SENSING AND MEASUREMENTS

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BME KÖZLEKEDÉSMÉRNÖKI ÉS JÁRMŰMÉRNÖKI KAR
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Sensing and measuring

Sensing: observing physical systems by quantities associated with excitations, states, and answers with the purpose of drawing conclusions on their structure and/or their behaviour.

The knowledge acquired by sensing is used for evaluating and/or controlling the system.

Sensing means some type of comparison:

- comparison to some limit of the quantity,
- comparison to some unit quantity ← measuring.

Measuring:

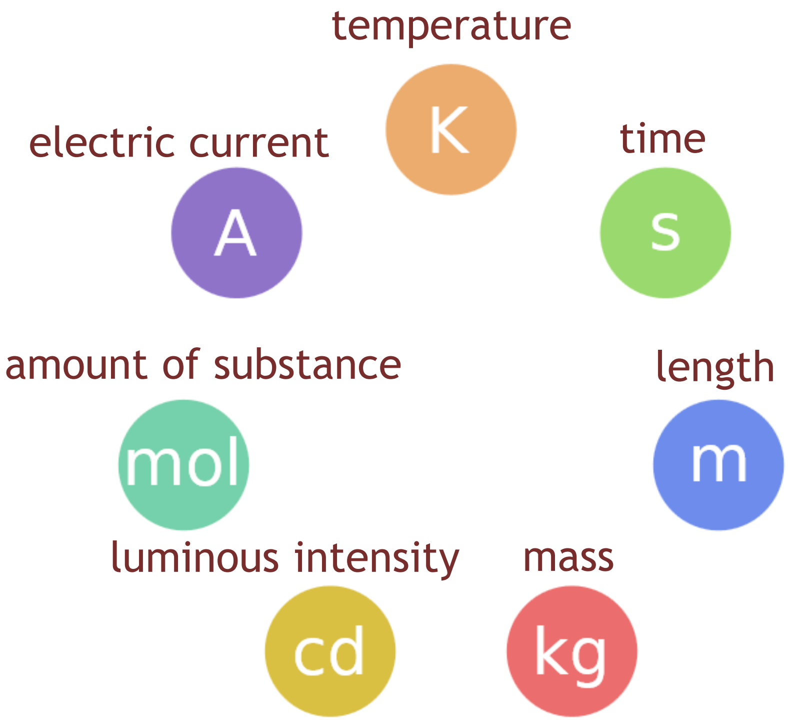
Comparison with a unit: determining the ratio of a quantity and a quantity unit.

Measuring, metrology

Metrology deals with the derivation of the units associated with quantities, with their physical realisation, and the principles of realising the measurements.

SI units (Le Système International d'Unités – International System of Units, 1960):

SI **base units**: kg, m, s,



Everything other: **derived units**, e.g.

Velocity – m/s

Pressure – kg/m^2

Electric voltage - $m^2 \cdot kg \cdot s^{-3} \cdot A^{-1}$

Metrology

The definition of the SI units (May 2019): (new)

Time: second (s) The duration of 9,192,631,770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the caesium-133 atom.

Length: meter (m) The distance travelled by light in vacuum in 1/299,792,458 second.

Mass: kilogram (kg) The kilogram is defined by setting the Planck constant h exactly to 6.62607015×10^{-34} J·s, where J = $kg\cdot m^2\cdot s^{-2}$.

Electric current: amper (A) The flow of 1.602176634×10^{19} times the elementary charge e (the charge carried by a proton) per second.

Temperature: kelvin (K) The kelvin is expected to be defined by setting the fixed numerical value of the Boltzmann constant k to 1.380649×10−23 J·K−1, where J = $kg\cdot m^2\cdot s^{-2}$.

mol (mol) The amount of substance of exactly 6.02214076×10^{23} elementary entities (the Avogadro number).

candela (cd) The luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency 5.4×10^{14} hertz and that has a radiant intensity in that direction of 1/683 watt per steradian.

Metrology


Meridian measurements

The definition of the SI base units has changed a lot since the beginnings, e.g. the **meter**:

According to Metre Convention 1875, Paris 1 m is 1/10,000,000 of the meridian through Paris between the North Pole and the Equator.

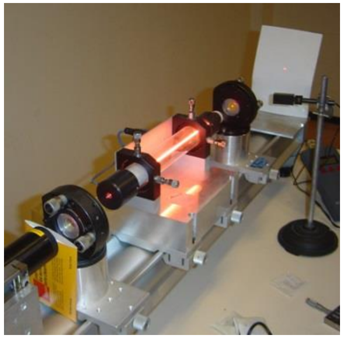

Pt-Ir etalon

According to the derivation of 1889 1 m is the length measured between two notches engraved on of a platina-iridium etalon in the temperature of the melting ice.

In1960 1 m was derived as 1,650,763.73 1650763.73 wavelengths in a vacuum of the radiation corresponding to the transition between the 2p10 and 5d5 quantum levels of the krypton-86 atom.

Krypton-86 lamp


In 1983 meter was defined as the distance travelled by light in vacuum in 1/299,792,458 second (the current definition). Realisation: wavelength of an iodine stabilized helium-neon laser.


He-Ne laser

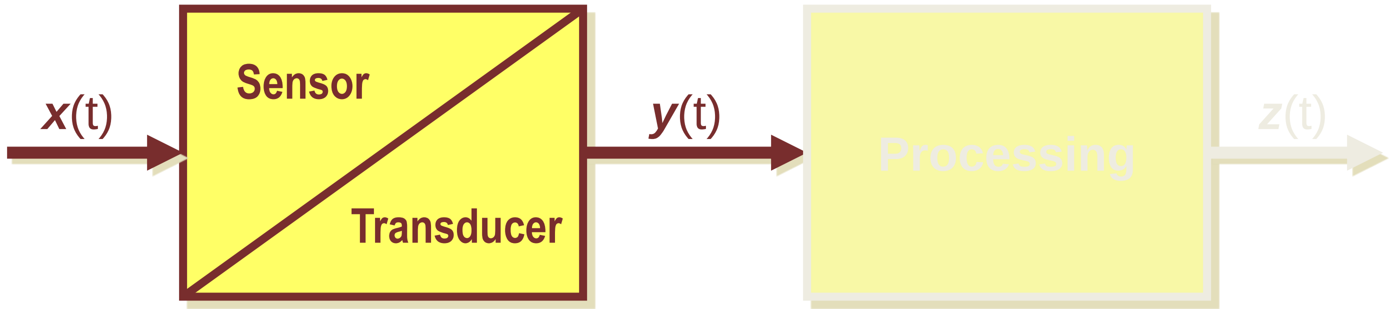
By successive redefinitions the relative uncertainty decreased from 10^{-7} to 10^{-11}.

Metrology

SI derived units possessing specific names:

Derived quantities	SI unit	Notation	Expressed with SI units	Expressed with SI base units
frequency	hertz	Hz		s^{-1}
force	newton	N		$m \cdot kg \cdot s^{-2}$
pressure	pascal	Pa	N/m^2	$m^{-1} \cdot kg \cdot s^{-2}$
energy	joule	J	$N \cdot m$	$m^2 \cdot kg \cdot s^{-2}$
power	watt	W	J/s	$m2 \cdot kg \cdot s^{-3}$
electric charge	coulomb	C		$s \cdot A$
electric potential difference, voltage, electromotive force	volt	V	W/A	$m^2 \cdot kg \cdot s^{-3} \cdot A^{-1}$
electric capacity	farad	F	C/V	$m^{-2} \cdot kg^{-1} \cdot s^4 \cdot A^2$
electric resistance	ohm	Ω	V/A	$m^2 \cdot kg \cdot s^{-3} \cdot A^{-2}$
electric conductivity	siemens	S	A/V	$m^{-2} \cdot kg^{-1} \cdot s^3 \cdot A^2$
magnetic flux	weber	Wb	$V \cdot s$	$m^2 \cdot kg \cdot s^{-2} \cdot A^{-1}$
magnetic induction, magnetic flux density	tesla	T	Wb/m^2	$kg \cdot s^{-2} \cdot A^{-1}$
inductivity	henry	H	Wb/A	$m^2 \cdot kg \cdot s^{-2} \cdot A^{-2}$
Luminous flux	lumen	lm	$cd \cdot sr$	cd
illuminance	lux	lx	lm/m^2	$m^2 \cdot m^{-4} \cdot cd = m^{-2} \cdot cd$
radioactivity	becquerel	Bq		s^{-1}
ionising radiation dose	gray	Gy	J/kg	$m^2 \cdot s^{-2}$
ionising radiation dose	sievert	Sv	J/kg	$m^2 \cdot s^{-2}$
planar angle	radian	rad		$m \cdot m^{-1} = 1$
spatial angle	steradian	sr		$m2 \cdot m^{-2} = 1$
catalythic activity	katal	kat		$s^{-1} \cdot mol$

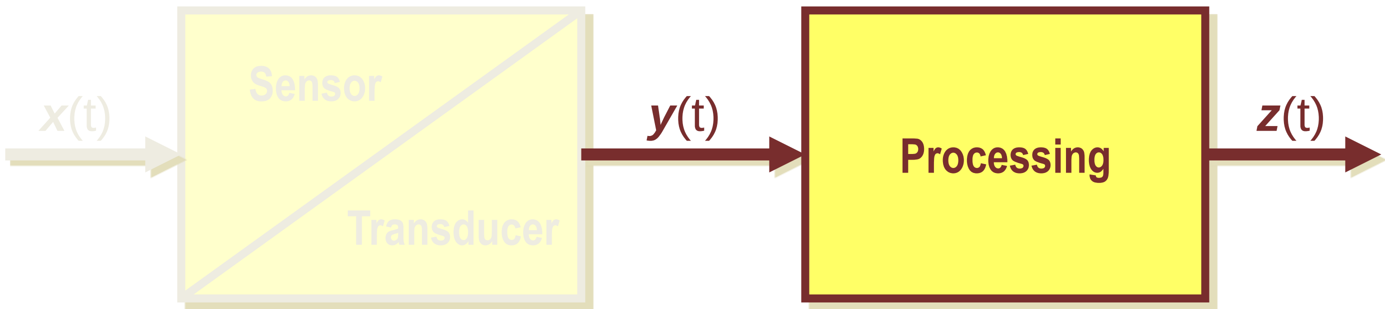
Sensors



Sensor / transducer: brings a physical quantity into a workable form (workable by a human or anautomaton)

Examples:
- Kinematic sensors: speedometer, tachograph
- Dynamical sensors: accelerometer, gyroscope
- Temperature sensors: thermocouple, resistance temperature device (RTD), thermistor
- Pressure sensor: manometer, barometer,
- Electrical sensors: voltmeter, current sensor
- Magnetic sensors: magnetic field detector, compass
- Composite sensors: video camera, GPS, LIDAR

Sensors



Processing is needed because the sensors usually do not produce the features needed by the user.

The (most typical) reasons:

- Measurement errors, inaccuracies,
- Noises,
- Unwanted internal and environmental effects,
- Crossover between measured parameters.

Sensors typically today

The physical quantities are transformed to

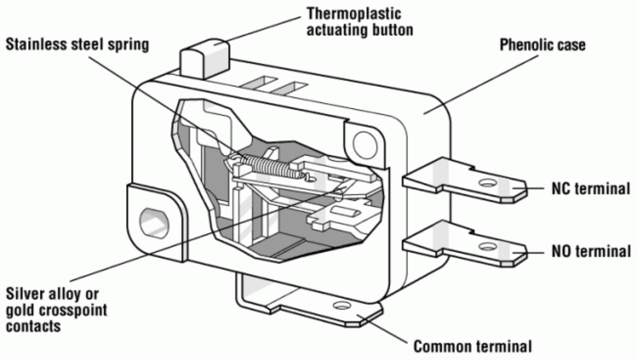
- electrical quantities: voltage, current, frequency, or
- quantities that can be measured by using electrical principles: electrical resistance, capacity, inductivity.

Classification of the sensors by the output generated:

- Analogous: the output quantity can be interpreted in continuous scale.
- Binary: the output varies between two discrete values – can be interpreted as logic levels.
- Digital: the output quantity can be interpreted in discrete numeric scale.

Sensors

Some simple examples:



Micro-switch (limit-switch)

- binary sensor: displacement or force to resistance zero/infinite

Potentiometer

- analog sensor: angle to resistance

Sensors

Some simple examples for optical sensors:

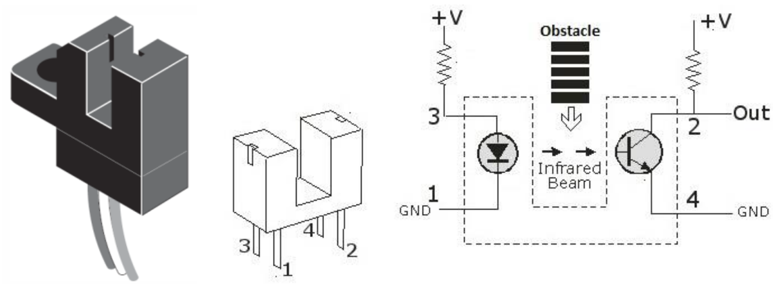
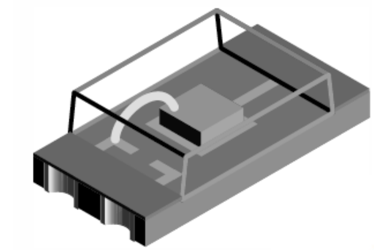


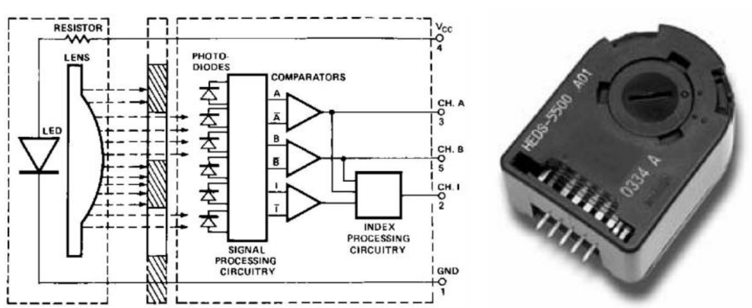
Photo-interrupter



ALS (ambient light sensor)

LDR (light-dependent resistor)

Light intensity sensors

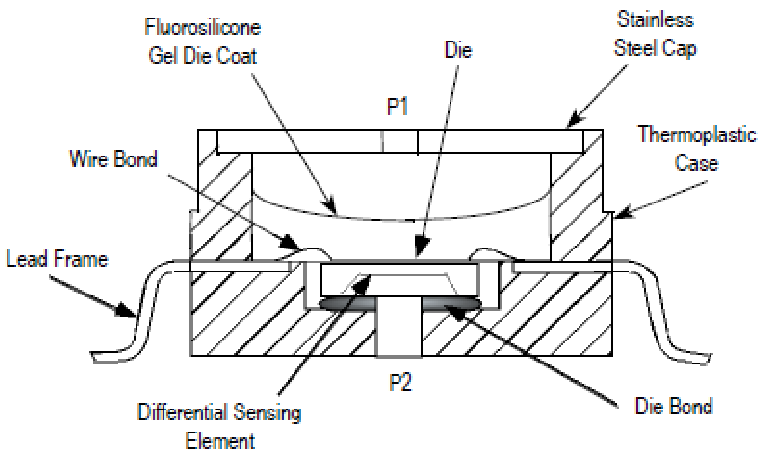


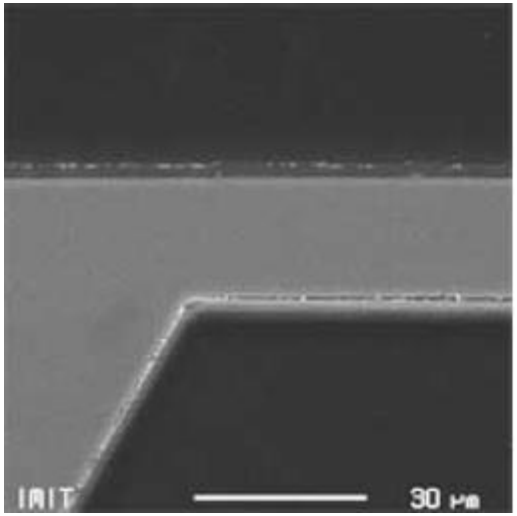
Optical rotary encoder

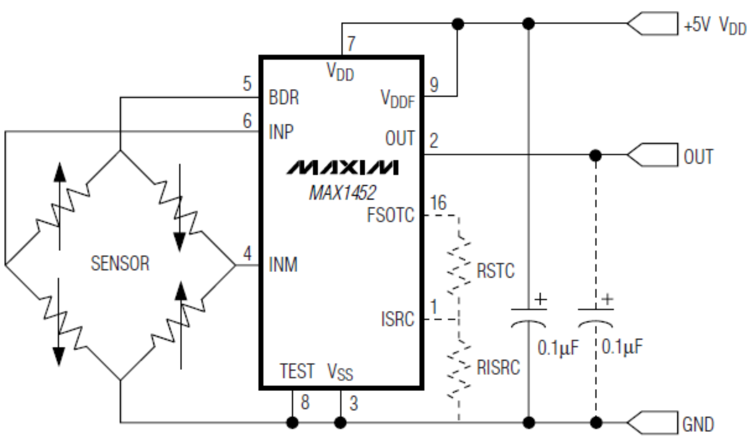
Infrared distance measurement sensor

Sensing and measurement

Semiconductor pressure sensor





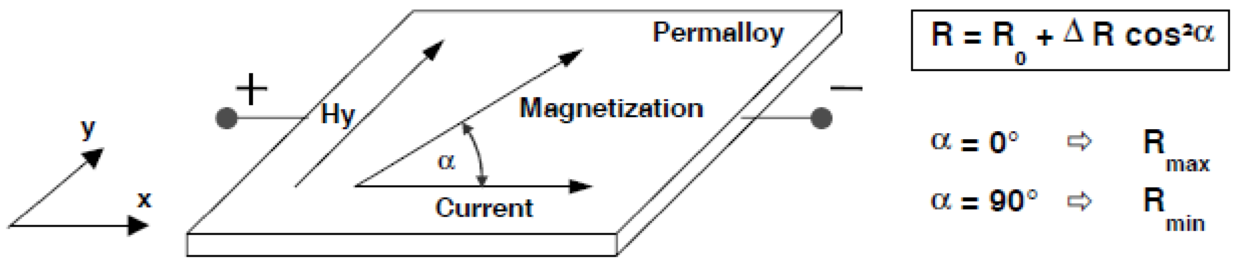


Pressure difference causes deformation on the thin Si disc (membrane).

The deformation causes changes in the resistance that can be measured by using the Wheatstone-bridge principle.

Sensing and measurement

Magnetic field sensor

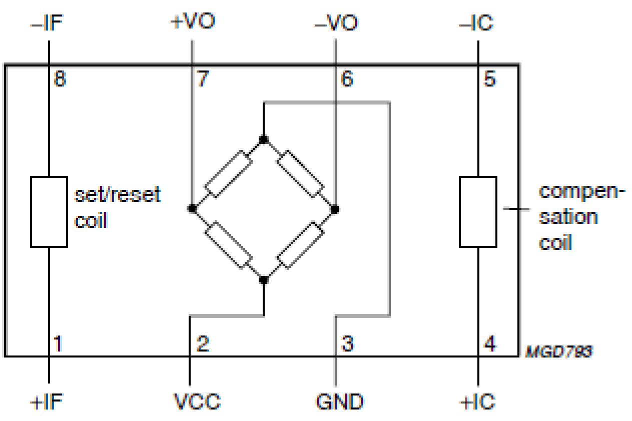


ferromagnetic material

Magnetoresistive effect:

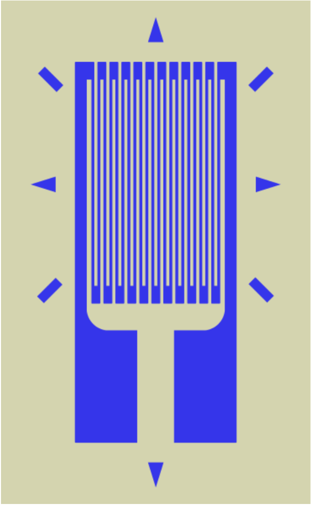
The magnetic field changes the electrical resistance of the permalloy material (an iron alloy).

Measurement: Wheatstone-bridge.



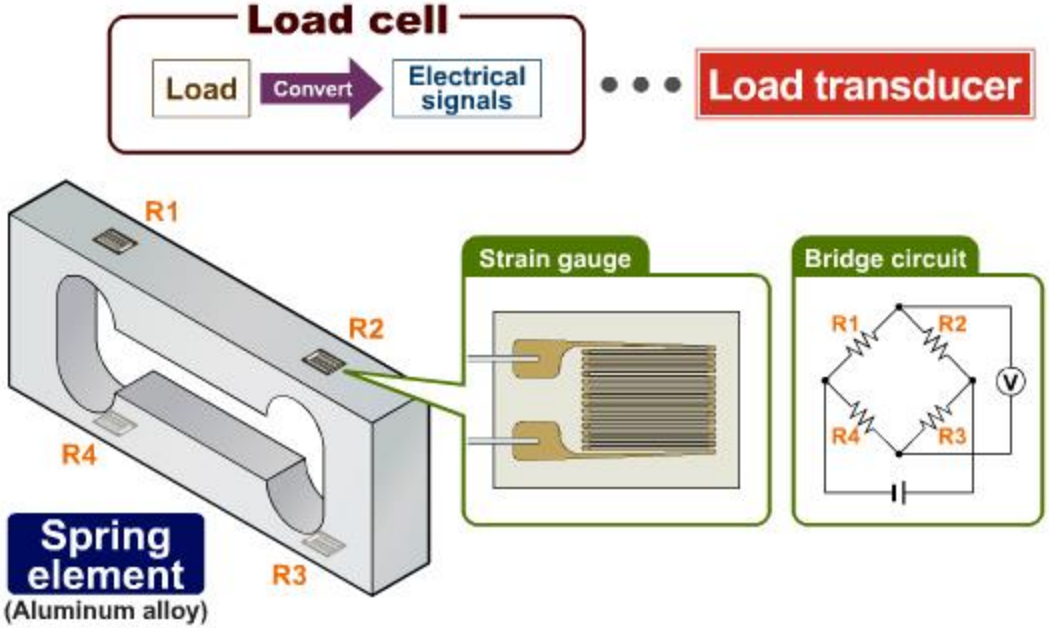
Sensing and measurement

Stain gauge stamp



Mechanical deformation (strain):

changes the resistance of a thin conductive layer.



Application example: weight cell.

Measurement: Wheatstone-bridge.

Temperature measurement

Temperature sensor options:

Binary temperature sensors (thermal switch, thermostat):

- Bimetal switch
- Liquid- or gas-filled bellows switch

Proportional (analog) temperature sensors:

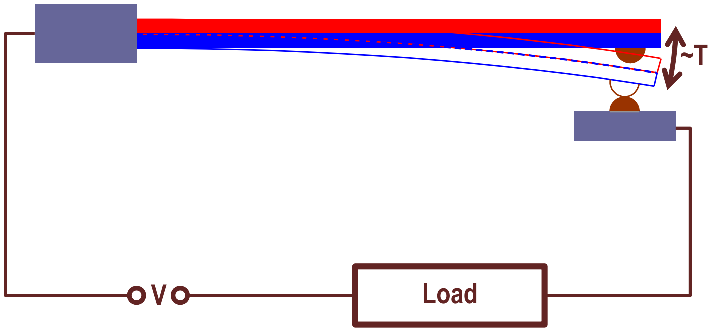
- Resistor Temperature Detector (RTD)
- Thermocouple(TC),
- Thermistor
- Semiconductor based temperature sensors
- Contactless infrared temperature sensors

Temperature measurement

Binary temperature sensors

Limit switch: if the temperature goes beyond some limit its state of a switch is changed between ON/OFF.

- Bimetal switch



Bimetal strip – rolled by two metal strips with different thermal expansion coefficients: due to different length increases of the two materials it is deflected.

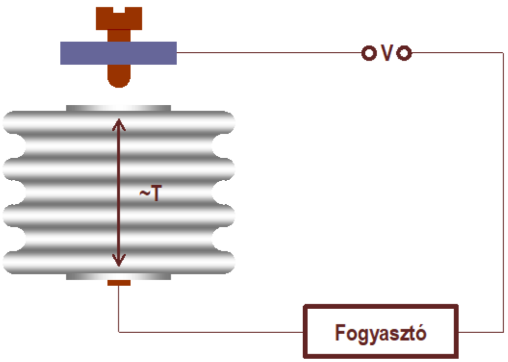
$$\varepsilon = \frac{L(T)-L(T_0)}{L(T_0)} = \alpha(T\text{-}T_0)$$

relative length difference

thermal expansion coefficient

Temperature measurement

- Liquid- or gas-filled bellows switch



Temperature dependence of a gas:

$$\frac{pV}{T} = const. \qquad \text{(unified gas law)}$$

The bellows keeps constant pressure:

$$V(T) - V(T_0) = \frac{k}{p}(T\text{-}T_0) \qquad L(T) - L(T_0) = \frac{k}{pA}(T\text{-}T_0)$$

$$V = LA$$

Temperature dependence of the volume of liquids:

relative change of volume

$$\varepsilon_V = \frac{V(T) - V(T_0)}{V(T_0)} = \gamma(V\text{-}V_0)$$

Volumetric thermal expansion coefficient

Temperature measurement

Resistor Temperature Detector (RTD)

Principle: temperature dependence of the resistance of conductive materials

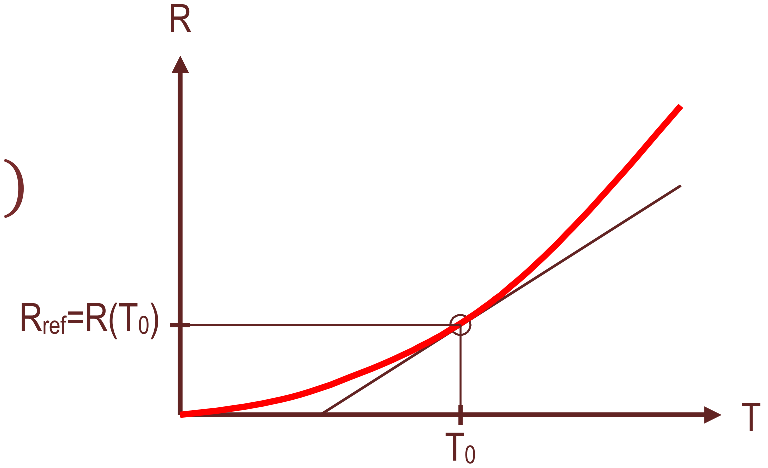
$$\frac{R(T)-R(T_0)}{R(T_0)} = \alpha(T\text{-}T_0) \quad R(T) = R(T_0)\,(1+\alpha\Delta T)$$

linear thermal coefficient

In the reality a nonlinear relationship is valid.

A 2nd order approximation:

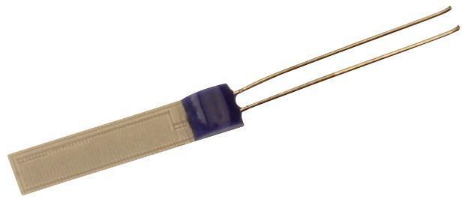
$$R(T) = R(T_0)\,(1+\alpha\Delta T+\beta(\Delta T)^2)$$

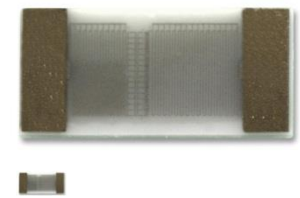


Higher order approximations: by the Taylor-expansion of the function R(T).

Temperature measurement

RTD: Pt100 – 100 Ω platinum is used most frequently





Standard: DIN IEC 751

Classes – according to tolerance:

A: ± [(0.15 + 0.002 | t |] °C
B: ± [(0.30 + 0.005 | t |] °C

Materials used:

Platinum	0.00385 Ω/Ω/°C	-260 – 850 °C
Copper	0.00427 Ω/Ω/°C	-100 - 260 °C
Nickel	0.00672 Ω/Ω/°C	-100 – 260 °C

Temperature measurement

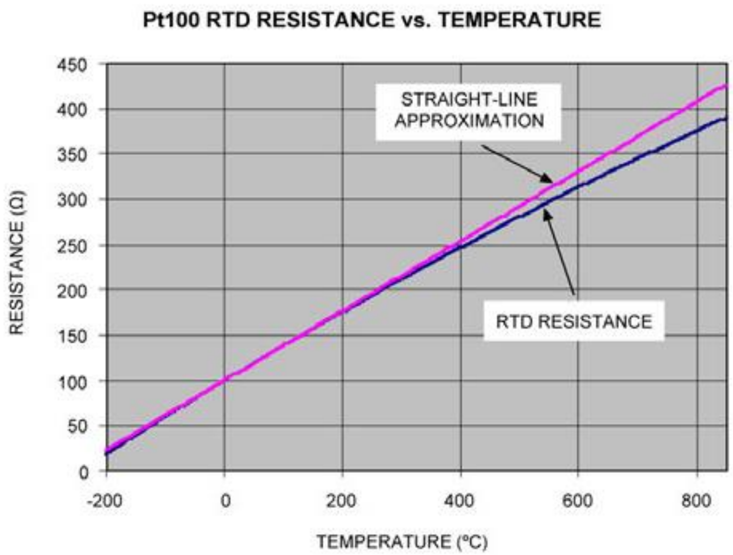
Characteristics of Pt100 RTD (according to IEC751):

- Nominal resistance at 100°C: 100Ω.
- Linear thermal coefficient α=0.00385 (average between 0 and 100 °C)
- More accurate – nonlinear – relationship:

$$R(T) = R_0\,(1 + aT + bT^2 + c(T\text{-}100)T^3)$$

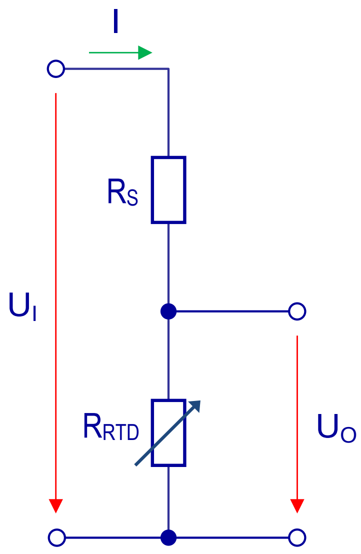
$$a = 3.90830 \times 10^{-3}$$
$$b = -5.77500 \times 10^{-7}$$
$$c = \begin{cases} -4.18301 \times 10-12 & 200°C < T < 0°C \\ 0 & 0°C < T < +850°C \end{cases}$$

(Callendar-Van Dusen equation)



Temperature measurement

Measurement with RTDs: voltage divider



Excitation by voltage generator:

$$U_0 = U_I \frac{R_{RTD}}{R_S + R_{RTD}}$$

← bias

nonlinear

Excitation by current generator

$$U_0 = I R_{RTD}$$

linear

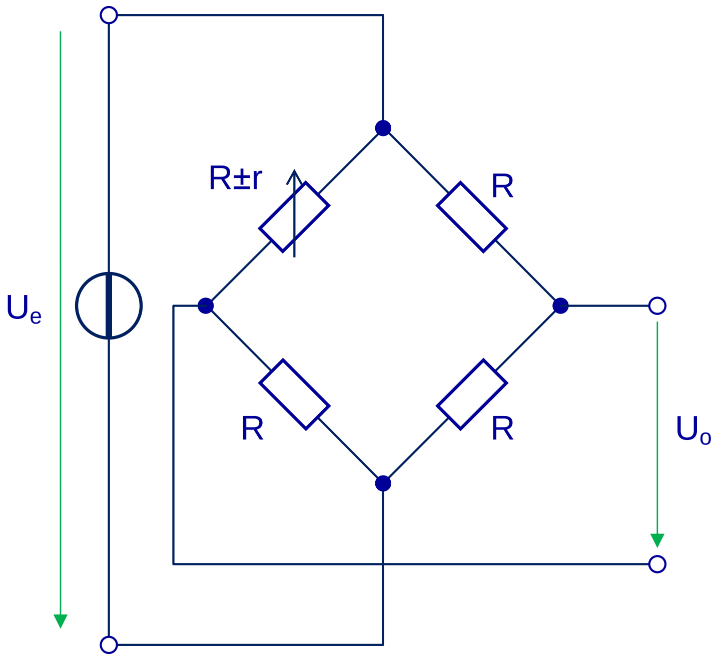
Excitation by constant current is more advantageous:

- no bias,
- The resistance of wiring does not affect the result.

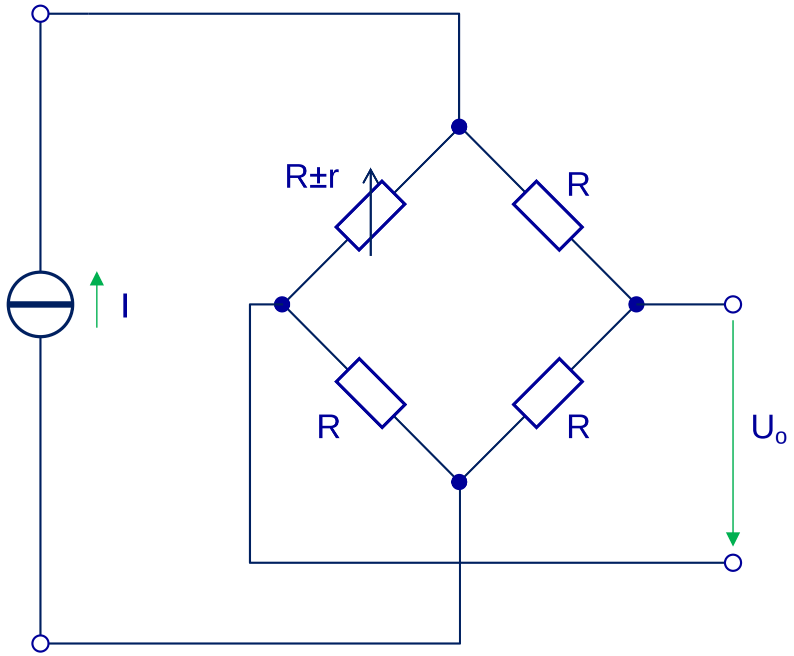
Temperature measurement

RTD measurement: Wheatstone-bridge

One element of the bridge is an RTD, the other ones are resistors with constant values. Output voltage U_o is measured.



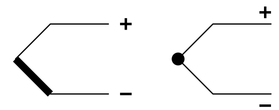
Excitation by voltage generator



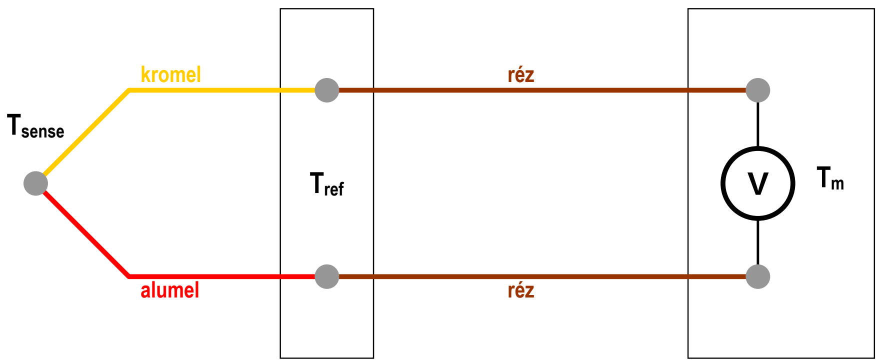
Excitation by current generator: it is usually more advantageous.

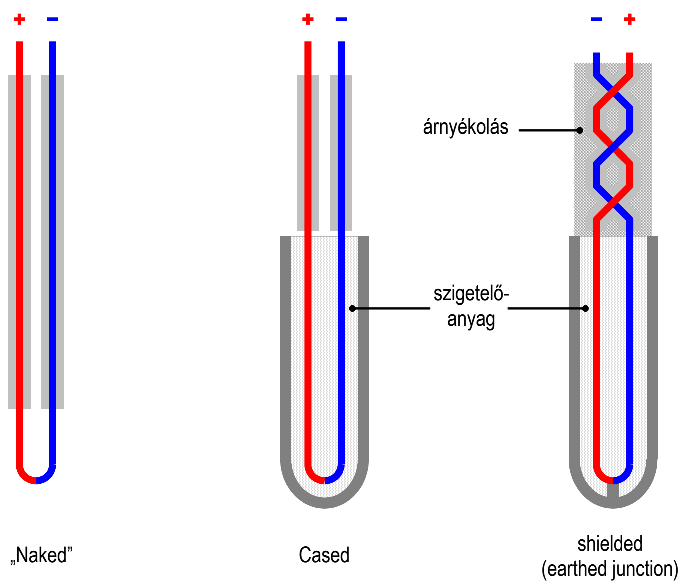
Temperature measurement

Thermo Couples (TC)



Thermoelectric (Seebeck) effect: mobility of electrons varies in different metals; this phenomenon results in different electric potential that can be measured – in a junction of different metals thermal voltage occurs.





K-type TC (according IEC 584)

chromel(+) - alumel(-)   41μV/°C

chromel: nickel (90%) – chromium (10%) alloy
alumel: nickel (95%) – manganum (2%) – aluminium (2%) - silicon (1%) alloy

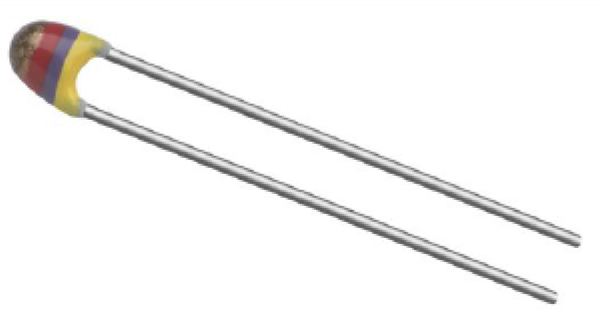
Temperature measurement

Thermistors

Resistors made of semiconductor ceramic material with

- NTC – negative temperature coefficient
- PTC – positive temperature coefficient

NTCs are most frequently used. The principal equation:



$$T = \frac{1}{A + B\ln(R) + C[\ln(R)]^3}$$

(Steinhart-Hart)

A, B, C are empirical constants
(can be found in catalogues)

Measurement:

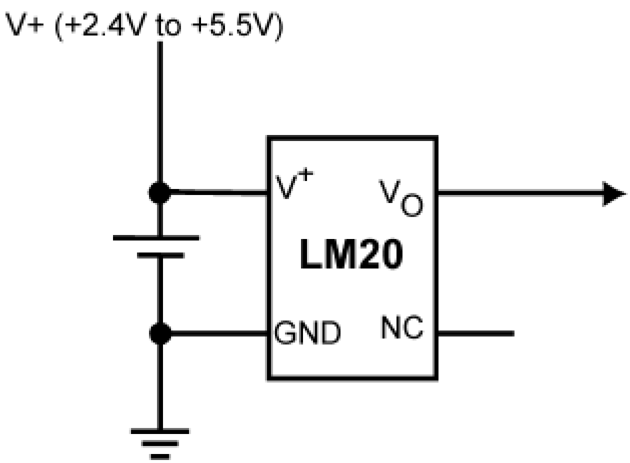
- voltage divider, or
- Wheatstone-bridge.

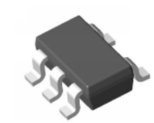
Temperature measurement

Semiconductor temperature measurement ICs, e.g.: LM20

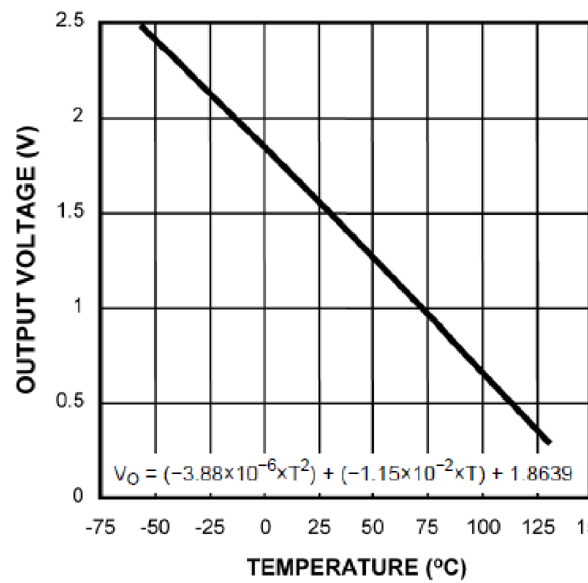
Operating principle: exploits the temperature dependence of the semiconductor PN junction (Si material).

Analog output quasi-linear sensor: $V_0 = -11.69\ mV/°C \cdot T + 1.8663\ V$





(SOT-23 case)



More exact nonlinear expression:

$$T = -1481.96 + \sqrt{2.1962 \cdot 10^6 + \frac{1.8639 - V_0}{3.88 \cdot 10^{-6}}}$$

$$V_0 = (-3.88 \cdot 10^{-6} \cdot T^2) + (-1.15 \cdot 10^2 \cdot T) + 1.86399$$

Position and attitude sensing

Position and attitude in an inertial system are relative quantities.

Absolute quantities :

- Accelerations of translations – a_x, a_y, a_z
- Angular rates of rotation – ω_x, ω_y, ω_z

Position, velocity and orientation angles are given:

$$s(t) = s_0 + v_0 t + \int_{t_0}^{t}\int_{t_0}^{t} a(\tau)\,d\tau$$

$$v(t) = v_0 + \int_{t_0}^{t} a(\tau)\,d\tau$$

$$\varphi(t) = \varphi_0 + \int_{t_0}^{t} \omega(\tau)\,d\tau$$

- Indefinite parameters are present in the equations.
- Their derivation can be realized with cumulative error.

Gyroscopic sensors

The means of sensing the orientation and the rotation of the objects; they realise angle or angular rate measurements.

Types according to the physical principle used:

- Mechanical (rotating) gyroscope
- Vibrating mechanical gyroscope
- Laser gyroscope

Mechanical rotating gyroscopes

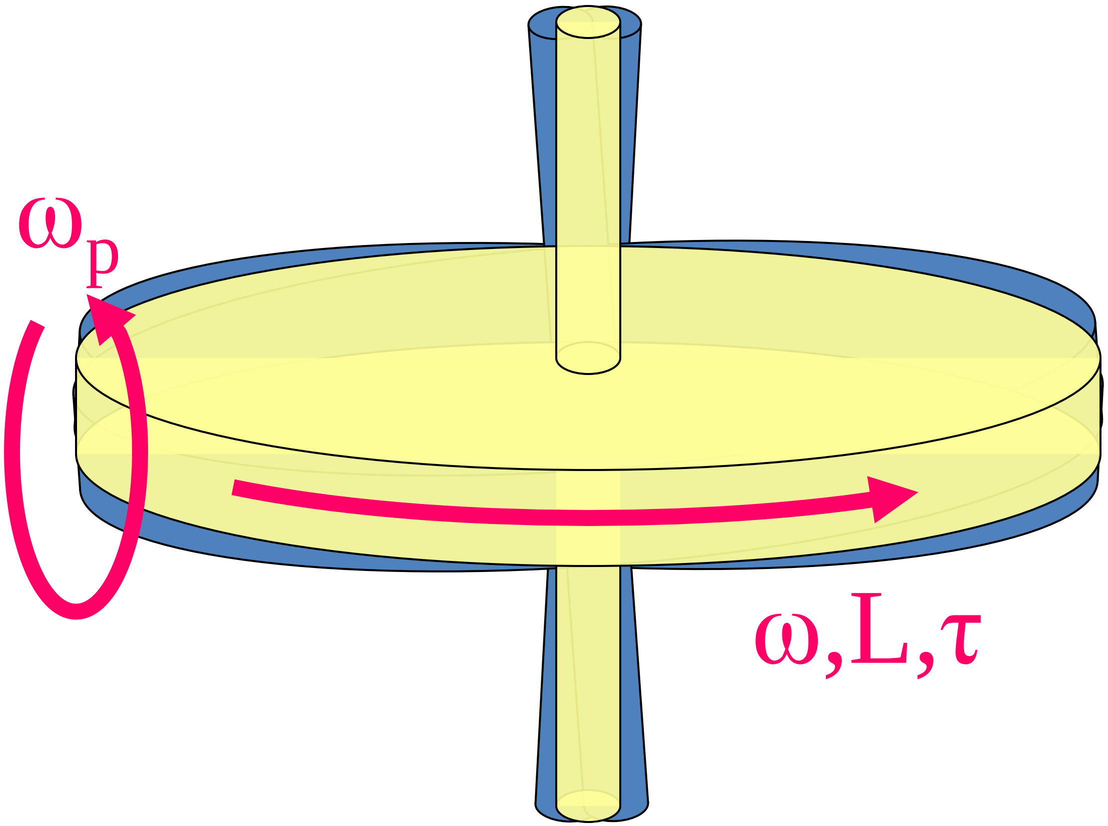
Physical principles:
- Newton axioms
- The impulse retention law

The rotating angle of a rotating rigid body is in stable equilibrium, i.e. it retains its position.

What does it mean? Is it standing? – No:

It rotates around a given direction along a cone – this is the phenomenon of precession.

Mechanical rotating gyroscopes



$$\tau = \frac{dL}{dt} = \frac{d(\Theta\omega)}{dt} = \Theta\beta$$

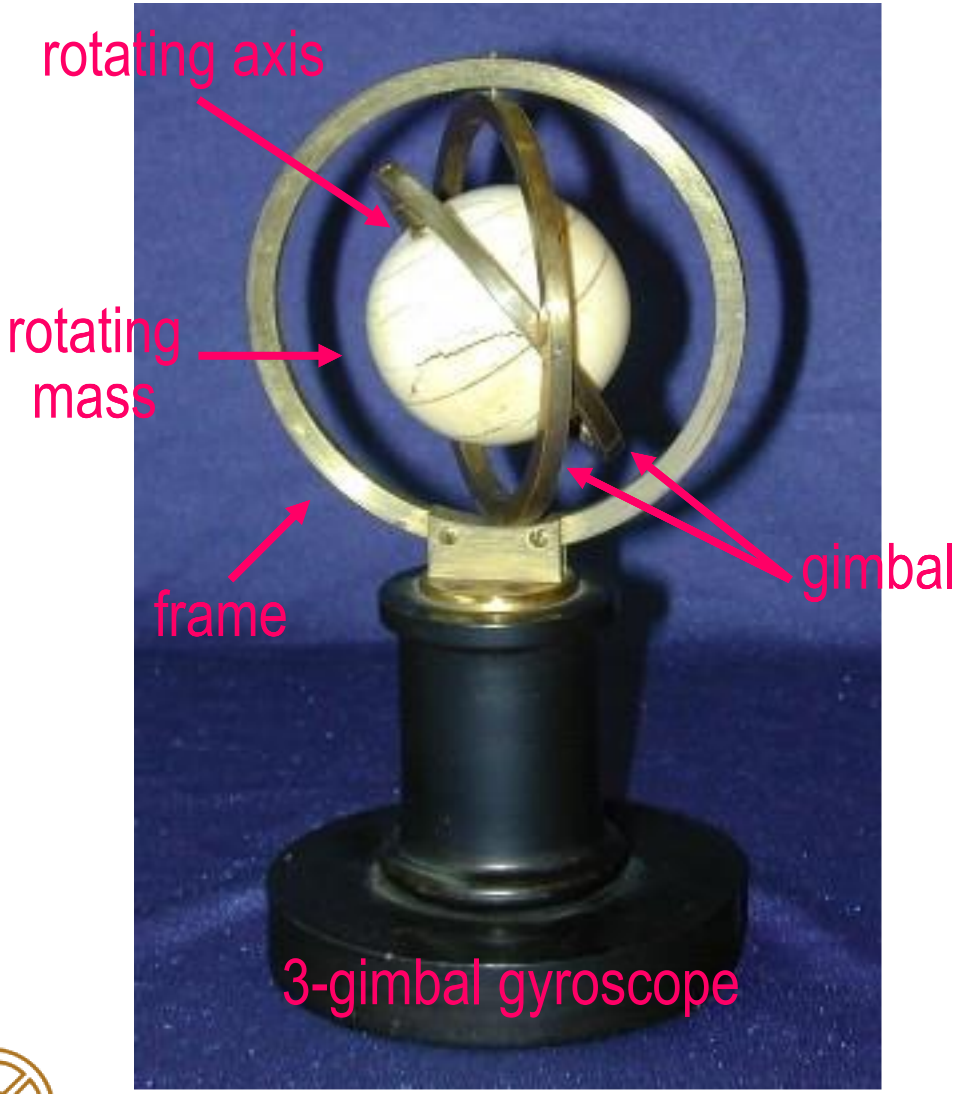
Precession:

- A torque perpendicular to the rotations axis occurs

$$\tau_p = \omega_p \times L$$

- Coriolis force coming from the rotation of the Earth
- Friction effects
- Random effects (small deflections in the geometry, and external forces)

History of gyroscopes



Johann Bohnenberger

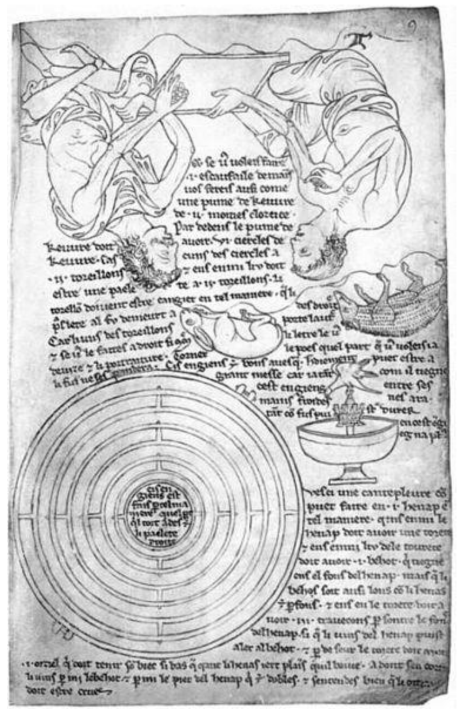
University of Tübingen
(1817)

- An experimental means for illustrating the spatial rotation of rigid bodies
- All the characteristics of a modern gyroscope are present

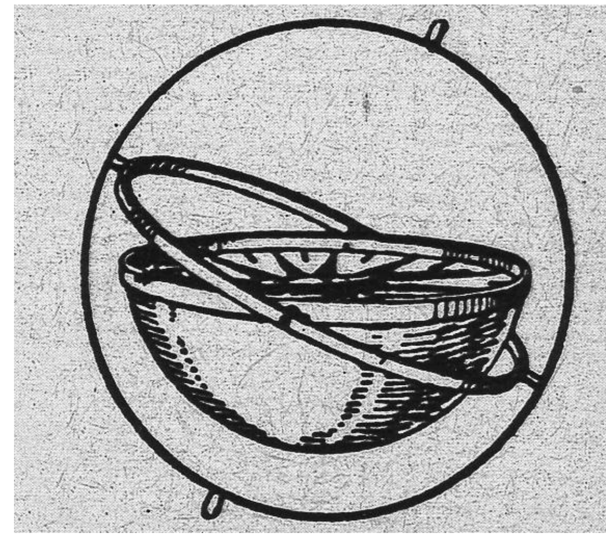
Ancient history of gyroscopes

Byzantine Philo (i.e. 280-220) – non-overturning ink pot

Ancient finding from Philippi (i.e. 350-250) – a sun-dial (watch)



(from cc. 1230)



A compass from the Middle Ages

Gerolamo Cardano (1501–1576)

cardan-suspension for coaches

History of gyroscopes

Léon Foucault
École Polytechnique,
Paris, 1852

It has been constructed by suggestion of Pierre-Simon Laplace for the purpose of demonstrating the rotation of the Earth

The name „gyroscope" is originated from Foucault.

Mechanical gyrocompass

… now in a practical application


Anschütz-Kaempfe gyrocompass

M.G. van den Bos, Hollandia, 1885

- Rotating by an electric motor
- High viscosity liquid filling for the attenuation
- Automatic setting in the geographical North (principle: the toque generated by the Coriolis force is 0 in this position).
- A product manufactured in high volumes.
- Many patents and priority dispute is connected with the invention.

Mechanical gyrocompass

Sperry gyrocompass

- Higher reliability than that of the magnetic compass
- Points to the geograpgical North(→ magnetic North differs from it – declination)
- It is widely used in marine ships
- Disadvantages: slow set-up, slow tracking of changes

Today:

- Laser gyrocompass
- GPS

is used instead.

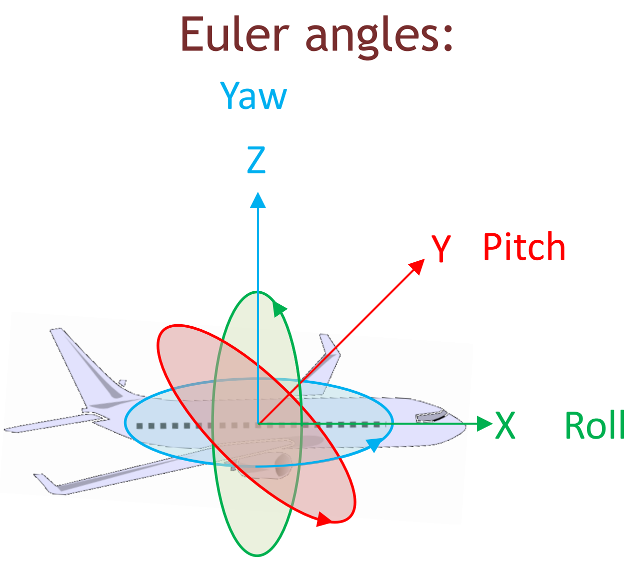
Gyroscopes in aerospace

Applications:

- Stabilising the motion of the air/space craft
- Controlling manoeuvres
- Navigation

Means:

- 1-axis gyroscopes
- 2-axis gyroscopes
- 3-axis gyroscopes
- „Gimbal lock" problem: 4th axis is needed
- Inertial Navigation Systems



1-axis gyroscope

Function:

- Detection deflection from one direction

Application:

- Stabilizing vehicle yaw motion
- Steering control

Example:

Honeywell JG7005 autopilot gyroscope, years 1950
A binary output device: in a deflection contacts are set ON or OFF

2-axis gyroscope

Function:

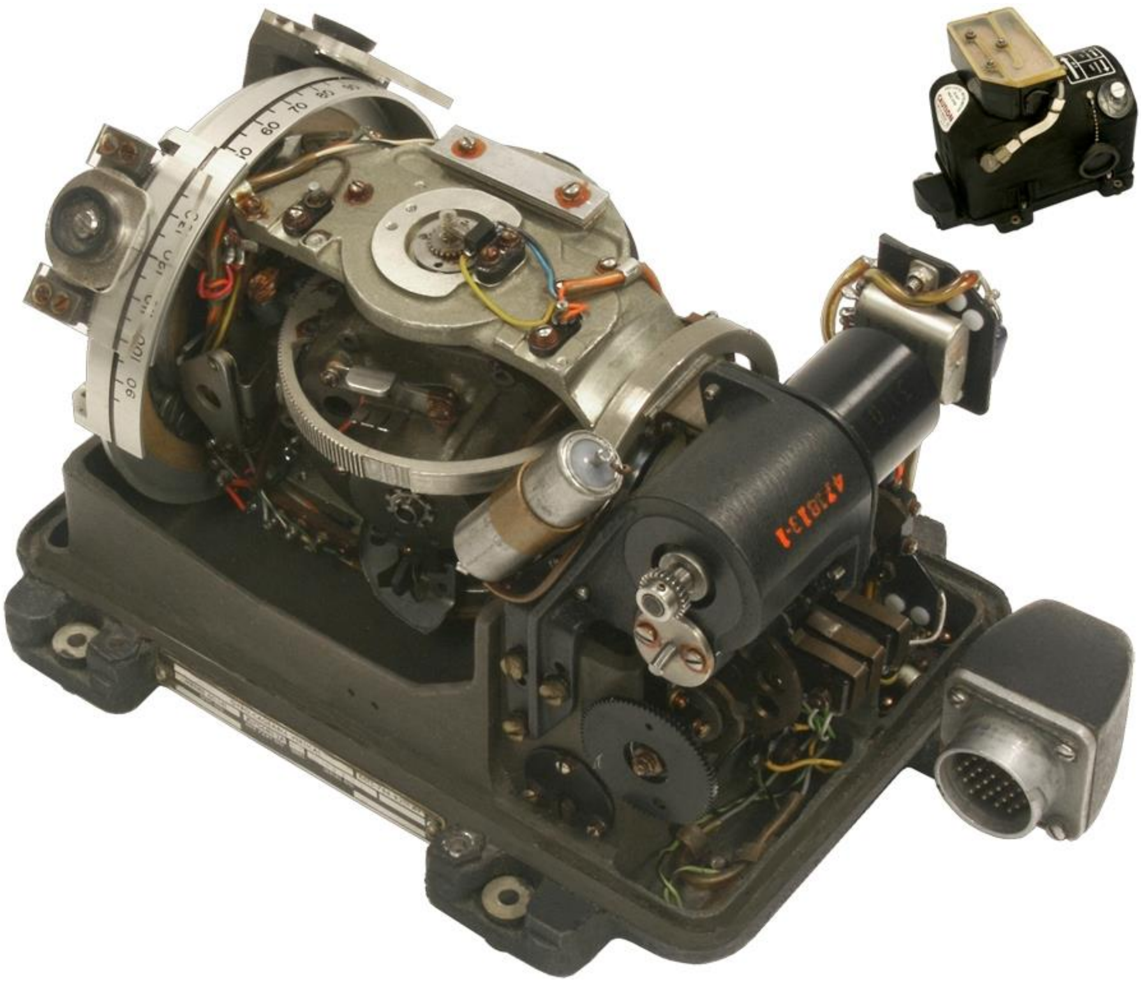
2D position tracking

Application:

- 2D attitude detection (artificial horizon)
- 2D position control

Example:

Honeywell JG7044N, years 1950

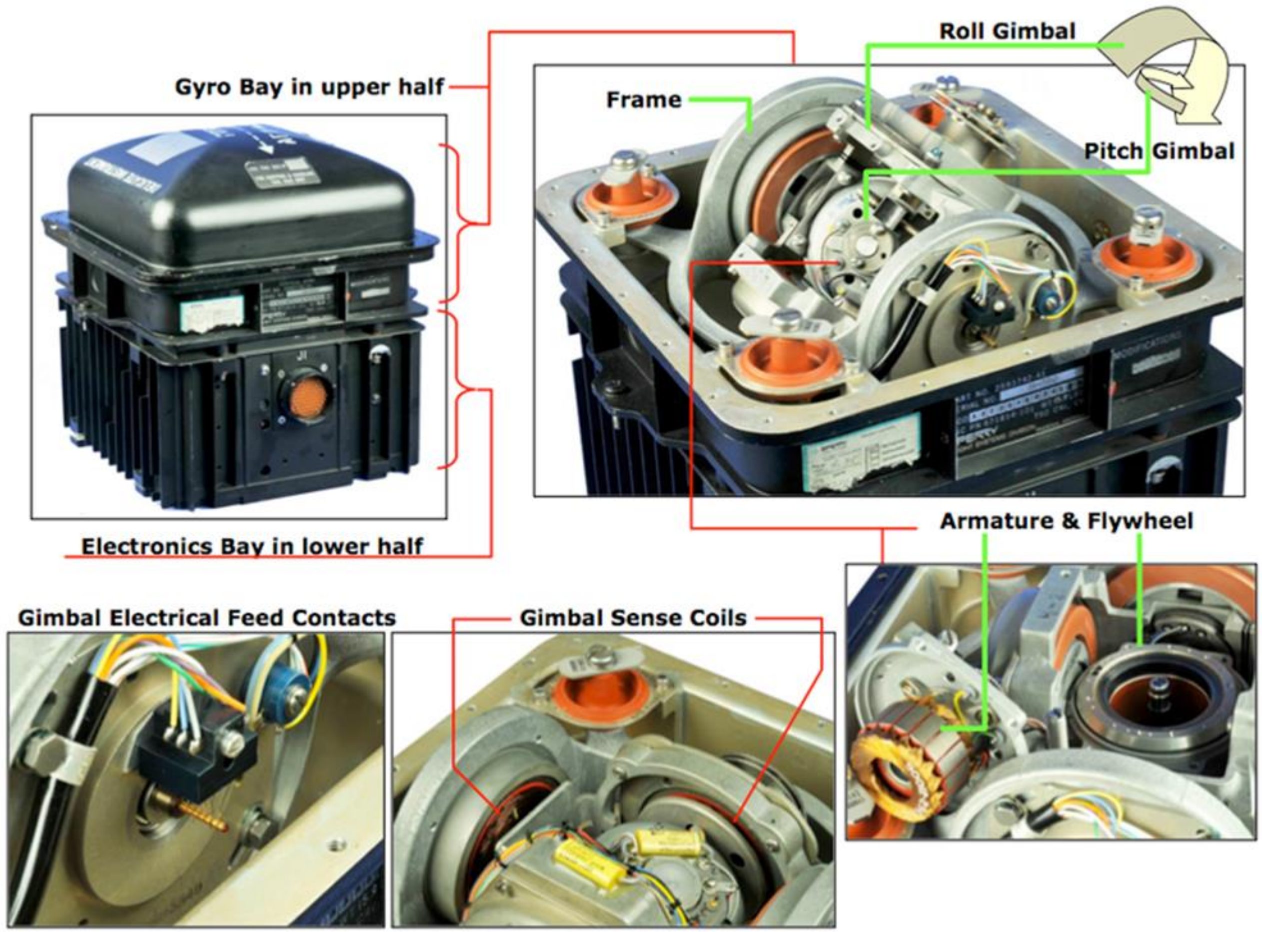


2-axis gyroscope

Boeing 747

Sperry vertical gyroscope

years 1970



3-axis gyroscope

Function:

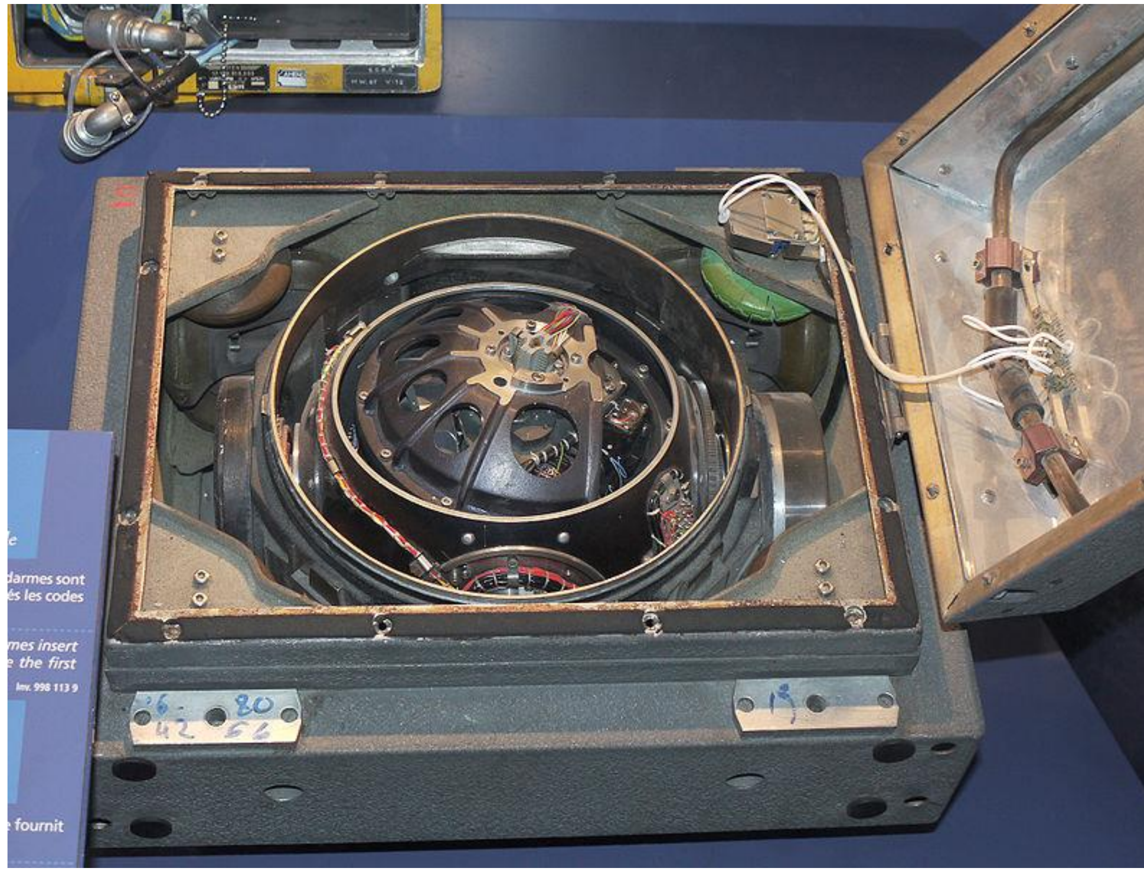
3-dimensional positioning

Application:

- 3D path tracking control

Example:

Inertial module an the S3 ballistic missile, 1966



3-axis gyroscope

... from the early space missions (Kennedy Space Center)

The „gimbal lock" problem

If the gyroscope does not detect the motion of the vehicle along one or more degree of freedom, a "lock" phenomenon occurs - the gyroscope looses one or more degrees of freedom.

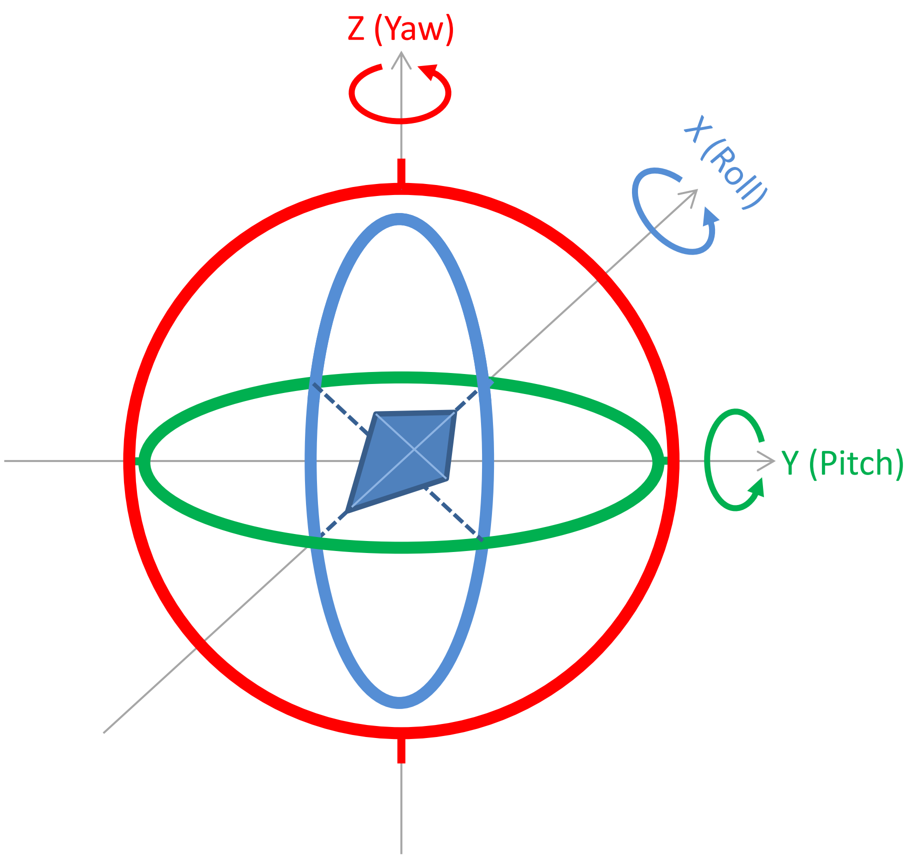
When does this happen?

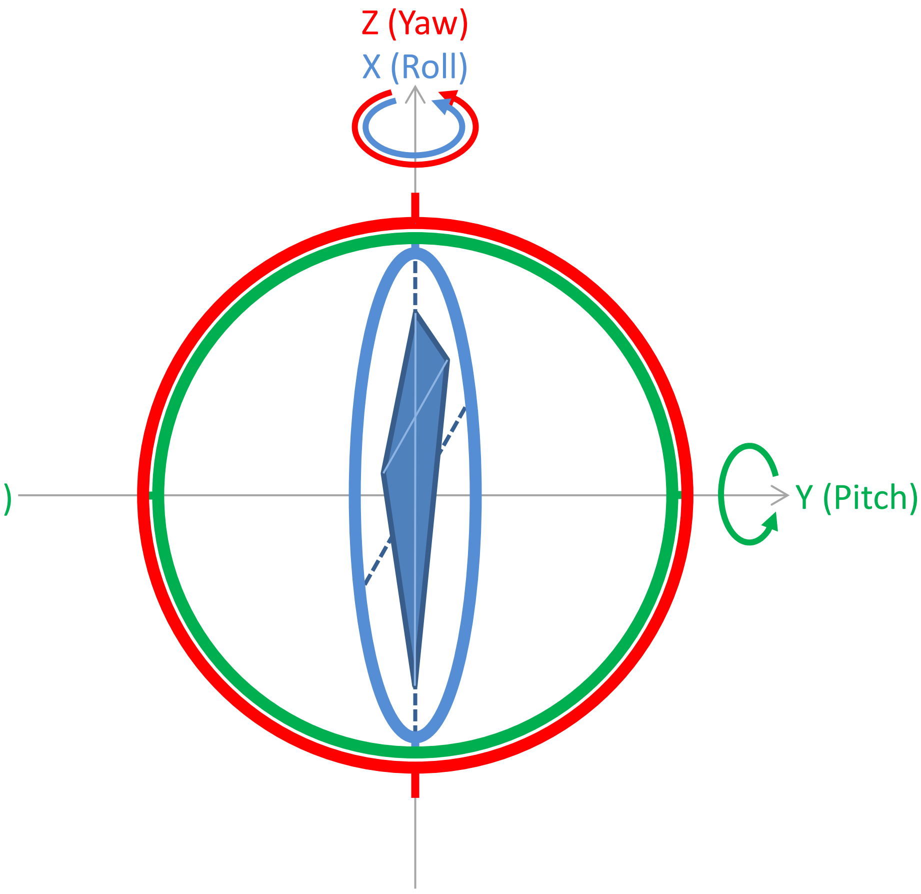
If two axes of rotation of a gyroscope fall in one plane.

Why is it called „gimbal lock"?

It only falls with a ring (gimbal) gyroscope.

The „gimbal lock" problem





Normal state.

X and Z axes of rotation coincide: **gimbal lock** – „roll" motion cannot be detected.

The „gimbal lock" problem

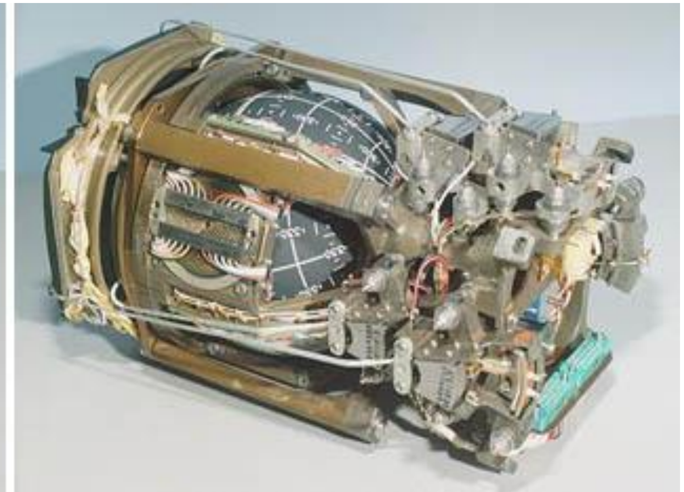
A notable case: during the Moon mission of Apollo 11 almost caused problem the gimbal lock – at angle 85° the on-board computer intervened erroneously, however the crew noticed the error and corrected it by restarting the IMU.

"How about sending me a fourth gimbal for Christmas?" – Mike Collins

Elimination of the gimbal lock phenomenon:

- Let's use a 4th redundant gimbal.
- Observe the critical condition and restart the gyroscope from a new position.
- Do not use rotating mechanical gyroscope.

The notable gyroscope

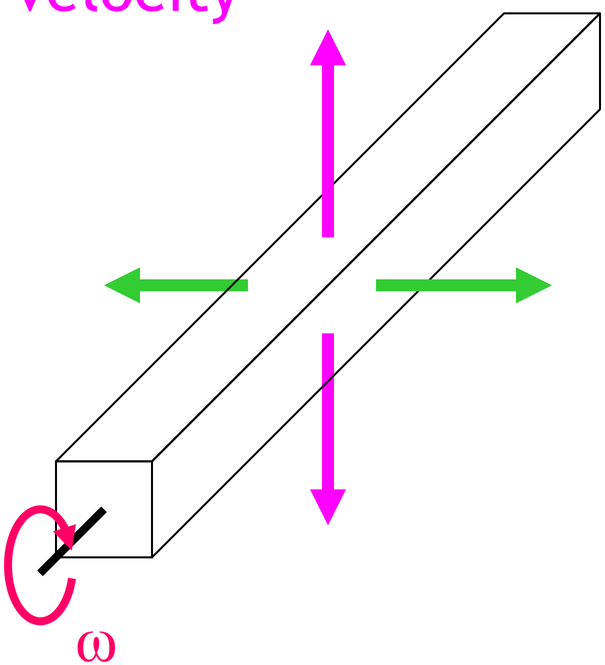


FDAI
(Flight Director Attitude Indicator)

Vibrating mechanical gyroscope

Principle: a vibrating flexible rod

Forced vibration rezgés
v_r velocity



in the case of rotation wit circular frequency ω

F_c Coriolis force $F_c = -m(\omega \times v_r L)$

Causes deformation perpendicularly to the forced vibration → measurable

Rezgőelemes giroszkóp

Megvalósítások:

Az alkalmazott technológia szerint:

- Piezokeramikus kristály
- MEMS – Micro ElectroMechanical System

A mérés elve szerint:

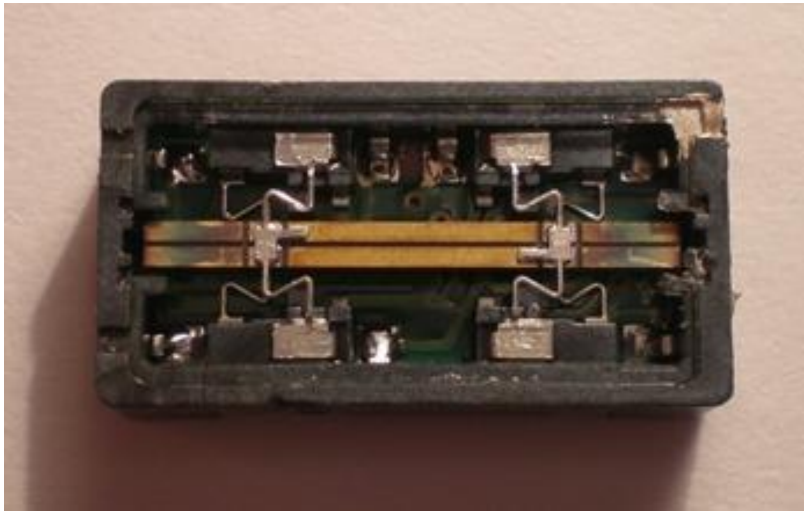
- Piezoelektromos hatás
- Kapacitív elvű elmozdulás-mérés

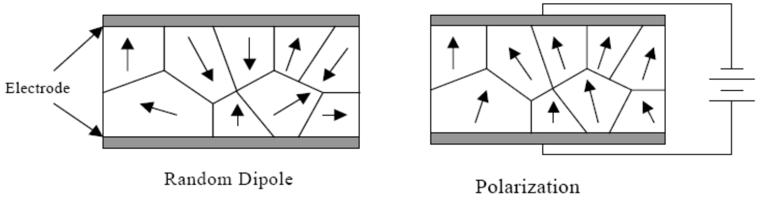
Vibrating mechanical gyroscope

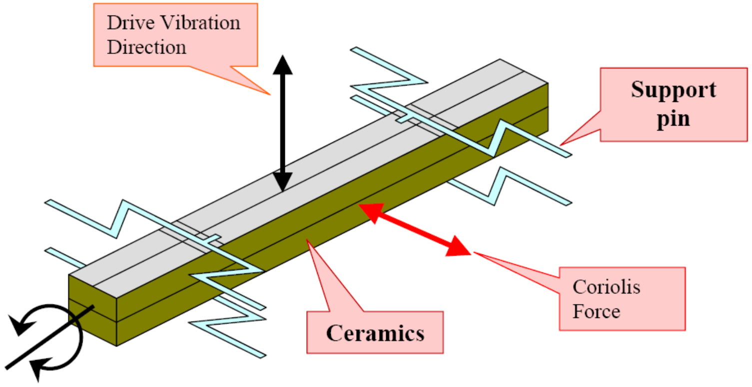
Piezoceramic crystal

Piezoelectric effect:

As a consequence of a deformation electric voltage appears in the opposite surfaces of the crystal.







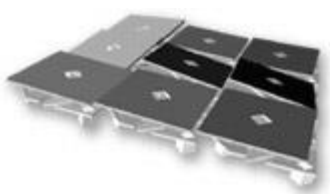
Ceramics Bimorph vibrator

Polarisation: the opposing charges are separating.

MEMS gyroscopes

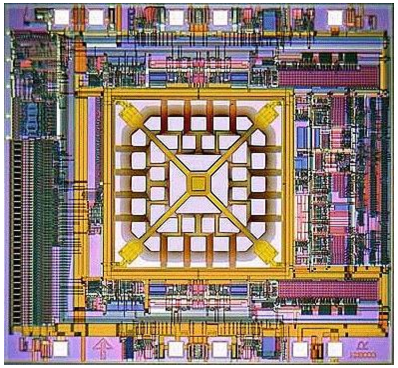
MEMS – Micro ElectroMechanical System

Fabrication a microscopic mechanicals system on a silicon wafer.



Typical MEMS circuits:

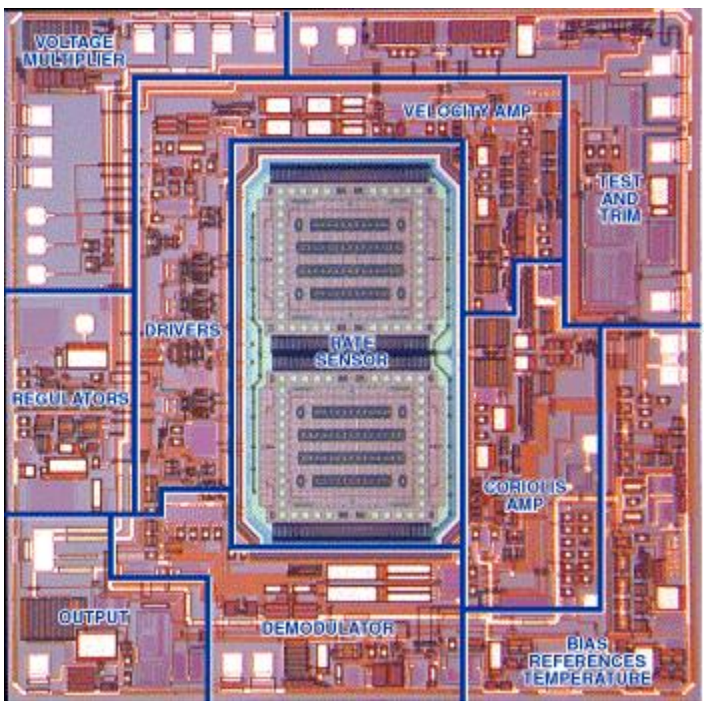
- Optical devices, i.e. adaptive mirror system (DLP)
- Sensors: acceleration, angular rate, pressure, etc.
- Micromotors and drives

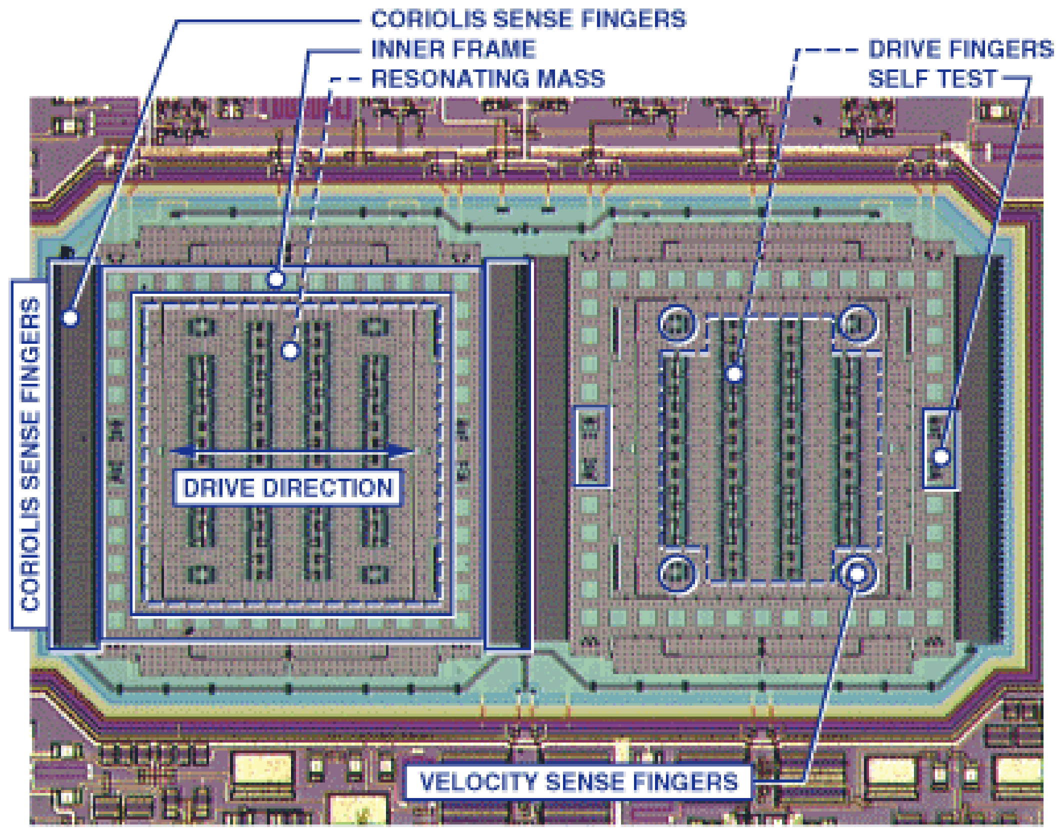


MEMS giroszkóp

A rezgő elem: szilíciumból kialakított rugalmas tartószerkezet.

Elektrosztatikus mozgatás – kapacitív elvű elmozdulás mérés.





MEMS gyroscopes

Advantages:

- Small sizes – example: 4 x 4 x 1 mm
- Mechanical stability an robustness
- High reliability, small fault rate
- Small consumption
- No „gimbal lock”

Disadvantages:

- Circuit noise
- Temperature dependence

Feature:

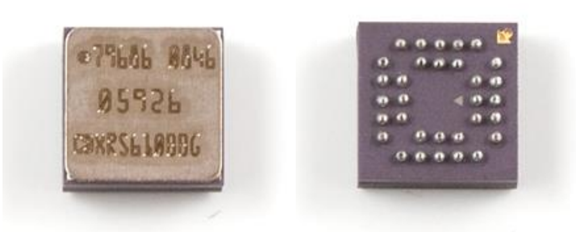
- Angular rate measurement: deriving orientation (angles) needs integration

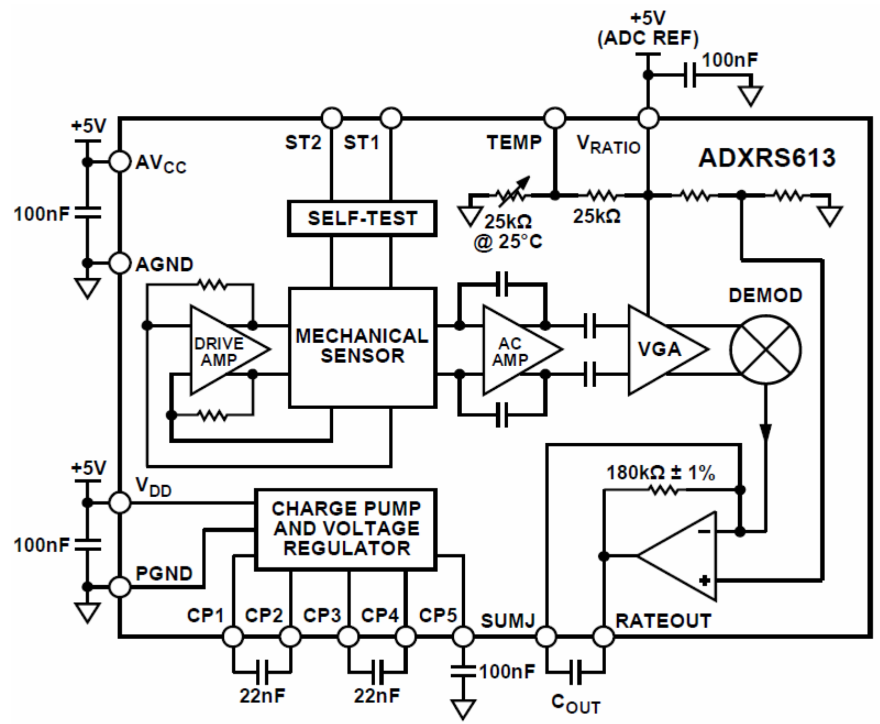
MEMS gyroscope

Analog Devices

ADXRS-613 - 1-axis angular rate sensor

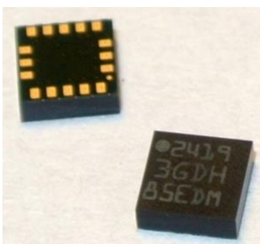
- Range ±150°/s
- Sensitivity 12.5mV/°/s
- Temperature drift 3%
- Noise 0.04 °/s/√Hz
- Bandwidth 3kHz
- 6.85 x 6.85 x 3,8 mm



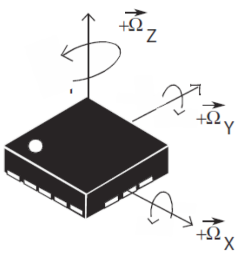


MEMS gyroscope

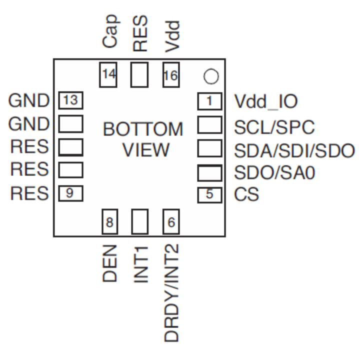
STM L3GD20H 3-axis digital output angular rate sensor

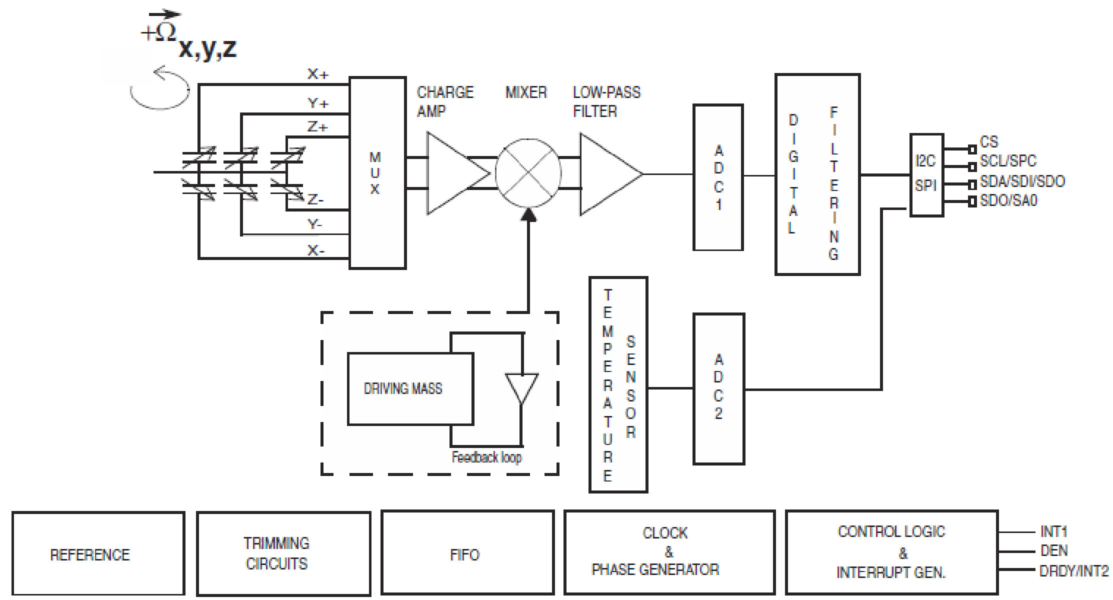


LGA-16 case 3x3x1 mm



(TOP VIEW)
DIRECTIONS OF THE DETECTABLE ANGULAR RATE





- I[2]C/SPI digital interface
- 11.9 – 757.6 Hz data rate
- ±245/500/2000 °/s range
- Temperature drift ±2%
- Noise 0.011 °/s/√Hz
- Linearity 0.2%

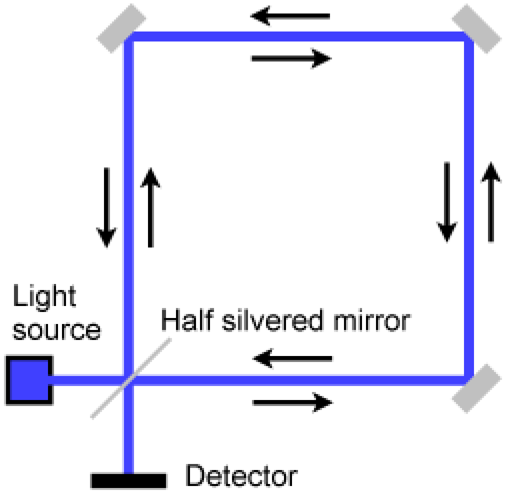
Laser gyroscope

Physical principle:

The Sagnac effect

Georges Sagnac (1869-1928)
French physicist

- Two opposite light beams ellentétes shows interference depending on the phase-difference.
- If the system is rotating with some angular rate, phase difference is affected, hence interference changes.



Sagnac interferometer

Possible measurement method: detecting the alteration of interference peaks – by the means of camera sensor.

Laser gyroscope

Types:

- Ring Laser Gyroscope (RLG)
- Fiber Optic Gyroscope (FOG)

Advantages:

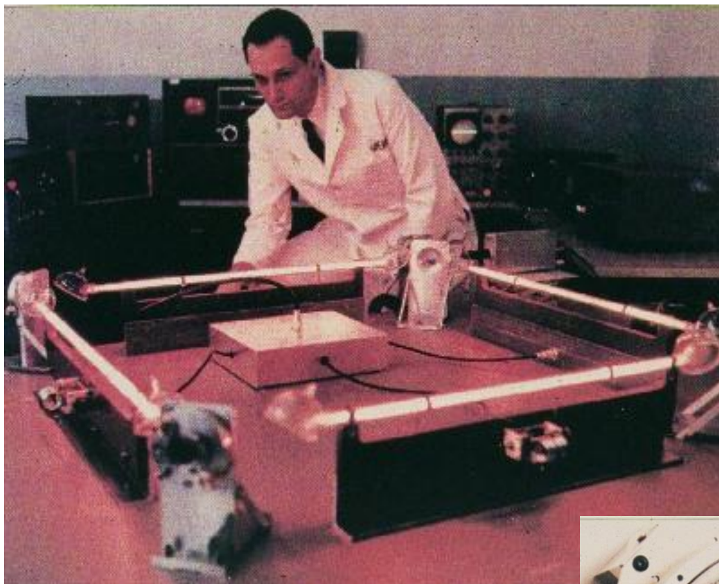
- High accuracy and sensitivity
- Extremely small noise

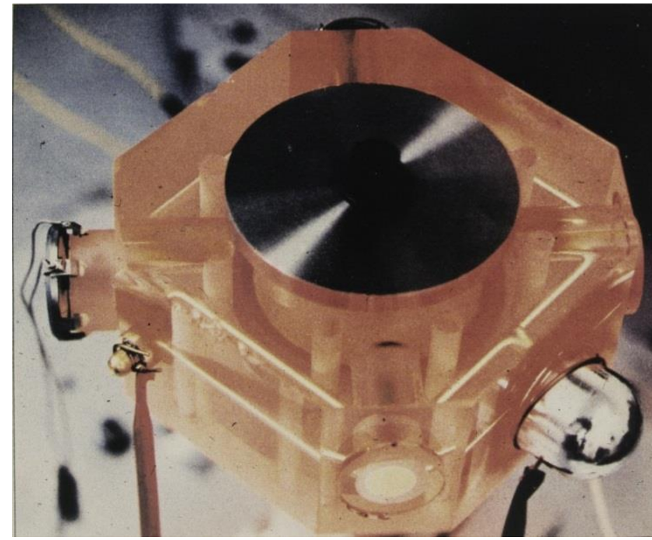
Disadvantages:

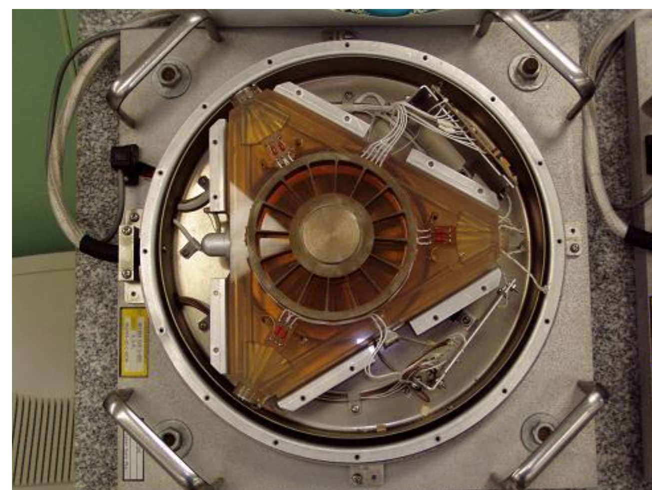
- Quite expensive

Laser gyroscope

- Ring Laser Gyroscope (RLG)

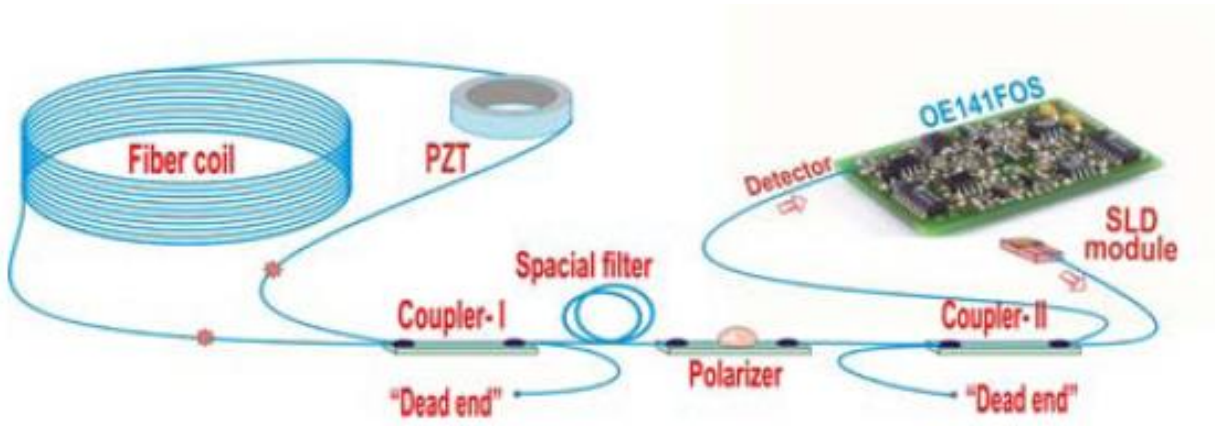






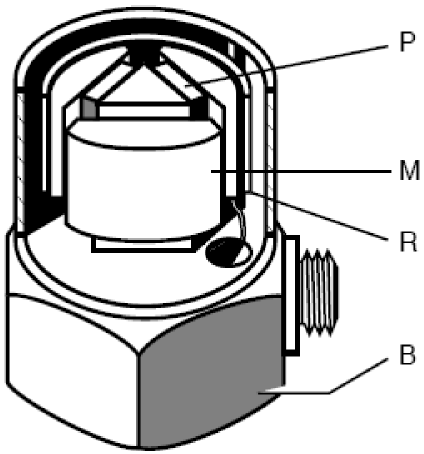
Laser gyroscope

- Fiber Optic Gyroscope (FOG)



Acceleration sensors

Physical principle: spring – mass



- Piezo-ceramic

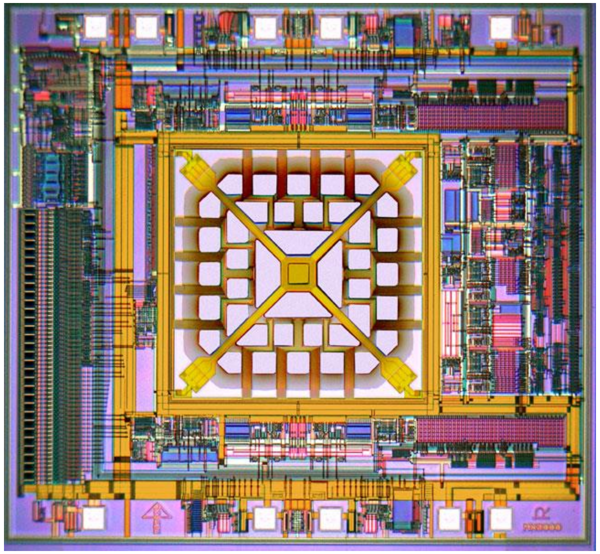
  Sensing by piezoelectric effect

- MEMS

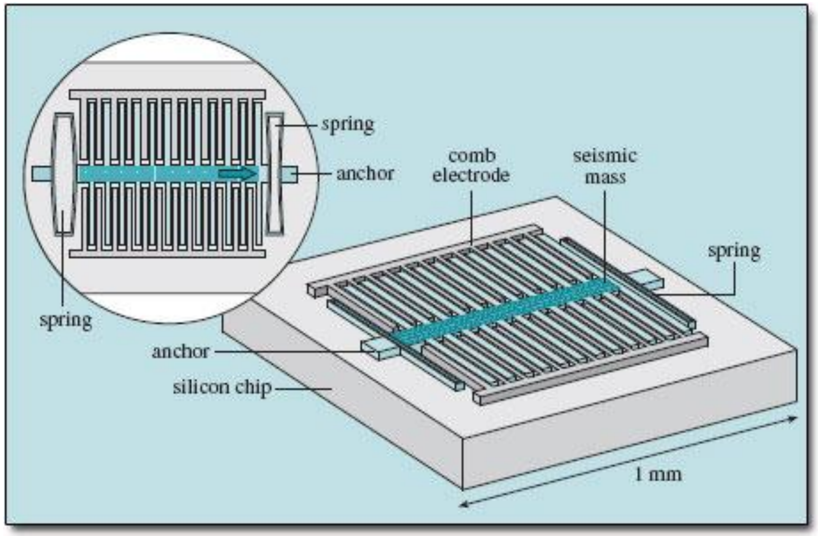
  Sensing by

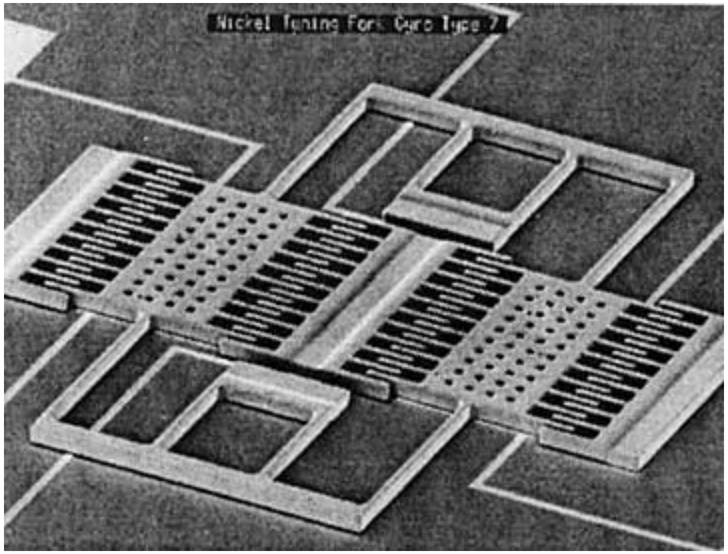
  - capacitive
  - thermal

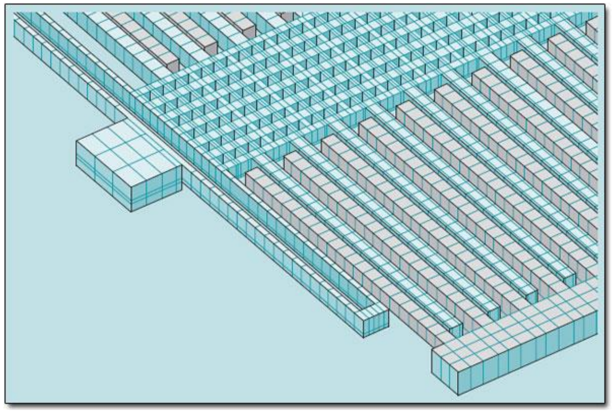
  effect.

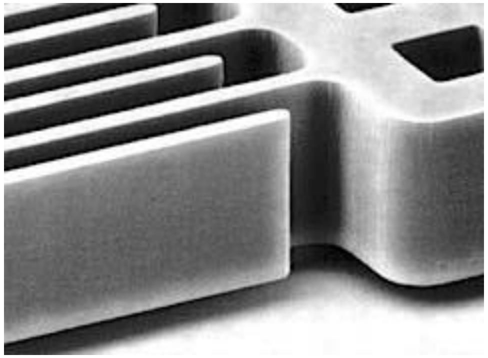


MEMS accelerometers









MEMS accelerometers

Advantages:

- Small sizes – 4 x 4 x 1.5 mm (3-axis)
- Immunity on environmental effects
- High reliability, low failure rate
- Low consumption
- Simple handling
- Low price

Disadvantages:

- Electrical noise
- Temperature dependence

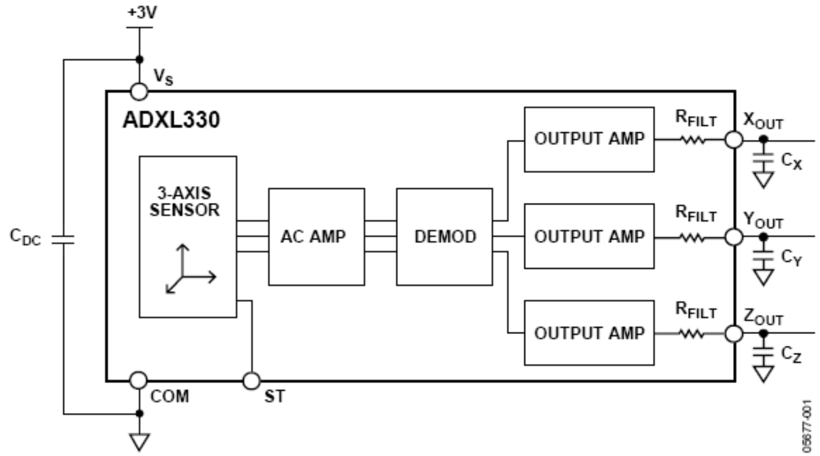
Feature:

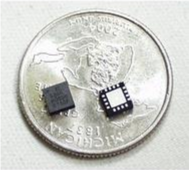
- Acceleration sensing: deriving position needs 2 integrations

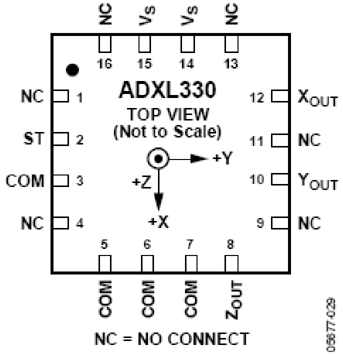
MEMS gyorsulás érzékelők

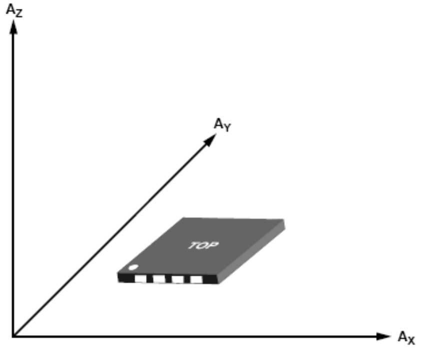
Analog Devices ADXL-330 - háromtengelyű gyorsulásérzékelő

- Méréshatár ±3g
- Érzékenység 300mV/g
- Linearitás ±0.3%
- Hőmérsékleti drift 1mg/ °C
- Zaj 300 µg/√Hz
- Sávszélesség 1.6kHz
- Méret 4 x 4 x 1.45 mm
- Ár < 10$





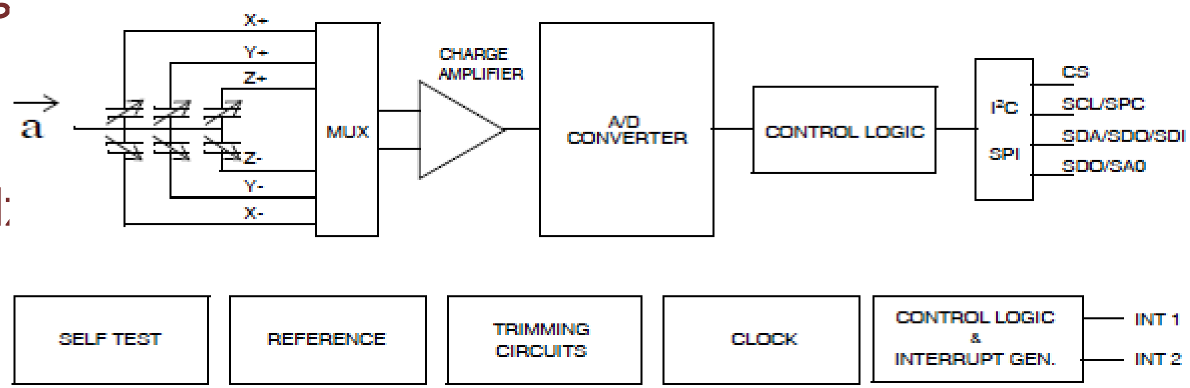


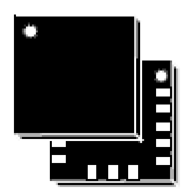


MEMS gyorsulás érzékelők

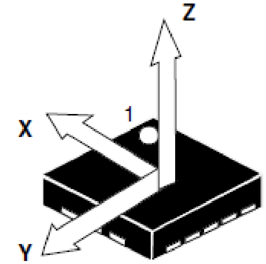
STM LIS331 háromtengelyű digitális kimenetű gyorsulás érzékelő

- Méréshatár ±2/4/8g
- I²C/SPI digitális interfész (12 bit)
- 50/100/400/1000 H data rate
- Érzékenység 1-3.9 mg/LSB
- Hőmérsékleti drift 0.01%/°C
- Zaj 218 μg/√Hz
- Méret 3 x 3 x 1 mm



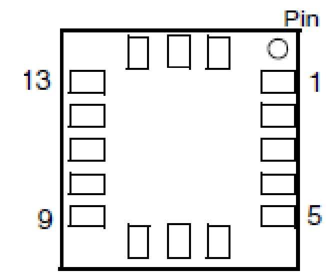


LGA 16 (3x3x1 mm)



(TOP VIEW)

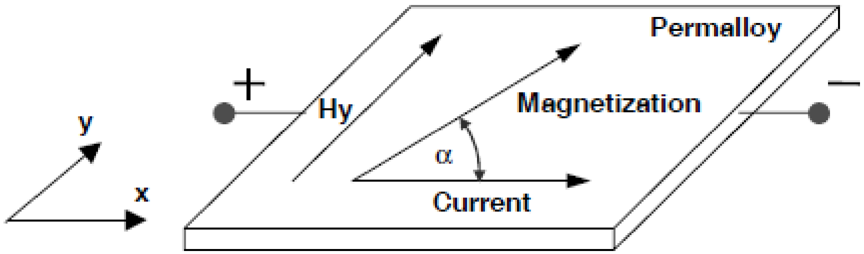
DIRECTION OF THE DETECTABLE ACCELERATIONS



(BOTTOM VIEW)

Magnetic compass

Magnetic field sensing



$$R = R_0 + \Delta R \cos^2\alpha$$

$\alpha = 0° \Rightarrow R_{max}$

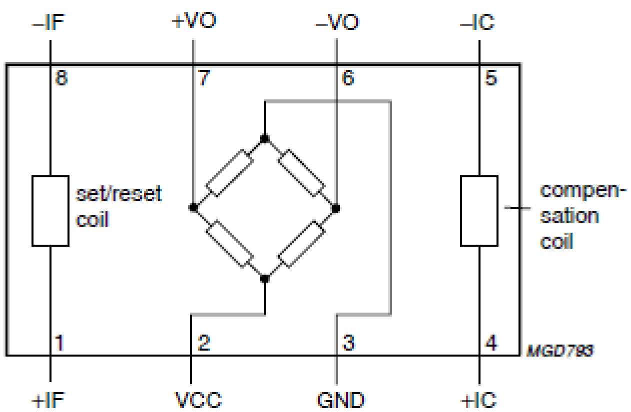
$\alpha = 90° \Rightarrow R_{min}$

Magnetoresistive effect:

Magnetic field alters the electric resistance of the permalloy material (an iron alloy).

Hall effect:

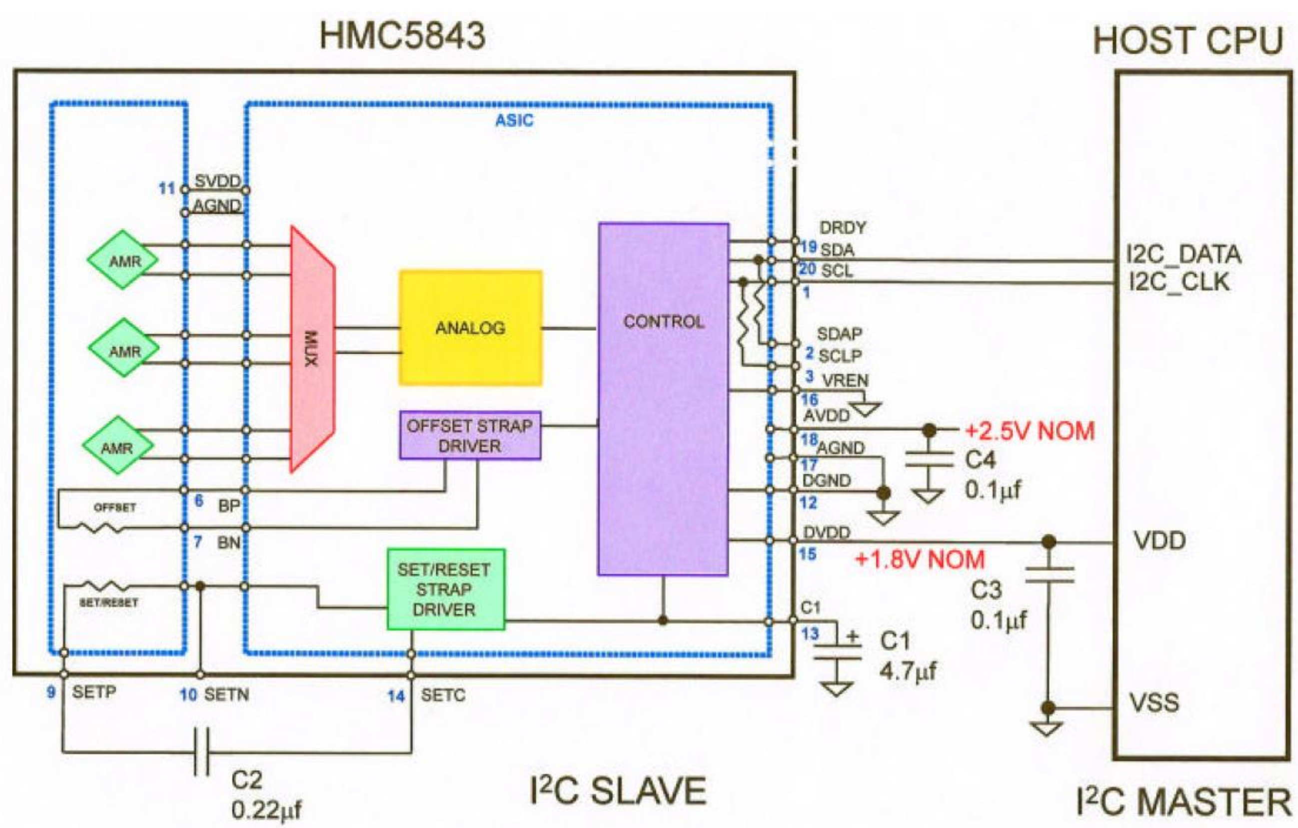
Electrons moving in magnetic field are effected by the Lorentz force, resulting in potential difference.

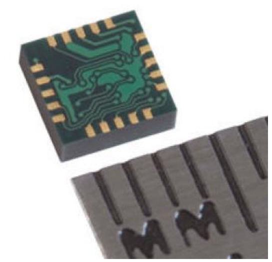


Measurement: Wheatstone-bridge.

Magnetic compass

Honeywell 3-axis digital compass HMC5843





4 x 4 x 1.3 mm case

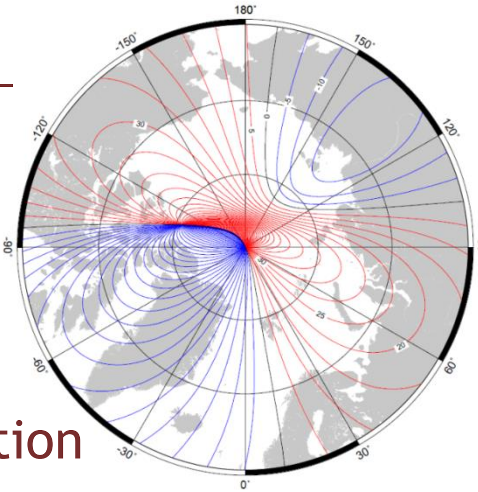
Digital interface

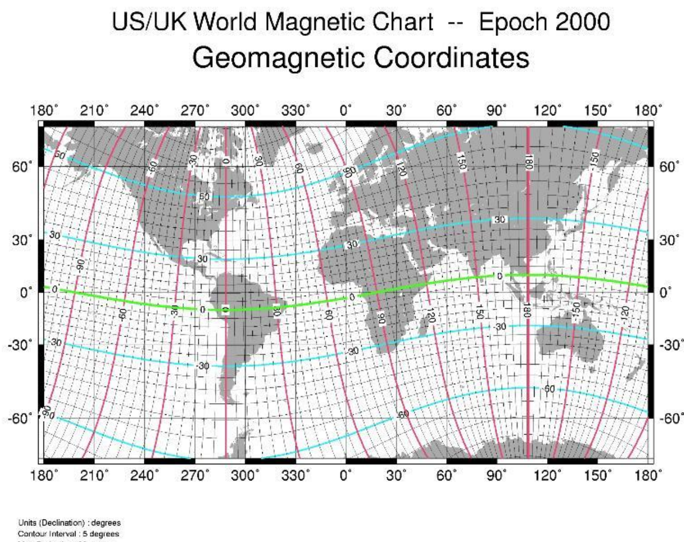
Automatic demagnetization

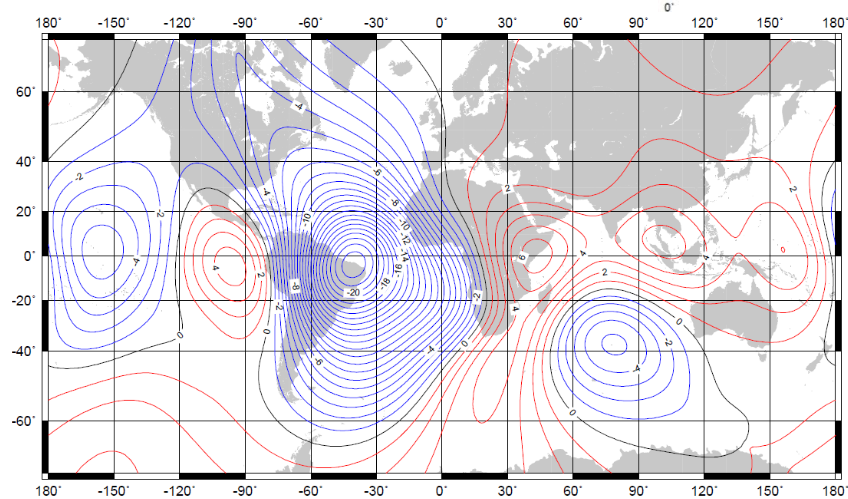
Magnetic compass

Problems:

- Disturbing magnetic effects in the environment – ferromagnetic objects, electric currents
- Remanent magnetization effects in the sensor
- Difference on the direction of the magnetic and geographic North – inclination
- Inhomogeneity in Earth magnetic field – declination







- Correction: declination maps, databases, applications.

Inertial Measurement Units (IMU)

IMU – Inertial Measurement Unit

- Gyroscopes and magnetometers, and other sensors with common control and processing
- Minimal requirements: measurement, ADC, preprocessing, filtering, scaling, calibration, error correction
- High end: deriving velocity, position, and orientation (Euler-angles, quaternions).

Contemporary realizations:

- Digital processing
- Applying embedded micro-computers.

Inertial Measurement Units (IMU)

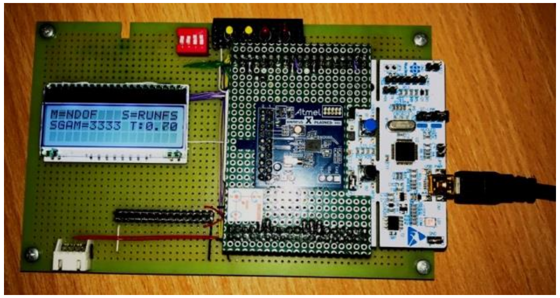
Bosch Sensortec BNO055 inertial sensor

In a single silicon wafer:

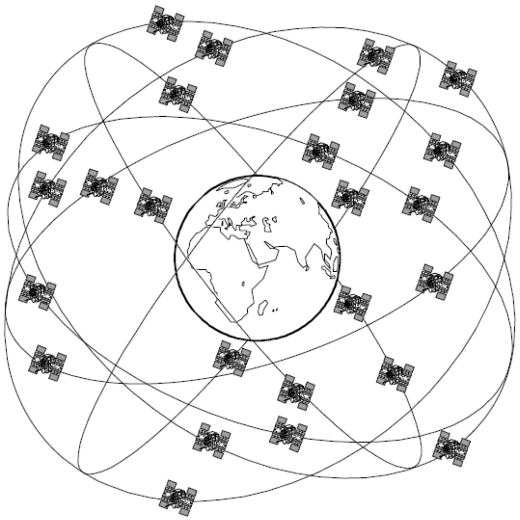
- 3-axis 14-bit digital output accelerometer
- 3-axis 16-bit digital digital output angular rate sensor
- 3-axis Earth magnetic field sensor
- 32-bit ARM Cortex M0+ microcontroller with Bosch Sensortec sensor fusion software.

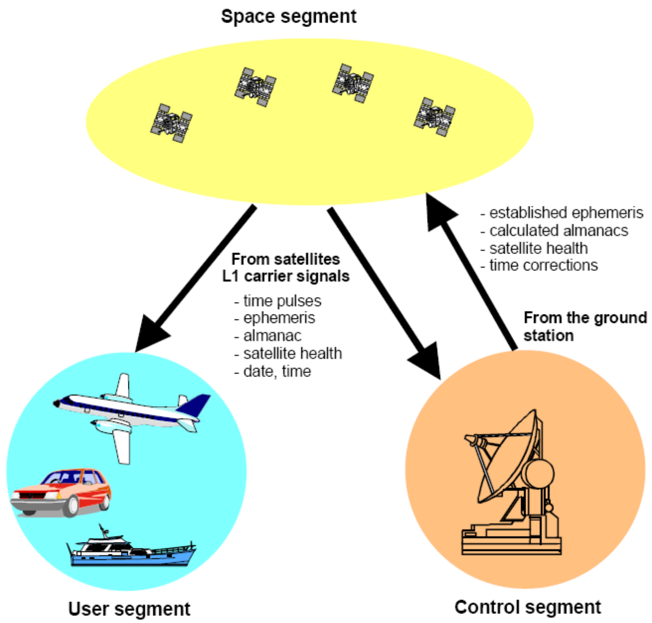
Extensions:

- Host microcontroller – high level digital signal processing, GPS fusion, Kalman filtering
- Communication – CAN / USB / Ethernet



Global Positioning System- GNSS

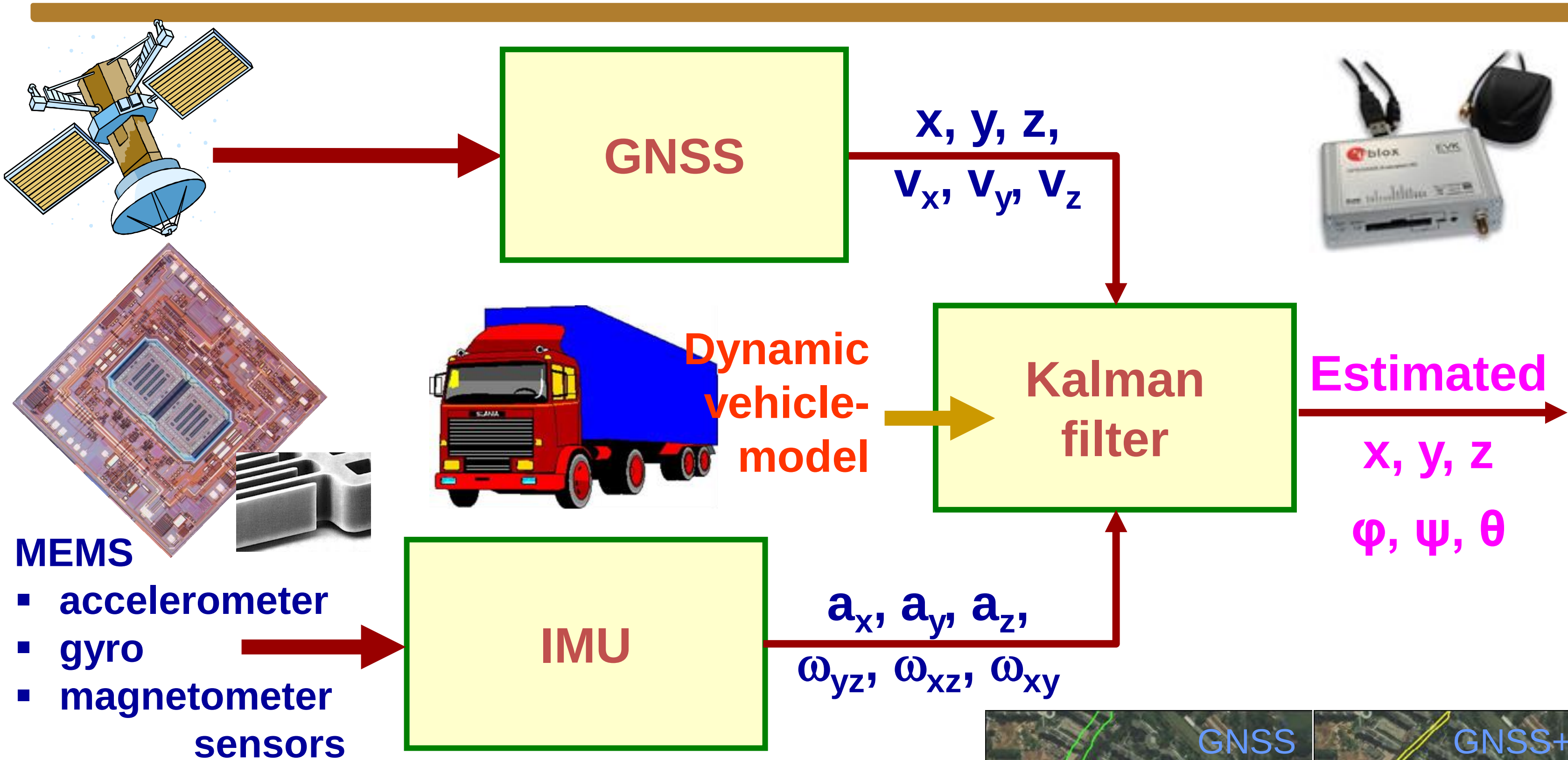




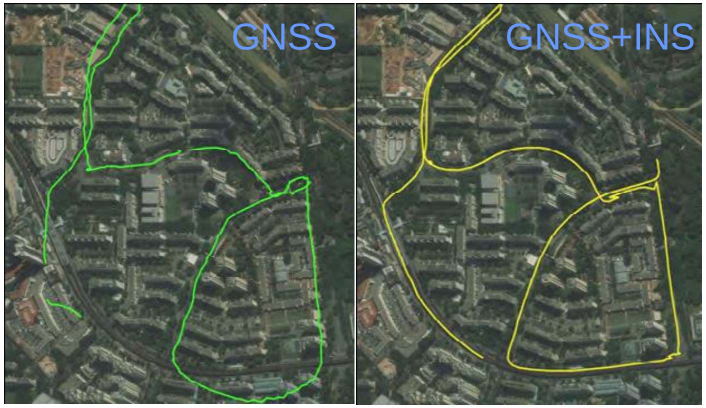
- GPS (USA)
- GLONASS (RU)
- Galileo (EU)
- BeiDou (China)
- IRNSS (India)

Problems:
- Limited accuracy
- Noises, uncertainties
- Reliability, availability

GNSS-INS positioning system



Higher
- accuracy
- availability
- reliability



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BME KÖZLEKEDÉSMÉRNÖKI ÉS JÁRMŰMÉRNÖKI KAR
32708-2/2017/INTFIN SZÁMÚ EMMI ÁLTAL TÁMOGATOTT TANANYAG