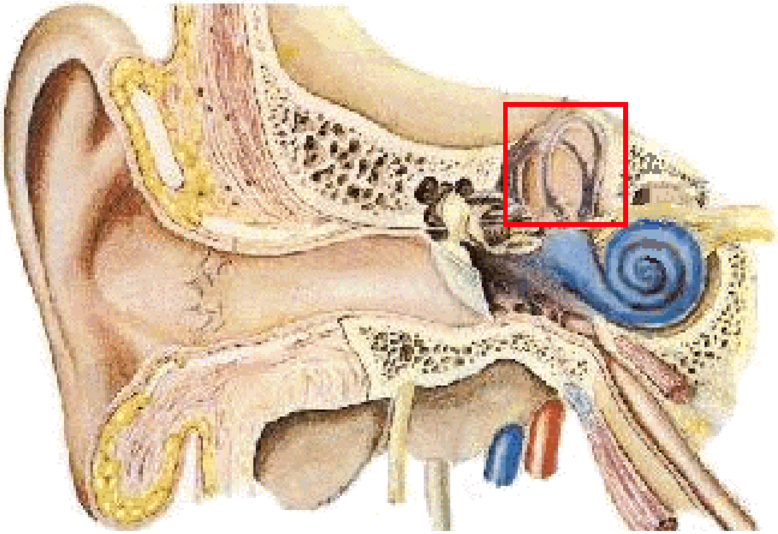
Proprioception
Some aquatic invertebrates

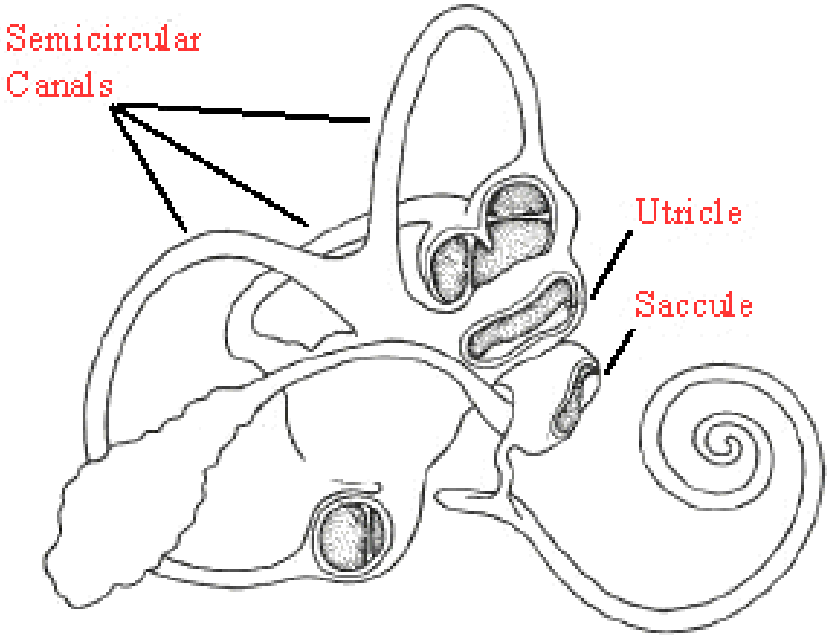
- To detect the motion of the whole body, the species have vestibular system based on a statocyst.
- Statolith (calcium nodule) affected by gravity (or inertia during motion) causes deflection of hair cells that activate neurons.



Human vestibular system

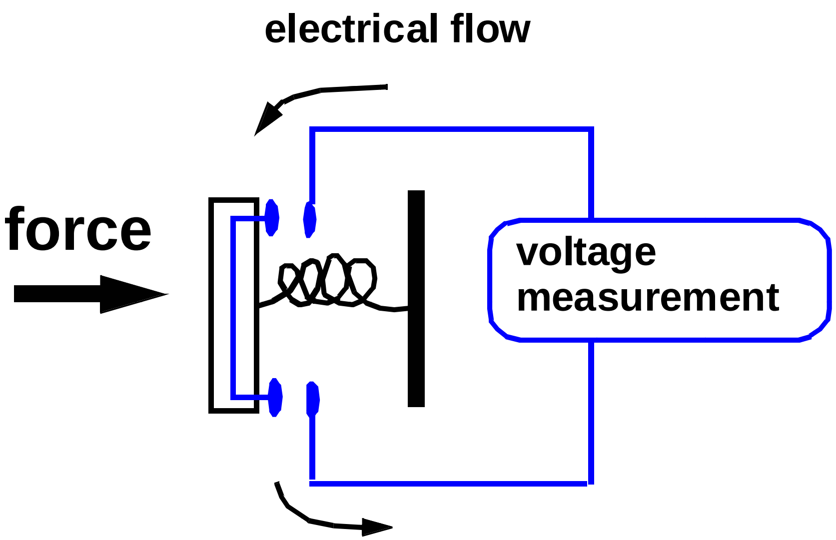
- Utricle *(vejčitý váček)* and Saccule *(kulovitý váček)* detect linear acceleration.
- Semicircular canals detect rotary acceleration in three orthogonal axes
- Fast vestibular-ocular reflex for eye stabilisation.



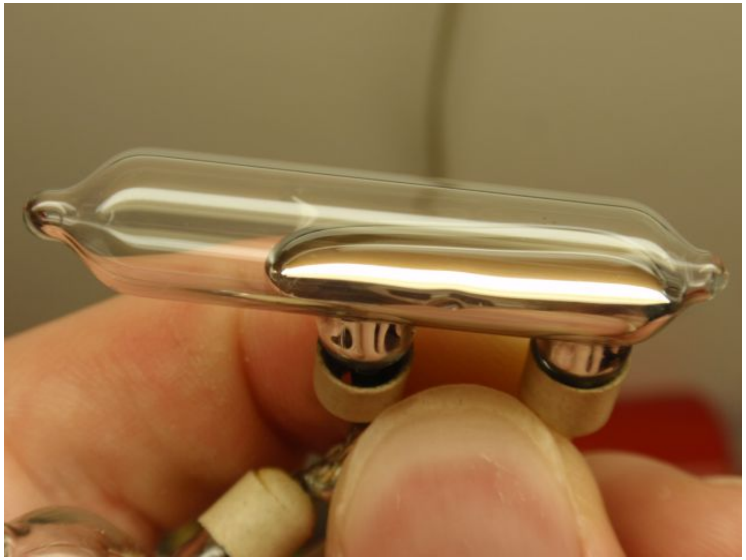


A simple on/off touch sensor

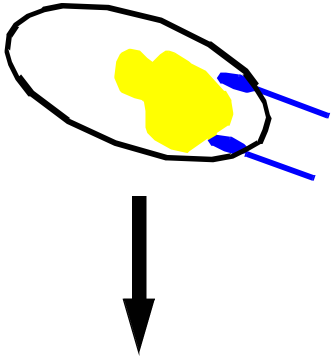
A simple switch



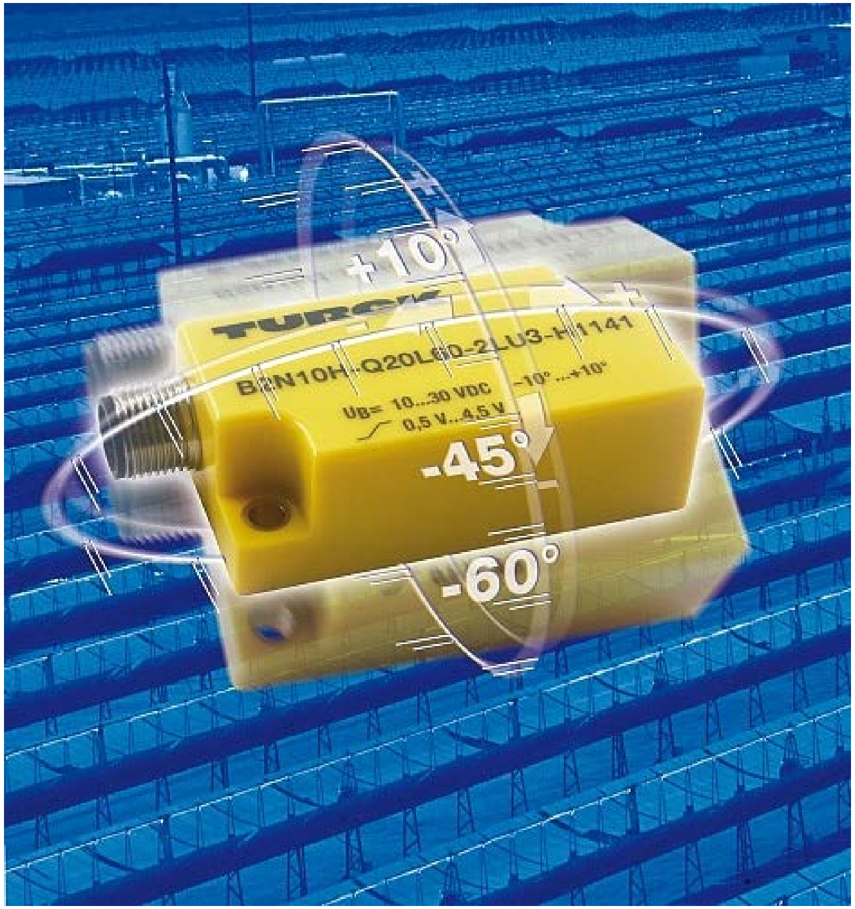
Tilt sensor



Mercury tilt switch, obsolete

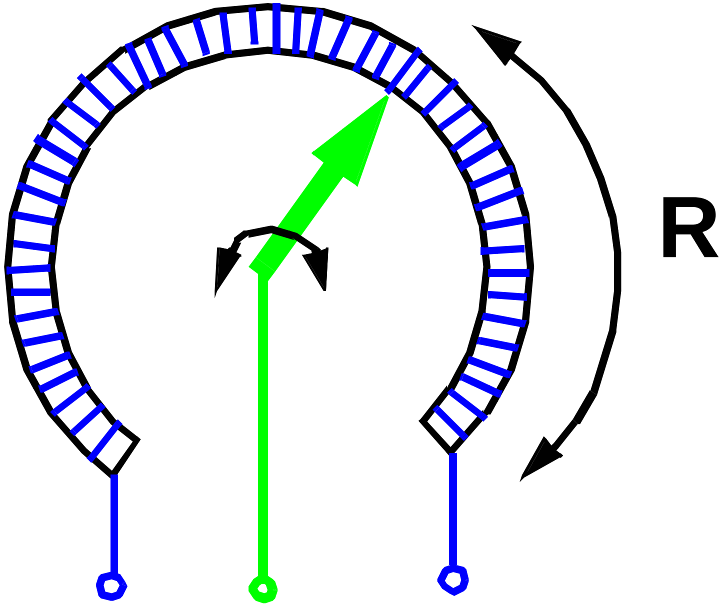


gravity



Dual axis inclinometer

Potentiometer

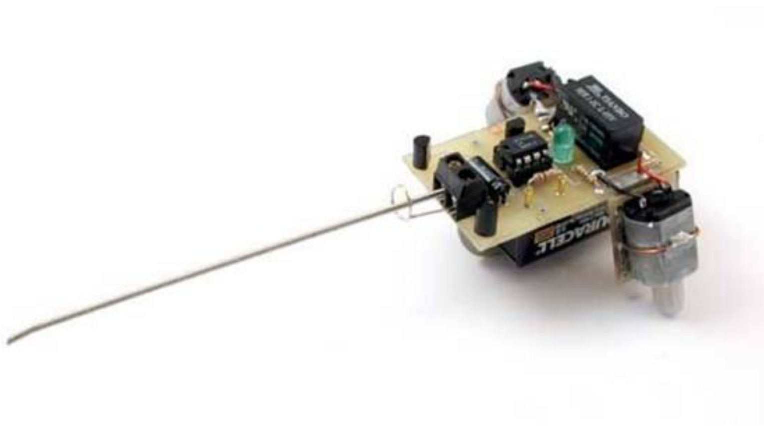


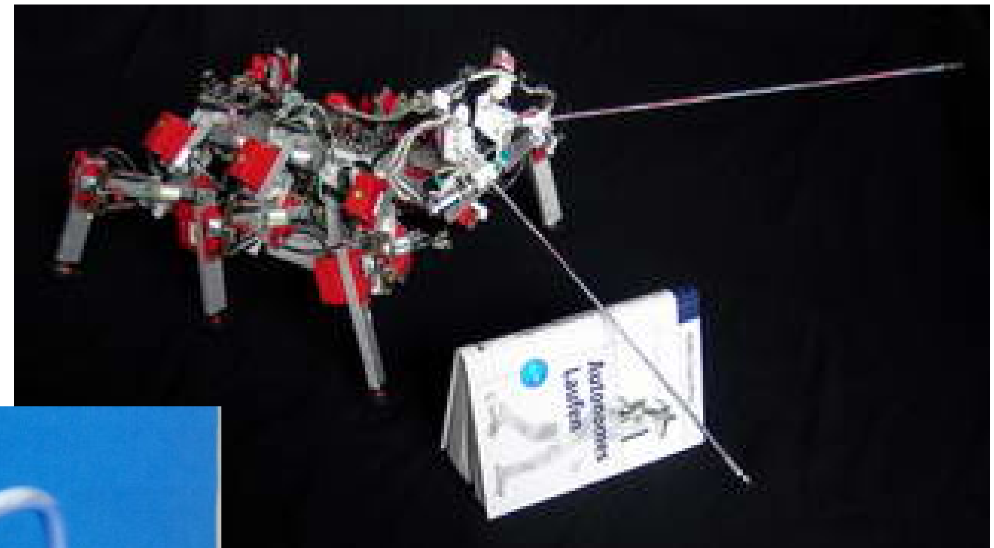
Resistance changes with the position of the dial

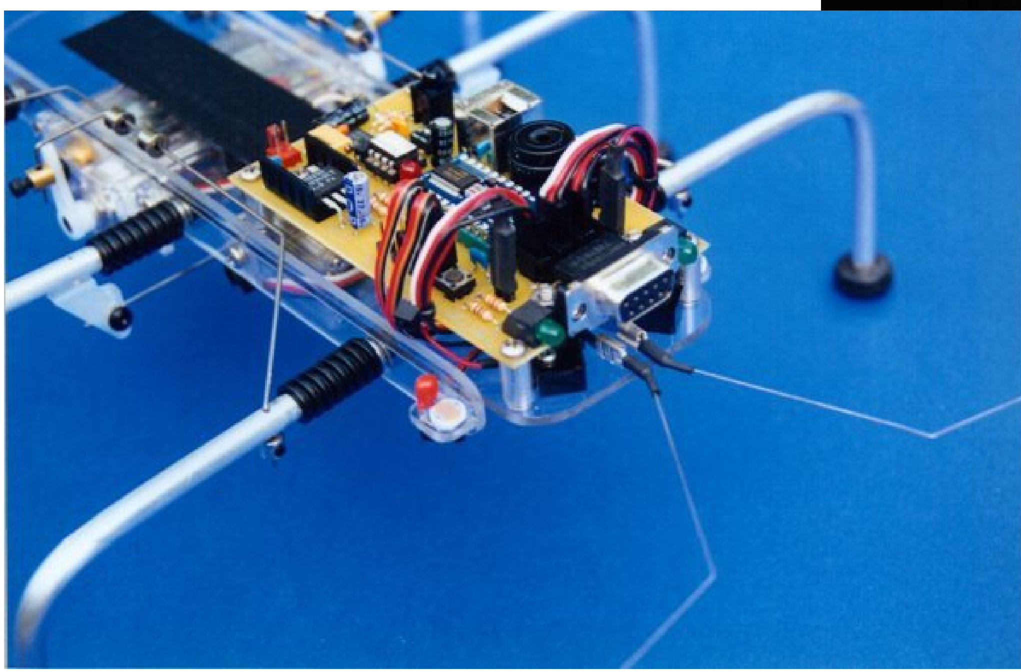
Whiskers

- Springy wire suspended through conductive “hoop”.
- Deflection causes contact with “hoop”.
- Reaches beyond robot a few centimeters.
- Simple, cheap, provides the binary output.

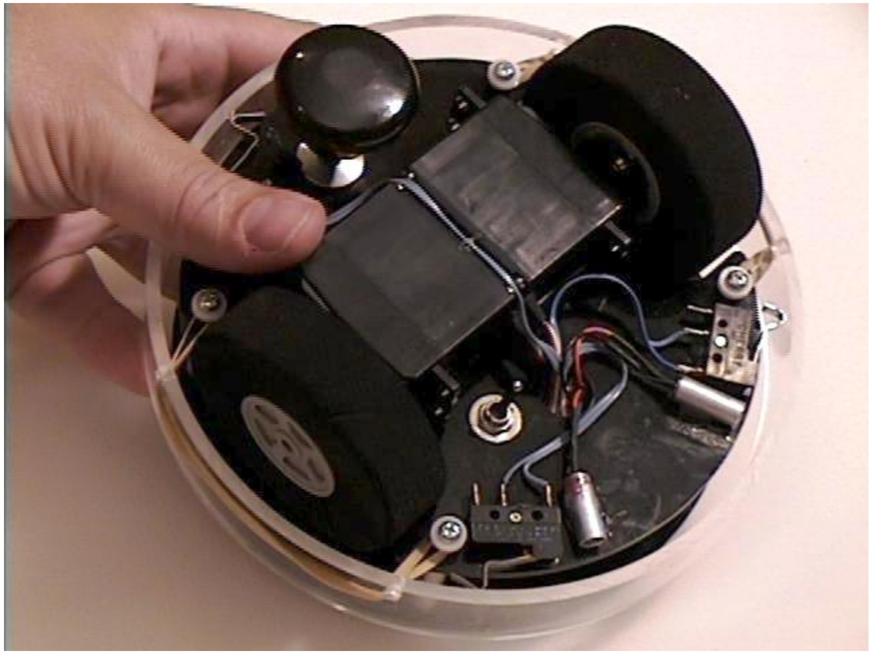
Whiskers examples

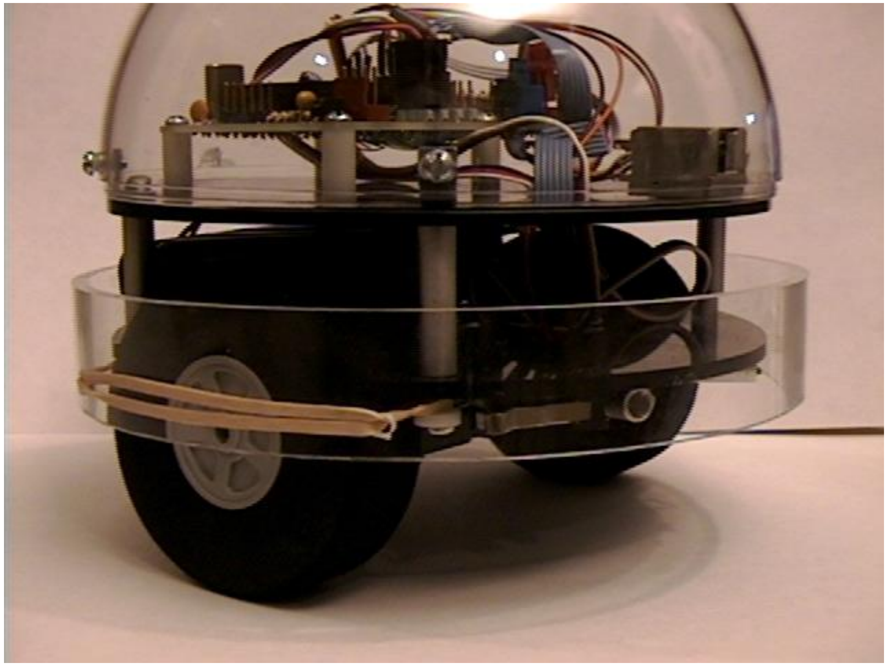






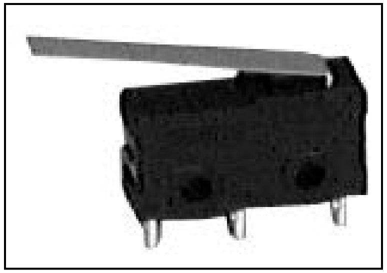
Bumpers



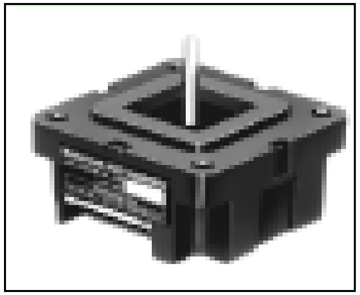


Examples of microswitches

- One-directional reed switch.



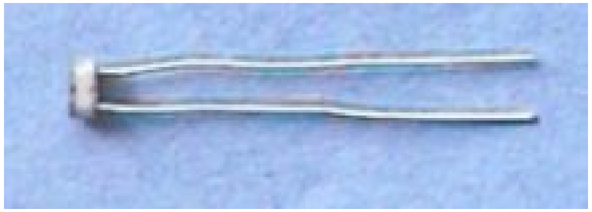
- Omni-directional reed switch.



- Roller contact switch.

Light sensors

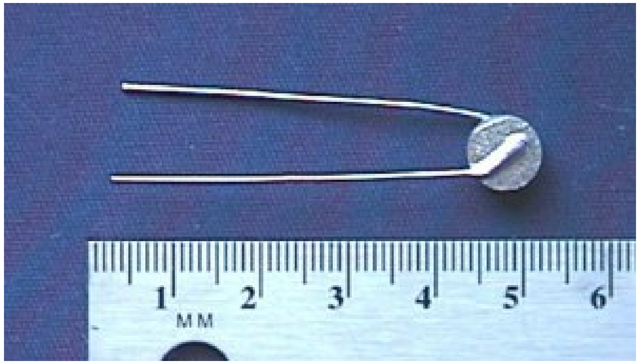
- Photoresistor.
- Photodiode.
- Differential photodiode.
- Phototransistor.



Photoresistor example

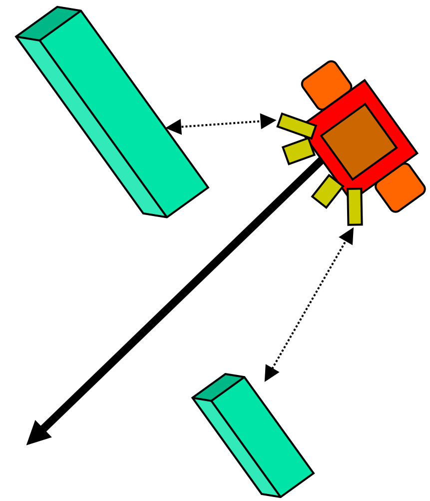
Thermal sensor

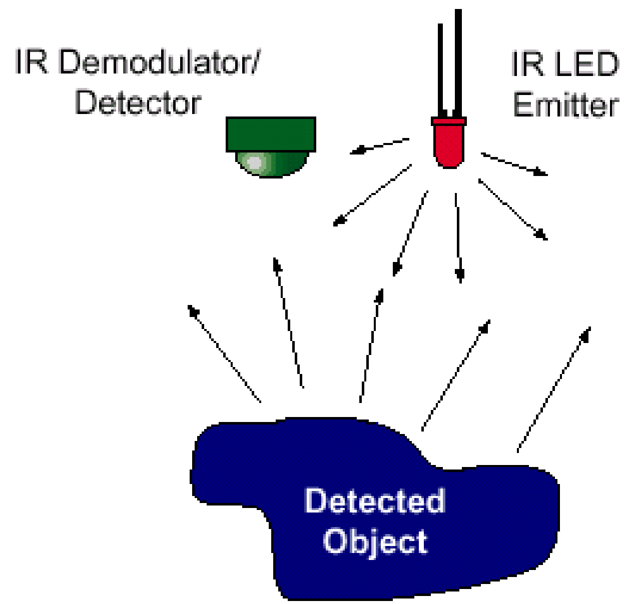
Thermal resistor (thermistor) example



Proximity sensors

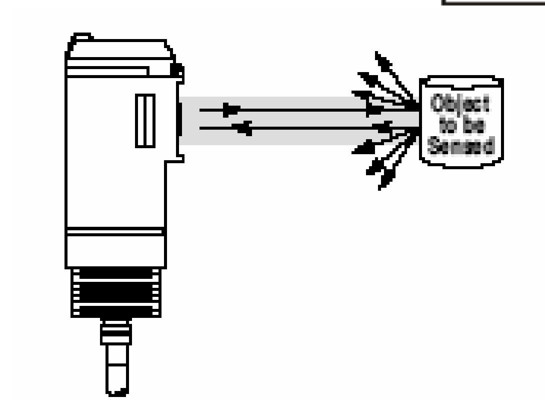
- Non-contact.
- Devices that can be used in areas that are near to an object to be sensed.
- Types:
  - Photocells.
  - Capacitance sensors.
  - Inductive sensors.



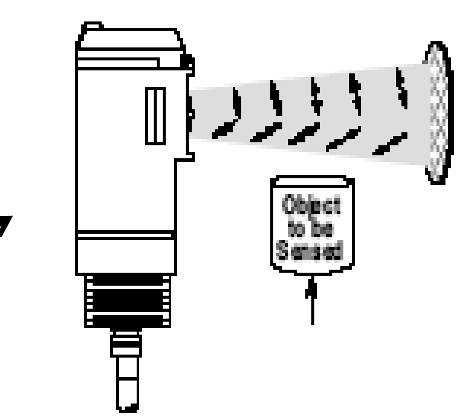


Photocells

- Emitters LEDs, receivers phototransistors.

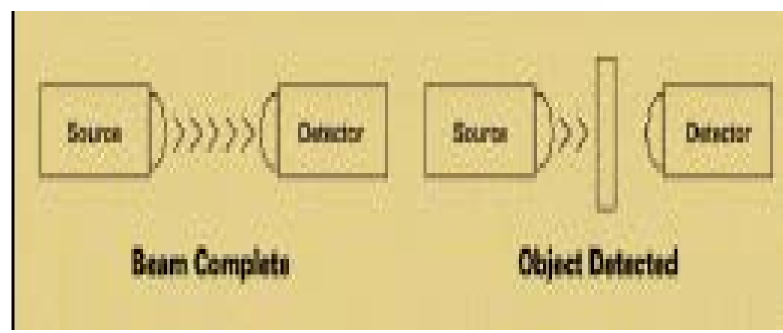


- Diffuse mode photosensor.



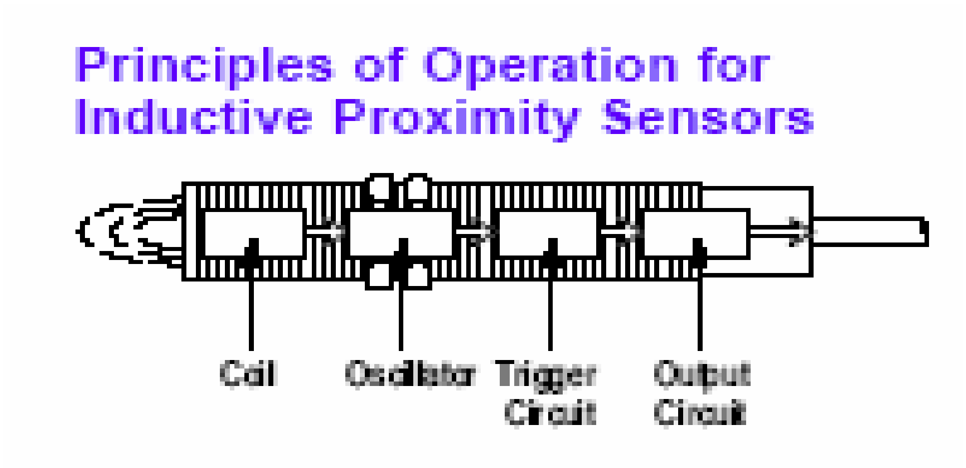
- Retro-Reflective Photosensors.

- Thru-beam detectors.



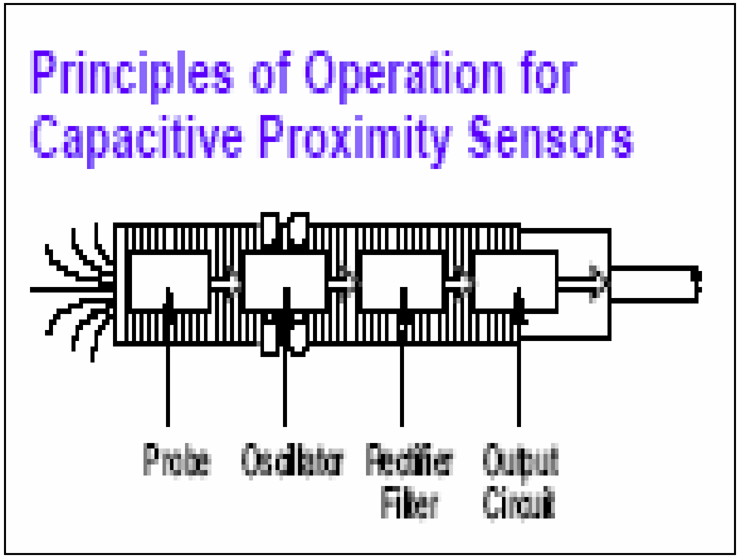
Inductive proximity sensors

- Detect Eddy current losses *(vířivý proud)*.
- Usually on/off mode only.
- They typically oscillate in ranges: 3 KHz – 1MHz.



Capacitance proximity sensors

- Generate an electrostatic field.
- Consists of probe, oscillator, feliciter filter, output circuit.
- In absence of a target, the oscillator is inactive.
- An approaching target raises capacitance, which triggers the oscillator.



Capacitive sensors, use example

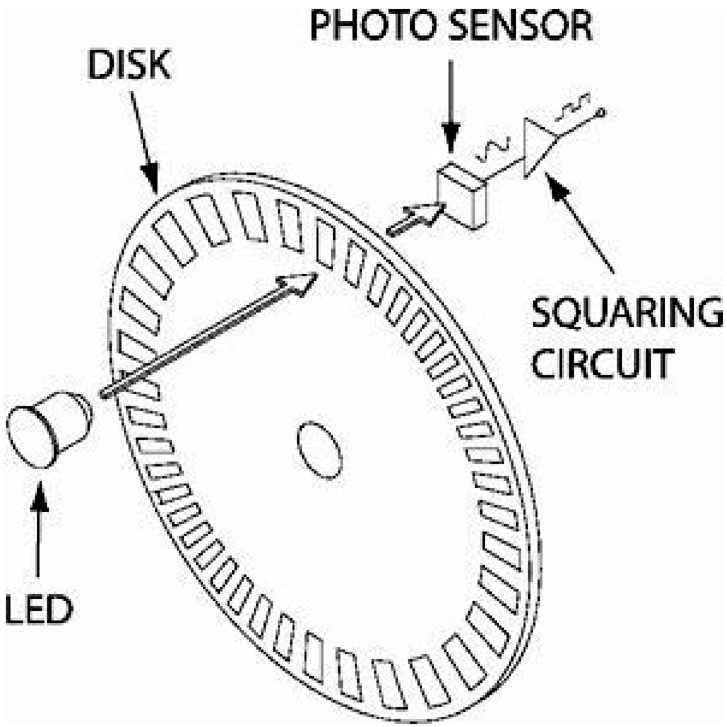
- When properly calibrated, the sensor can detect any higher dielectric material thru any lower dielectric material.
- Typical Application of Capacitive Sensor: Detecting Liquid (H_2O) levels in bottles.

Position Sensors

- Potenciometer
- Resolver
- Optical Encoders
  - Relative position
  - Absolute position

Wheel / motor encoders

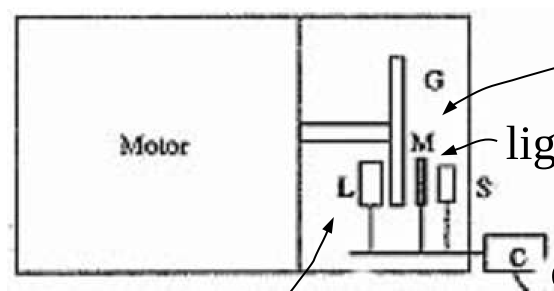
- Measure position, speed, direction of revolution of the wheel.
- **Odometry** - wheel movements can be integrated to get an estimate of the robots position.
- Typical resolutions of 2000 increments per revolution.
- Either relative or abslute.



Optical encoders 1

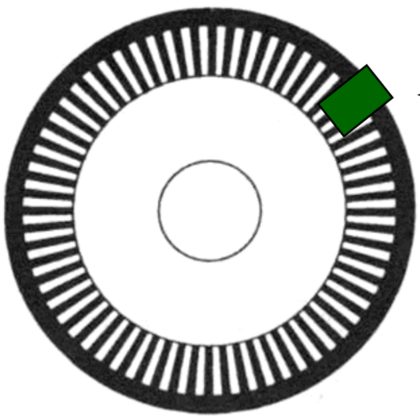
- Relative position

mask/diffuser



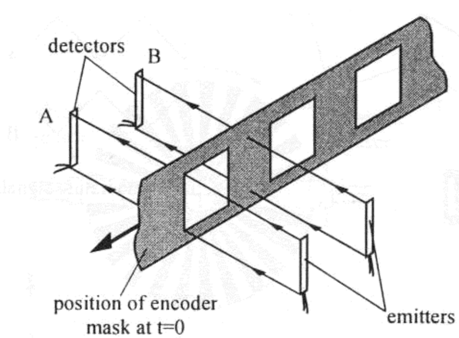
light sensor

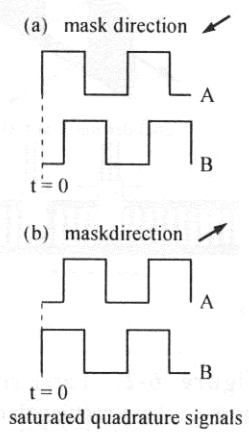
decode circuitry

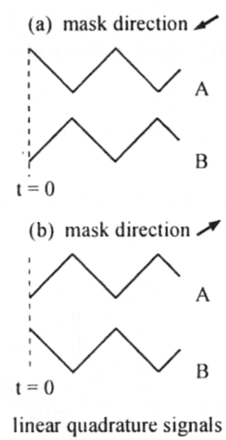


light emitter

grating







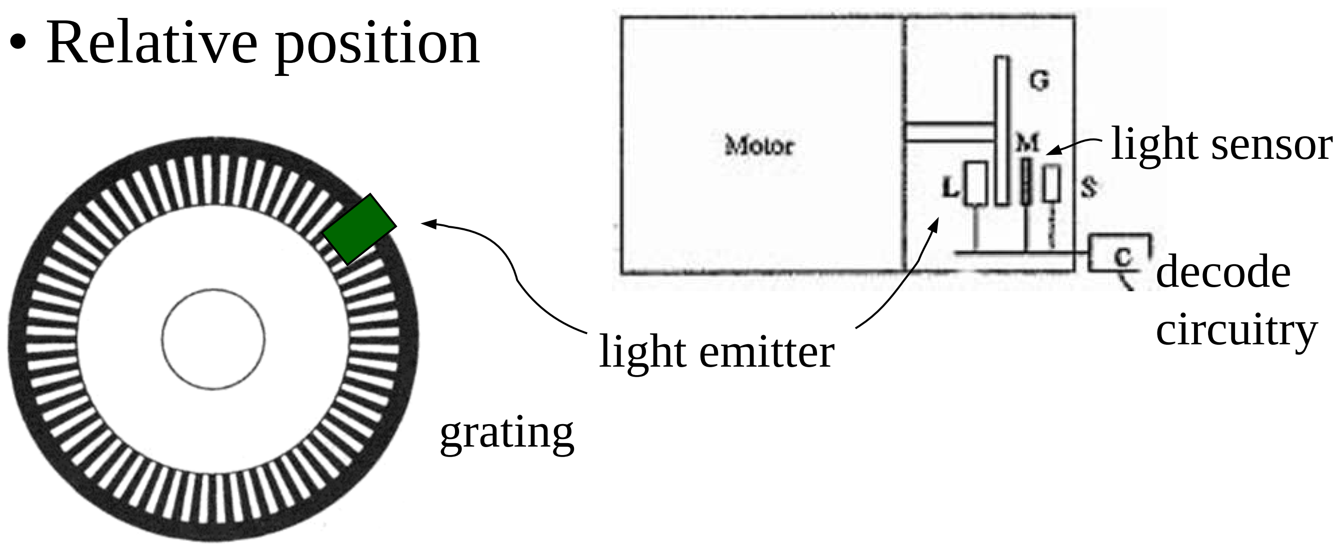
A diffuser tends to smooth these signals

Ideal

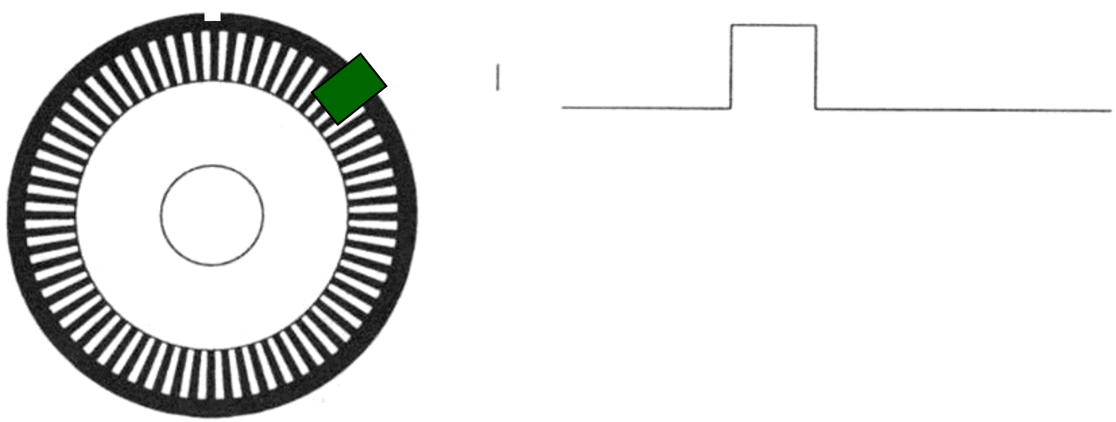
Real

Optical encoders 2

- Relative position

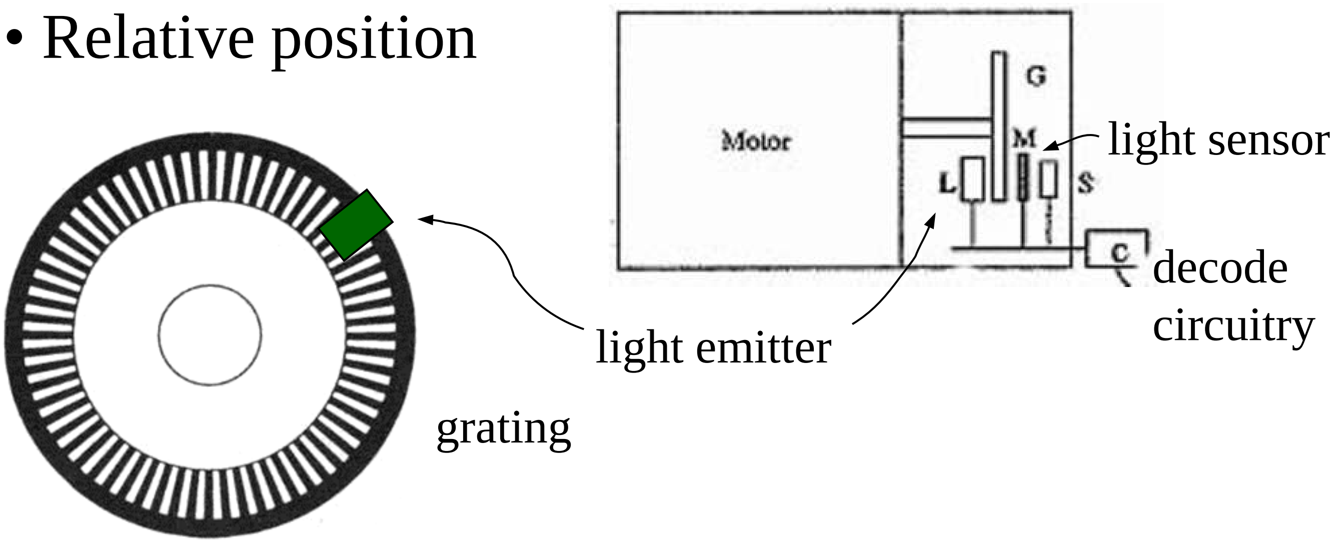


- direction
- resolution

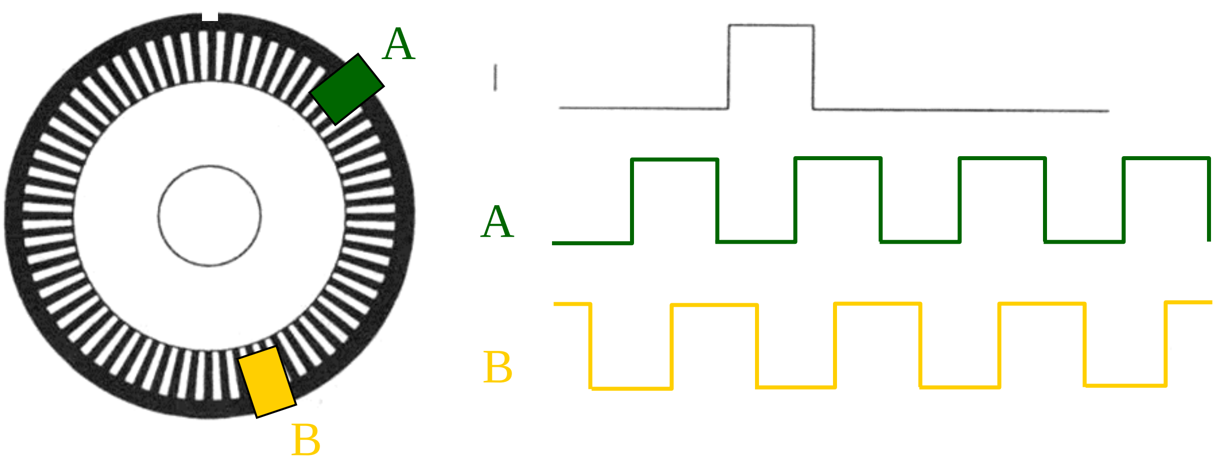


Optical encoders 3

- Relative position



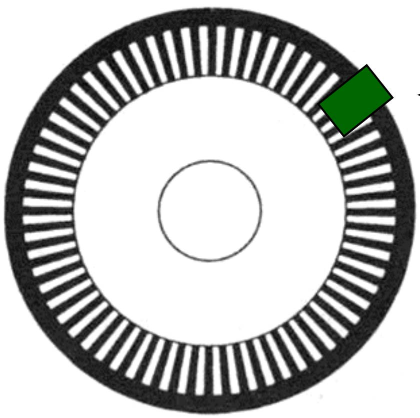
- direction
- resolution

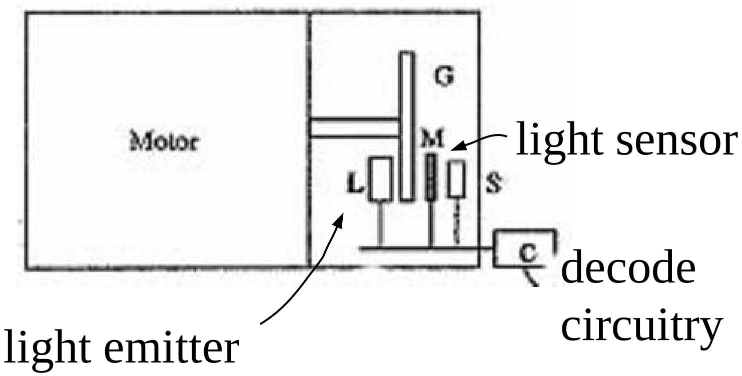


A lags B

Optical encoders 4

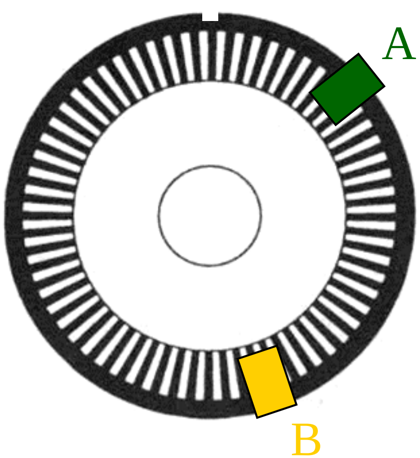
- Relative position

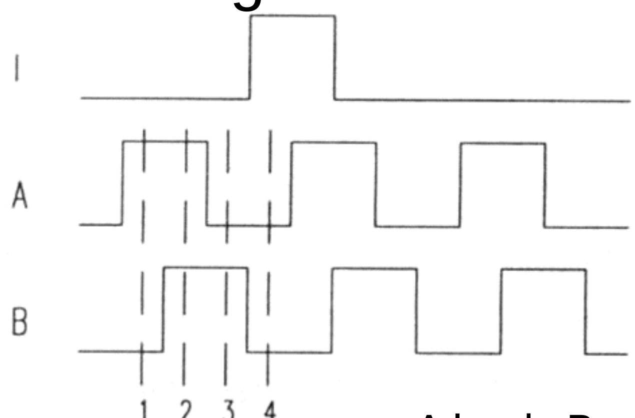




- direction
- resolution

Phase lag between A and B is 90 degree



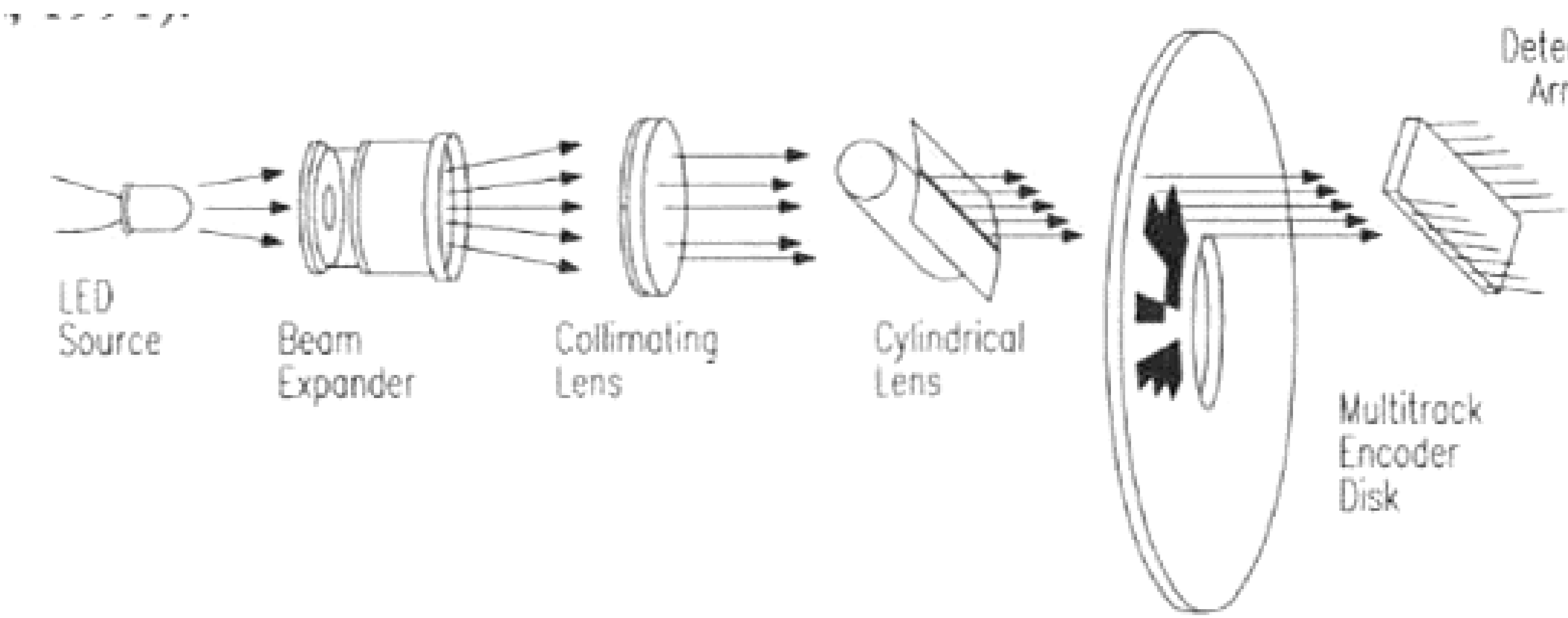


State	Ch A	Ch B
S_1	High	Low
S_2	High	High
S_3	Low	High
S_4	Low	Low

A leads B

Optical encoders 5

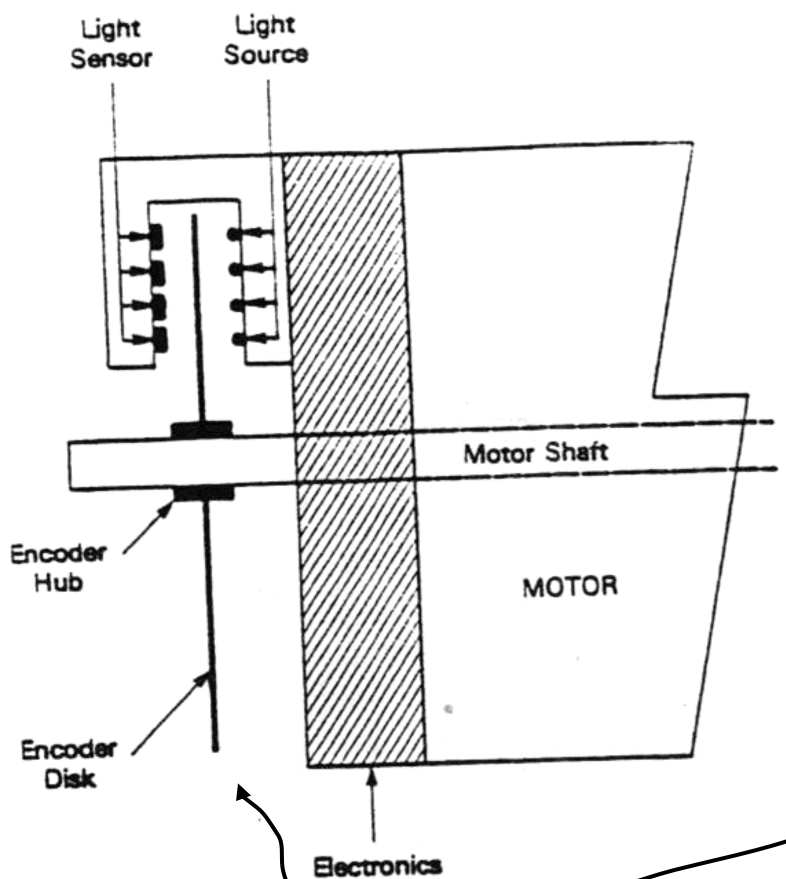
- Detecting absolute position

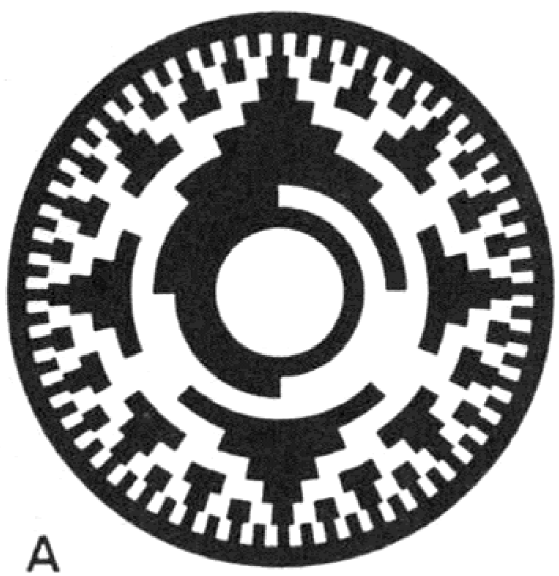


something simpler ?

Optical Encoders

- Detecting absolute position

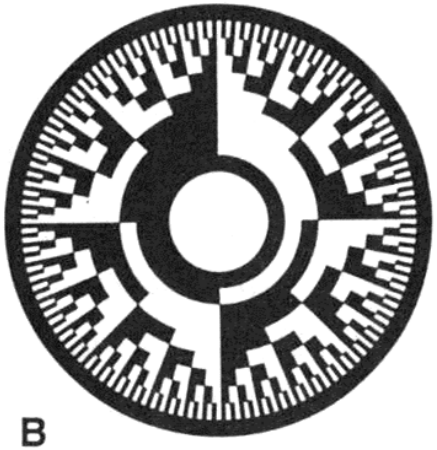




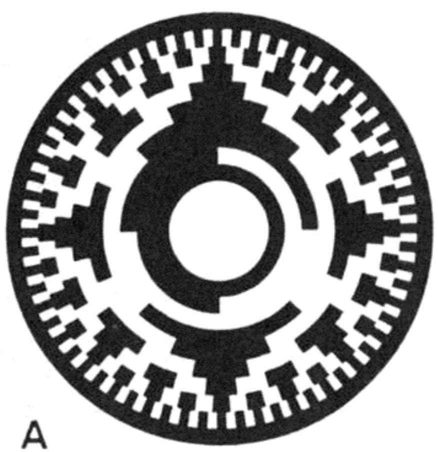
wires ?

Gray code

#	Binary	
0	0	000
1	1	001
2	10	011
3	11	010
4	100	110
5	101	111
6	110	101
7	111	100
8	1000	
9	1001	



B



A

among others...

Resolver

- Has a similar function principle as a stepper motor.

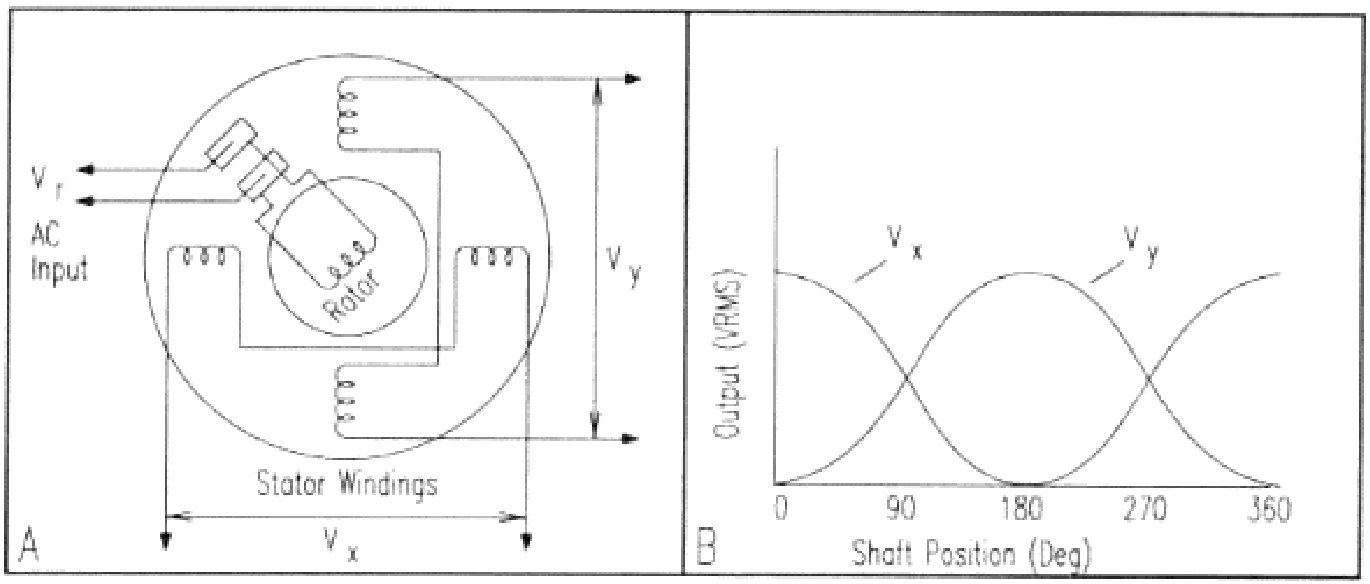


Figure 2-4. The outputs of the two orthogonal stator windings in a *resolver* are proportional to the sine and cosine of the applied rotor excitation (adapted from Tiwari, 1993).

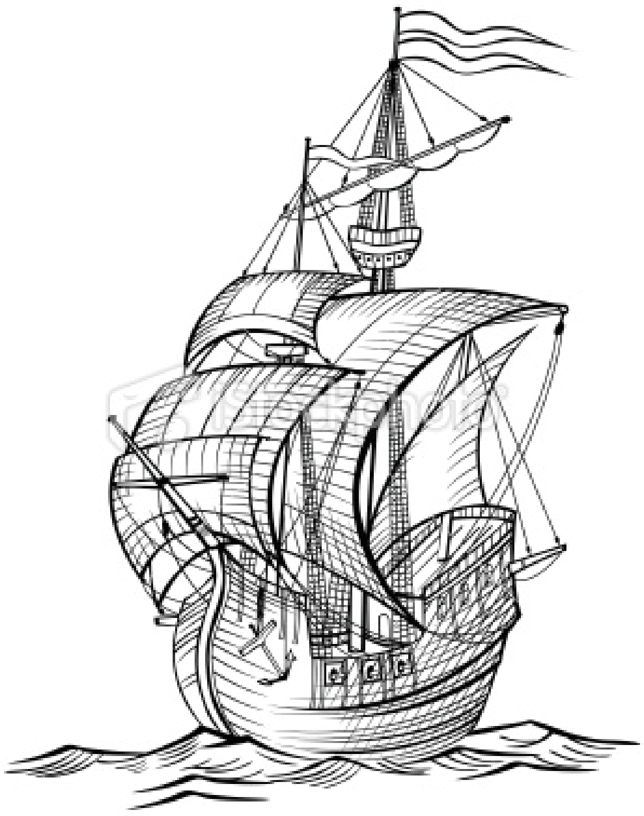
Heading sensors

- Heading sensors can be proprioceptive (gyroscope, inclinometer) or exteroceptive (compass).
- Allow, together with appropriate velocity information, to integrate movement to a position estimate.
- Used to determine the robots orientation and inclination.
- This procedure is called **dead reckoning** (from ship navigation).

Dead reckoning

Webster dictionary definition:

The determination without the aid of celestial observations of the position of a ship or aircraft from the record of the courses sailed or flown, the distance made, and the known or estimated drift.

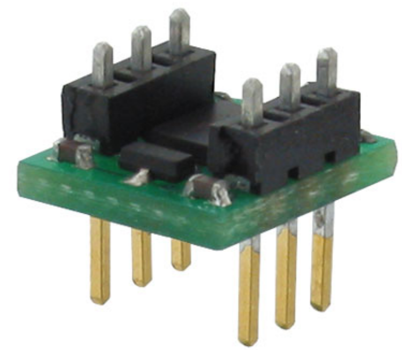


Compass

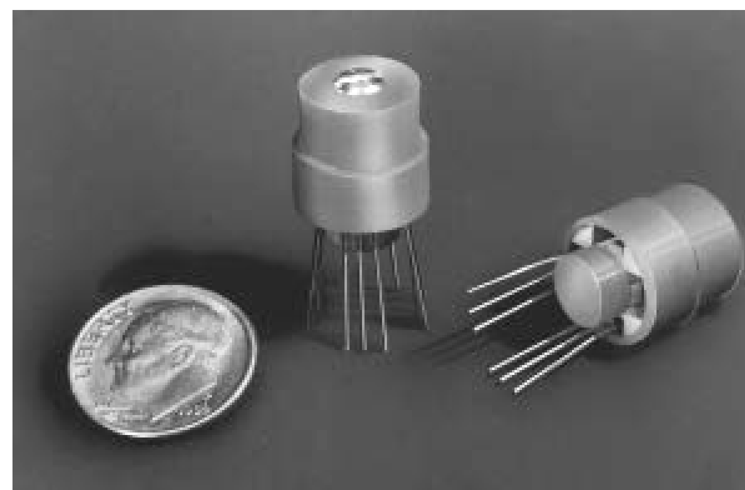
- The compass has been around since at least 2000 B.C.
- The Chinese suspended a piece of natural magnetite from a silk thread and used it to guide a chariot over land.
- Absolute measure for orientation based on Earth magnetic field.

Compass 2

- Several ways how to measure Earth magnetic field:
  - Mechanical magnetic compass.
  - Direct measure of the magnetic field (Hall-effect, magneto-resistive sensors).

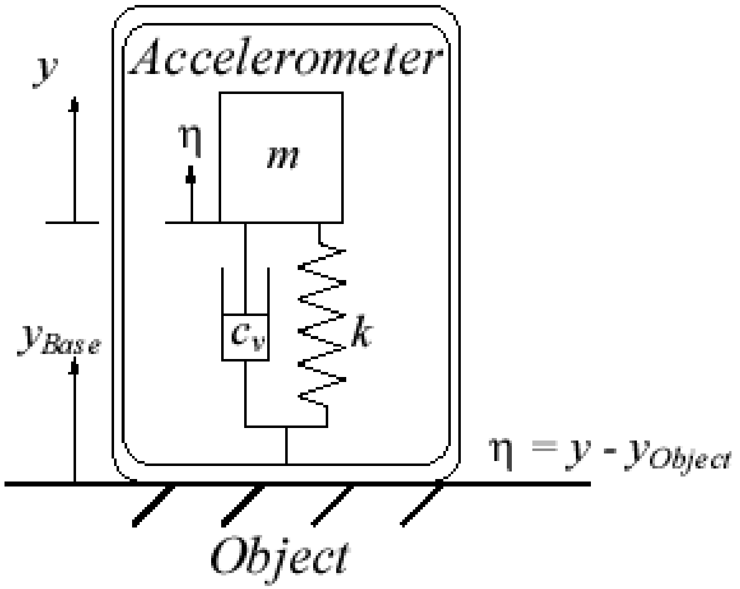


- Major drawback
  - Weakness of the earth's magnetic field.
  - Easily disturbed by magnetic objects or other sources.
  - Not feasible for indoor environments.



Accelerometer

- By virtue of Newton's second law (F = ma) a sensor may be made to sense acceleration by simply measuring the force on a mass.
- Sensing force:
  - Magnetic.
  - Capacitive.
  - Piezoelectric.

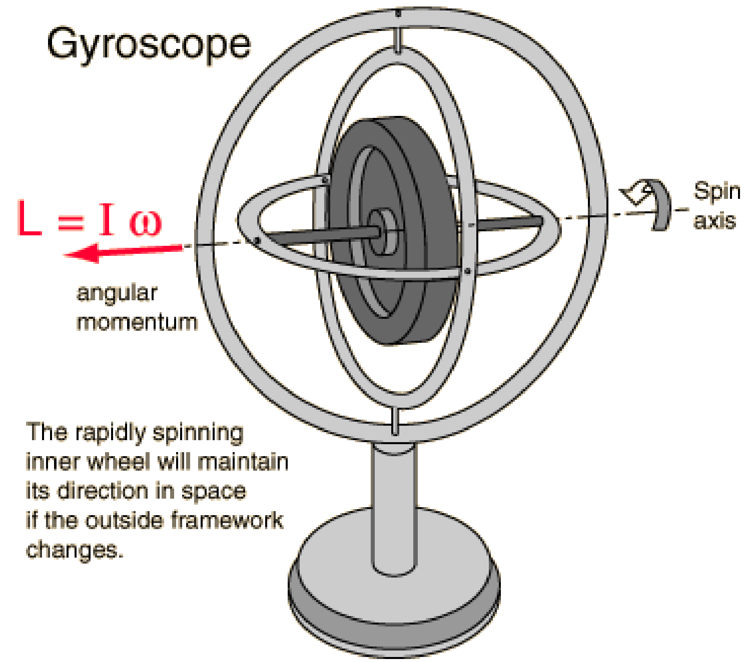


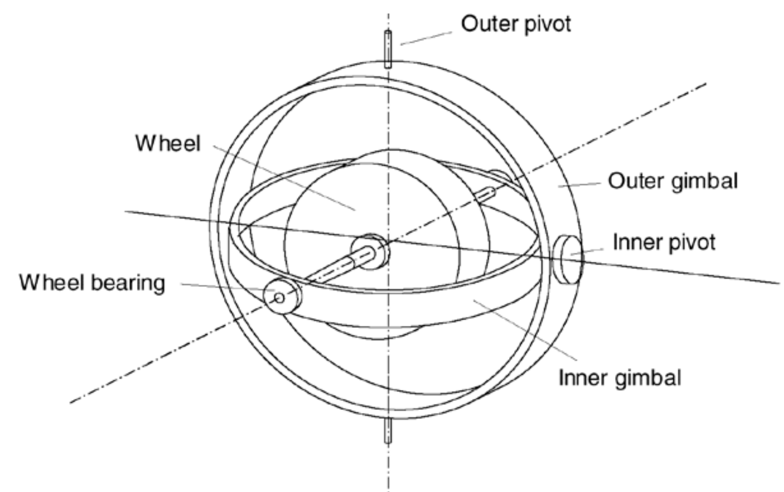
Gyroscope

- Heading sensors, that keep the orientation to a fixed frame.
- Gyroscopes are used in aeroplanes, Segways.
- Two gyroscope principles:
  - Mechanical (flywheel).
  - Electrical.

Mechanical gyroscope

- A torque is applied to the frame of the gyro around the input axis,
- The output axis will rotate as shown in a motion called precession.
- This precession now becomes a measure of the applied torque and can be used as an output to, for example, correct the direction of an airplane or the position of a satellite antenna.





Mechanical gyroscope 2

- No torque can be transmitted from the outer pivot to the wheel axis.
- Spinning axis will therefore be space-stable.
- Quality: approx. 0.1° in 6 hours.

The gyroscope was invented by Jean Bernard Léon Foucault, a French physicist, in 1852. He originally began studying medicine but gave that up as he was afraid of blood!

Electronic gyroscope

- First commercial use started only in the early 1980s when they where first installed in aeroplanes.
- Heading sensors using two monochromic light (or laser) beams from the same source.
- One is traveling in a fiber clockwise, the other counterclockwise around a cylinder.

Electronic gyroscope 2

- Sagnac effect.
- Laser beam traveling in direction of rotation has a slightly shorter path -> shows a higher frequency.
- Difference in frequency Δf of the two beams is proportional to the angular velocity.

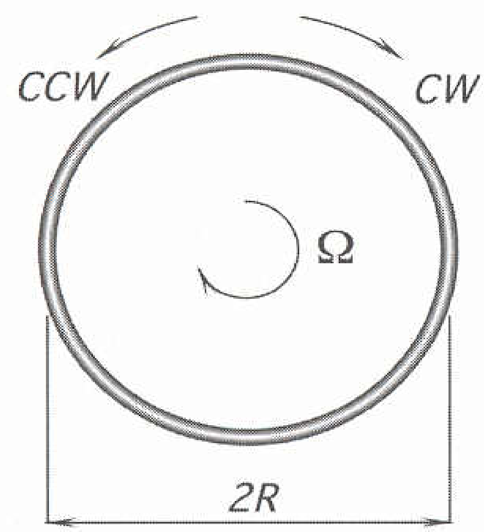
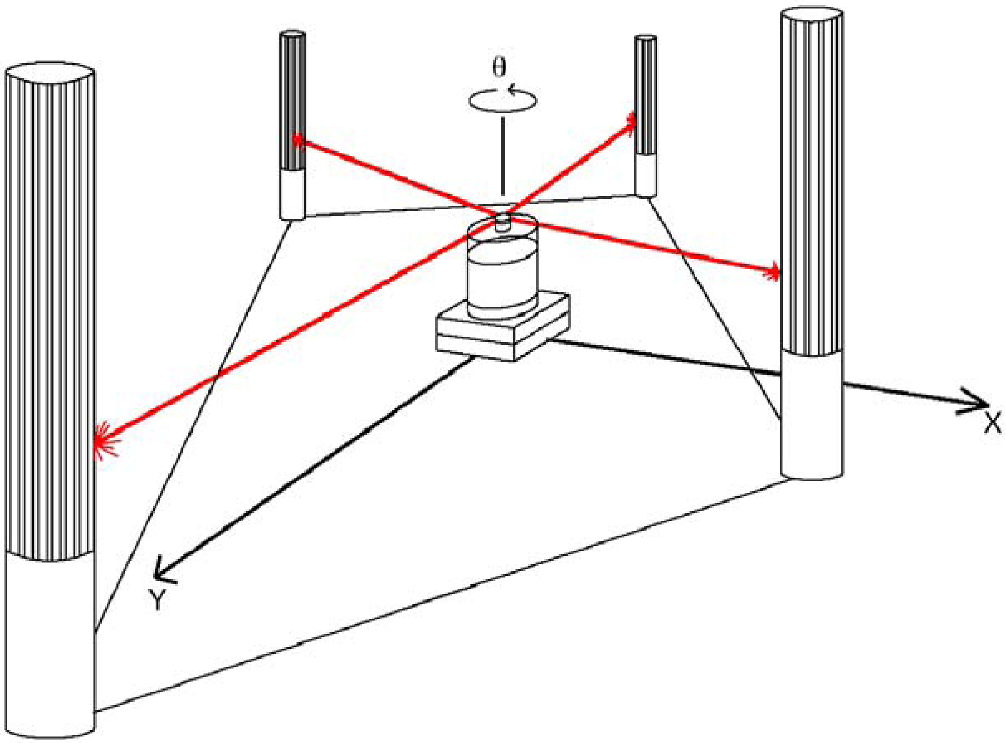


Fig. 8.13. Sagnac effect.

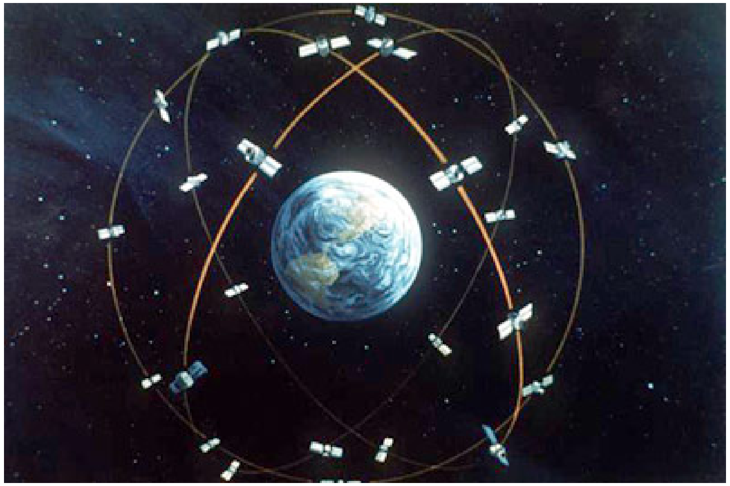
Ground-Based Beacons

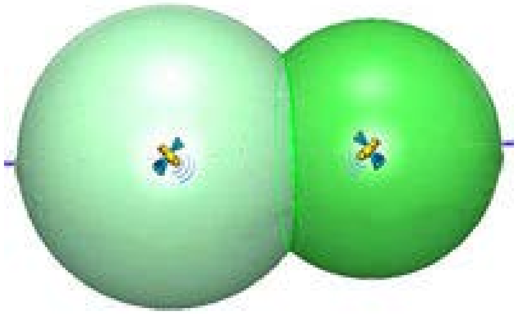
- Active, passive.
- Human use beacon-based navigation.
  - Natural beacons (landmarks) like stars, mountains or the sun
  - Artificial beacons like lighthouses.
- Used often indoors.
- Outdoors GPS.



Global Positioning System

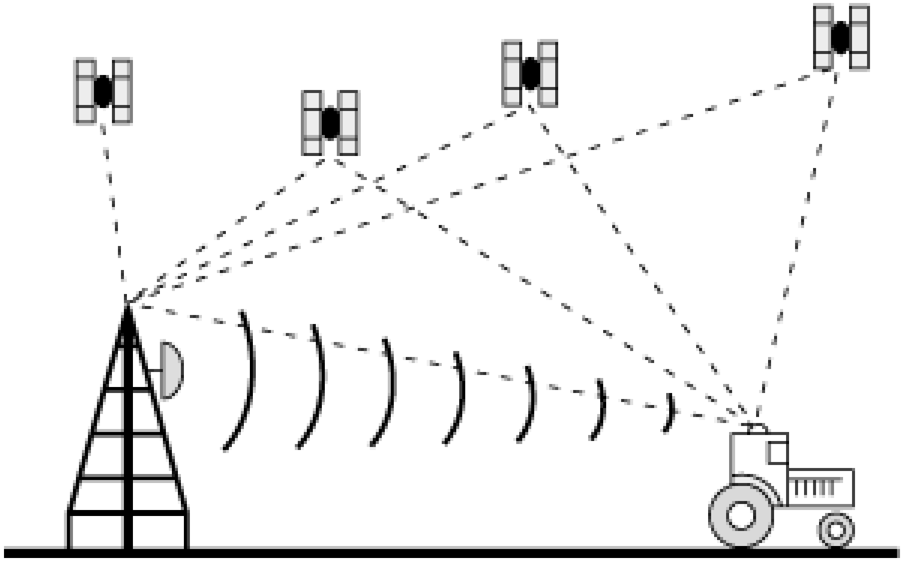
- 1 satellite = distance.
- 2 satellites = intersection of two spheres.
- 3 satellites = circle.
- ≥ 4 satellites = unique solution.
- Precision up to a few meters.





Real-time differential GPS

- Correction with respect to a base station with known position.
- Improved location accuracy, from the 15 m nominal GPS accuracy to about 10 cm for the best implementations.



Differential GPS System