Robotics III: Sensors and Perception in Robotics

Chapter 02: Internal Sensors

Tamim Asfour

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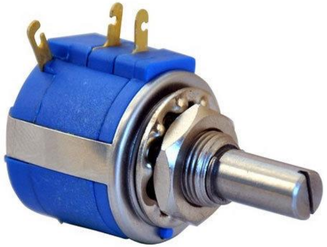

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Introduction to Sensors

Sensors: Definition

- Sensors are devices that can sense and **measure physical properties** of the environment
  - Temperature
  - Luminance
  - Weight
  - Distance
  - …

- Sensors deliver **low-level information** about the robot's environment
- This information is
  - limited
  - inaccurate
  - noisy (imprecise)

- Therefore, sensors return an **incomplete description** of the world

Sensors: Definition (II)

- Sensors are physical devices that
  - receive a **signal or stimulus** and
  - react to it with an **electrical signal**

- Any sensor is an **energy converter**
  - No matter what you try to measure, you always deal with energy transfer from the object of measurement to the sensor

- Sensors range from simple to complex in the amount of information they provide:
  - A switch is a simple on/off sensor
  - A human retina is complex sensor consisting of more than a hundred million photosensitive elements (rods and cones)

Sensors: Definition (III)

- Sensors constitute the perceptual system of a robot

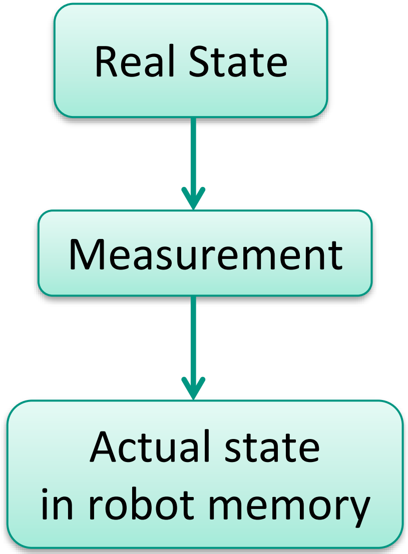
- Sensors allow to close the feedback control loops that secure efficient and autonomous operation of robots in real-world applications

- A robot's intelligence depends on
  - the quality and quantity of information provided by its sensors
  - the ability to process and processing speed of sensory input

- Types of senses are called sensory **modalities**
  - Multi-modal sensory data

Sensors: Definition (IV)

- Sensors are devices that measure the attributes of the world
- Sensors do not provide state/symbols, but rather (raw) data, i.e. signals, or physical quantities!
- We have to determine the state of a robot based on the sensor signals
- Therefore, we need to process the signal, for instance, by means of feature extraction, pattern recognition, etc.

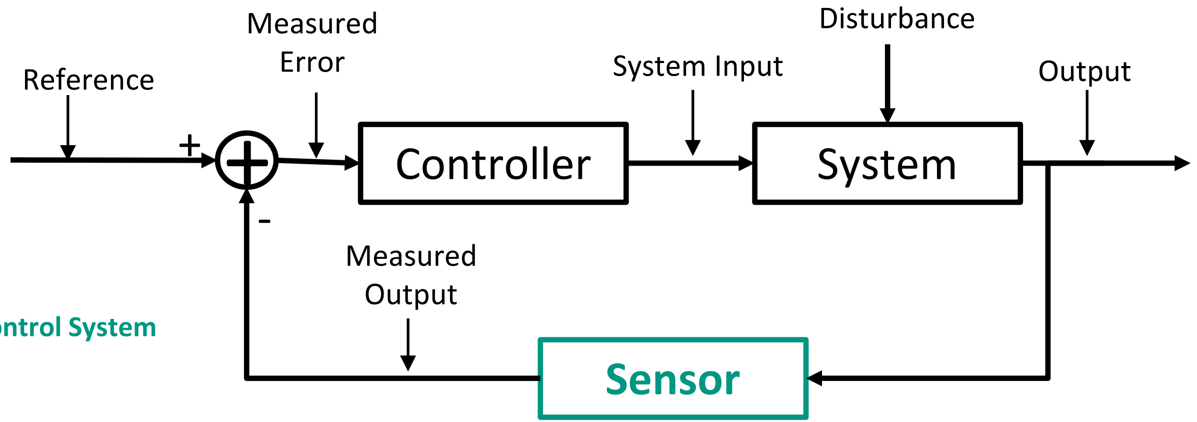


Sensors: Definition (V)

Sensor: (lat.: Sensus = „capable of sensitivity")

Definition

System that converts a physical quantity and translates it to an appropriate (electrical) signals



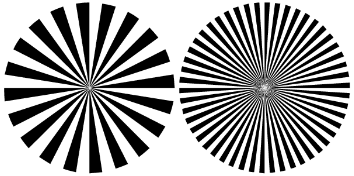
Closed-loop Control System

Characteristics of Sensors (I)

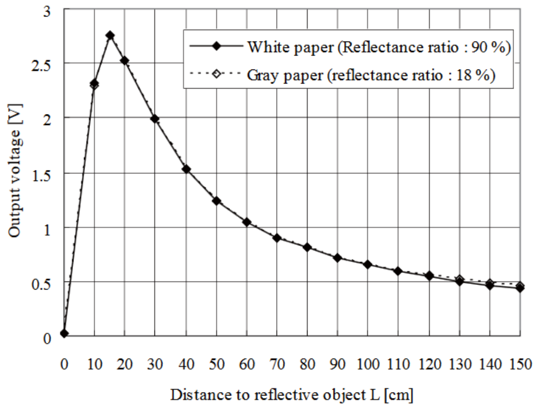
- **Range/Span (Messbereich):** [min,max]
  - Range of input signals that can be measured and converted
- **Resolution (Auflösung):** Smallest change in the input signal that can be detected
  - Example: An incremental joint encoder generating 1024 pulses per revolution (10 Bit) has a resolution of

$$\frac{1\,revolution}{1024\,pulses} \times \frac{360\,degrees}{revolution} = 0{,}3516\,\frac{degrees}{pulse}$$

- **Sensitivity (Empfindlichkeit)**: Change of the sensor output relative to a change in the signal
  - A linear sensor has constant sensitivity over the entire range
  - Can be depicted as characteristic curve of a sensor



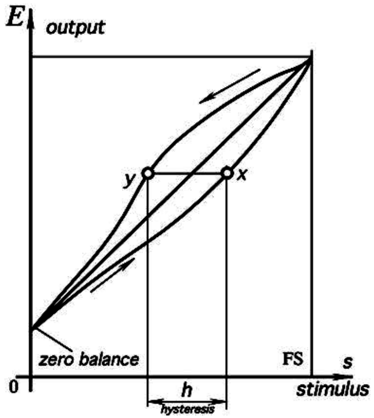
Optical encoder discs of different resolutions



Non-linear characteristic curve of an infrared distances sensor

Characteristics of Sensors (II)

- **Accuracy (Genauigkeit)**: Discrepancy between actual and measured value. Error sources can be:
  - Bias (Offset): Constant error over the entire range
  - Hysteresis (Hysterese): Error dependent on the history of change
  - Random noise (Zufälliger Fehler, Rauschen)
- **Repeatability (Wiederholgenauigkeit):** Ability to produce identical outputs for the same input signal
- **Bandwidth**: Range between the lowest and highest cutoff frequencies (slowest and fastest change in the input signal that can be correctly measured by the sensor)
- **Response Time**: Time delay from change in input to change in output
- **Linearity**: Constancy of output/input (accounting for constant bias)



Hysteresis

From Fraden, J.: Handbook of Modern Sensors

Sensor Types – Analog vs. Digital

Karlsruher Institut für Technologie

- **Analog Sensors:**
  - Provide analog output signals (continuous)
  - Need analog-to-digital (A/D) conversion
  - Examples:
    - Analog infrared distance sensor
    - Microphone
    - Analog compass
- **Digital Sensors:**
  - Provide digital output signals (discrete)
  - Outputs may be of different form:
    - Synchronous serial: bit by bit data reading
    - Parallel: Multiple digital output lines (e.g. 8 or 16)
  - Examples:
    - Digital camera
    - GPS

Sensor Types – Active vs. Passive

- **Active Sensors:**
  - Emit some form of energy into the environment → require energy for operation
  - Measures the feedback to understand the environment
  - Examples:
    - Infrared sensor
    - Laser range finders
  - More robust, less efficient

- **Passive Sensors:**
  - Monitor the environment without affecting it
  - Receive energy already in the environment
  - Examples:
    - Vision camera
    - Gyroscope
    - Temperature probes
  - Less intrusive, but depends on environment

Sensor Types – Implementation

- **Mechanical Systems:** require a physical contact between the robot and the sensor. Frequently, they are integrated in the robot body.
- **Acoustic Systems:** employ ultrasound frequencies and use the directionality and the time-of-flight measurement of sent and received signals, for instance, to compute distance.
- **Electromagnetic Systems:** also use the directionality and the time-of-flight measurement like in acoustic systems. In both cases, a free "line of sight" between the transmitter and the receiver is required.
- **Magnetic Systems:** employ the spatial configuration of static magnetic fields of the Earth and solenoids for the calculation of the position.
- **Optical Systems:** use appropriate vision cameras (monocular, binocular, omnidirectional)

Sensor taxonomy

Elementary Sensors

Recording of a measured value and image signal

Exp.: Photodiode, CCD

Integrated Sensors

Additional signal processing: amplification, filtering, linearization, normalization

Exp.: CMOS

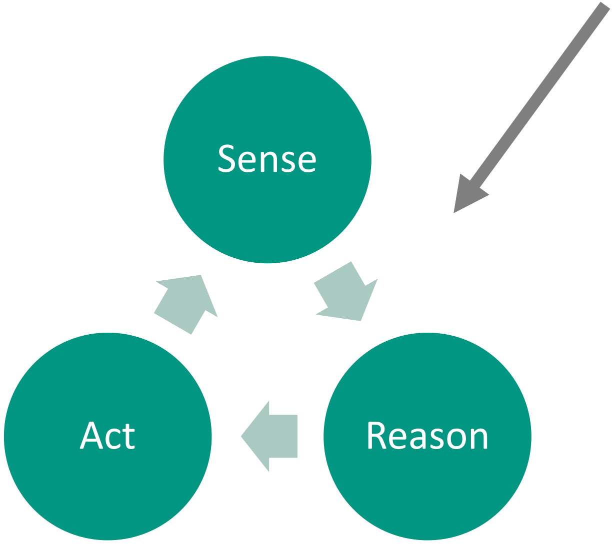
Intelligent Sensors

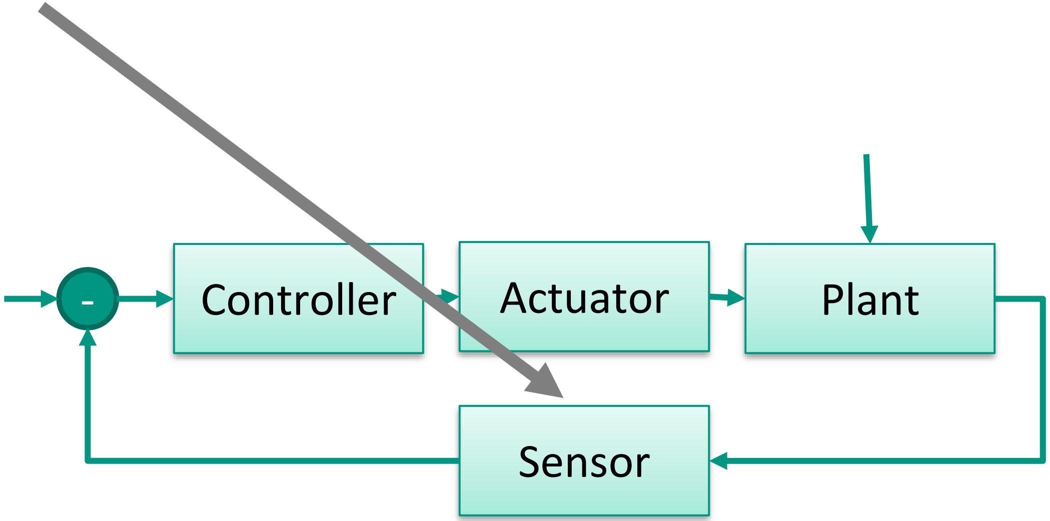
Integrated sensor with computer-controlled evaluation. Output: processed data

Exp.: Digital camera with face-recognition

Sensors in Robotics

- **Closed-Loop Control** plays a fundamental role in robotics
- **Sensors** are always part of a closed-control loop
- **Perception** is enabled by sensors





Sensors in Robotics - Problems

- **Task:**
  - Capture the state of the environment

- **Problems:**
  - Sensors provide only partial information about the environment
    - → Choice of „suitable“ sensors
  - Modeling the sensor characteristics
    - → Determine the relationship between real world and measurement results
  - Digital evaluation of sensory measurements
    - → Basics of digital signal processing and machine vision
  - Use of multiple sensor types and in multi-sensor systems
    - → Fusion of measured values.

Sensors in Robotics – Examples

- Cameras
  - RGB
  - RGB-D
  - Stereo
- Joint angle encoders
  - Incremental (relative) encoders
  - Absolute encoders
- Inertial sensors
  - Accelerometers
  - Gyroscopes
  - IMUs
- Force/torques sensors
- …

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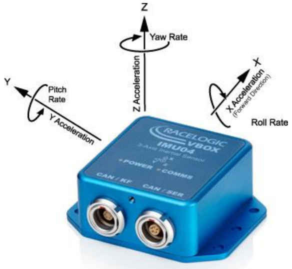

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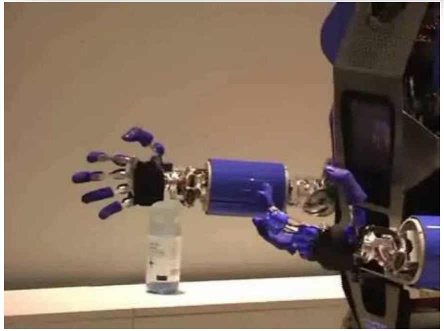
Example: Sensors in ARMAR-III

- 7 DOF head with foveated vision
  - 2 cameras in each eye
  - 6 microphones
- 7-DOF arms
  - Position, velocity and torque sensors
  - 6D FT-sensors
  - Sensitive skin
- 8-DOF hands
  - Finger position sensors
  - Tactile sensors
- Holonomic mobile platform
  - 3 laser scanners



Example: Sensors in ARMAR-6

- Sensor-Actuator-Controller Units in each arm joint
  - Incremental position (motor)
  - Absolute position (output)
  - Torque (output)
  - Motor current
  - IMU
  - Temperature sensors (motor, motor controller, gear)
- Head
  - RGB-D (Azure Kinect)
  - 2 RGB cameras (Point Grey Flea)
  - Stereo-sensor (Roboception rc_visard)
- Mobile base
  - Absolute position torso (draw wire sensor)
  - 2 laser scanners
  - Wheel positions (incremental)

Internal and External Sensors

Sensors in robotics

Internal sensors

Measurement of the **internal state**

(Joint angle encoders, torque sensors, IMU)

External sensors

Information about **state of the environment**

(Cameras, distance/laser sensors)

Internal Sensors – Examples

- **Position sensors**
  - Optical encoders
  - Magnetic encoders
  - Potentiometers
  - Draw wire sensors
- **Force sensors**
  - 1D force sensors
  - 6D force/torque sensors
- **Torque sensors**
  - Analog
  - Digital
- **Inertial sensors**
  - Accelerometers
  - Gyroscopes
- **Integrated attitude sensors**
  - IMUs
  - AHRS

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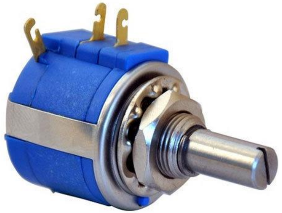

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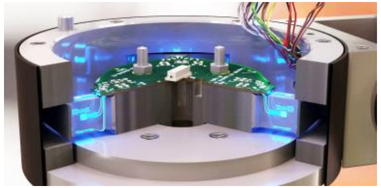

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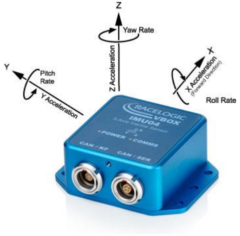

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Internal Sensors – Overview

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Internal sensors

Position sensors

- Incremental encoders
- Absolute encoders

…

Force sensors

- Force sensors
- Force / Torque sensors

Torque sensors

- Analog
- Digital
- …

Inertial sensors

- Accelero-meters
- Gyros
- IMUs
- …

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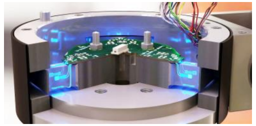

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Internal Sensors – Overview

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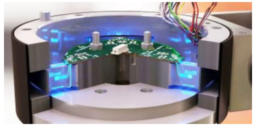

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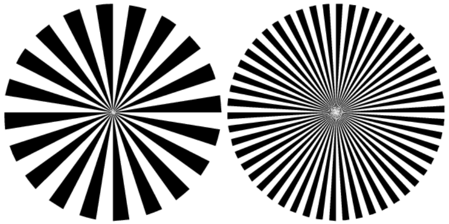
Internal Position Sensors

- Internal position sensors measure the joint displacements of the robot:
  - **Rotary joints → Angular sensors**
  - **Prismatic joints → Distance sensors**
- Three most widely spread sensor technologies for rotary position encoders are:
  - Optical
  - Magnetic
  - Potentiometers
- One can differentiate between different rotary encoders by the way they are mounted:
  - On-axis
  - Off-axis



Optical encoder discs

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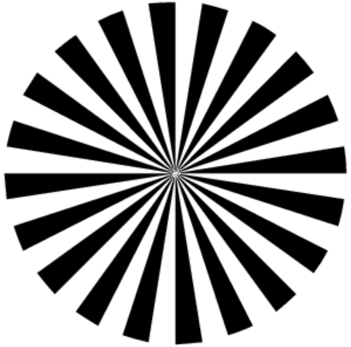
Magnetic off-axis position sensor

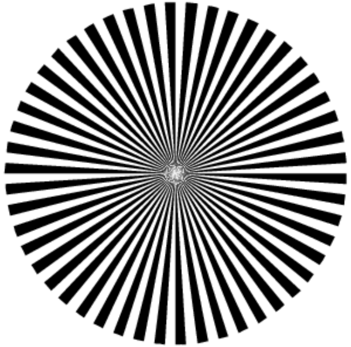
Incremental Encoders

Optical Encoders

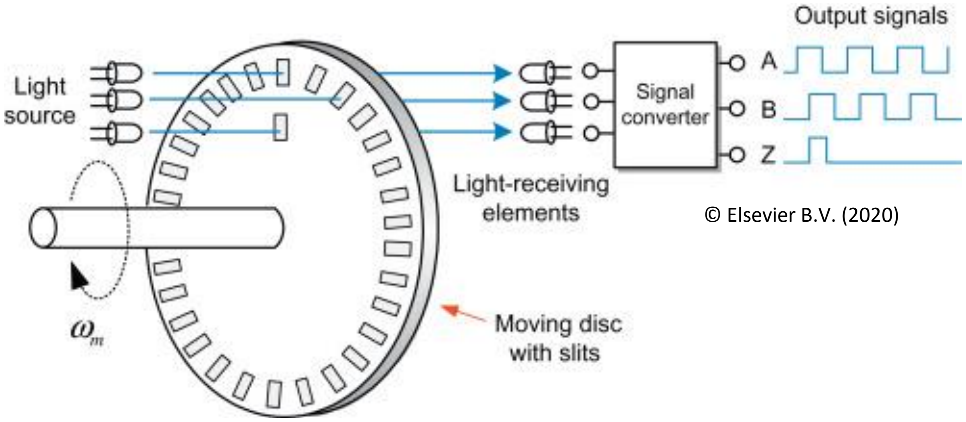
- Sense the angular or translational displacement of a robotic joint using optical measurement methods

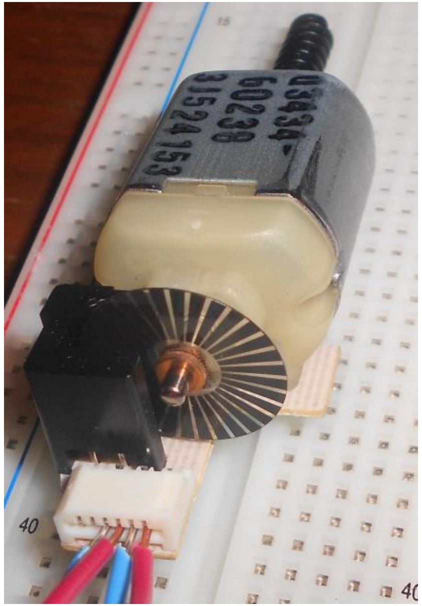
- **Principles of operation:**
  - Sending light through a partially transparent encoder disc
  - Measure reflections of a partially reflective disc
  - Correlation between successive camera images (optical flow, e.g. in a computer mouse)
- **Types:**
  - **Incremental encoder:** Only changes in the position (increments) are detected. The absolute position cannot directly be obtained.
  - **Absolute encoder:** The sensor can measure the absolute position at any given time





Incremental Optical Encoders





Incremental optical encoder with partially transparent disc attached to a small DC motor

Principle: **Partially Transparent encoder disc**

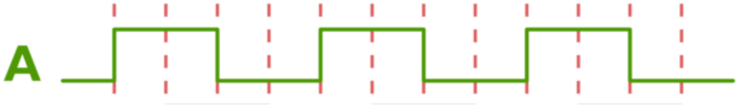
- Light source shines on detector
- Partially transparent encoder disc periodically interrupts the light beam
- The interruptions are detected and summed up to form the position values

Reflective encoders count the reflected light impulses (disk not transparent); otherwise, similar operation

Single-track Optical Encoders (Angle)

Only one code track and one signal line

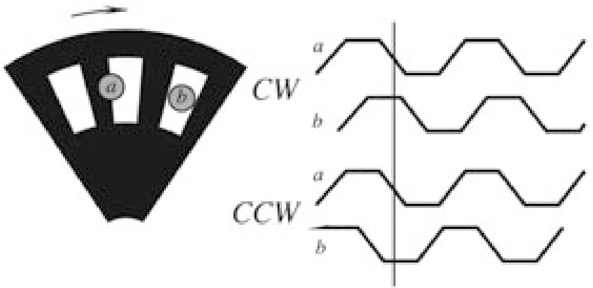
- **Advantages**
  - Very simple to construct
  - Cheap
  - Only one light source (LED)
  - Only one detector (phototransistor)
  - Only one signal line needs to be processed
- **Problem**
  - Direction of rotation remains unknown



Single-track encoder disc of the ASURO educational robot

Quadrature Encoders (Angle and Direction)

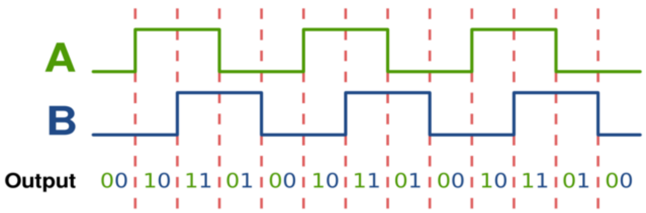
- A second, phase-shifted code track enables detection of the direction of rotation
- Phase-shift is typically 90°



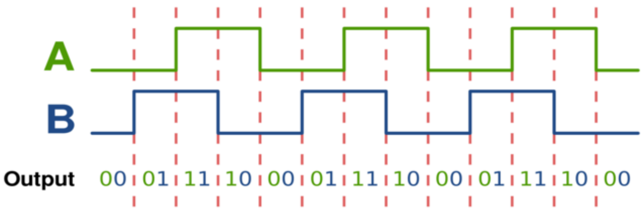
From Fraden J.: Handbook of Modern Sensors

Operation principle *quadrature encoder*:

- At every signal edge, the polarity of that edge (rising, falling) and the state of the other signal (high, low) are sampled
- This information encodes the direction



Forward rotation



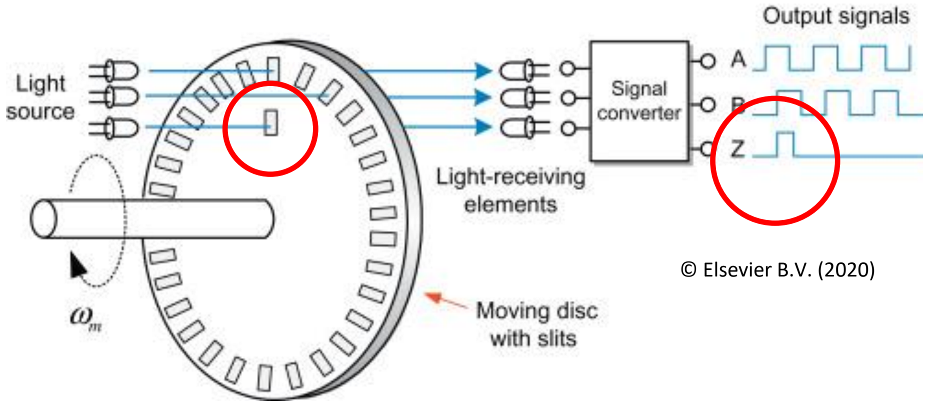
Backward rotation

Triple-track Optical Encoders (Angle, Direction, Initial Position)

Fundamental **problem** with incremental encoders: The **initial position is unknown**

Solution:

- Adding a third track and a third light source/detector pair to encode an initial position
- This enables finding a defined initial pose within one rotation



Still a Problem:

- In case that the range of motion is larger than one rotation, the initial position cannot be encoded

Magnetic Incremental Encoders

- The encoder disc consists of a magnetized ring with **alternating polarity**
- A sensor IC detects the changes in polarity as the disc rotates
- The IC comprises two magnetic field sensors that produce a **phase-shifted quadrature signal**
- The most common sensor principle uses the **Hall-effect**
- **Cheaper** and **more robust** than optical encoders for medium resolutions

Magnetic encoder disk with quadrature encoder IC

Homing with Incremental Encoders

- A system with incremental encoders initially does not know in which configuration its joints are (information is lost at power-off)
- After start-up, known initial positions need to be reached
  - Marked by third encoder track
  - Marked by limit switches
  - Marked by mechanical hard-stop
- From there any desired initial position can be reached → **Homing**

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Homing of a USB conference cam after power-on

Homing of ARMAR-IIIa

Absolute Encoders

Absolute Encoders

Measure the **absolute position** of a joint **at any time**

- No information is lost due to power-off
- No need for a homing procedure
  - Faster readiness for action of the entire robotic system!
- Interface not only transmits signal edges („ticks“) but the entire position information

Disadvantages compared to incremental encoders:

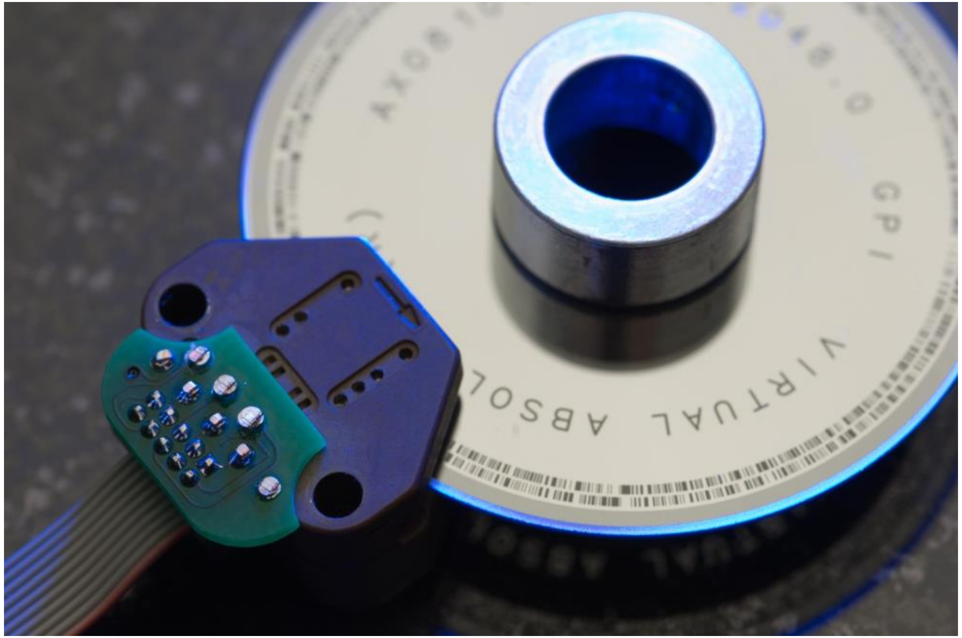
- More complex mechatronics
- Higher data throughput, more complex protocols
- More expensive

Magnetic off-axis position sensor

Encapsulated optical on-axis absolute encoder

Optical Absolute Encoders

- A light source shines through a structured encoder disc
- Each position along the encoder disc creates a unique light pattern on the detector array
- The light pattern is converted into a position value and transmitted via a digital interface



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Codes for Optical Absolute Encoders

Binary code

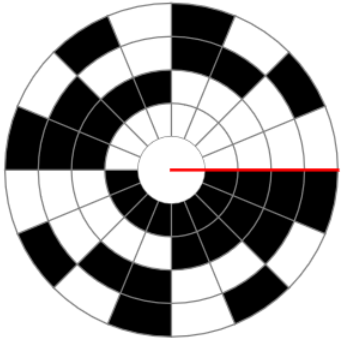
- Transparent patches at a given position are interpreted as logical ones
- Position is encoded as binary number
- **Problem**: During the transition between two positions, two bits might not change at the exact same time, causing **erroneous transient states**

Gray code

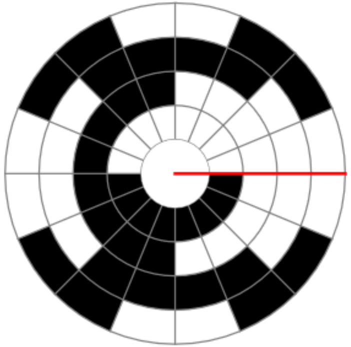
- In Gray-code discs **only one bit changes between two adjacent positions**
- Transient states do not occur

Interactive visualisation with erroneous transient states:
https://demonstrations.wolfram.com/GrayCodesErrorReductionWithEncoders/

Binary



Gray



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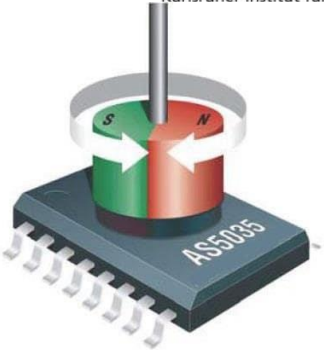
Magnetic Absolute Encoders I

On-axis encoders

- A single magnet rotates with the shaft
- The sensor IC is fixed, positioned in very close proximity to the magnet
- An array of Hall-sensors within the IC detects the orientation of the magnetic field and computes the position

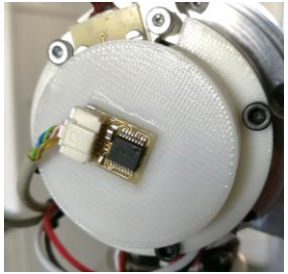


Advantages

- Mechanically simple
- Relatively cheap

Disadvantages

- Not well suited for hollow shafts
- High demands on distance and centricity



Magnetic on-axis absolute encoder IC on the shoulder of ARMAR-4

Magnetic Absolute Encoders II

Off-axis encoders

- A magnetic code ring with complex magnetization rotates with the shaft
- Each position (within the resolution) has its unique magnetic fingerprint
- A magnetic read-head detects the position

Advantages

- Very high resolutions possible ($0.7 \cdot 10^{-4}$ deg)
- Enables absolute position measurement on **hollow shafts**

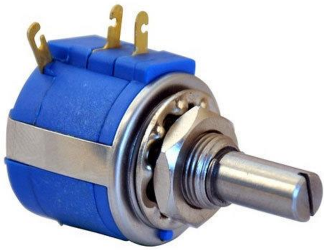
Disadvantages

- Complex and expensive
- Vey high demands on distance and centricity

Magnetic off-axis absolute encoders in different sizes as used in ARMAR-6

Potentiometer (Variable Resistor)

- Resistors that change their resistance according to the position of a slider
- Implemented as variable voltage divider with three connections
- The voltage ratio can be converted into a position
- Well suited for low-cost applications with low demands on compactness and precision



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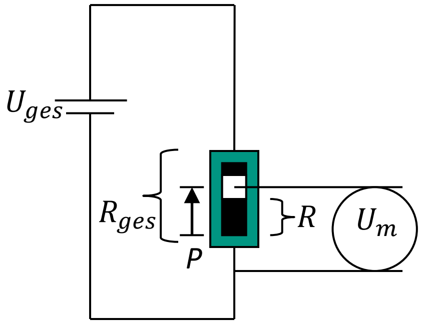
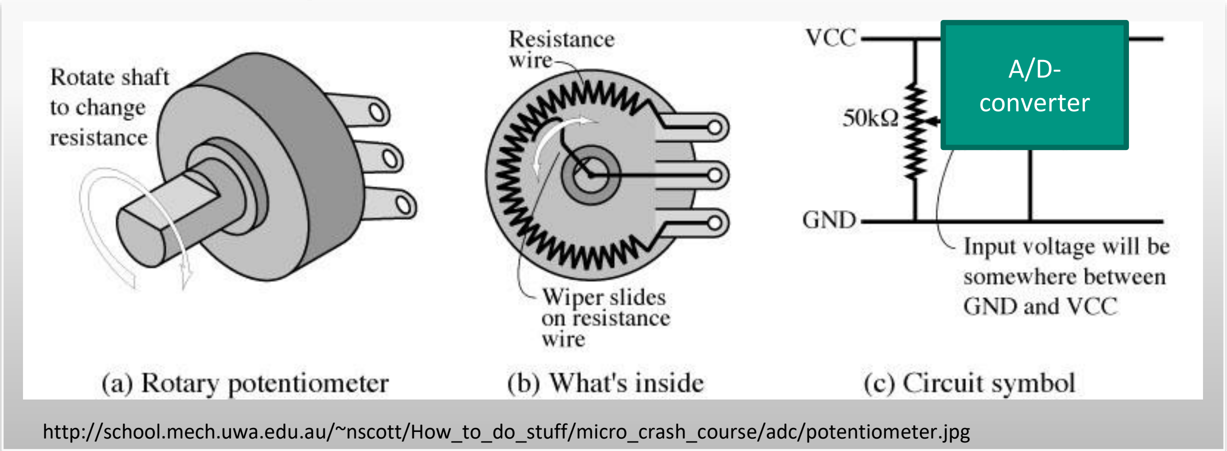
Deriving the position from the voltage U_m

- Across the entire potentiometer drops a voltage of U_{ges}
- Voltage U_m scales proportionally to P from $0V$ to U_{ges}
- $U_m = \frac{R}{R_{ges}} U_{ges} \sim P$



Potentiometer – Connections

- Potentiometer are analog sensors
- The voltage signal requires digitization
- The resolution of the analog-to-digital converter (ADC) determines the resolution of the sensor system



Inner workings, connections and example schematic of a rotary potentiometer

Potentiometer – Styles

Rotary potentiometer

- Absolute position measurement of rotational motion
- Sub-styles:
  - Single-Turn: Range of maximum one revolution (most common)
  - Multi-Turn: Range of up to 10 (or even more) revolutions

https://partnership.bourns.com/bu/bu_prec.shtml

Multi-turn rotary potentiometer with a measurement range of ten revolutions

Linear potentiometer

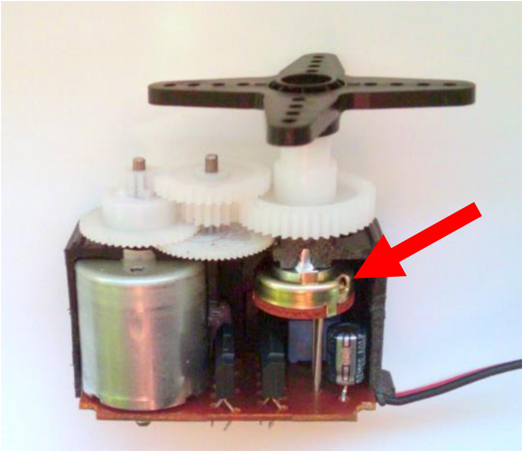
- Absolute linear position measurement
- Available in a large variety of measurement ranges

https://de.wikipedia.org/wiki/Potentiometer#/media/File:Faders.jpg

Potentiometer – Applications

- Often used as absolute position sensors in low-cost applications
- **RC (radio control) servo motors**
- User interfaces (rotary dials)

Hexapod robot equipped with RC servo motors



Cross-section of a RC servo motor with potentiometer for position feedback at the output shaft

Draw Wire Sensors (Absolute Encoders)

- Suitable **for long linear movements** (e.g. hydraulic pistons)
- Linear motion unwinds a string from a rotating drum
- A potentiometer, incremental or absolute encoder measures the rotation of the drum

Advantages

- Precise measurement of long linear displacements
- Range: 50mm – 5000 mm
- Easy to integrate
- Robust

Disadvantages

- Relatively large
- Actuator must compensate for the restoring force of the drum spring

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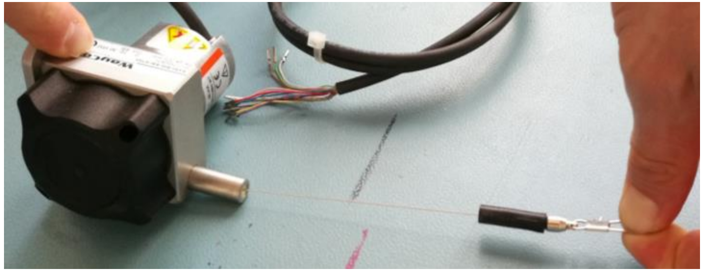


Draw wire sensor used to measure the torso extension of ARMAR-6

Interfaces for Absolute Encoders

Interfaces for Digital Absolute Encoders – I²C

- Inter-Integrated Circuit (I²C)
- Synonym: TWI (Two Wire Interface)
- Developed 1982 by Philips Semiconductors

Operating principle

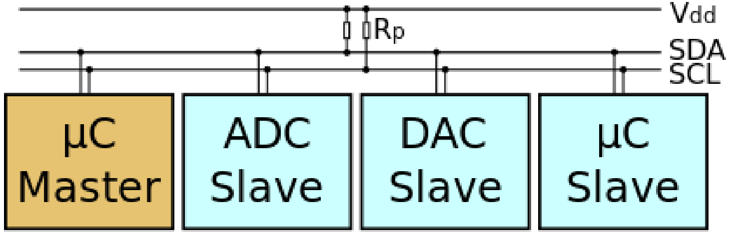
- Master-Slave Bus for communication between ICs
- Each slave has unique address (7-10 bit address space)
- Two physical lines: Serial clock (SCL) and Serial data (SDA)
- Bidirectional

Advantages

- Simple wiring even for large number of devices/sensors

Disadvantage

- Comparatively slow (standard: 0,1Mbit/s)
- In "Ultra Fast-mode": 5 Mbit/s (Unidirectional)



https://de.wikipedia.org/wiki/I%C2%B2C

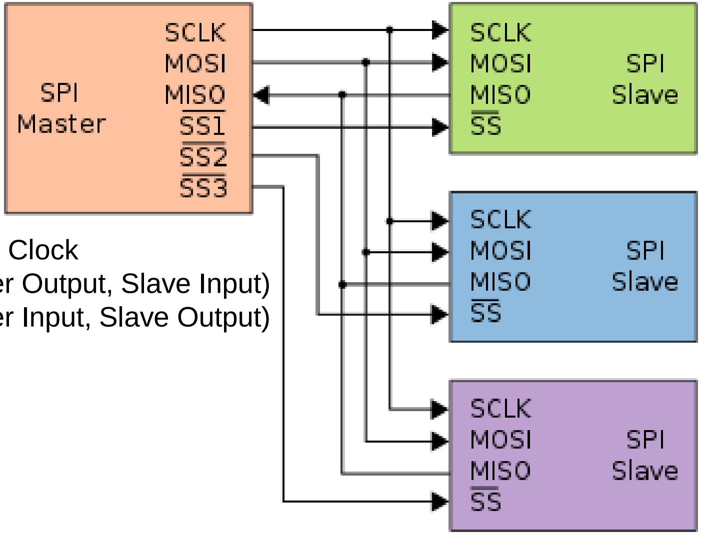
I²C-network with one master and three slaves

Interfaces for Digital Absolute Encoders – SPI

- Serial Peripheral Interface (SPI)
- Developed 1980 by Motorola
- Relatively loose definition with lots of possible variations

Operating principle

- Master-Slave bus with four physical lines
- Each slave is addressed by the master via a dedicated *chips select signal* (Slave Select: SS)



SCLK: Serial Clock
MOSI (Master Output, Slave Input)
MISO (Master Input, Slave Output)

https://de.wikipedia.org/wiki/Serial_Peripheral_Interface

SPI-network with master and three slaves (Star topology)

Advantages

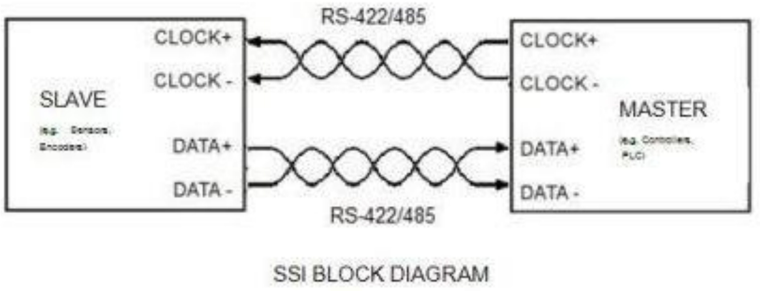
- Very simple on the software side (because arbitration via chip select signals)
- Speed defined by the master clock

Disadvantage

- Higher circuit complexity compared to I^2C

Interfaces for Digital Absolute Encoders – SSI

- „Synchron Serielle Schnittstelle“ (SSI)
- Developed in 1984 by Max Stegmann GmbH



https://de.wikipedia.org/wiki/Synchron-Serielle_Schnittstelle

Operation principle

- Uni-directional Point-to-Point connection
- Two twisted wire pairs (data and clock)
- Twisted wire pairs for differential signal transmission

Advantages

- High electrical robustness (designed for reliability in industrial applications)
- Very simple transmission protocol

Disadvantages

- High cabling complexity due to twisted pairs
- Limited topologies (point-to-point)

Internal Sensors – Overview

Internal sensors

Position sensors
- Incremental encoders
- Absolute encoders
- …

Force sensors
- Force sensors
- Force / Torque sensors

Torque sensors
- Analog
- Digital
- …

Inertial sensors
- Accelero-meters
- Gyros
- IMUs
- …

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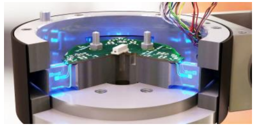

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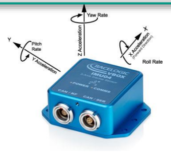

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Force Sensors

- Force sensors allow to measure forces that
  - Occur within the robot (internal)
  - Occur between the robot and the environment

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Types

- 1D force sensors
- 3D force sensors
- 6D force/torque sensors
- …

Applications

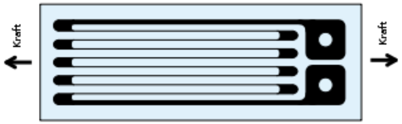
- Measurement of internal forces (e.g. in Bowden cables)
- Measurement of contact forces (e.g. ground contact, haptics, tactile-servoing, …)
- Measurement of interaction forces (Human robot interaction/collaboration)

Preliminaries

STRAIN GAUGES, A/D CONVERSION, MEASURING RESISTANCE

Resistive Strain Gauges

- Strain gauges transform micro-deformations into a change of their electrical resistance: **piezo-resistive effect**
- Effect is amplified by a series connection of many windings
- Using a **measurement bridge**, the change in resistance is converted to a change in voltage
- This voltage can be amplified and measured



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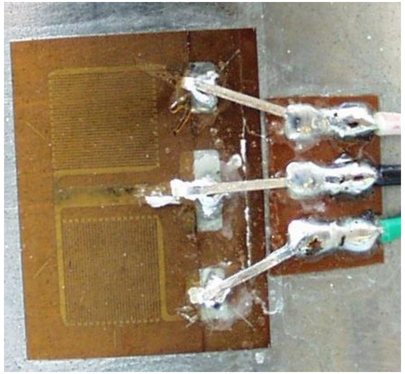

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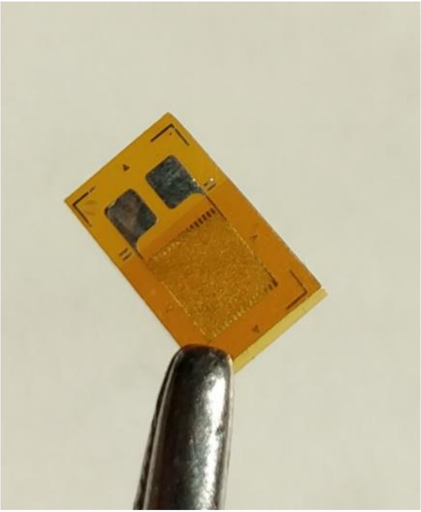


Piezoresistive Effect (I)

- The underlying principle of strain gauges is the fact that materials change their electrical resistance when deformed

- Causes for this:
  - Change in **geometry** (occurs for all materials; effect is small)
  - Change in the **specific resistivity** (very strong effect in piezo-electric materials)

Piezoresistive Effect (II)

- Electric resistance of the unloaded strain gauge depends on the specific resistivity ρ, the length l and the cross-section A (with D being the wire diameter):

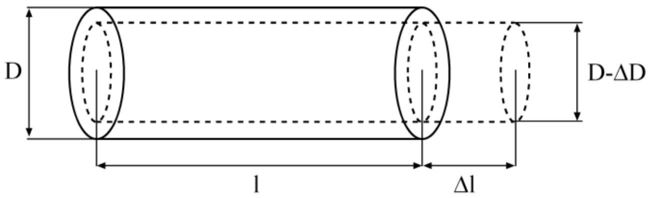
$$R = \rho \cdot \frac{l}{A} = \rho \cdot \frac{4l}{D^2\pi}$$

- Under strain load, **length**, **cross-section**, and **specific resistivity** of the wires change:

$$R + \Delta R = (\rho + \Delta\rho) \cdot \frac{4(l + \Delta l)}{(D - \Delta D)^2\pi}$$

- Re-arranging the equation above and introducing the elongation ϵ as well as the sensitivity coefficient k, one obtains the relation between elongation and change in resistance:

$$\frac{\Delta R}{R} = k \cdot \frac{\Delta L}{L} = k \cdot \epsilon$$

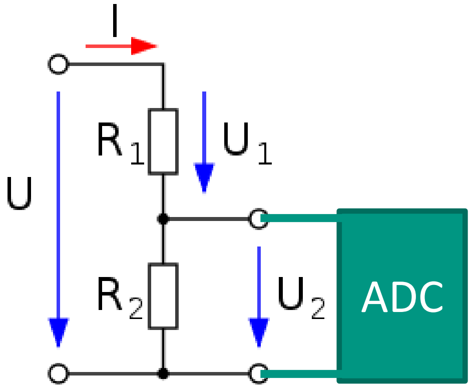


Measuring Resistance

An electrical resistance can be measured as a voltage using a **voltage divider circuit**.

Example

- The variable resistor R_2 shall be determined by measuring the voltage U_2
- R_1 is a fixed reference resistor
- $\boldsymbol{R_2 = \frac{U_2}{U}(R_1 + R_2)}$



https://de.wikipedia.org/wiki/Spannungsteiler#/media/Datei:Einfacher-unbelasteter-Spannungsteiler.svg

Problem

- The ADC measurement range is U
- If the **change in resistance of U_2 is small compared to U** only a small fraction of the ADC‘s range will be exploited

→ **lower resolution, Solution:** Wheatstone bridge

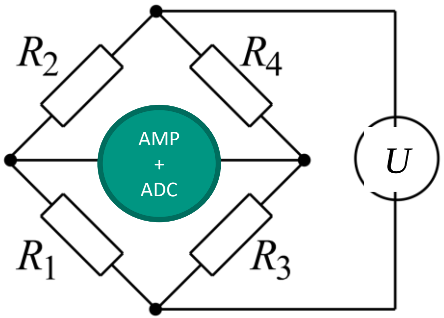
Wheatstone Bridge

- A Wheatstone bridge in conjunction with an amplifier allows to measure **very small changes in resistance** with **high resolution**
- It consists of two voltage dividers (R_1 and R_2 as well as R_3 and R_4) that operate from the same supply voltage
- An ADC measures the **differential voltage V_G** („detuning“) of the two voltage dividers (not with reference to GND)
- This small voltage difference can be amplified (AMP) to cover the entire range of the ADC

  → **Using the entire range of the ADC even for small changes**

Smart arrangement of the resistors/strain gauges allows **disturbance suppression/compensation**

- Temperature compensation
- Torsion deflection compensation
- Elongation compensation



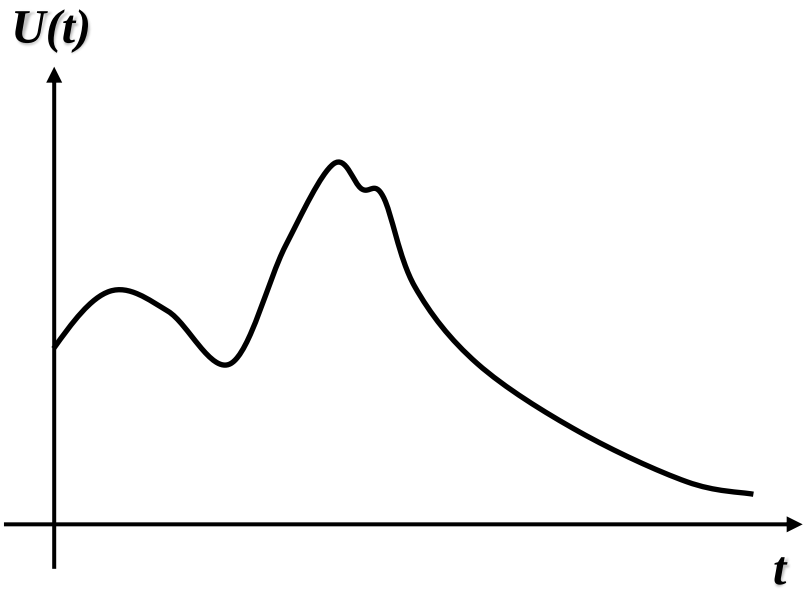
https://de.wikipedia.org/wiki/Wheatstonesche_Messbr%C3%BCcke#/media/Datei:WhBr_Diagonalbild.svg

Analog-to-Digital Conversion

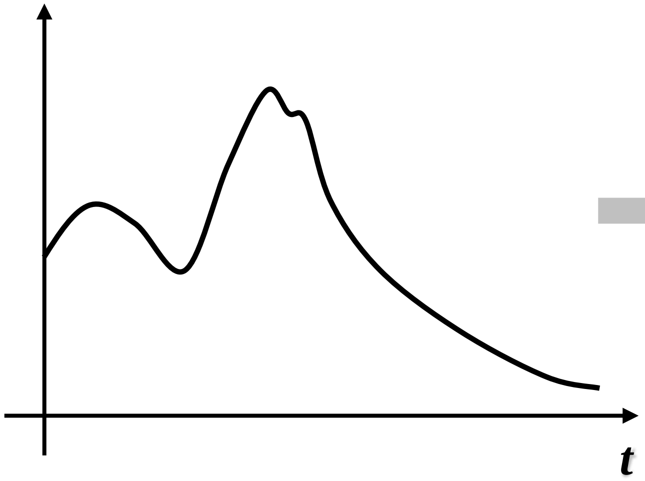
- Continuous signal -> Digital signal

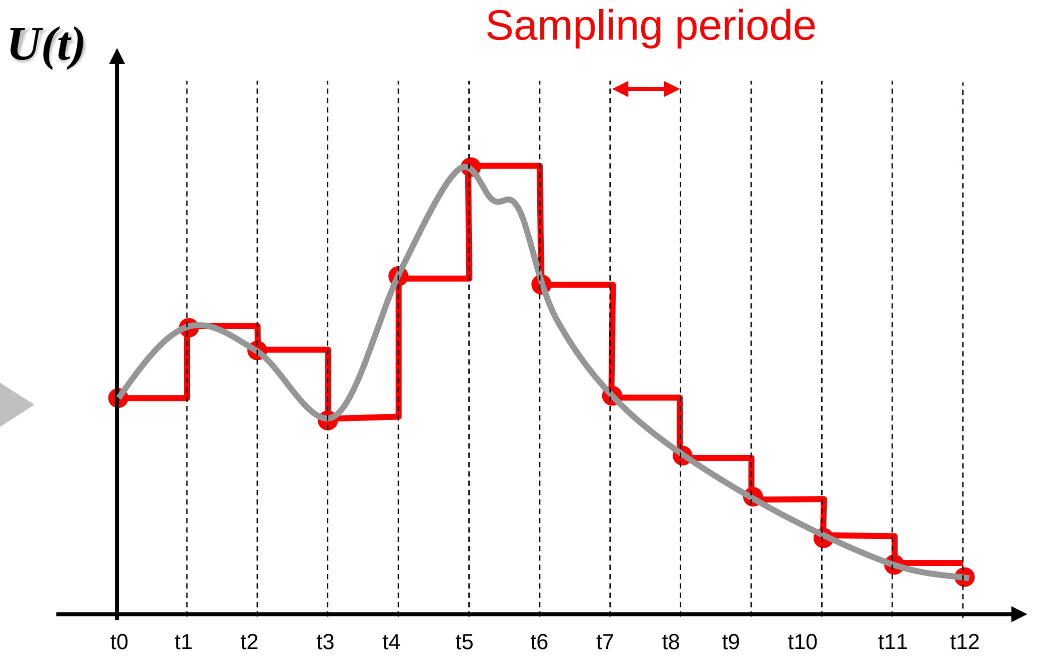
- **Nyquist–Shannon sampling theorem!**

  Reproduction of the original signal is only possible if the sampling rate is higher than twice the highest frequency of the signal.



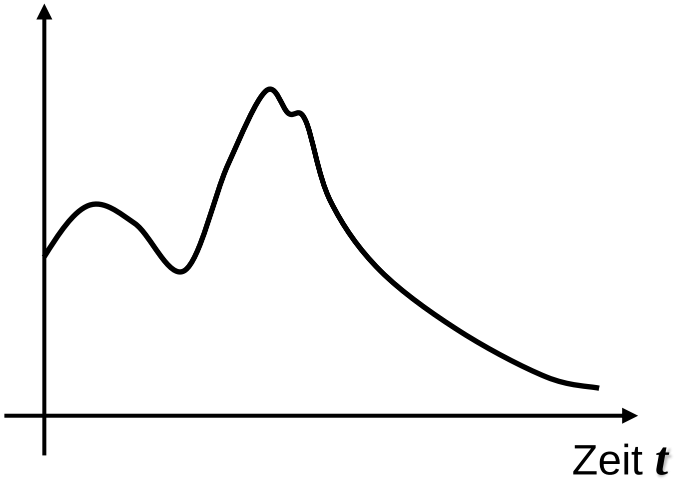
Analog-to-Digital Conversion

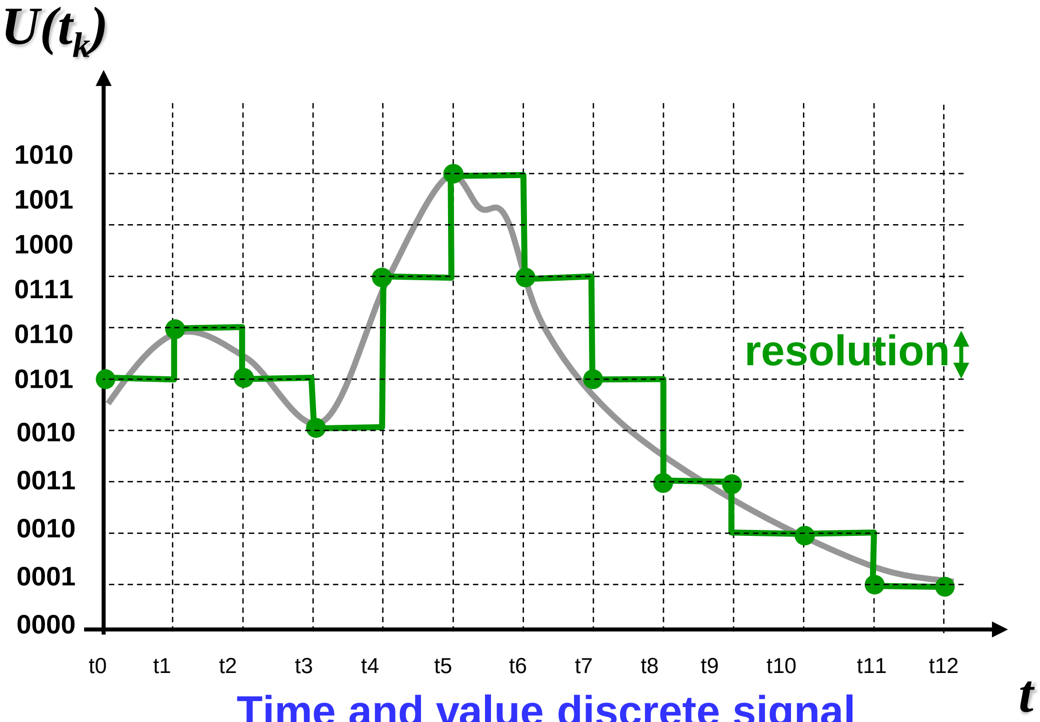




Time discrete, value continuous signal

Analog-to-Digital Conversion

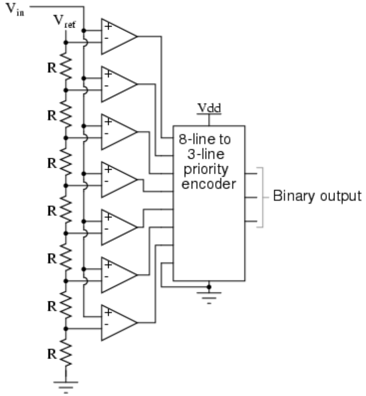




Time and value discrete signal

Analog-to-Digital Conversion (ADC)

- Crucial component in many sensor systems
- Digitization of a voltage V_{in} in relation to a reference voltage V_{ref}
- **Characteristics** (among others):
  - Resolution (in Bits)
  - Signal-to-Noise
- **Example ADS1220** (low-noise differential ADC used for torque-sensing in ARMAR-6)
  - 24-Bit resolution
  - Integrated analog and digital signal processing
  - Integrated temperature sensor for temperature compensation
  - SPI-Interface



https://sub.allaboutcircuits.com/images/04256.png

Operation principle of an 8-Bit ADC

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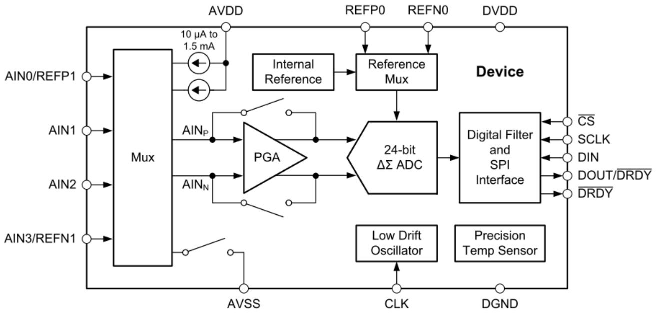

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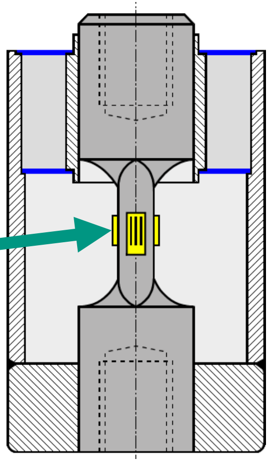
Block Diagram of ADS1220 Chip Internals

1D Force Sensors

1D Force Sensors

- **Principle of operation:** A sensor element deforms when subjected to mechanical load
- The deformation is converted to an electrical signal either
  - Resistively (with strain gauges)
  - Capacitively (Microelectromechanical systems MEMS)
- The force can be calculated from the electrical signal
- Within the specified range, the produced signal is proportional to the load

The sensors described in this lecture are analog and require subsequent A/D conversion of the sensors signal



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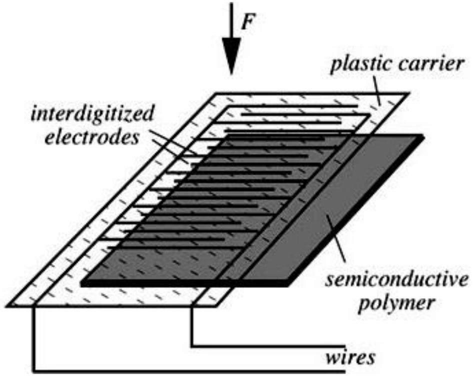
1D force sensor (working principle and example)

Force Sensing Resistors (FSR)

- Type of electrical resistors that change their **resistance** due to mechanical deformation
- Large change in resistance, used in voltage dividers

Principle of operation

- The two connectors lead to two interwoven „combs“ that are not connected
- The combs are covered by a conductive polymer
- When pressed, the conductive polymer shorts the two traces together with a resistance that depends on applied force



From Fraden, J.: Handbook of Modern Sensors

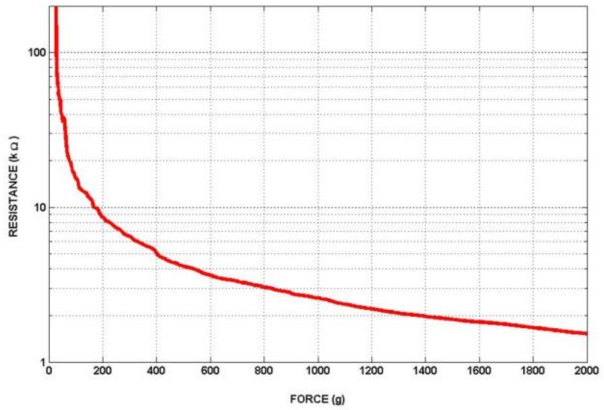
Force Sensing Resistors (FSR)

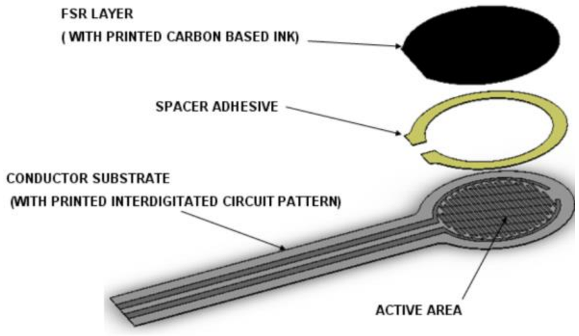
Advantages

- Change in resistance is much larger than in strain gauges
  - **No need for differential measurement**
  - Can be interfaced via a voltage divider and a simple microcontroller with integrated ADC
- **Very low cost**

Disadvantages

- Very low accuracy (rather qualitative than quantitative measurement)
- Measured value depends on many factors, not only on the load





https://www.rapidonline.com/pdf/182546_in_en_01.pdf

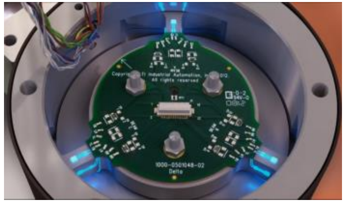
6D Force/Torque Sensors

6D Force/Torque Sensors

- Measure the **3D force vector** and the **3D torque vector**
- Commonly used in **robotic end-effectors** (hands, feet)
- Produce **six analog signals** (integrated Wheatstone bridges) that need to be digitized and converted into force and toque values

  $$(Fx, Fy, Fz, Tx, Ty, Tz)^T = \boldsymbol{M} \cdot (\text{analog signals})^T$$

  With $\boldsymbol{M}$ being the 6x6 calibration matrix
- **Very Expensive** (ca. 5000€)



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Animated inner view of a force/toque sensors with highlighted strain gauges

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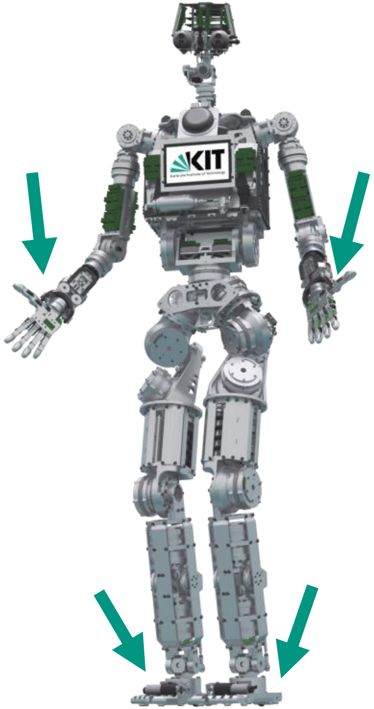
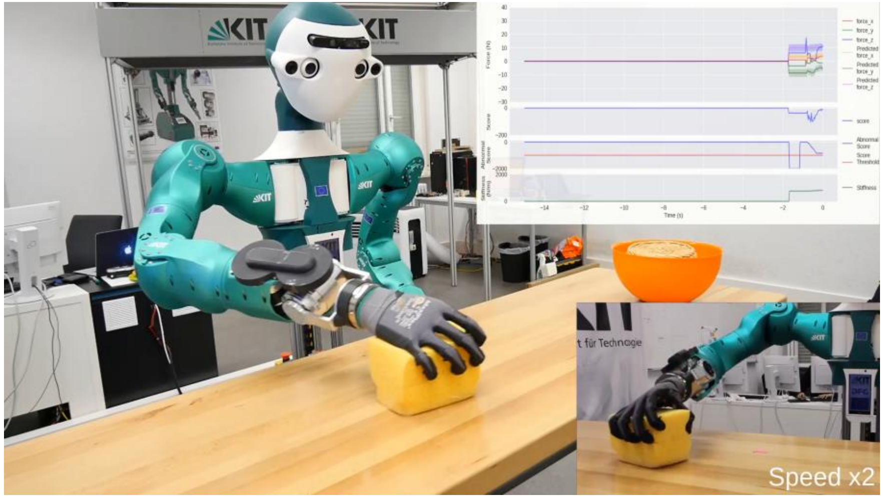
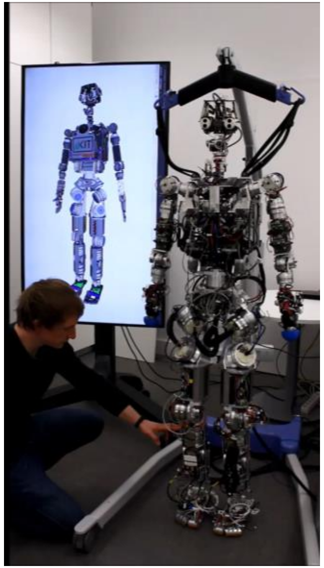


6D Force/Torque Sensors – Application

- Precise measurement of the **ground reaction wrench** (forces and torques)
  - Enables computing the pushing forces along the robot‘s body
- Contact force/torque of the hand with the environment
  - Enables compliance adaptation



In the wrist: for compliance adaptation



In the anke: reaction forces

Internal Sensors – Overview

Internal sensors

- **Position sensors**
  - Incremental encoders
  - Absolute encoders
  - …
- **Force sensors**
  - Force sensors
  - Force / Torque sensors
- **Torque sensors**
  - Analog
  - Digital
  - …
- **Inertial sensors**
  - Accelero-meters
  - Gyros
  - IMUs
  - …

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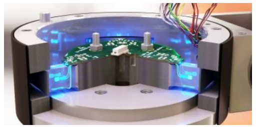

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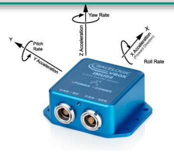

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Torque Sensors

- Measure the torques in the robot joints
- Necessary as feedback sensors in **joint torque control**
  - For human-robot interaction
  - For compliant reaction to external contacts

Operation principle

- Determine the **torsional deformation** of the output shaft (between the gear and the output flange)
  - **strain gauges**
  - high precision position encoders

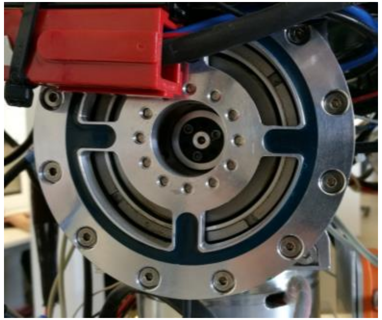
Torque Sensors – Analog I

Spoke wheel type

- Sensors consists of a milled spoke wheel
- The spokes act as **bending beams**
- Bending of the spokes is proportional to the torque acting **between the inner and the outer ring**
- **Strain gauges** on the spokes measure the bending
- The spokes are wired to form a complete **Wheatstone bridge**
- Digitization of the analog signal with **internal or external ADC**

Spoke wheel type torque sensor of the DLR light-weight arm

Image taken from: Hirzinger, Gerhard, et al. "Torque-controlled lightweight arms and articulated hands: Do we reach technological limits now?." The International Journal of Robotics Research 23.4-5 (2004): 331-340.



Spoke wheel type torque sensor on ARMAR-4

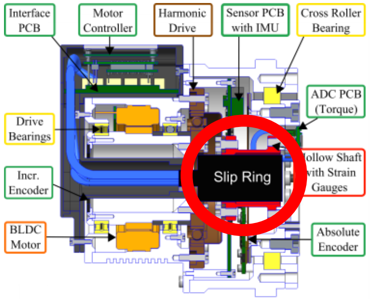
Torque Sensors – Analog II

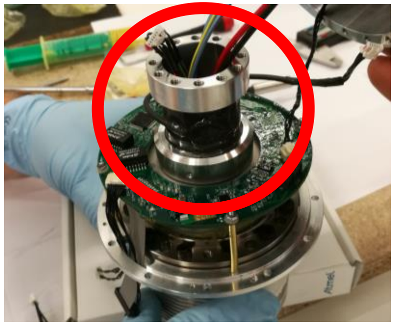
Torsional shaft type

- The sensor consist of a **thin-walled hollow shaft** between the gear and the output flange
- The hollow shaft undergoes **torsional deformation** due to the acting torque
- **Strain gauges** detect the deformation (while compensating temperature and bending effects) and are wired as **Wheatstone bridge**
- The voltage is digitized using a **differential ADC** and linearly converted into a torque value

Advantages

- Small installation space
- High precision
- High stiffness





Torsional shaft type torque sensor in a sensor-actuator-controller unit of ARMAR-6

Rader, S., Kaul, L., Weiner, P. and Asfour, T., *Highly Integrated Sensor-Actuator-Controller Units for Modular Robot Design*, IEEE International Conference on Advanced Intelligent Mechatronics (AIM), pp. 1160-1166, 2017

Torque Sensors – Digital

Torsional shaft type

- Torsional shaft at the actuator output (like in the analog case)
- Deformation is measured using a digital **absolute encoder** between the two flanges of the hollow shaft
  - The encoder is mounted on the output side
  - The magnetic disc is mounted on the input side

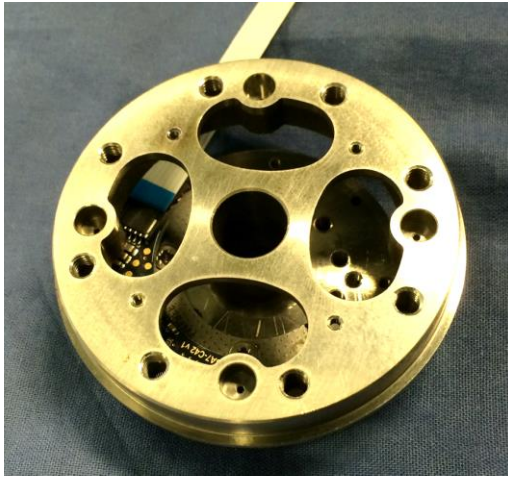
Advantage

- No need for A/D conversion

Disadvantage

- Resolution limited by encoder resolution (not utilizing the encoder‘s full range)

Image taken from: Baccelliere, Lorenzo, et al. "Development of a human size and strength compliant bi-manual platform for realistic heavy manipulation tasks." *Intelligent Robots and Systems (IROS), 2017 IEEE/RSJ International Conference on*. IEEE, 2017.



Encoder-based torque sensor

Internal Sensors – Overview

Internal sensors

Position sensors
- Incremental encoders
- Absolute encoders
- …

Force sensors
- Force sensors
- Force / Torque sensors

Torque sensors
- Analog
- Digital
- …

Inertial sensors
- Accelero-meters
- Gyros
- IMUs
- …

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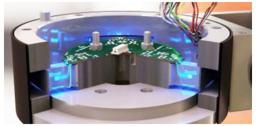

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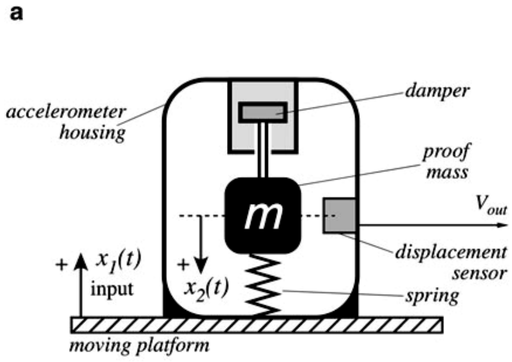
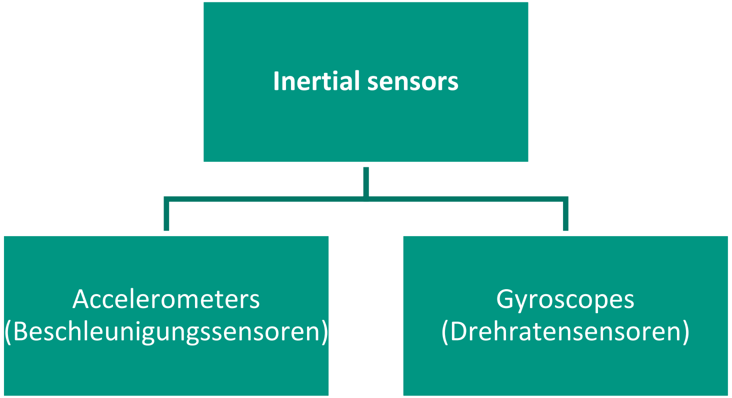
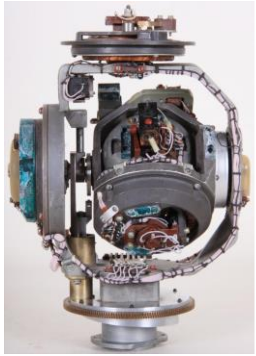
Inertial Sensors

Sensors that measure effects based on the inertia of a proof mass



From Fraden, J.: Handbook of Modern Sensors





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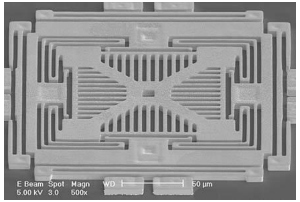
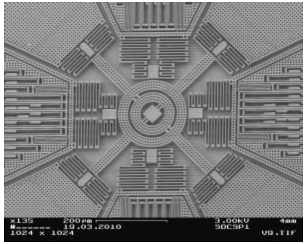


http://secondelmb.free.fr/edc2/activites/act3.html

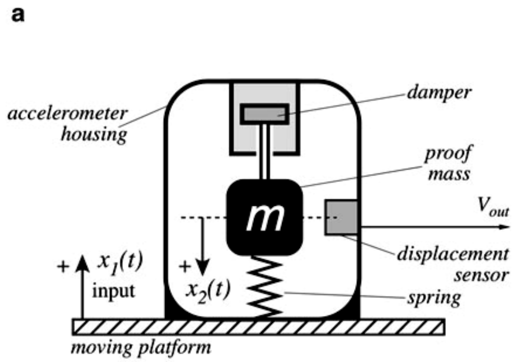


http://www.geekmomprojects.com/wp-content/uploads/2013/03/mems_gyroscope.jpg?resize=300%2C240

Inertial Sensors – Applications

Accelerometer measure their **acceleration** in space

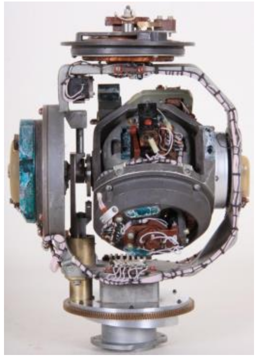
- Applications:
  - Vibration measurement
  - Crash-detection (airbags)
  - Touch detection
  - Head-crash avoidance for falling external hard drives
  - ….



From Fraden, J.: Handbook of Modern Sensors

Gyroscopes measure their **rotational velocity** in space

- Applications:
  - Navigation (rockets, planes, submarines, …)
  - Image stabilization (e.g. in smartphones)
  - …

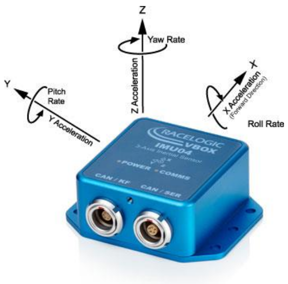


https://www.ostron.de/out/pictures/z3/kreiselbaugruppe_mig21_03_z3.jpg

Inertial sensors – Applications (IMUs)

The combination of accelerometers and gyroscopes in one package is called **Inertial Measurement Unit** (IMU)

- Acceleration measurement in all three spatial axes
- Rotational rate measurement around all three spatial axes
- Often combined with additional magnetometers



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IMUs allow for **robust measurement of the absolute orientation** (in the earth‘s inertial system)

- Requires fusion of different sensor modalities
- Different filters are commonly used for this fusion (Kalman, complementary, …)

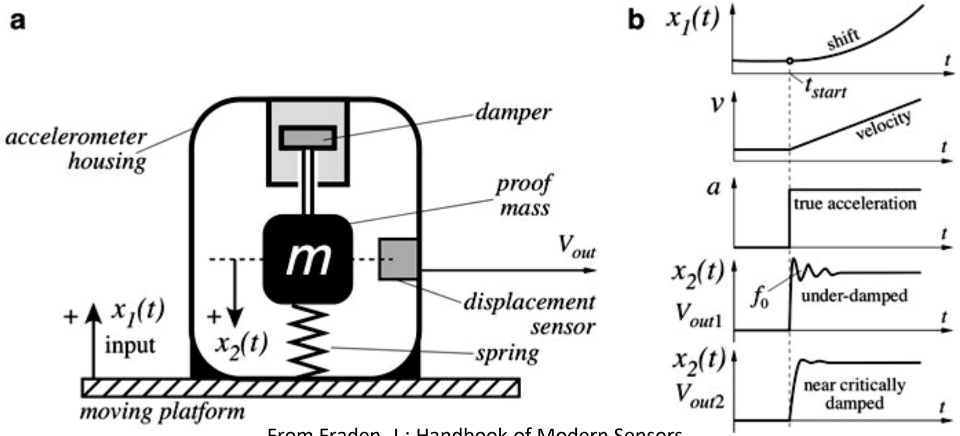
https://oscarliang.com/ctt/uploads/2013/06/Quadcopter-flying.jpg

Accelerometers

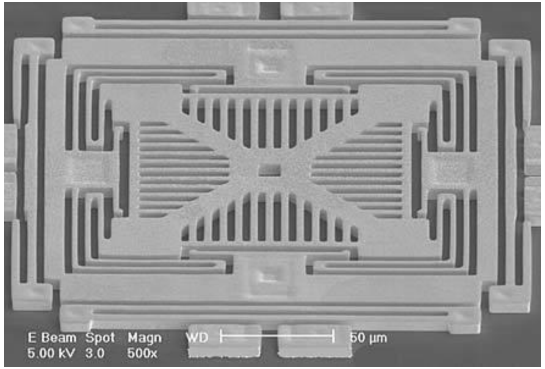
Accelerometers

Underlying measurement principle: Detect the effects of acceleration on a **seismic proof mass**

- **Most common:** Deflection measurement on a **spring-mass system**
- Accelerometers exist on a large variety of scales and use various implementations of the spring-mass-system



From Fraden, J.: Handbook of Modern Sensors



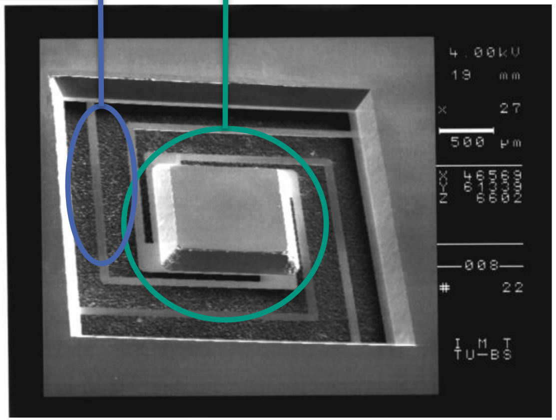
http://secondelmb.free.fr/edc2/activites/act3.html

Spring-mass systems for acceleration measurement on different scales and measurement principles

Piezoresistive Accelerometers

Principle of operation:

- Acceleration causes force on a seismic proof mass
- The generated force deforms a piezoresistive sensor element
- Due to the piezoresistive effect, the sensor element changes its resistance in accordance to the force
- A Wheatstone bridge is used to measure the deformation
- → See slides on strain gauges



Micro mechanical piezoresistive accelerometer made form silicon

Accelerometers (Capacitive)

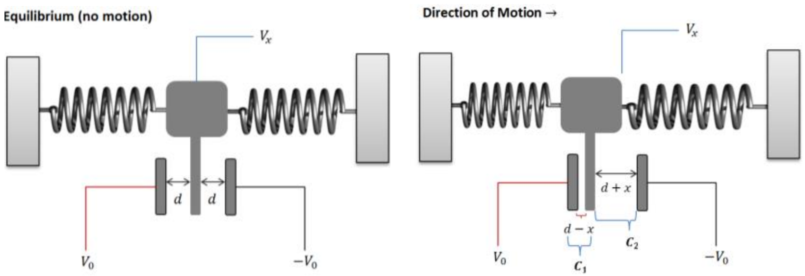
- The seismic proof mass is part of a capacitor
- A displacement causes a change in the capacitor's capacity
- The change in capacity can be measured and converted into an acceleration

Differential capacitor

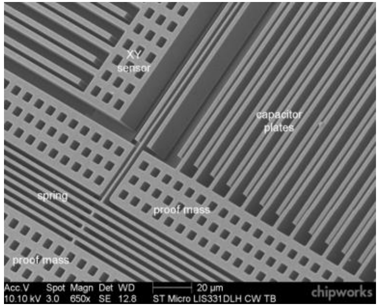
- The seismic mass is (part of) the middle electrode
- Measured using an AC bridge circuit (not in this lecture)

Plate capacitor

- The seismic mass is (part of) the plate
- Change in capacity due to the displacement of the plate



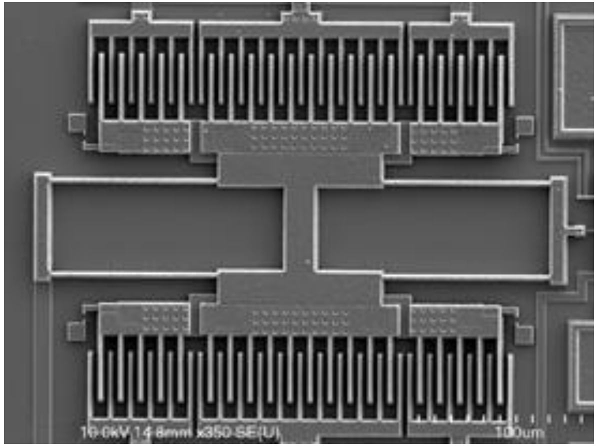
https://makersportal.com/blog/2017/9/25/accelerometer-on-an-elevator



https://www.rs-online.com/designspark/its-a-small-world-after-all

MEMS Accelerometers (capacitive)

- MEMS = **Micro Electro Mechanical System**
- Most commonly manufactured using stereo lithography and etching (sensor sizes on the micrometer scale)
- Most common accelerometer type (by far!)
  - Mobile phones
  - Cameras
  - …



http://bilderlustige.bid/mems-accelerometer-principle.html

Micro-mechanical single-axis accelerometer made from silicon

Principle of operation

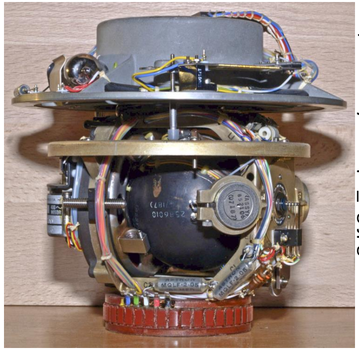
- Elastically suspended „combs“ form a plate capacitor
- Change in capacity due to deformation of the comb structure

Gyroscopes

Mechanical Gyroscopes

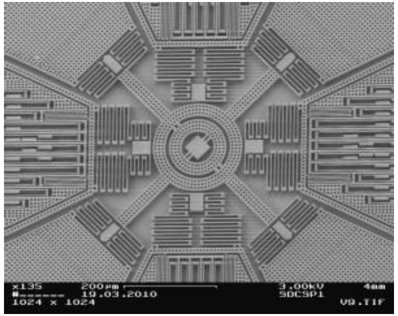
Use the Coriolis force on a moving proof mass to detect their rate of rotation in the inertial system

- Implemented as **spinning gyroscope** (macro-mechanical)
  - In earlier times used for navigation and attitude control of planes, submarines, rockets, …
  - Rarely used in robotics



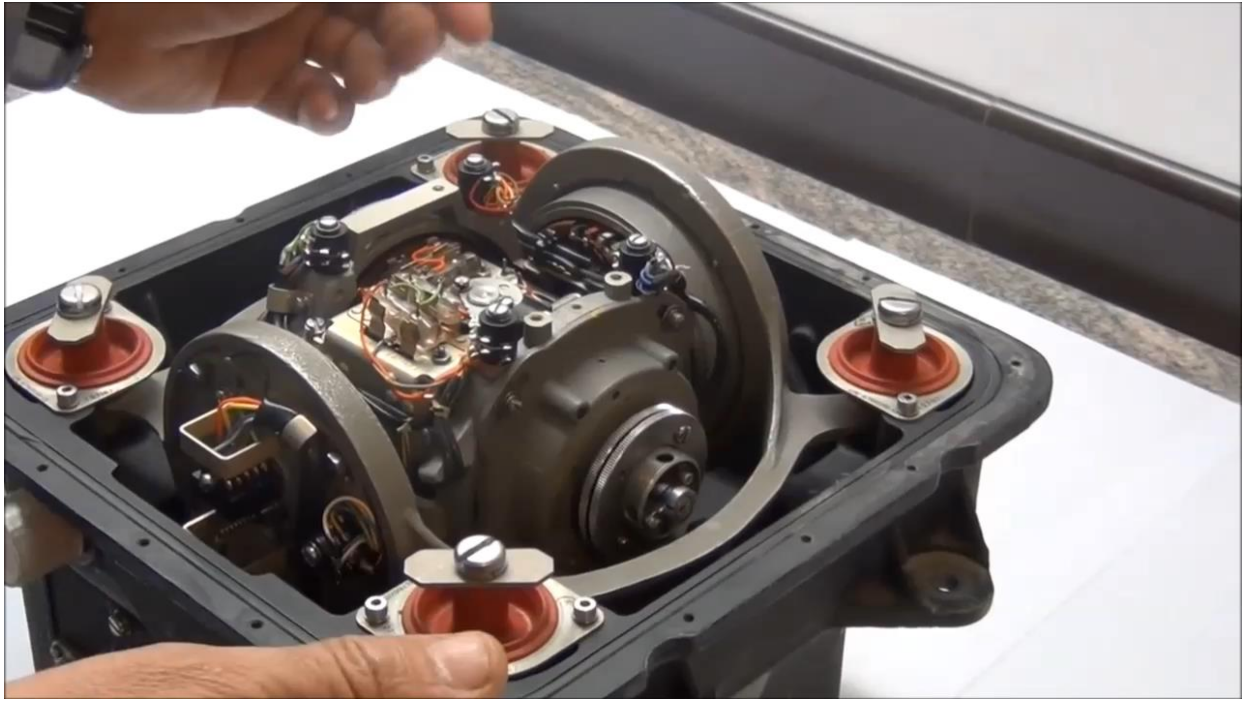
https://de.wikipedia.org/wiki/Kreiselinstrument#/media/Datei:Gyroscope_hg.jpg

- Implemented as **vibrating element** (MEMS)
  - Very small (μm) and very cheap
  - Mass production (smart phones)
  - Most common gyroscope found in robotic applications



http://www.geekmomprojects.com/wp-content/uploads/2013/03/mems_gyroscope.jpg?resize=300%2C240

Macro-Mechanical Gyroscope – Demonstration



https://www.youtube.com/watch?v=VycrS3VYjeM

Macro-Mechanical Gyroscopes – Spinning Gyros

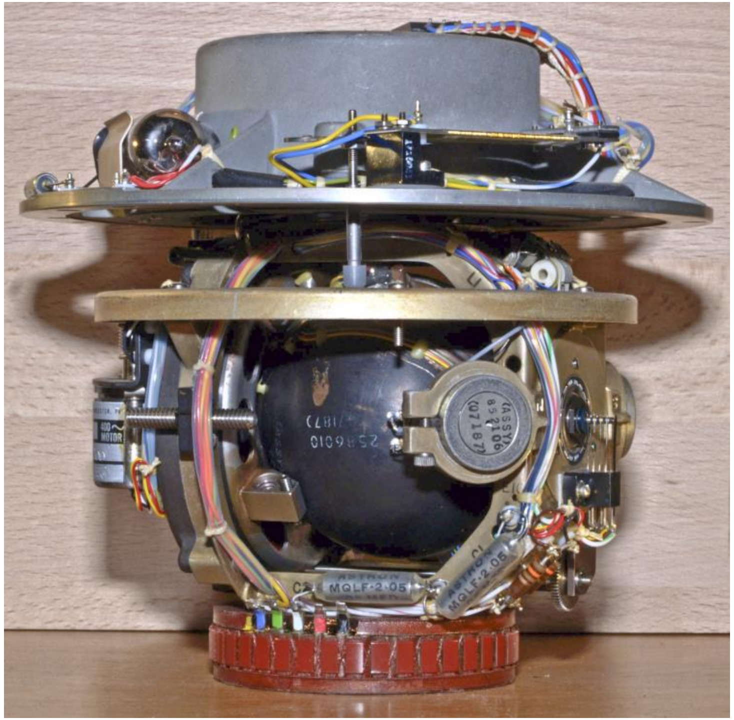
Advantages

- Directly measure the orientation, not the angular velocity

Disadvantages

- Mechanically very complex
- High maintenance
- Very expensive
- Large installation space
- Drift caused by friction or asymmetries of the spinner

→ Rarely used nowadays

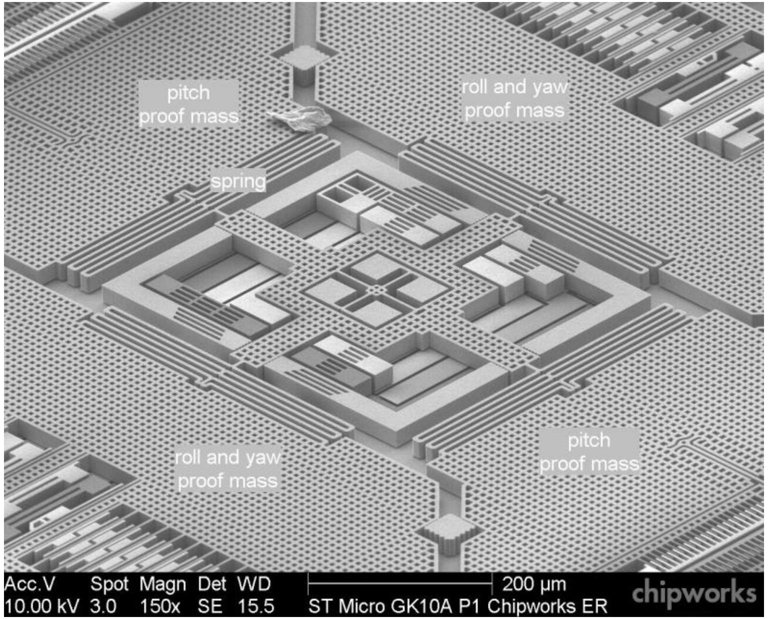


https://de.wikipedia.org/wiki/Kreiselinstrument#/media/Datei:Gyroscope_hg.jpg

Mechanical Gyroscopes – MEMS

Micromechanical vibratory gyroscopes

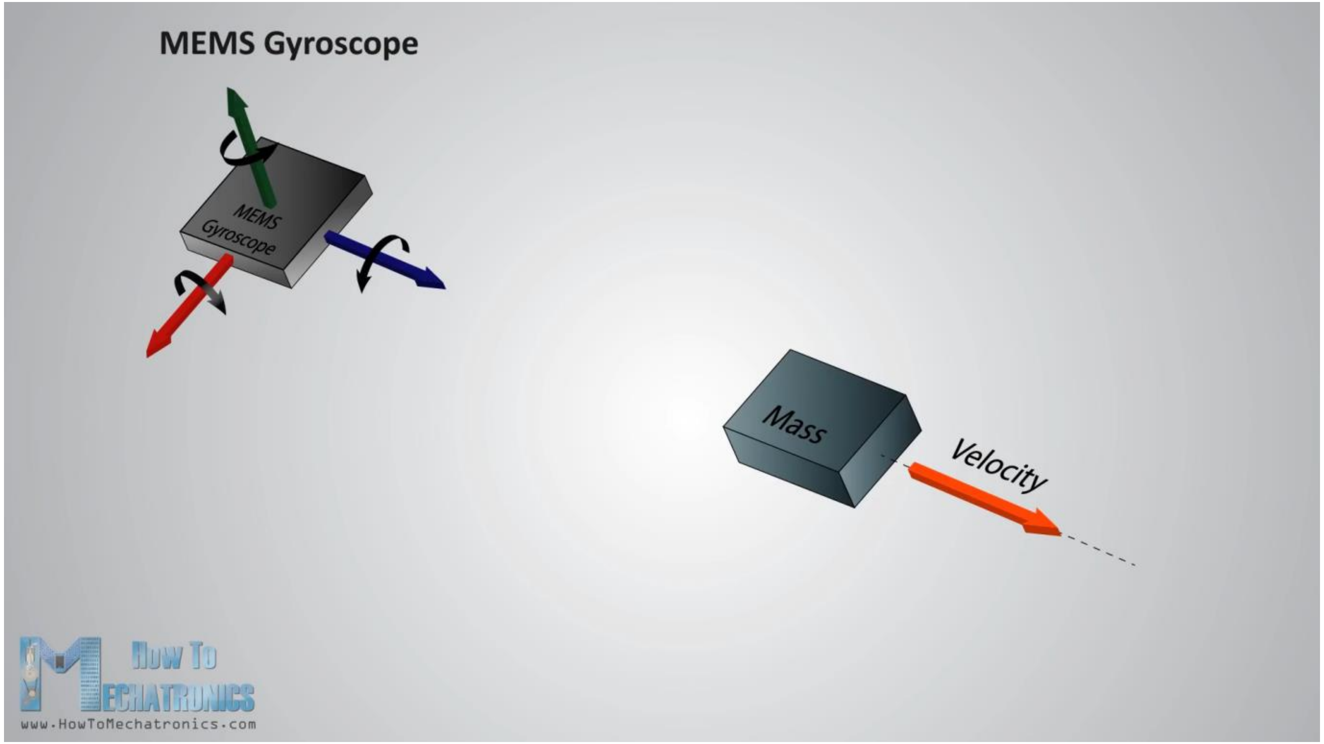
- A **high frequency vibration** is excited in an elastic micro-structure (**primary oscillation**)
  - Driven either electro-statically or with piezoelectric actuation
- When rotating, the Coriolis acceleration causes a **secondary oscillation**
- The amplitude of the secondary oscillation is measured and can be converted into the rate of rotation
  - Measurement usually capacitive



Micromechanical 3-axis rotational rate gyro

http://memsjournal.typepad.com/.a/6a00d834522 5f869e20148c7d54d63970c-pi

Micromechanical Vibratory Gyroscopes



https://www.youtube.com/watch?time_continue=11&v=eqZgxR6eRjo

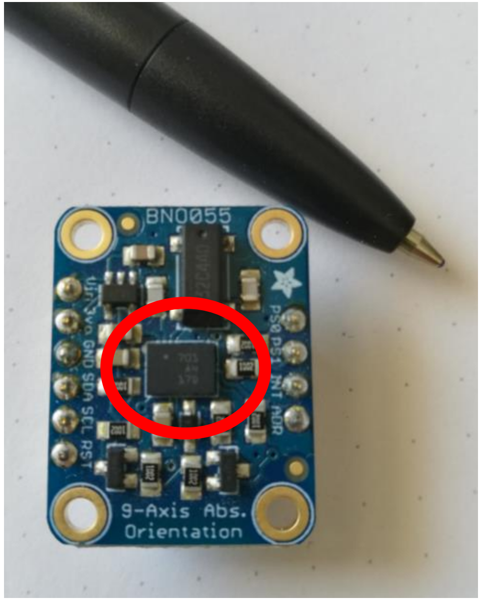
Micromechanical Vibratory Gyroscopes (MEMS)

Advantages

- Very small
- Extremely cheap due to mass production from silicon
- Maintenance free

Disadvantages

- Drift depends on temperature
- Not precise enough for inertial navigation



Modern orientation sensor with (among others) integrated 3-axis gyroscope and 3-axis accelerometer on a single IC

Optical Gyroscopes

- **Underlying principle:** Observation of the shift in interference lines of two laser beams when rotating
- „Sagnac-Interferometer“

- **Ring laser gyroscope (RLG)**
  - Laser beams from a common source go in different directions around a center, guided by mirrors

https://de.wikipedia.org/wiki/Laserkreisel#/media/Datei:Ring_laser_gyroscope_at_MAKS-2011_airshow.jpg

- **Fiber optic gyroscope (FOG)**
  - Laser beams from a common source go in different directions around a center within an optical fibre (with many windings)

https://www.hydro-international.com/content/article/how-does-inertial-navigation-work

Orientation from Gyroscopes

Most commonly the variable to be measured is the rotational rate, not the orientation

- To derive the orientation from a gyroscope, the measured values need to be **numerically integrated over time (dead reckoning)**
- Errors in the measurement are amplified by the integration
  - → **Orientation drift**
- **Due to the integration, the accuracy of the gyroscopic measurement is of very high importance for inertial navigation**

Approximate values of orientation drift using different sensors technologies:

	RLG	FOG	MEMS
Drift [°/h]	0,001 - 10	0,1 - 50	5 - 18000

Wendel, J.: Integrierte Navigationssysteme : Sensordatenfusion, GPS und Inertiale Navigation

Gyroscopes - Classification

MEMS

Advantages
- Small
- Cheap
- Easy to integrate

Disadvantages
- Poor accuracy
- High drift

Applications
- Smartphones, cameras, drones, **robotics**,…

FOG

Advantages
- Very precise
- Cheaper than RLG
- Robust

Disadvantages
- More expensive and bigger than MEMS

Applications
- **Robotics**, planes, submarines, rockets

RLG

Advantages
- Extremely precise
- Very little drift

Disadvantages
- Expensive and big
- High technical complexity

Applications
- Military (missiles, submarines, …)

Summary – Force, Torque and Inertial Measurements

- Force Sensors
  - 1D and 3D Force Sensors or 6D Force/Torque Sensors
  - Conversion of physical deformation to digital signal is required (Analogue-to-Digital Converter)
    - Capacitively (MEMS)
    - Resistively (Strain Gauges)
- Torque Sensors
  - Measurement of torsional deformation via strain gauges (analogue) or absolute angular displacement (digital)
- Inertial Sensors
  - Accelerometers measure **acceleration** in space
  - Gyroscopes measure **rotational velocity** in space

Inertial Measurement Units

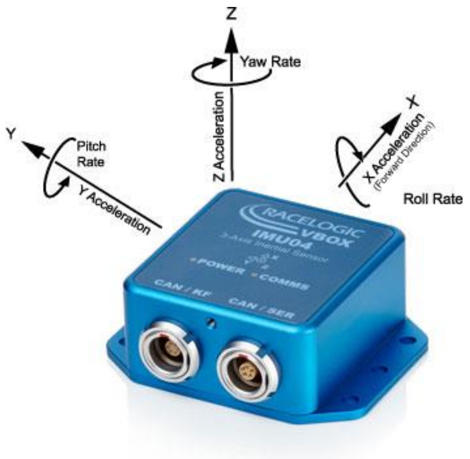
Inertial Measurement Units (IMU)

The **combination of gyroscopes and accelerometers** is called *Inertial Measurement Unit, IMU*

- Usually both sensor modalities cover **all three spatial axis**, making the IMU a **6D sensor**
- Most common application: 3D orientation measurement

MEMS-based IMUs are mass-produced and an be found in many places in our daily lives

- Smartphones
- Drones
- Game-controller
- Human motion capture
- Robotics (gaze stabilization, balancing)
- ….



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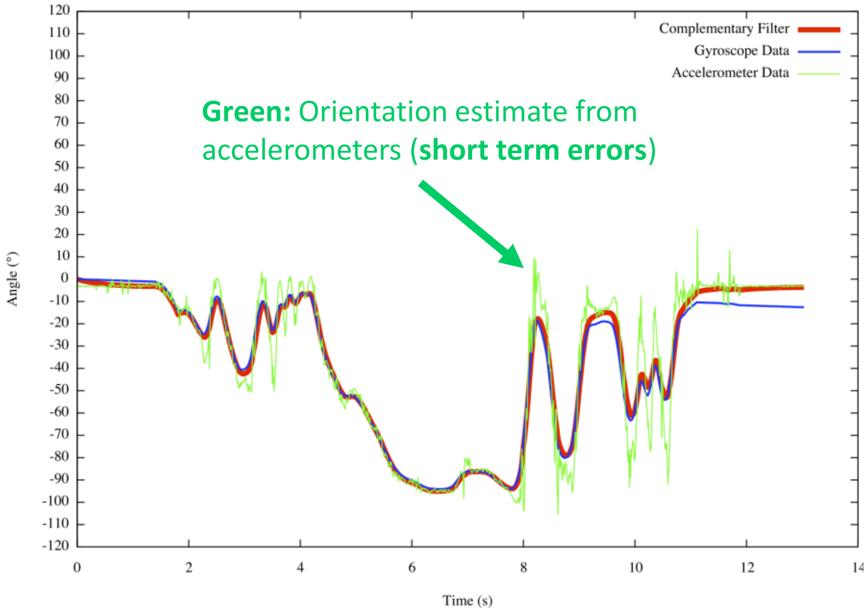
Orientation Sensing with Accelerometers

In IMUs, the two axes of orientation relative to the horizon (roll, pitch) can be derived from accelerometers

From accelerometers

- The direction of the gravity vector is measured and gives an estimate of the **absolute** orientation (in the absence of motion-induced accelerations)
- **Advantage**: Two axes of orientation are directly obtained, no drift
- **Disadvantage**: Accelerations that are not due to gravity cause (short term) errors in the measurement



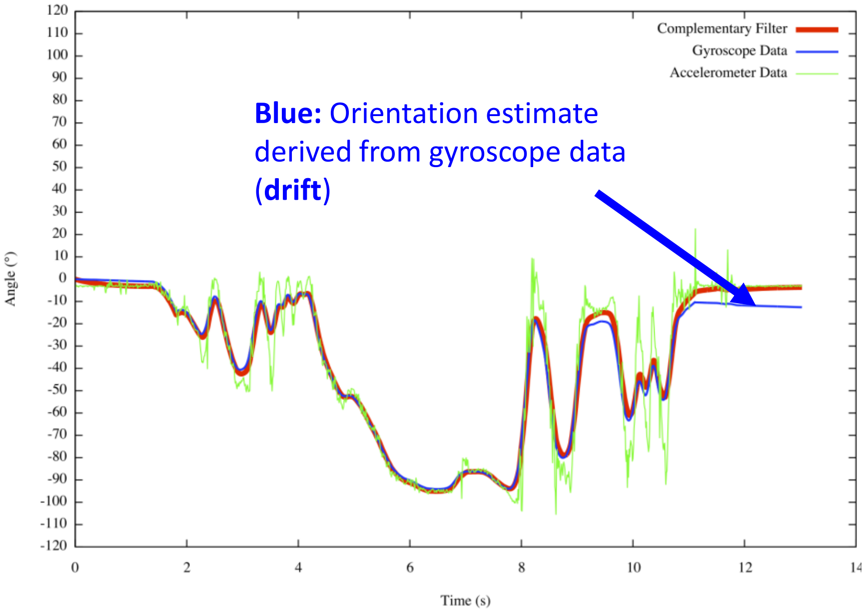
http://www.pieter-jan.com/images/Complementary_Filter.png

Orientation Sensing with Gyroscopes

In IMUs, the measurement of the two axes of orientation relative to the horizon (roll, pitch) can be enhanced using gyroscopes

From gyroscopes

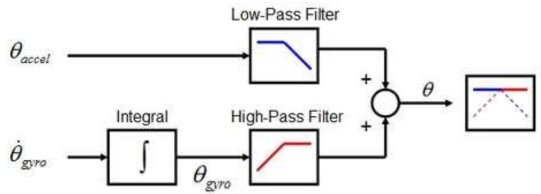
- The rotational velocities/rates are integrated numerically and provide an estimate of the orientation **relative** to the initial orientation
- **Advantage**: Measurement is not affected by linear accelerations (motions) and does not show short-term spikes
- **Disadvantage**: Only **relative** orientation w.r.t. initial orientation; drift caused by the numerical integration cannot be avoided



http://www.pieter-jan.com/images/Complementary_Filter.png

Sensor Fusion in IMUs

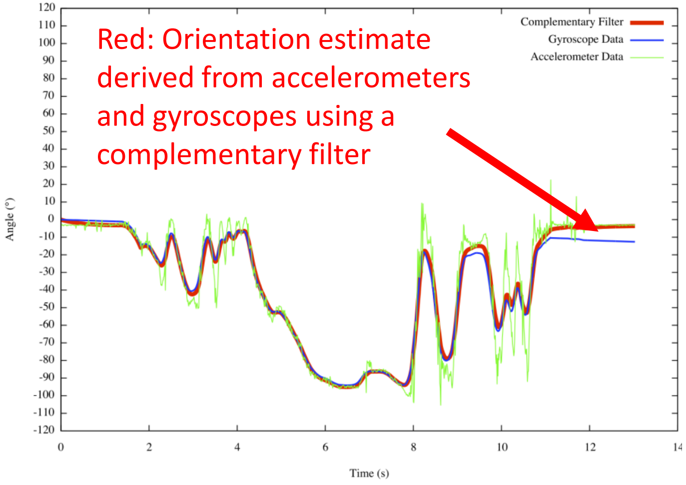
- To combine the advantages of both sensor types, the sensor modalities need to be fused
- Different **filter algorithms** are available
- Common methods:
  - Kalman filter
  - Complementary filter (simpler)



https://i.stack.imgur.com/GTkB0.jpg

Example (complementary filter)

- The plot shows the fusion of the angle estimates derived from both sensor modalities
- The filtered estimate does not have spikes (thanks to the gyroscope) and does not drift (thanks to the acceleration sensors)



http://www.pieter-jan.com/images/Complementary_Filter.png

AHRS and INS

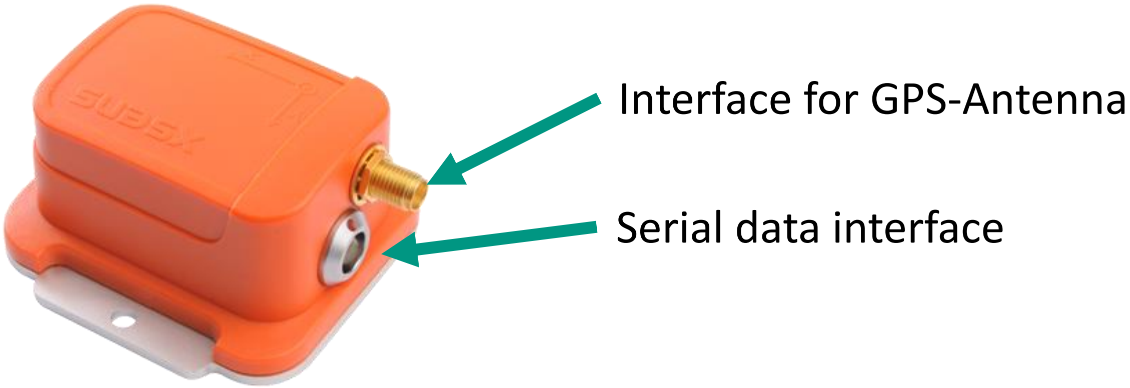
Attitude Heading Reference System (AHRS) - I

AHRS are an extension of IMUs with more sensor modalities and integrated signal processing for advanced orientation sensing

- **Problem when only using inertial sensors:**
  - Orientation about the horizontal axes (*Attitude*: Roll, Pitch) can be determined very well, **but**
  - Drift about the vertical axis (*Heading*) can not be compensated for as gravity does not provide any information there
- **Solution**
  - Addition of more sensor modalities
  - Most commonly a 3-axis magnetometer
  - Provides a **drift-free reference (magnetic north) for the rotation around the vertical axis (yaw)**
- **Result**
  - A **9 DOF sensor** for the drift-free orientation measurement around all three spatial axes

Attitude Heading Reference System (AHRS) - II

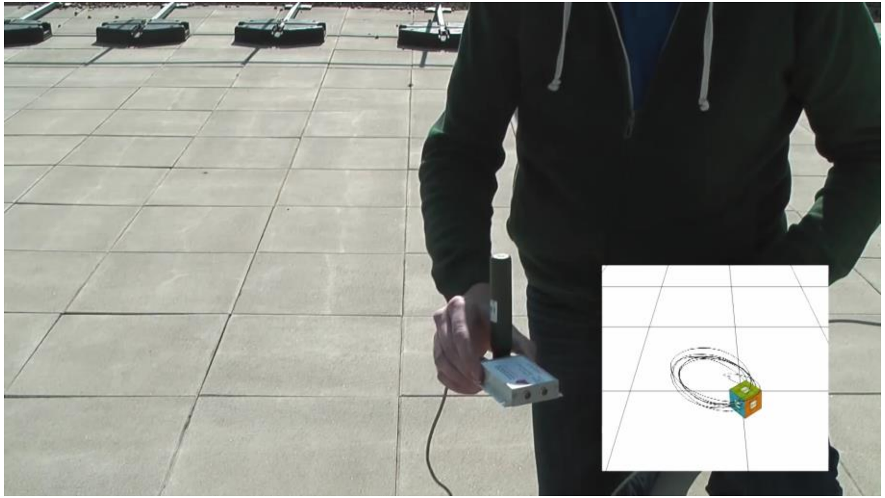
- AHRS integrate the signal processing and provide the **computed orientation** as well as the sensor‘s raw readings
- Other than magnetometers, other sensor modalities can also improve the orientation estimate, above all **GPS** and **barometric pressure sensors**



MEMS-AHRS with integrated GPS-receiver and barometric pressure sensor

Inertial Navigation Systems (INS)

- *Inertial Navigation System (INS*) provide the orientation and also the global position and velocity with high accuracy
- Consists of an AHRS and possible additional sensor modalities
- Application in (autonomous) airplanes, submarines, land vehicles, missiles, …



https://www.youtube.com/watch?v=ymuhJ6pt52o