B0-Introduction to measurement

Outline

Non idealities in measurement of sensors

Proprioceptive sensors

Exteroceptive sensors

Some basics on signal processing

Sensors for robotics

- The term sensors defines the set of all the possible (usually) electro–mechanical systems that convert physical phenomena to measurable signals, (typically voltages or currents).

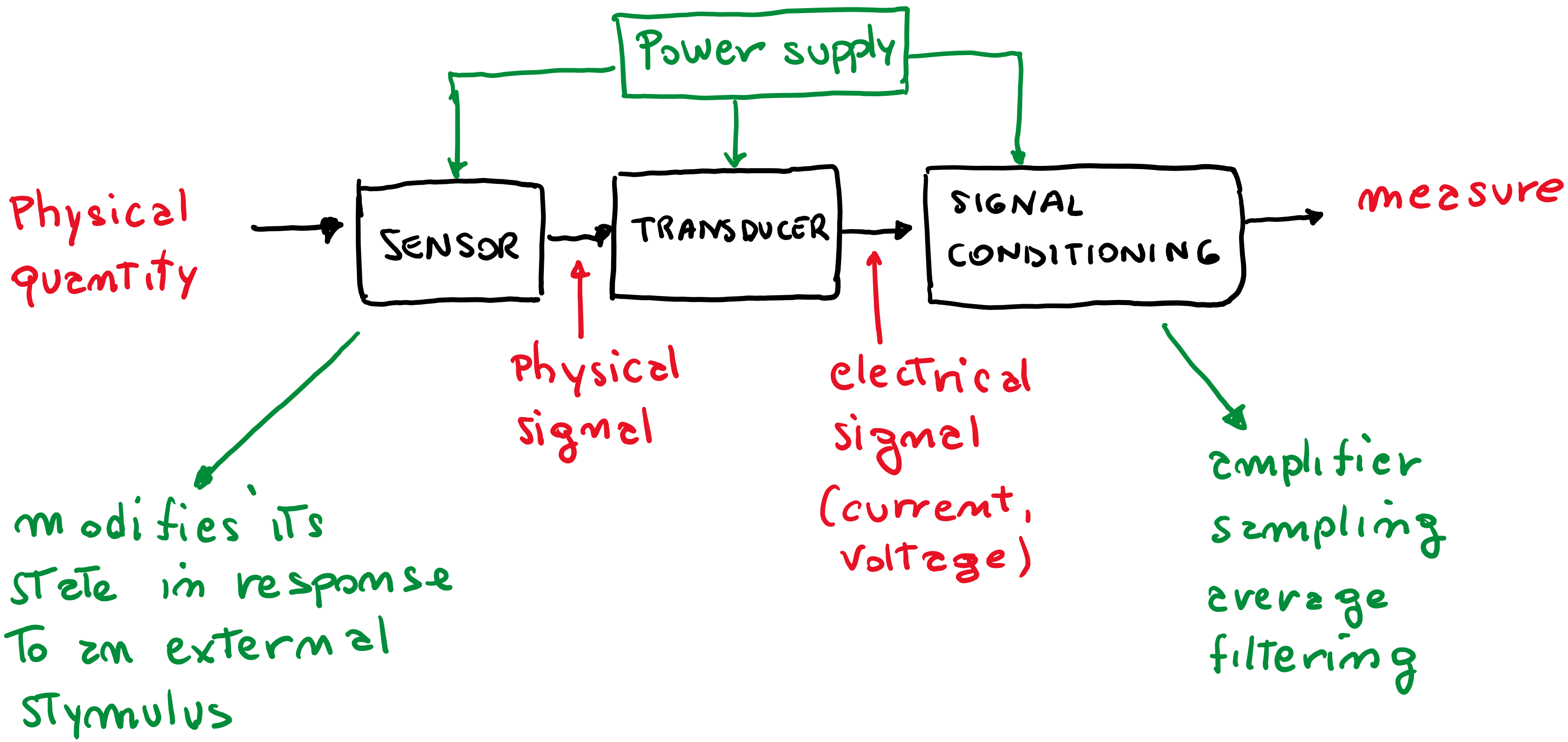
- Sensors are sensitive to different physical quantities and convert them in electrical, mechanical signals. The basic physical phenomena typically measured with sensors include:
    - angular or linear position;
    - acceleration;
    - temperature;
    - pressure or flow rates;
    - stress, strain or force;
    - light intensity;
    - sound.

- The transducer associated to the sensor, transforms them into electrical signals useful to elaborate the information conveyed

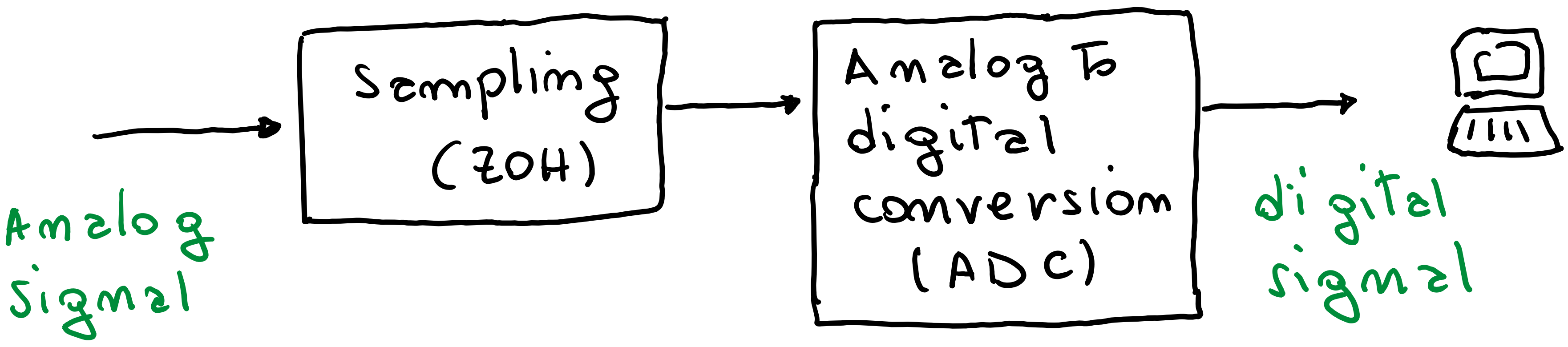
- For us a sensors incorporates the **transducer**

- The measurement often requires signal conditioning (e.g. amplifier).

Measurement Chain

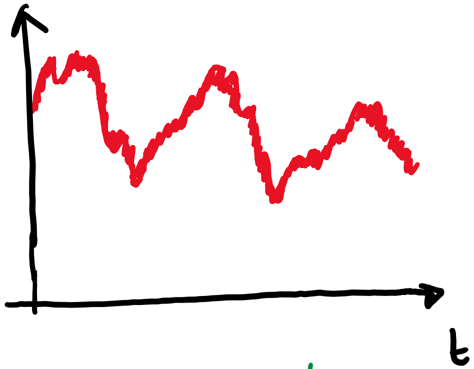


Signal conditioning

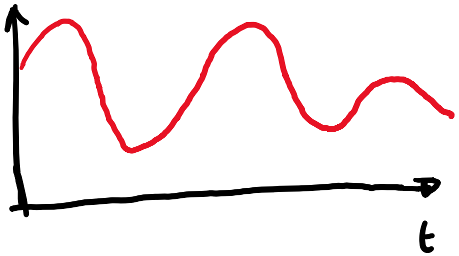


Sensor critical observations

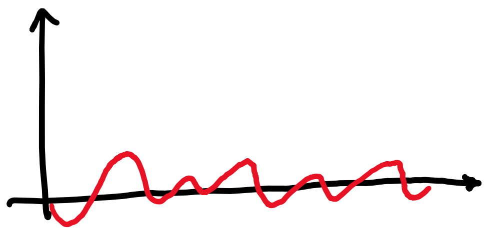
- Real sensors convert an input phenomena to an output of a different type
- This transformation relies upon a manufactured device, with limitations and imperfection. Therefore real sensors are noisy and difficult to be modeled



measured variable



signal: That contains useful informations for control (eg. motion of a joint)



disturbance: might contain info useful for diagnostics (e.g. cogging torque in motor)

noise: does not contain useful informations (electromagnetic noise/ digitalization)

Signal to noise ratio: level of a desired [signal](#) to the level of background [noise](#).

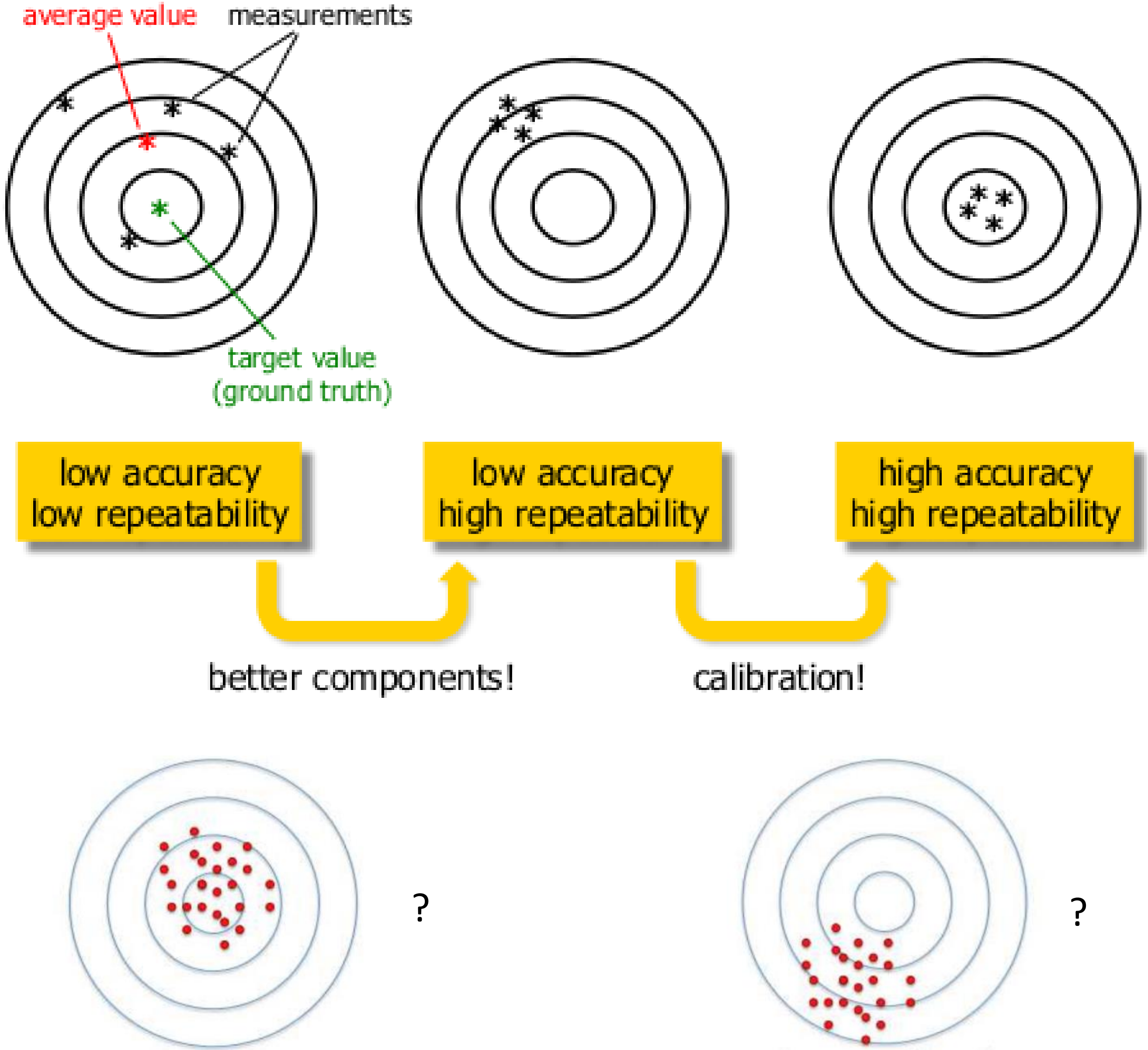
Properties of a measurement system

A measurement system is mainly characterized by some parameters, directly derived from metrology:

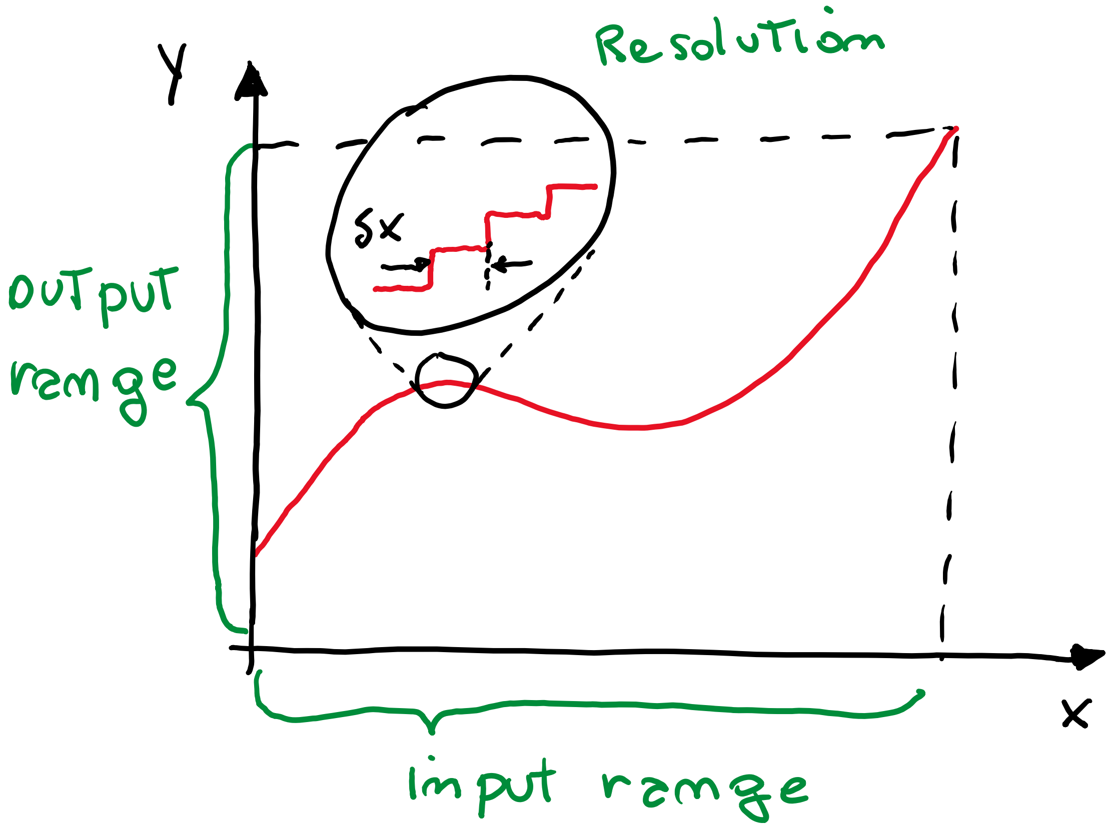
- Uncertainty: estimate of our level of “not knowledge” of the measurand i.e., the quantity to be measured. Measure ± uncertainty
- Accuracy: how close the measurement is to the ground truth. A measurement is said to be more accurate when it offers a smaller measurement error. It can be improved by calibration that is usually performed when they are manufactured or installed. Usually related to the sensor.
- Repeatability: capability of the sensor to reproduce similar measured values over consecutive measurements of the same constant input quantity. Repeatability is usually expressed numerically by standard deviation and variance (Statistical distribution of measurements). Depends on the components of the measurement chain.
- Stability: capability of keeping the same measuring characteristics over time/temperature (similar to accuracy but in the long run)

Note: In a robotic manipulator the accuracy/repeatability can be different in different points of the **workspace**

Accuracy VS repeatability



Sensor characteristics (datasheet)



x = real quantity

y = measured quantity

Range: the range of the measurable inputs and the range of the associated outputs.

Sensitivity: the ratio between the variation of the sensor output and the correspondent variation of the measurand.

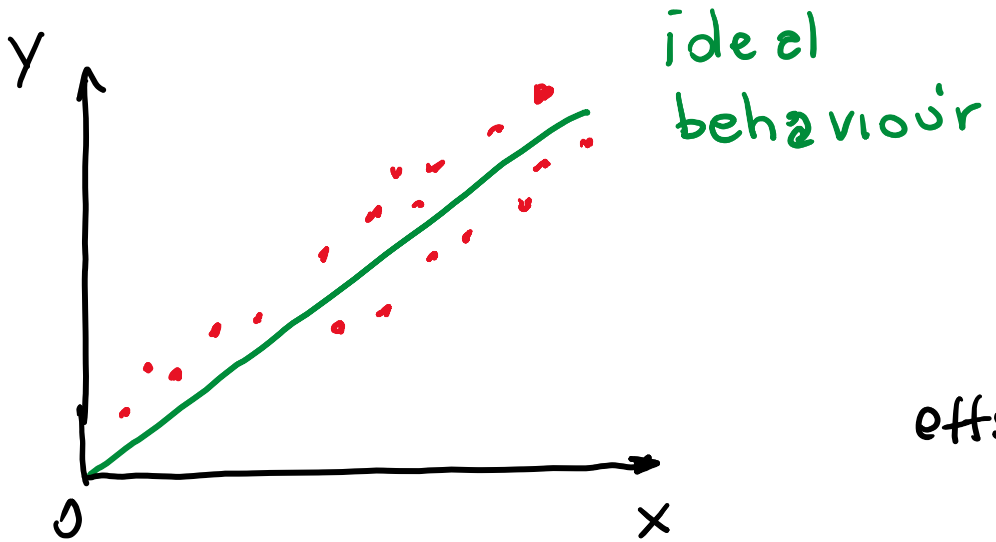
Resolution: the smallest increment that the sensor can detect (due to quantization).

Dynamic Response: the frequency range for nominal operation of the sensor (e.g., loadcells or microphones). Typically, there is an upper operation frequency, while a lower frequency is occasional.

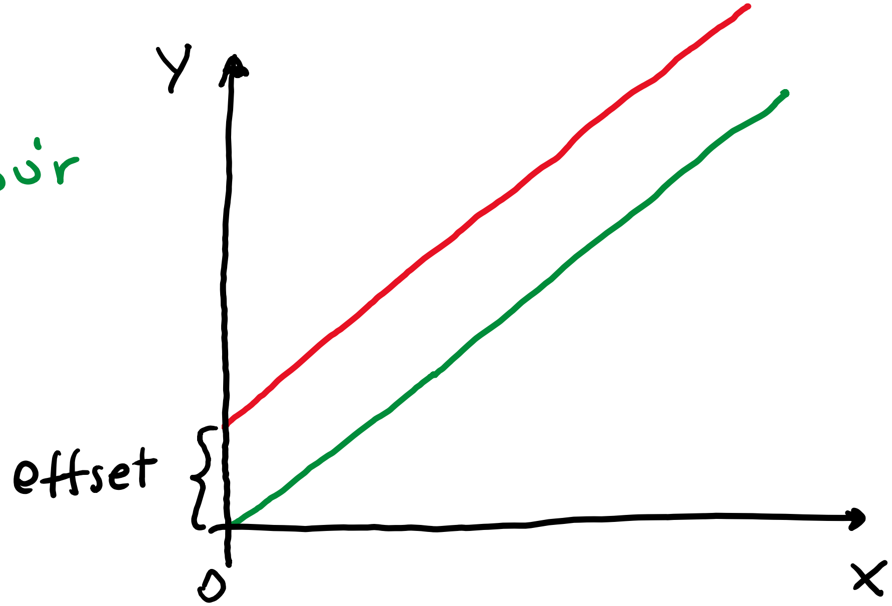
Types of measurement errors

- **Random errors:** are (like the name suggests) completely random. They are **unpredictable** and **can't be replicated** by repeating the experiment again. They can be reduced increasing the number of measurements.

- **Systematic errors:** produce consistent errors, if you repeat the experiment, you'll get the same error. Can be compensated /corrected.

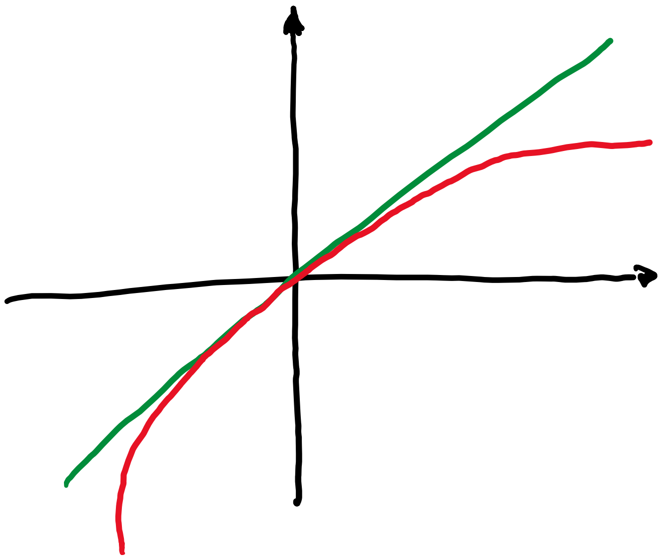


Random error

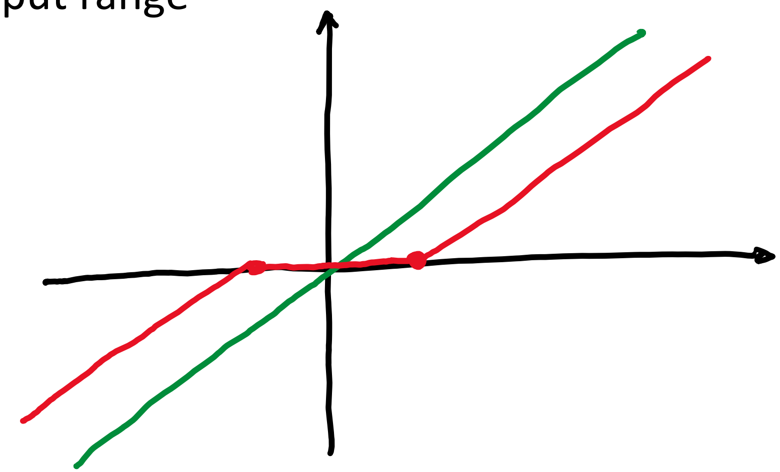


Offset/bias: offset error
value of the measured output for zero input (example of systematic error)

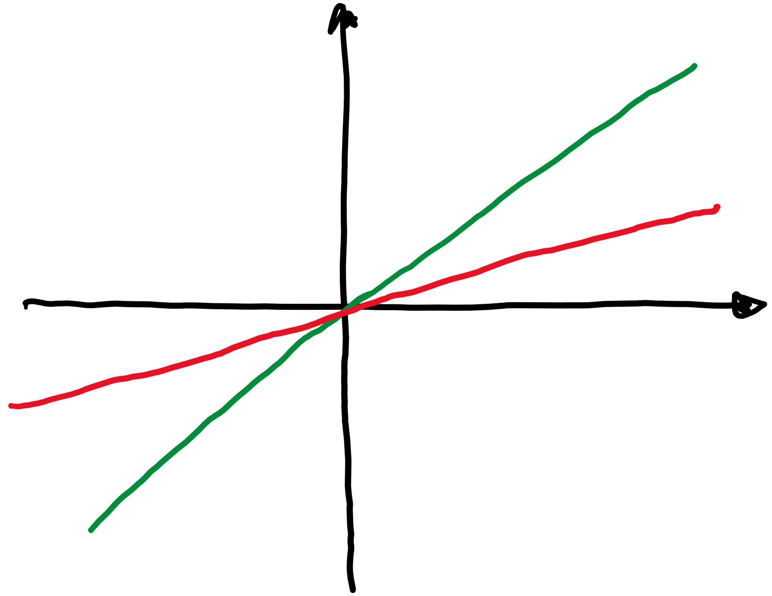
Examples of systematic errors



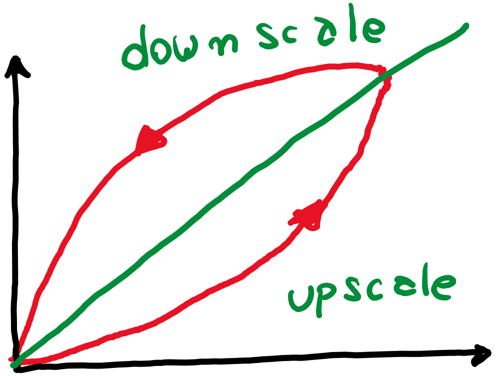
linearity error: maximum deviation of the measured output from the straight line that best fits the real characteristics, defined as % of the output range



Dead zone



Scaling factor



Hysteresis error

B1-Sensors in robotics

proprioceptive sensors

Classes of sensors for robots

Proprioceptive sensors: measure the internal state of the robot (position and velocity of joints, acceleration of links/base):

- encoders, accelerometers, gyroscopes.

- Usage: motion control, kinematic calibration, identification of dynamic parameters

Exteroceptive sensors: measure external quantities that represent the robot interaction with the environment:

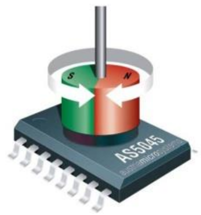
- load-cells, torque sensor at robot joints (strain gages), 6D F/T sensors, contact sensors, proximity, vision, sound, smoke, distance sensors.

- Usage: control of interaction with the environment, obstacle avoidance in the workspace, presence of objects to be grasped, localization in a map

Example of usage of sensors in robotics

- **proprioceptive**:
  - Joint positions (encoders)

  - Base orientation, velocity, acceleration (IMU)



- **exteroceptive**:
  - Joint torques: loadcells (left), torque sensors (right)

  - Infrared cameras

  - Stereo cameras

  - Laser cameras (Lidar)

Position sensors

Provide an electrical signal proportional to the displacement (linear or angular) of a mechanical part with respect to a reference position:

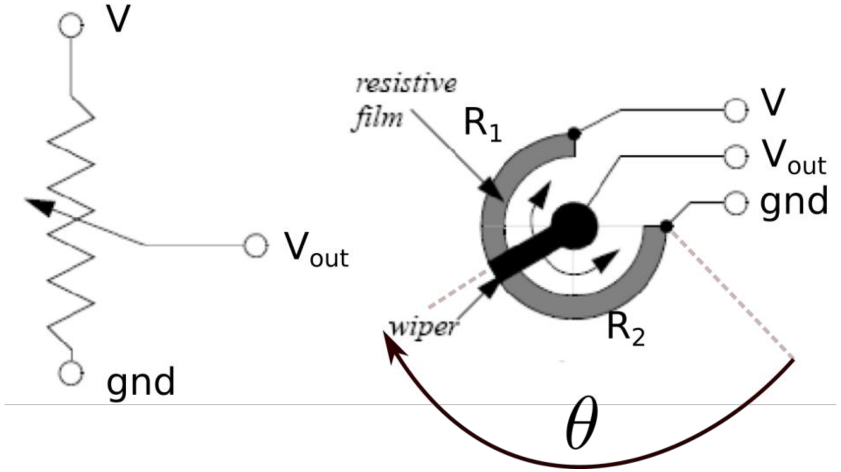
- linear displacements: potentiometers, linear variable-differential transformers (LVDT)

- angular displacements: **optical encoders** (digital), Hall sensors, potentiometers

The sensors for angular displacement are the most used in robotics, since also linear displacements are obtained through rotating motors and suitable transmissions

Potentiometer

- The potentiometer is a resistor, normally made with a thin film of resistive material. A brush can be moved along the surface of the resistive film.
- Potentiometers measure the angular (or linear) position of a shaft using exploiting the variable resistance between the brush and one of the terminals.
- As the brush moves toward one end there will be a change in resistance proportional to the travelled distance



$$V_{out} = V\frac{R_2}{R_1 + R_2}$$

R_1: resistance between brush and supply

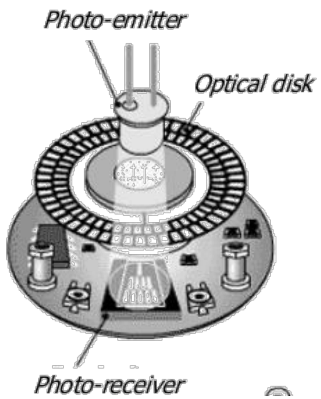
R_2: resistance between brush/2 terminal

$$V_{out} = V\frac{\theta}{\theta_{max}}$$

- Potentiometers are popular because they are inexpensive, and do not require special signal conditioners.
- Potentiometers have limited accuracy, normally in the range of 1% and they are subject to mechanical wear.

Encoders

- Optical encoders use rotating disks with optical windows.



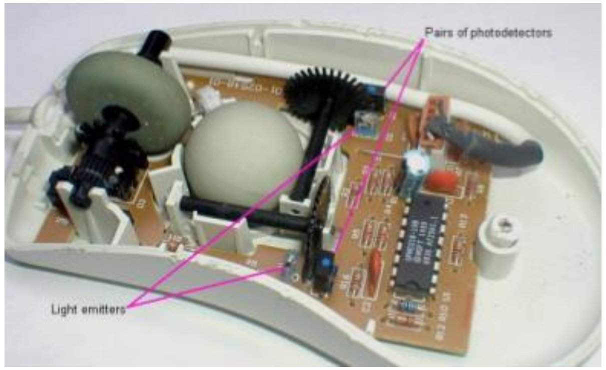
- The light from emitters passes through the openings in the disk to detectors.

- As the encoder shaft is rotated, the light beams are broken.

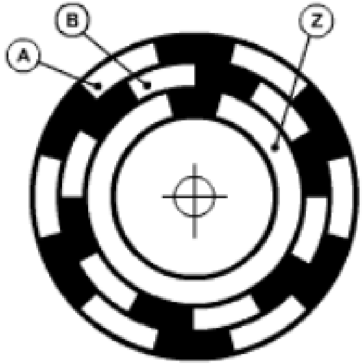
- They have digital output

- There are two fundamental types of encoders: **absolute** and **incremental (relative)**

Incremental (relative) encoders



- It consist of:
  - an optical rotating disk with **two** tracks, alternating transparent and opaque areas (windows).
  - (infrared) light is emitted by LEDs and sensed by photo-receivers



- Typical encoders will have from 2 to thousands of windows per ring (e.g. 80000).

- These windows will create light "pulses" during the motion that will be converted into electrical pulses.

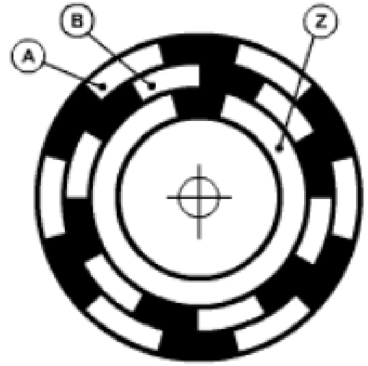
- **incremental** angular displacements are measured by counting the trains of pulses. There are at most N_c "counts" per revolution

- Resolution = 360deg / N_c

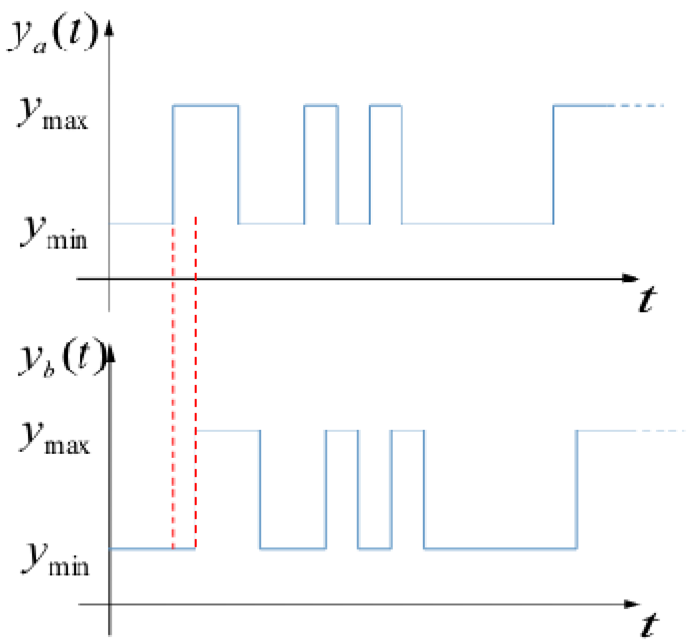
- To improve the resolution of the relative encoder we only need to add more windows to the existing ring (i.e. increase N_c)

Principle of functioning

- The output signals of the incremental encoder, therefore, are square waves.
- the two A and B tracks (channels) have a relative phase of 90° (i.e. they are in quadrature) allowing to detect the **direction of rotation**.

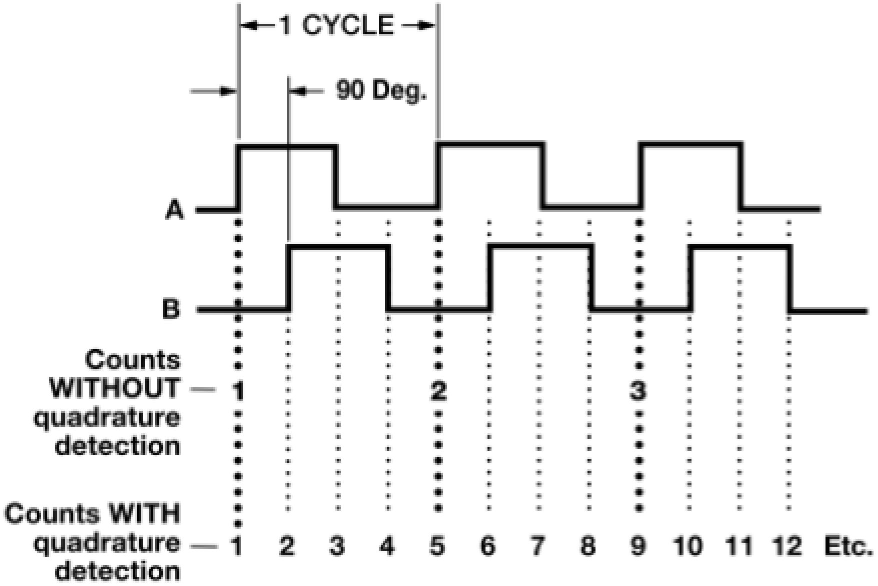


- If A leads B, the motor is rotating clockwise. If B leads A, counter-clockwise.

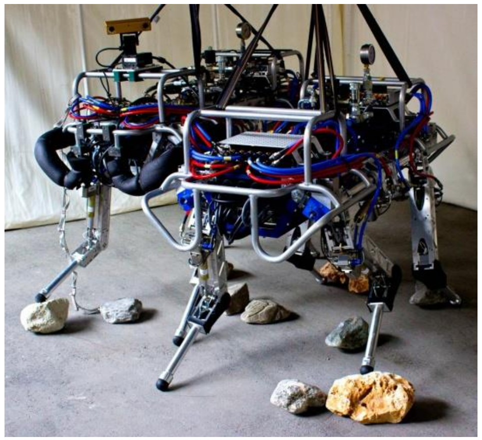


- If the encoder only rotates in one direction then a simple count of pulses from one ring will determine the total distance.
- Increasing the velocity of the shaft, the signals period is decreased.
- Readings will always start from zero
- Relative encoders require a calibration phase when turned on. This usually requires motion of an axis until it reaches an extreme position marking the end of the range (e.g., **homing** position for manipulators)

Example of quadrature detection



- to improve the resolution (4×), both the leading and trailing edges of signals A and B are used to generate pulses
- This way an incremental encoder with N_c = 20000 (electrical) cycles provides a count of N_c = 80000 pulses/turn after electronic multiplication

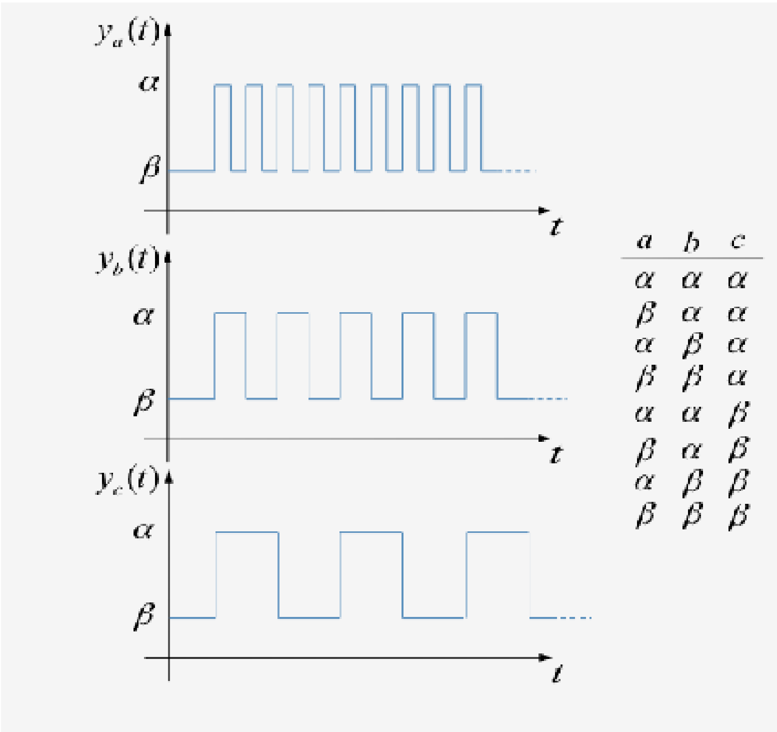


- its final resolution is (mechanical) 360°/80000 = 0.0045°
- AWAGO encoder mounted on HyQ

Absolute encoders

An absolute encoder **directly** measures the angle of the shaft. The same shaft angle always produces the **same** sensor reading.

- The output is normally a number coded in **binary** or **Gray** code (less reading errors)
- The absolute encoder has N rings, the outer ring is the most significant digit, the inner ring is the least significant digit of the code. More rings (and more emitters/detectors) implies more bits and therefore higher resolution

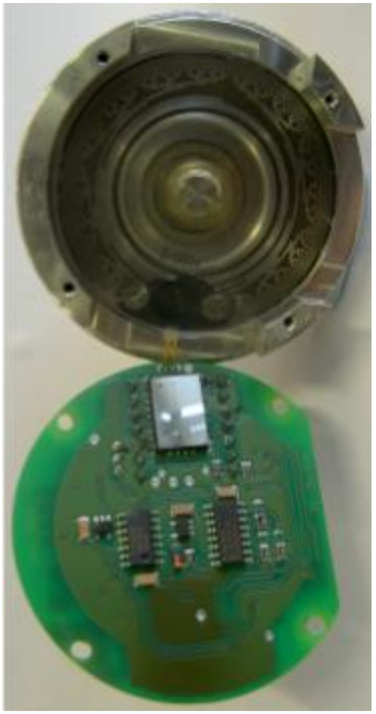


Example 3bit absolute encoder

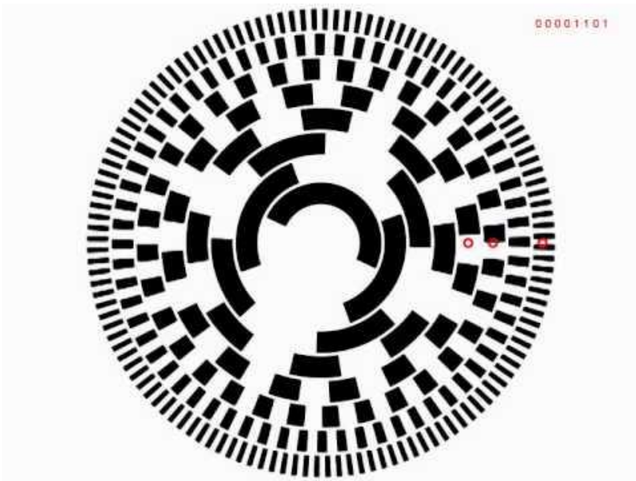
Decimal	Binary	Gray
0	000	000
1	001	001
2	010	011
3	011	010
4	100	110
5	101	111
6	110	101
7	111	100

- As for relative encoders, logic circuits and/or software are used to get the digital output (counts)

13-bit absolute encoder opened:



Absolute encoder wheel with a Gray code.



Big advantage of absolute encoders: ready to measure at start (no “homing”)

Quantization Error in Encoders

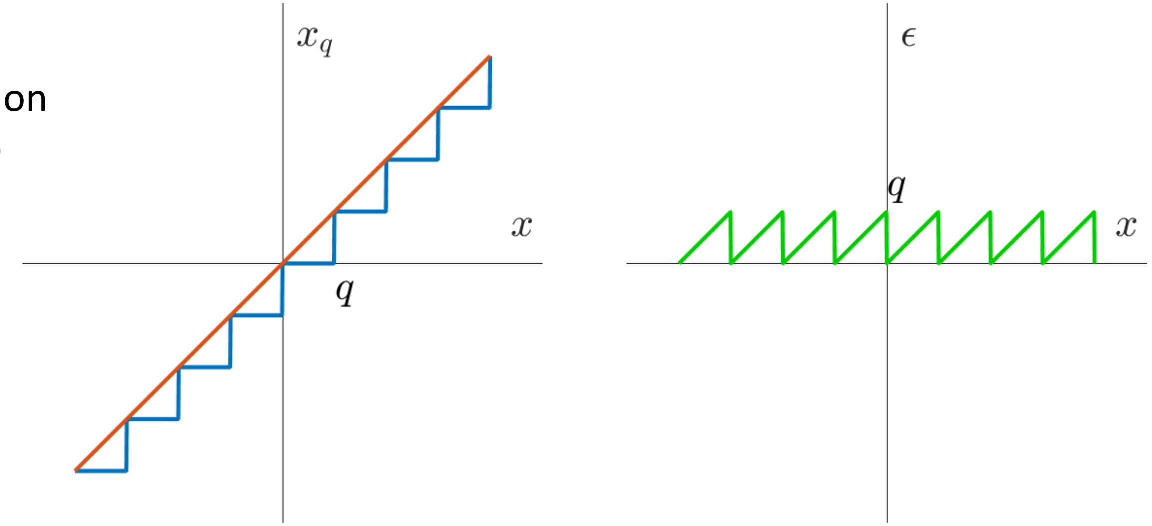
true value of the measured variable

error of representation (random variable)

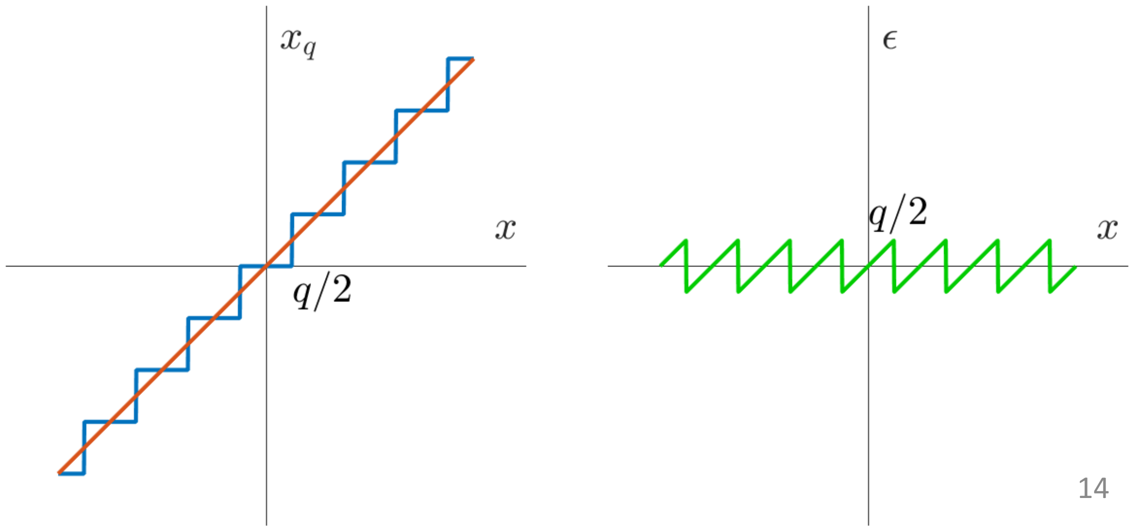
$$x = x_q + \epsilon$$

quantized measure

Truncation



Rounding



Having n bits, the quantization level(resolution) of an encoder is

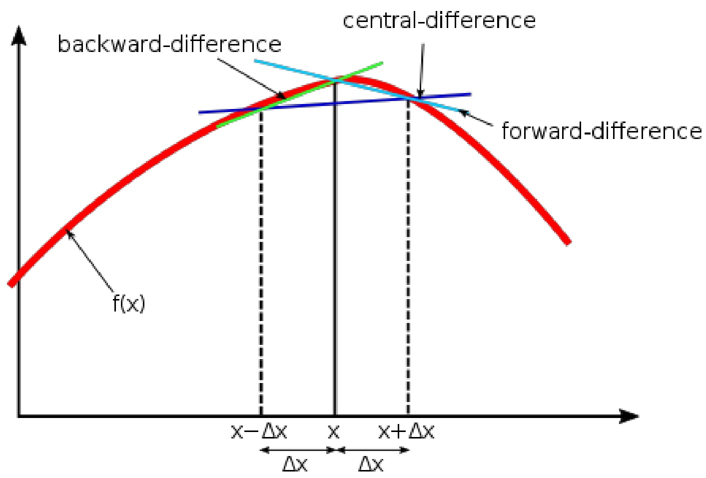
$$q = \frac{2\pi}{2^N}$$

Indirect measure of velocity – quantization noise

The rotation velocity can be determined by:

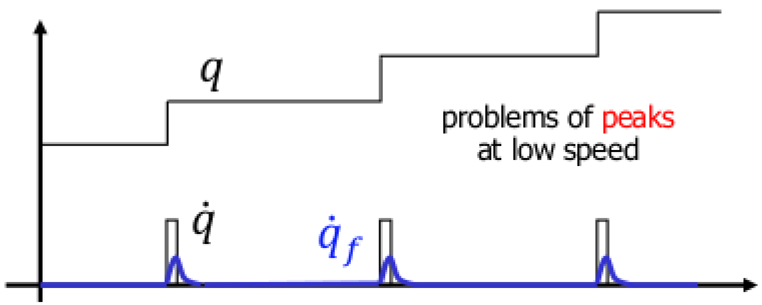
- measuring the time between pulses (not practical at high speed).
- numerical differentiation of digital measures of position
  - to be realized on line with Backward Differentiation Formulas (BDFs)

$$\boxed{\dot{q}_k = \frac{1}{T_s}\left(q_k - q_{k-1}\right)}$$



↑ directly from encoder measurements

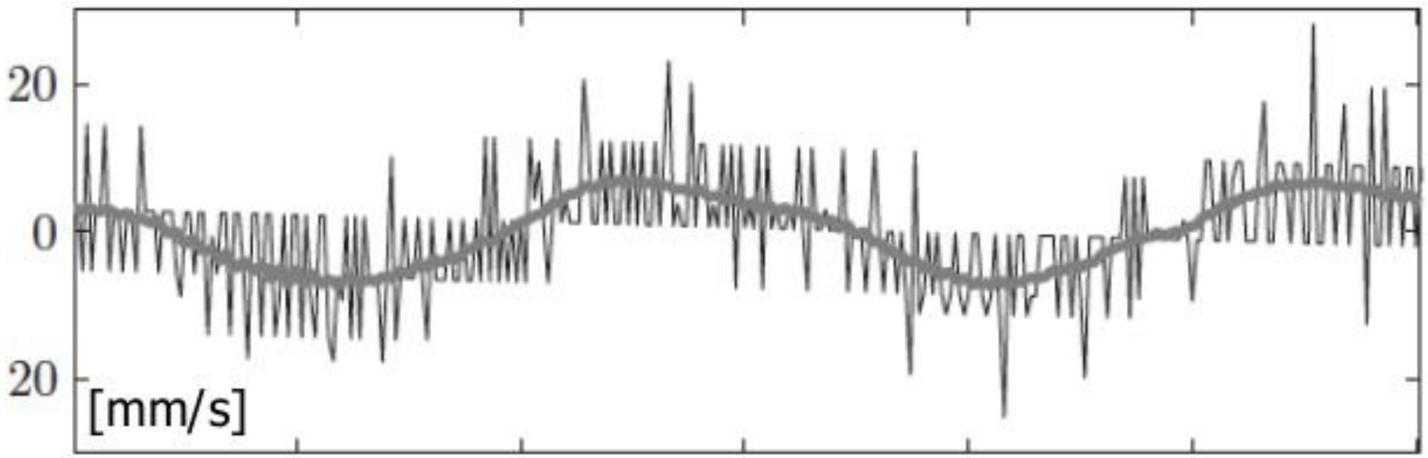
⊖ Numerical differentiation causes quantization noise at low speeds (i.e. spikes)



Quantization noise

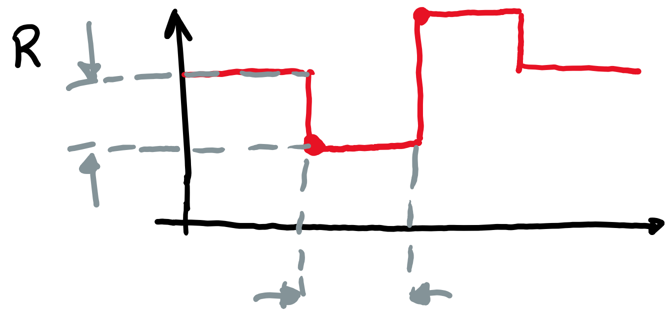
Filtering techniques can be used to mitigate quantization noise, but they introduce **delays**

numerical velocity and its filtered estimate



Minimum measurable speed

⊖ There is a minimum bound on the speed that can be measured depending on the sampling frequency



- assume 12 bit encoder and
  $T_s = 0{,}001$ s

  $R = \frac{360°}{2^{12}} = 0{,}087°$ Resolution

- minimum speed : 1 change in 1 sampling interval

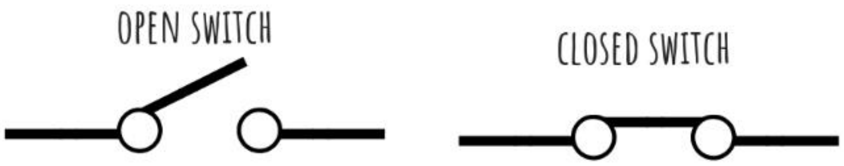
$\frac{0{,}087}{0{,}001} = 87°/s$ ⇒ minimum measurable speed !

⇒ increase resolution (# bits)

⇒ reduce sampling frequency ⊖

Contact switch

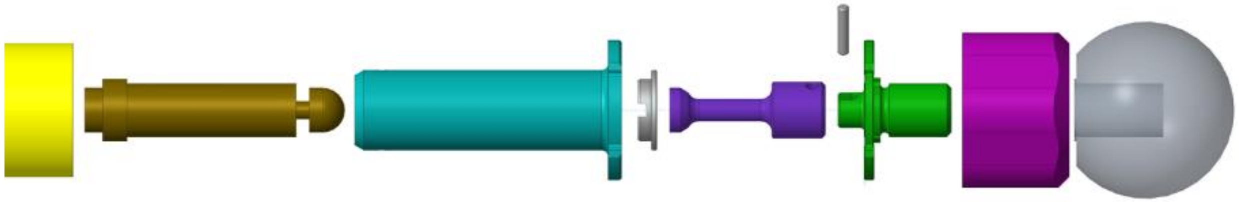
- A switch is an electrical component that can break an electrical circuit, interrupting the current or diverting it from one conductor to another.



- A contact switch allows electricity to flow between its two contacts when held in. When the button is released, the circuit is broken (non--latching switch)

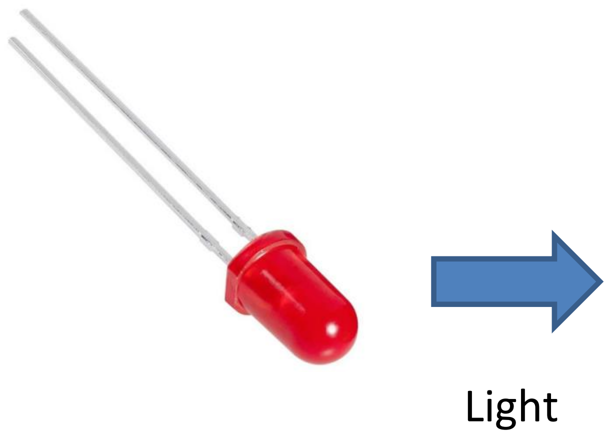
- The information coming from the switch is then binary: ON/OFF.

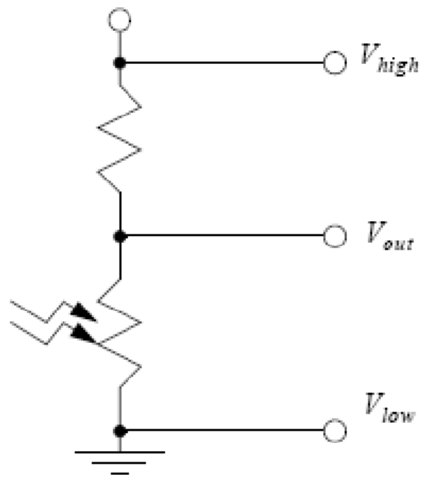
Exploded view of the HyQ contact sensor

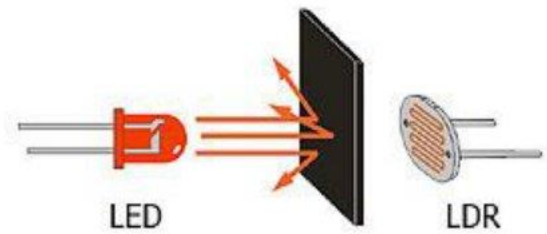


Light dependent resistors (LDR)

- Its resistance varies according to change in the intensity of light.
- changes from high resistance (>Mohms) in bright light to low resistance (<Kohms) in the dark. The change in resistance is non-linear, and is also relatively slow (ms).
- They are also known as photo-resistors
- They can work in synergy with a photo-emitter (e.g. LED)
- Can be read through a simple voltage divider







Inertial sensors

- The typical quantity measured by the inertial sensors are the first or second derivatives of the position or orientation of the mechanical body they are attached to.
- Examples of inertial sensors are: accelerometers, gyroscopes, magnetic compasses, inclinometers
- An IMU (inertial measurement unit) embeds in a single package:
    - Accelerometer: linear /angular acceleration
    - Gyroscope: angular velocity
    - Magnetometer: heading w.r.t the north pole
    - Inclinometer: detects orientation with respect to gravity vector (roll/pitch)

Industrial grade (2-3 k €) **Tactical grade (20-30k€)** **Navigation grade (?)**

Microstrain GX3

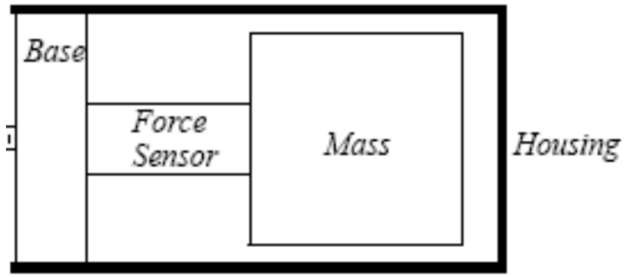
KVH 1750

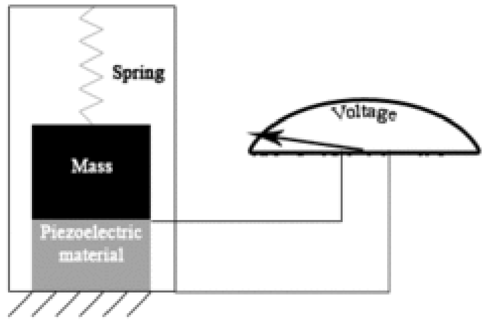
Cost

Accelerometers

- measure of linear acceleration based on inertial forces (no "touch"). units: [m/s2] or gravitational acceleration [g] (non-SI unit: 1g ≈ 9.81 m/s2)

- measure acceleration using a mass suspended on a force sensor (often a small piece of piezoelectric material mimicking a spring)





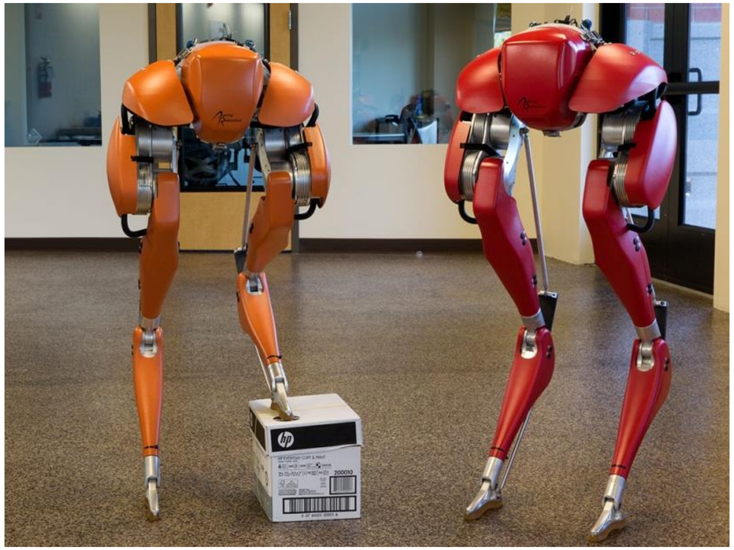
$$F = ma \text{ and } F = kx \Rightarrow a = \frac{kx}{m}$$

- There are different principles for converting mechanical motion in an electrical signal:
  - crystals (quartz), better linearity & stability, wide dynamic range up to high frequencies, no moving parts, no power needed
  - Piezo-resistive: for high-shocks, measures also static acceleration (g), needs supply
  - modern solution: small MEMS (Micro Electro-Mechanical Systems) provide integrated circuit accelerometers at a very low cost. One common use is for airbag deployment systems in cars.

Accelerometers

- An accelerometer measures the acceleration along an axis. By combining three accelerometers with orthogonal axes, we have a three dimensional accelerometer.

- multiple applications: from vibration analysis to long range navigation



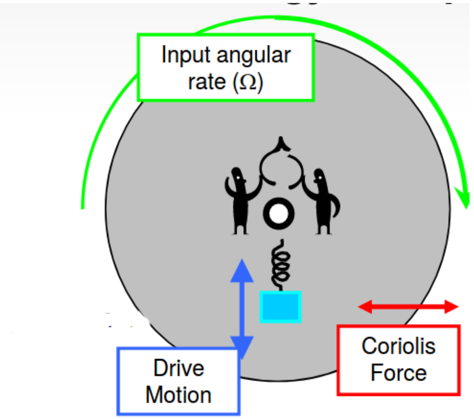
Can be used for collision detection in some parts of the manipulator

Are essential in the locomotion of legged robots

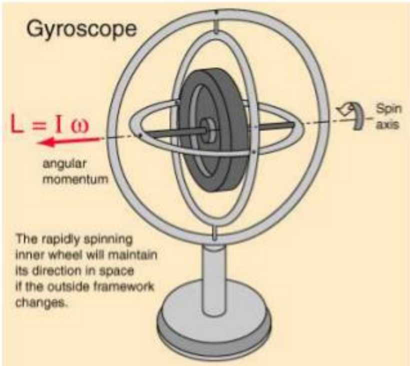
3-axial MEMS accelerometer on the forearm of a KUKA KR15/2 [DLR/Sapienza, 2007]

Gyroscopes

- Sense the **angular velocity** of a body
- In a similar way to the accelerometer, a gyroscope relies on measuring the **Coriolis** force that is generated when a mass is **moving** and **rotating** inside the cage of the sensor.
- the **Coriolis force** is a **fictitious force** that acts on **objects** that are in **motion** within a **frame** of reference that rotates with respect to an inertial **frame**
- The Coriolis force scales with the angular velocity of the frame.
- Angular velocity drive motion (V_d) and Coriolis force (F_c) are always located on there axes orthogonal to each other



$$F_c = 2m\omega V_d$$



- In the past they were build with spinning masses (Gimbal). Nowadays, gyroscopes are built using MEMS or optical laser–based solutions rather than mechanical system.

www.youtube.com/watch?v=ty9QSiVC2g0 www.youtube.com/watch?v=ti4HEgd4Fgo

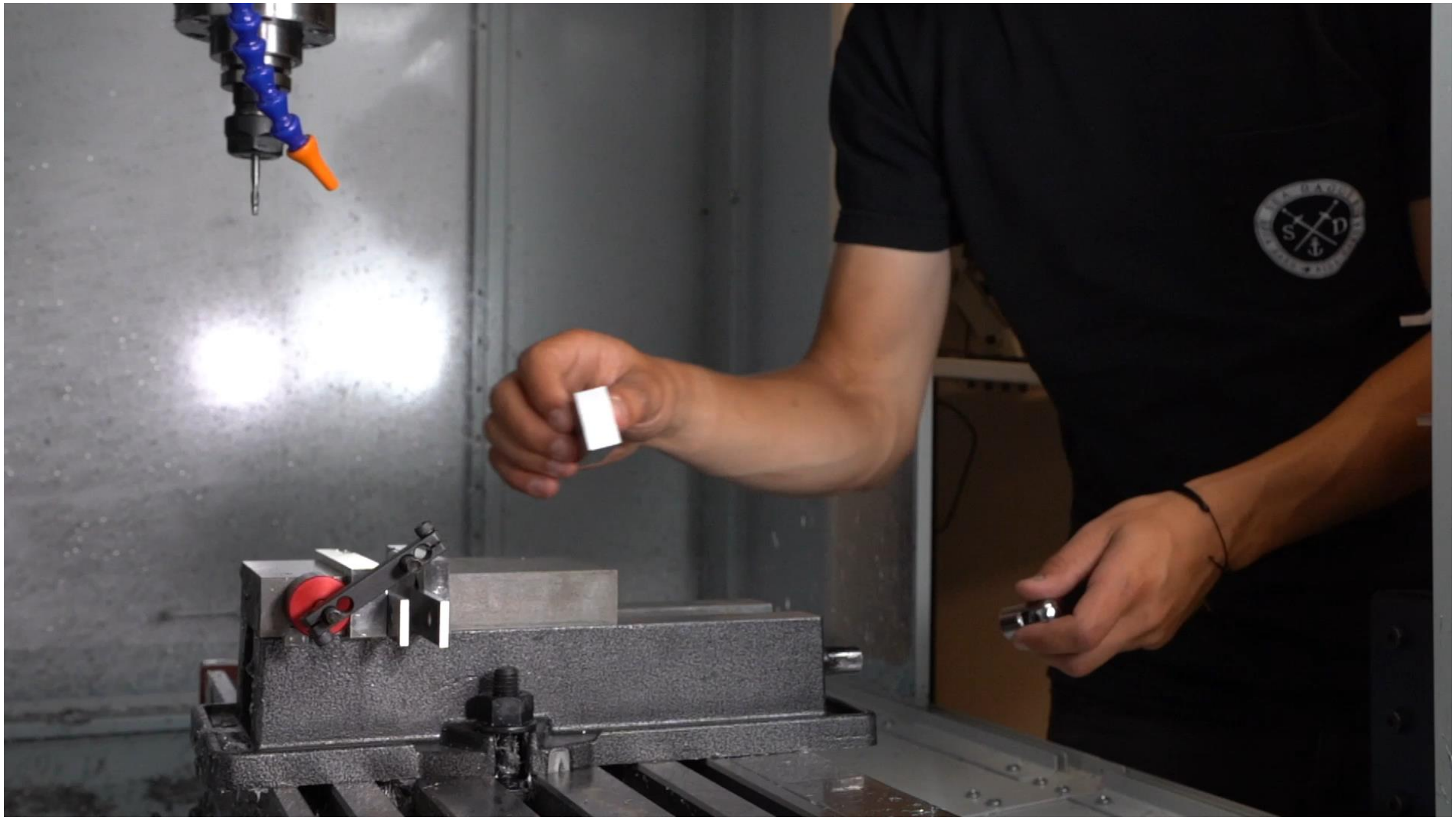
B2-Sensors in robotics

exteroceptive sensors

Force sensors: motivations

What if you want to grasp an egg?

- Used to both measure actuation and **interaction** forces/torques



Strain gauges

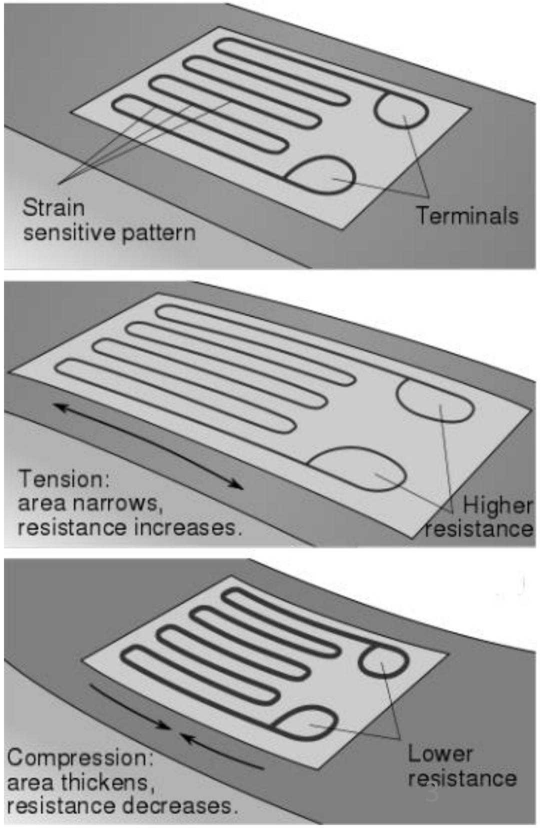
- For electrical motor driven joints, the torque can be measured by simply measuring the **current** in the armature of the motor (but it includes load friction).

- Otherwise the torque/force can be **indirectly** sensed from the measure of **deformation** of an elastic element subject to the force or torque to be measured

- To capture this deformation, several sensors can be built according to different physic principles depending on the nature of the sensing element: capacitive or resistive change, piezoelectric or on optical interpherometry

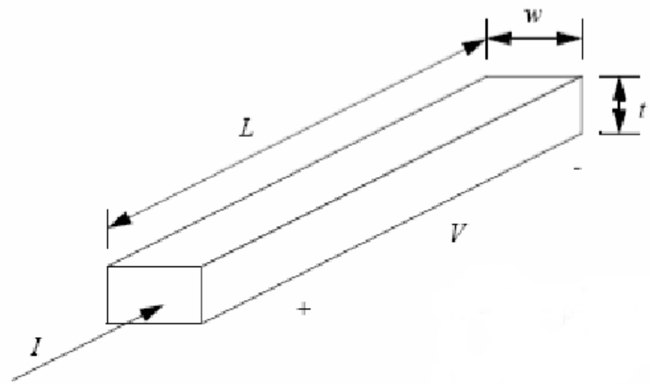
- because of its **ruggedness** and **simplicity** the mostly used is the **strain gauge**: it uses the variation of the **resistance** R of a metal conductor

- The wire is glued to the surface of a part, so that it undergoes the same strain as the part (at the mount point).



Strain gauges

- Strain gauges measure relative deformation (strain) of a material using the change in resistance of a wire. If the wire is deformed, it takes a new dimension (i.e. its length L and cross-section S vary) and resistance.
- If the deformation makes the wire longer (Young's modulus), the cross sectional area decreases (Poison's ratio) => The resistance R increases



$$R = \frac{V}{I} = \rho \frac{L}{A} = \rho \frac{L}{wt}$$

Resistivity

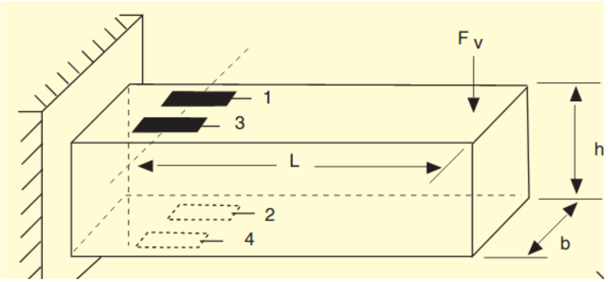
- The Gauge(or gage)-factor is a commonly used measure of strain gauge **sensitivity**:

$$GF = \frac{\Delta R / R}{\underbrace{\Delta L / L}_{\text{Strain } \varepsilon}}$$

"Strain" is defined as the ratio of the change in length to the initial unstressed reference length (relative deformation).

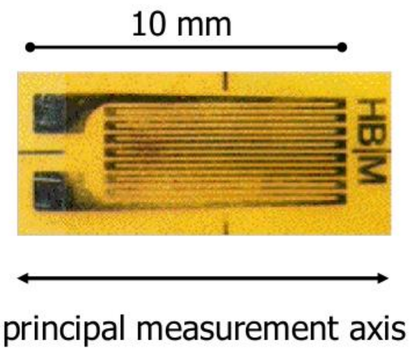
Operating Strain [μstr]	± 2000
Linearity	better than $\pm 1.5\%$ for $1500 \mu mm/mm$
Gage factor	140
Resistance R [Ω](at $25°C$)	500 ± 50

Mounting of gauges



- Gages should be mounted in the direction of the normal stress (compression or tension)

- These gauges are sold on thin films that are glued to the surface of a part. The process of mounting strain gages involves surface cleaning, application of adhesives, and soldering leads to the strain gages.



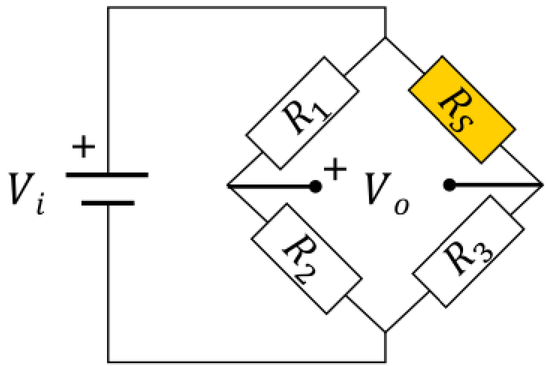
- A strain gage must be small for accurate readings, so the wire is actually wound in a uniaxial or rosette pattern (longer conductor and bigger resistance change, higher sensitivity)

- Strain gauges are inexpensive, and can be used to measure a wide range of strains with accuracies under 1%

- Gauges require **calibration** before each use. This often involves making a reading with no load, and with known loads applied.

Reading strain gages

A) **Single-point** Wheatstone bridge connection

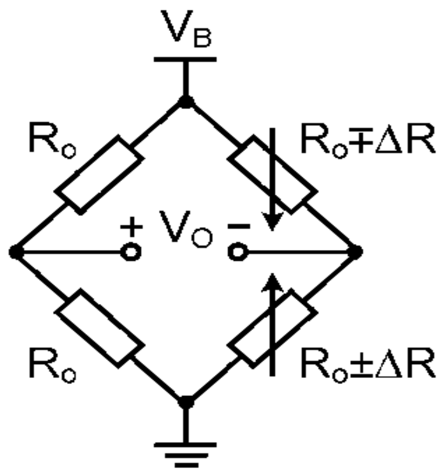


R_1 , R_2, R_3 very well matched (≈ R)

R_s ≈ R at rest (no stress)

$$\boxed{V_o = \left(\frac{R_2}{R_1 + R_2} - \frac{R_3}{R_3 + R_S}\right) V_i}$$

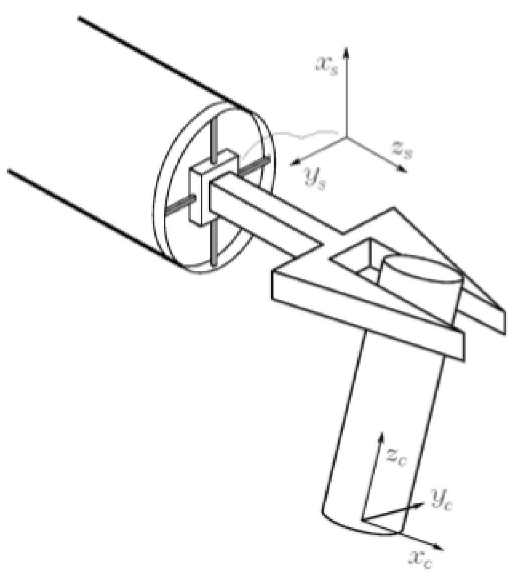
B) **Two-point** bridges have 2 strain gauges connected oppositely (double sensitivity)



- They suffer for **drift** with temperature, because resistance is changing also with temperature: if gage and fixed resistors have the same dependence on T (e.g. they are thermally coupled) variations are automatically compensated

Contact sensors (6 axis F/T sensor)

- Usually mounted at the wrist, one part of the sensor is directly connected to a link the other is connected to the elastic part of the sensor
- How many gages? there should be at least one such element in any direction, along/around which a force or moment measure is needed



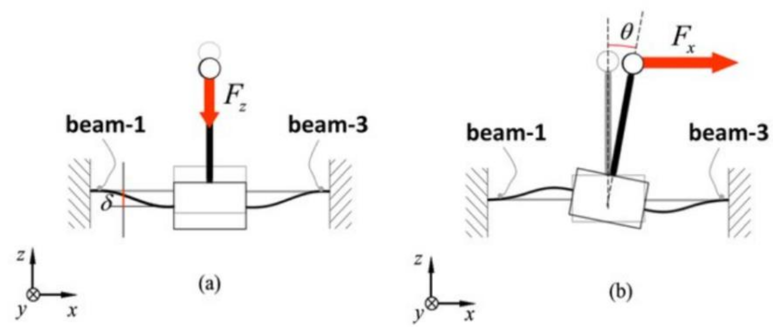
ATI series
Mini45 model: about 6 K€

Model	Max Fx,Fy*	Max Tx,Ty*	Weight**	Diameter**	Height**
Nano17	±50 N	±500 N-mm	0.0091 kg	17 mm	14 mm
Nano25	±250 N	±6 N-m	0.064 kg	25 mm	22 mm
Nano43	±36 N	±500 N-mm	0.041 kg	43 mm	11 mm
Mini40	±80 N	±4 N-m	0.05 kg	40 mm	12 mm
Mini45	±580 N	±20 N-m	0.091 kg	45 mm	16 mm
Gamma	±130 N	±10 N-m	0.25 kg	75 mm	33 mm
Delta	±660 N	±60 N-m	0.91 kg	94 mm	33 mm
Theta	±2500 N	±400 N-m	5 kg	150 mm	61 mm
Omega160	±2500 N	±400 N-m	2.7 kg	160 mm	56 mm
Omega190	±7200 N	±1400 N-m	6.4 kg	190 mm	56 mm

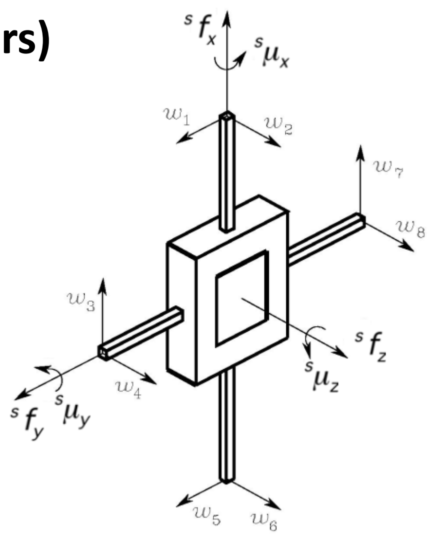
Maltese-cross configuration

4 deformable elements (spokes):

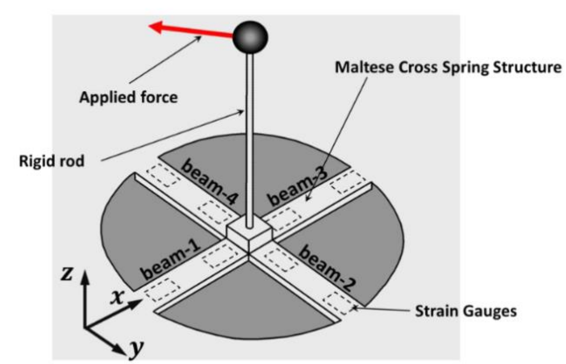
- For 6 axis measure: two pairs of strain gauges are mounted on opposite sides of each element (8 pairs)
- Each pair of strain gauges is glued so as to undergo opposite deformations (e.g., traction/compression) along the main axis of measurement



6 –axis (8 pairs)

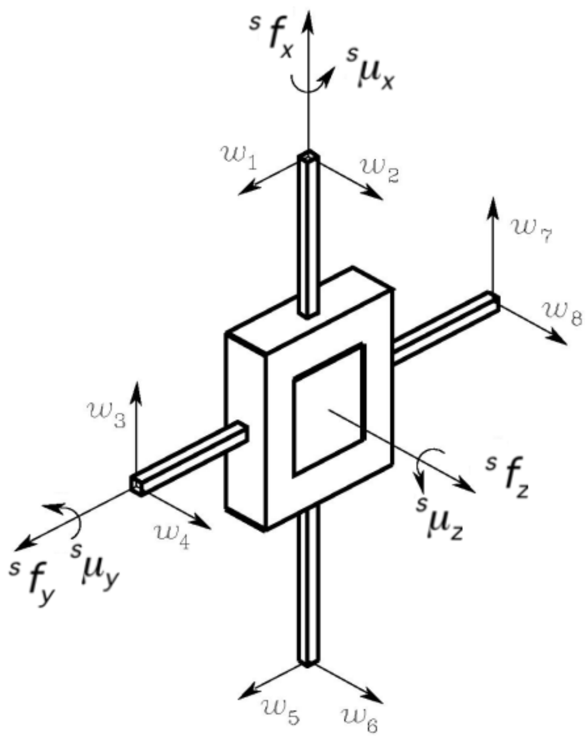


3 – axis (4 pairs)



- since a complete “decoupling” of these measurements is hard to obtain, there are N ≥ 6 such deformable elements

6D F/T measurements



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

force / Torque measured at the sensor frame

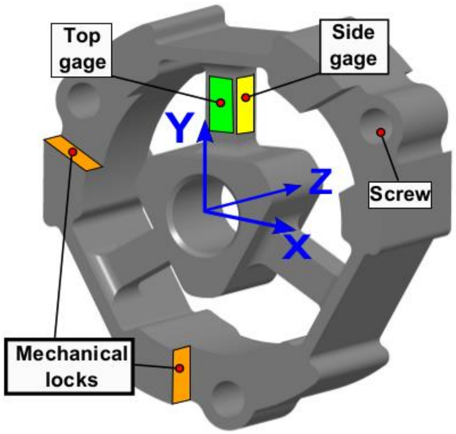
calibration matrix

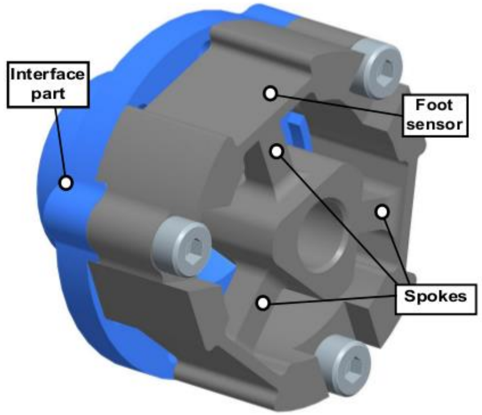
output of the wheatstone bridge

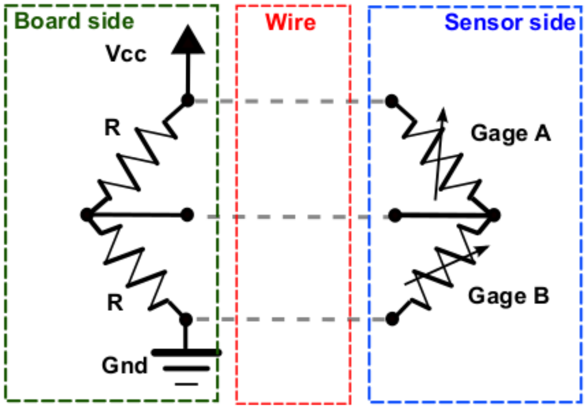
- **Calibration**: means to obtain the elements of the calibration matrix. This means applying a **known** force/moment, collect the correspondent voltages and perform a least square regression
- Use a variety of loads to identify all the entries of the matrix

Other configurations 6 axis (3 spokes – 6 pairs)

[M.Focchi PhD thesis]

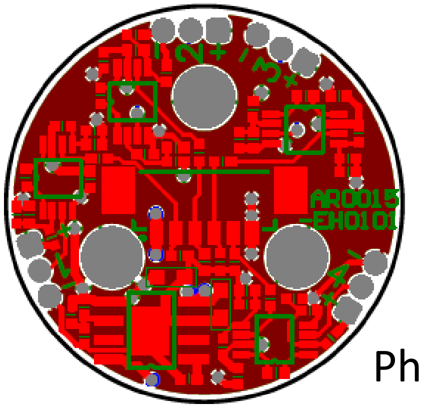




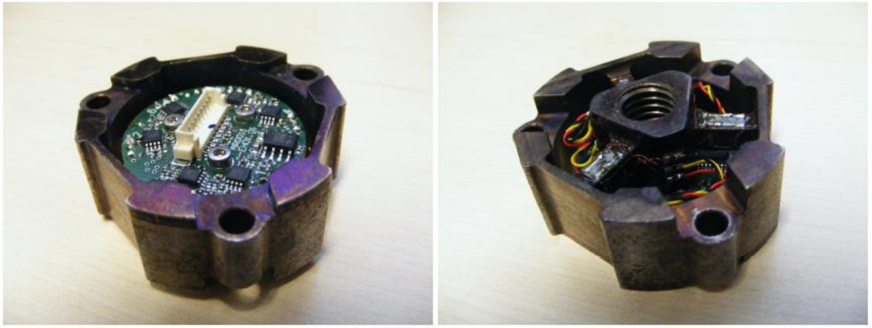


- To improve the signal to noise ratio the gauge wires must be as short as possible. This requires that the amplification of the signals must be done **close** to the sensing elements

Amplification board



Phil Hudson



Application of F/T sensor

Active assembly with F/T sensor

Surface finishing with F/T sensor

Vision sensors: passive and active sensors

Passive sensors:

- passive sensors gather target data through the detection of light, radiation, heat or other phenomena occurring in the environment **without** external devices.

- Commonly, the passive sensors used in robotics are **cameras/image sensors**.

Active sensors:

- An active sensor uses external projecting devices that emit light wavelength, signal or patterns to interact with the scene.

- The data generated by this external source are gathered by the sensor to deduce information on the environment around the robot.

- 2 types of active sensors used in robotics : Structured-Light and time-of-flight.

(Passive) distance sensors: camera (or image sensor)

- The task of a camera as a vision sensor is to measure the intensity of the light reflected (passive sensor) by an object and convert it into a 2D image
- A photosensitive element, termed **pixel** is employed, which can transform light energy into electric energy
- Most are CMOS based (Complementary Metal Oxide Semiconductor): each pixel is a photodiode, directly providing a voltage or current proportional to the instantaneous light **intensity**
- The photosensitive sensor of the camera is composed by an **array** of several million of pixels (megapixels)

- A camera is a complex system comprising several devices other than the photosensitive sensor, i.e., a shutter, a lens and analog preprocessing electronics.
- Measurement are taken following the **projective** geometry

(+): high resolution

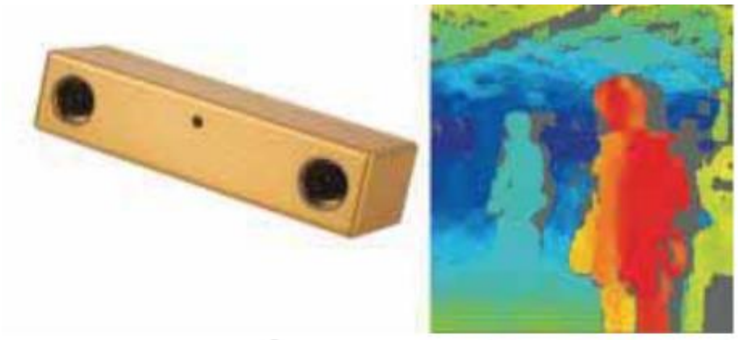
(-): not working properly in absence of "features"

(-): some computer vision tools are required to obtain 3D data…

Bandwidth Problem

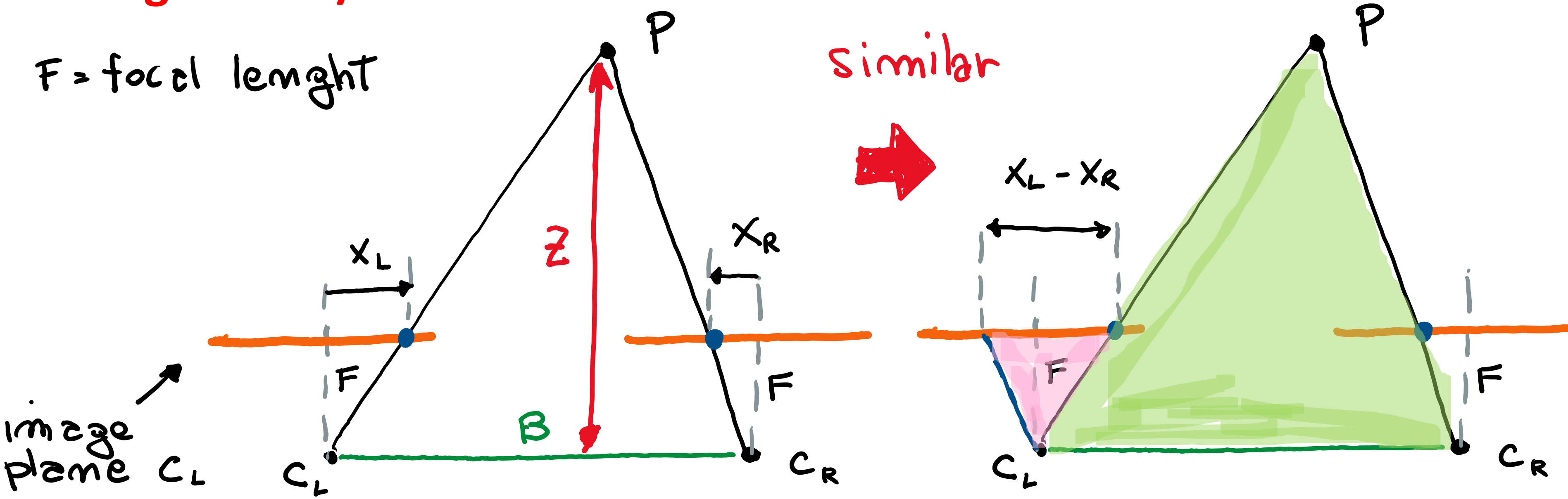
- Let's see how much bandwidth we need to transfer an image…
- Frame size: N_y = 576 pixel, N_x=768
- $Q = N_x * N_y$ = 442368 pixel/frame = 0.44 Mpixel/frame
- Let's encode in **gray** scale (not even color!): 8 bit per pixel
- Frame frequency f (typical for human perception): 25 Hz
- Bandwidth = 8*Q *f = 8*442368 *25= 88473600 byte/s = 84.3 Mbyte/s → high bandwidth is required! → Compression

Stereo-cameras



- To reconstruct the 3D scene from 2D camera images, the most common method is the stereo-vision that consists in recover the **depth** information from two images using the concept of **triangulation**.
- In traditional stereo vision, two cameras (stereo-cameras), displaced horizontally from one another, are used to obtain two differing **views** on a scene in a manner similar to human **binocular vision**
- By comparing these two images, the depth information can be obtained in the form of a **disparity map**, which encodes the difference in horizontal coordinates of **corresponding** image points.
- The values of this disparity map are inversely proportional to the scene depth at the corresponding pixel location.

Triangulation / stereo-vision



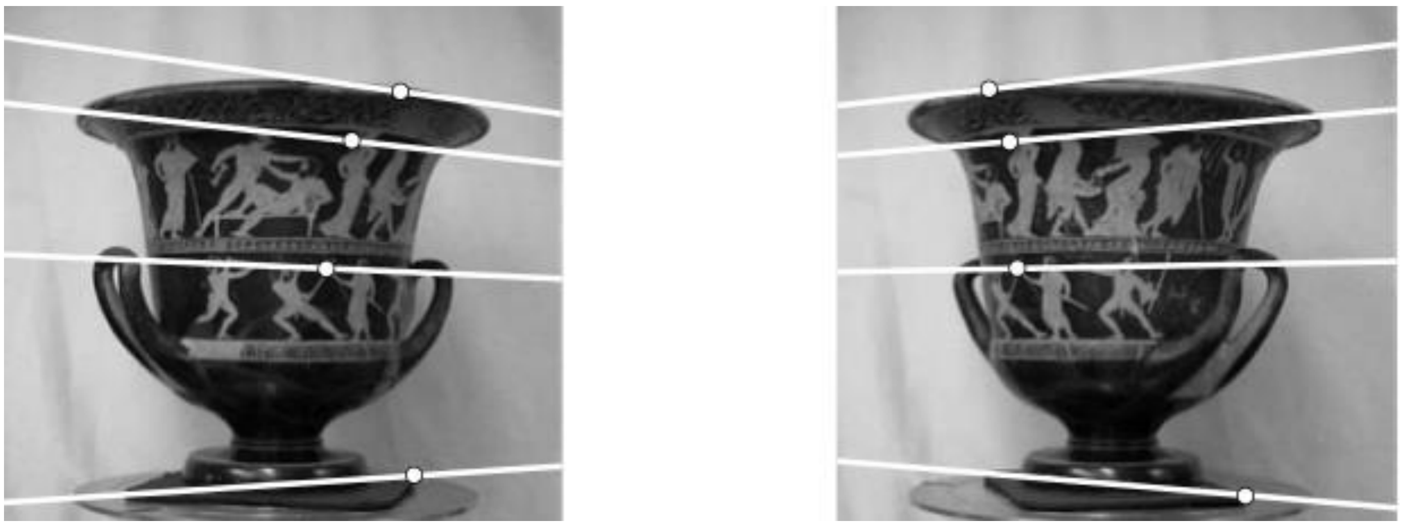
- Two cameras (C_L and C_R) and their corresponding image planes are placed at a B distance (**baseline**) from each other.
- Some point P is captured in the images at offsets X_L and X_R. The blue points are the projections of P on the image planes.
- the difference X_L and X_R is called the **disparity** for the point P, and is equal to the displacement between the two image points X_L and X_R
- Considering triangles similarity the distance Z to the point (**depth**) can be calculated from the following formula:

$$\frac{Z}{B} = \frac{F}{X_L - X_R} \Rightarrow \boxed{Z = B\frac{F}{X_L - X_R}}$$

- In order to calculate depth Z, however, the difference of X_L and X_R needs to be established.

Feature correspondence/stereo matching

- Before finding the disparity we need to find feature correspondences (matches) between left and right camera images



A pair of images with superimposed corresponding points

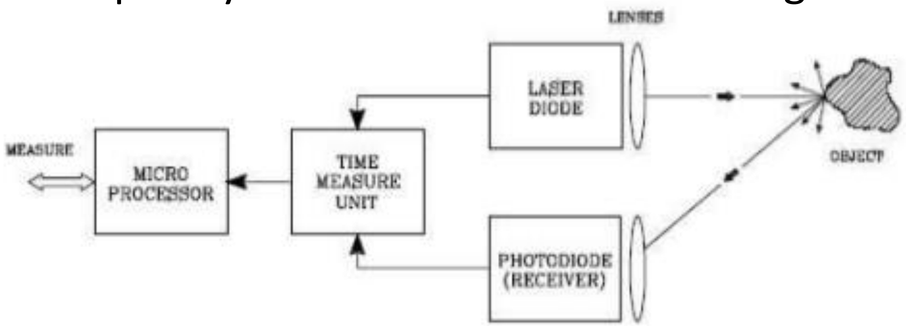
- If we find matches we can derive the depth of all pixels in an image
- If the feature matching is wrong, the point P will be wrongly computed
- If the stereo-camera looks to a white wall without any feature it cannot do 3D reconstruction

OpenCV library

- Open source computer vision and machine learning software library
- The library is used extensively in companies and research groups
- more than 2500 optimized algorithms, which include state-of-the-art computer vision: produce 3D point clouds from stereo cameras, detect and recognize faces, identify objects, classify human actions in videos, track camera movements, track moving objects, extract 3D models of objects
- Supports C++, Python, Java and MATLAB interfaces and supports Windows, Linux, Android and Mac OS
- written natively in C++ and has a templated interface

(Active) distance sensors: time-of-flight sensors

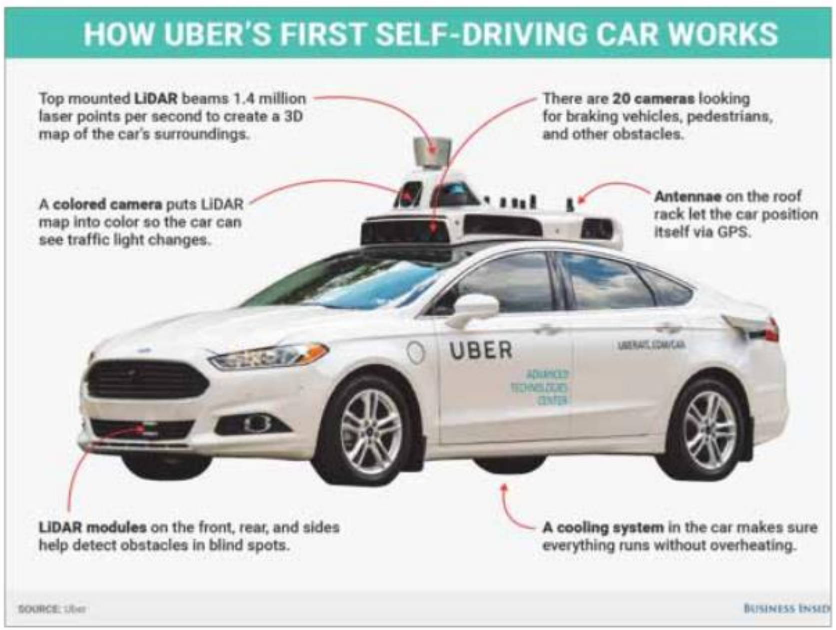
- compute the distance of an object by measuring the time that a pulse of laser (coherent light source) takes to travel from the source to the observed target and back to the detector (usually collocated with the source).
- A **coherent** light source is usually preferred to other light sources because it generates bright beams with lightweight sources, it is unidirectional (parallel beams on long distances) and the single-frequency sources allow easier filtering.



- this round-trip travel time provides the 3D position of the object surface point, using the speed of light and the ray projection angle.
- limitations on the accuracy of these sensors are based on the minimum observation time (and thus the minimum distance observable), due to the temporal accuracy of the receiver
- Time-of-flight cameras in principle perform **point-to-point** reconstruction. To detect more than one point, normally the beam is “swept” by a mirror rather than moving the laser and the detector themselves (mirrors are lighter and less prone to motion damage).

LiDAR (Light Detection And Ranging)

- Most famous time-of flight-sensor (apart from the RADAR, wavelength order of cm) is the **LiDAR** (ultraviolet, wavelength order of micron)
- LiDAR is commonly used to make high-resolution (offline) maps (the resolution is related to the wavelength) or in self-driving cars (online)
- Laser waves are reflected even from very small objects

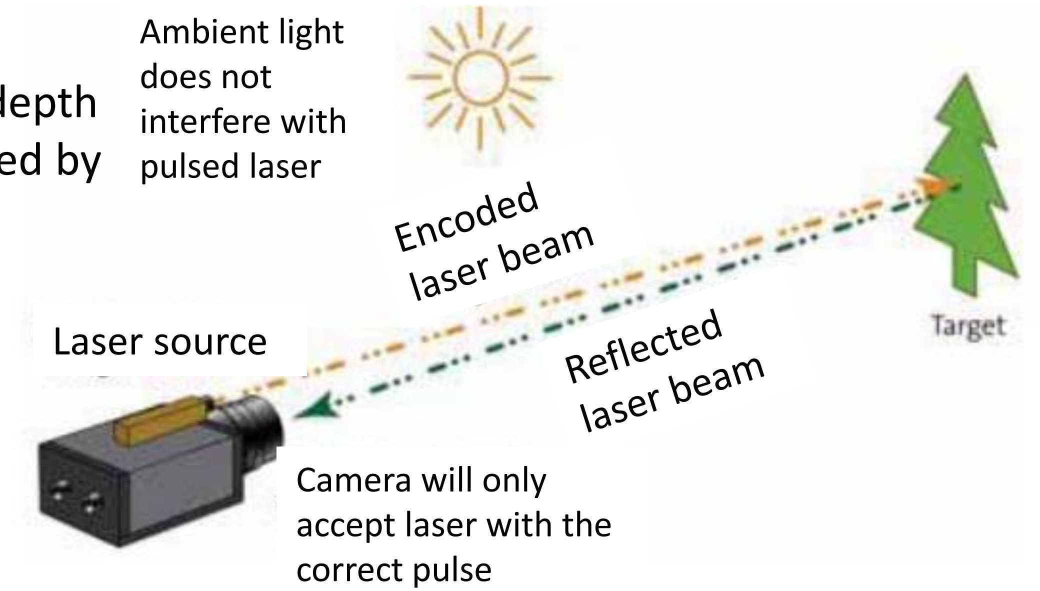


LiDAR sensor (Velodyne) and generated raw data

(Active) distance sensors: time of flight sensors

- (+): These cameras can cover large distances and also provide accurate depth estimation, the coverage is only limited by the allowed laser power

- Amplitude and frequency modulated strategies have been adopted for close range distance measurements



- (+): not sensitive to light condition (suitable for outdoor applications)

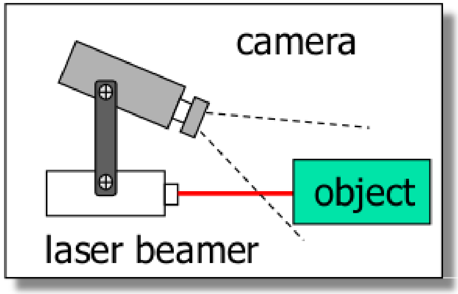
- (-): very expensive

- (-): scanning difficulties with reflective surfaces

- (-): low resolution w.r.t 2D cameras (sparse map)

(Active) distance sensors: Structured light

- Structured-light based sensors project bi-dimensional patterns to estimate the depth (distance) information of the object surface points.



- The main role of the projected patterns is to establish correspondences between the known pattern and the camera measurements

- This variation encodes the scene depth information which can be recovered using a triangulation tool

(+): advantage versus stereo-camera, since it projects a pattern, it does not get "confused" on uniform surfaces cause there are no features on the object to match

(+): cheap, light, small, low energy

(-): sensitive to light condition (usable only for **indoor** application)

Structured light sensor: Kinect V

Example: kinect, a camera + structured linght 3D sensor

- RGB camera (with 640×480 pixel)
- depth sensor (**infrared** emitter + infrared camera)
- range: 0.5÷5 m
- data rate: 30 fps
- cost: < 90 €

- The depth is associated to all the points in the RGB camera

- By post processing you can track human motion

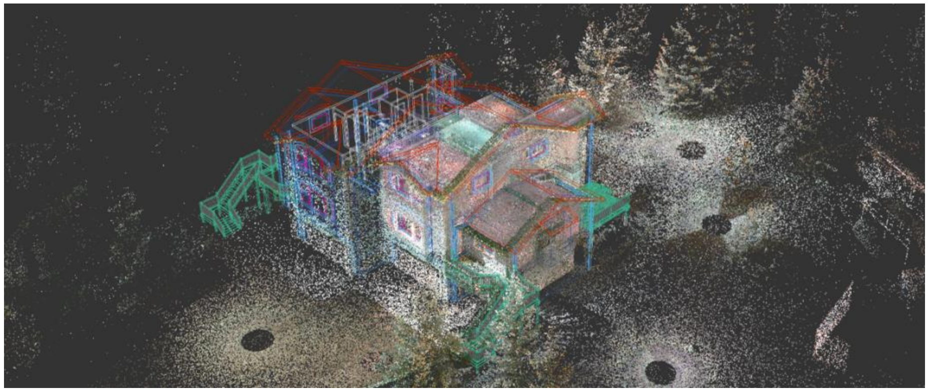
"skeleton" extraction and human motion tracking

More resources:

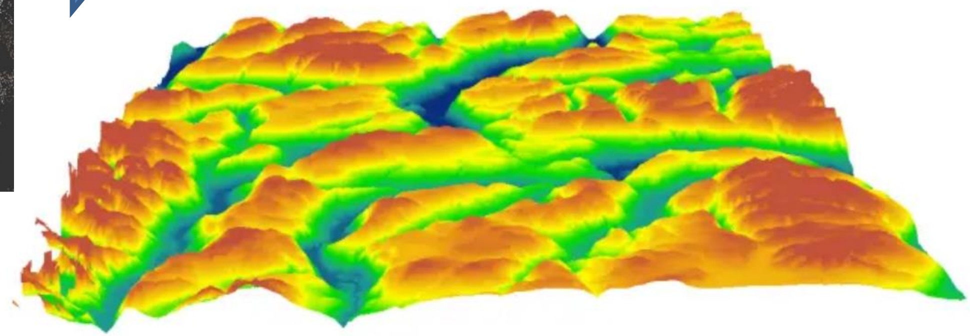
http://pages.cs.wisc.edu/~ahmad/kinect.pdf

Point cloud can be used for online mapping

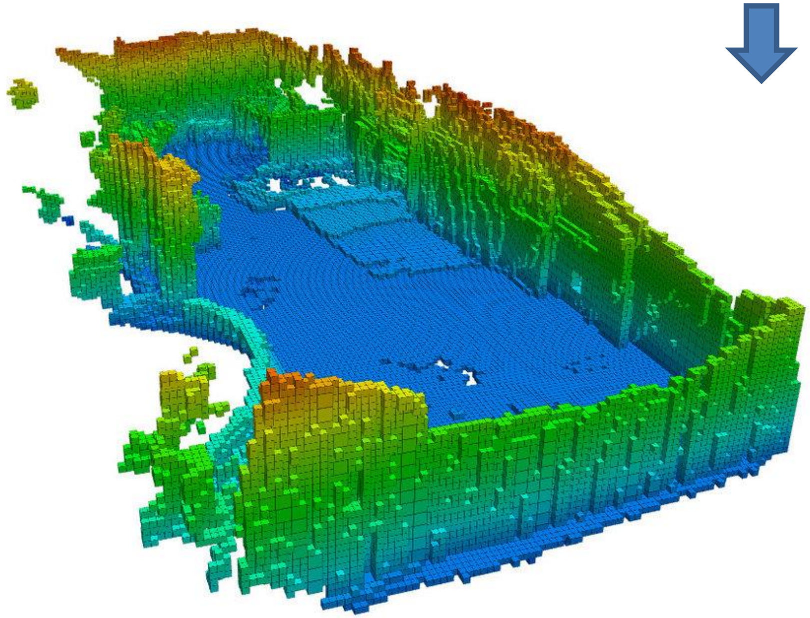
We have different representations that can be reconstructed starting from the acquired point cloud

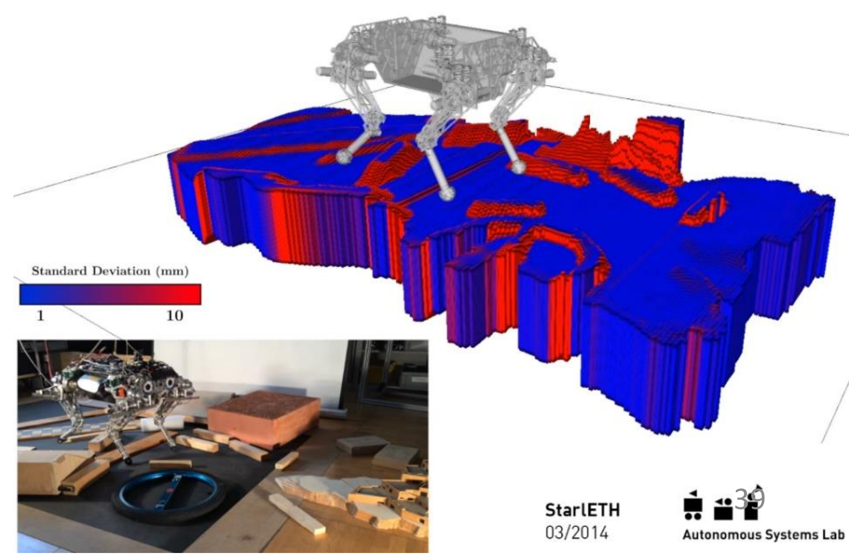


Height map or elevation map (2.5D)

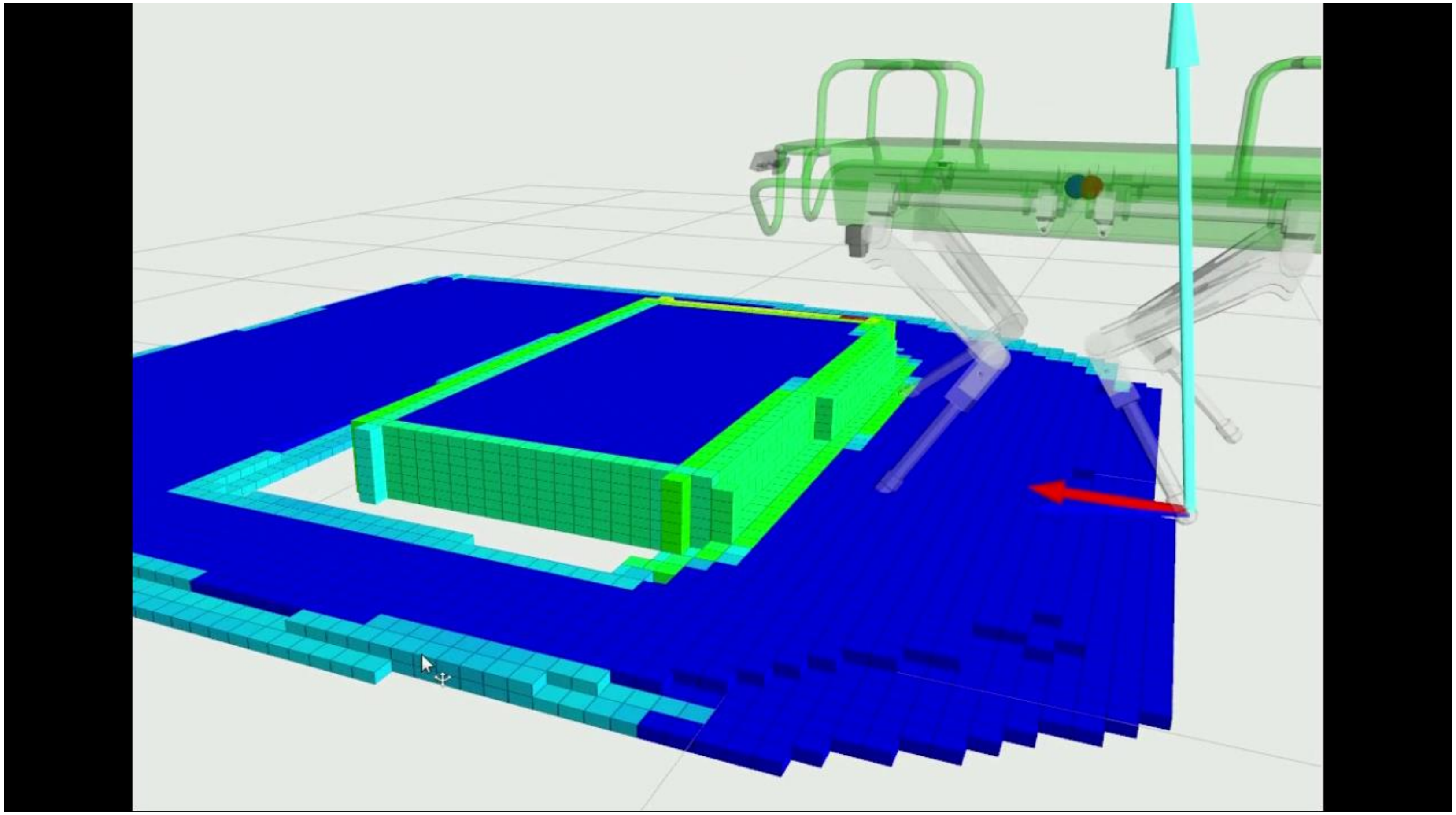


Octomap (3D), occupancy map





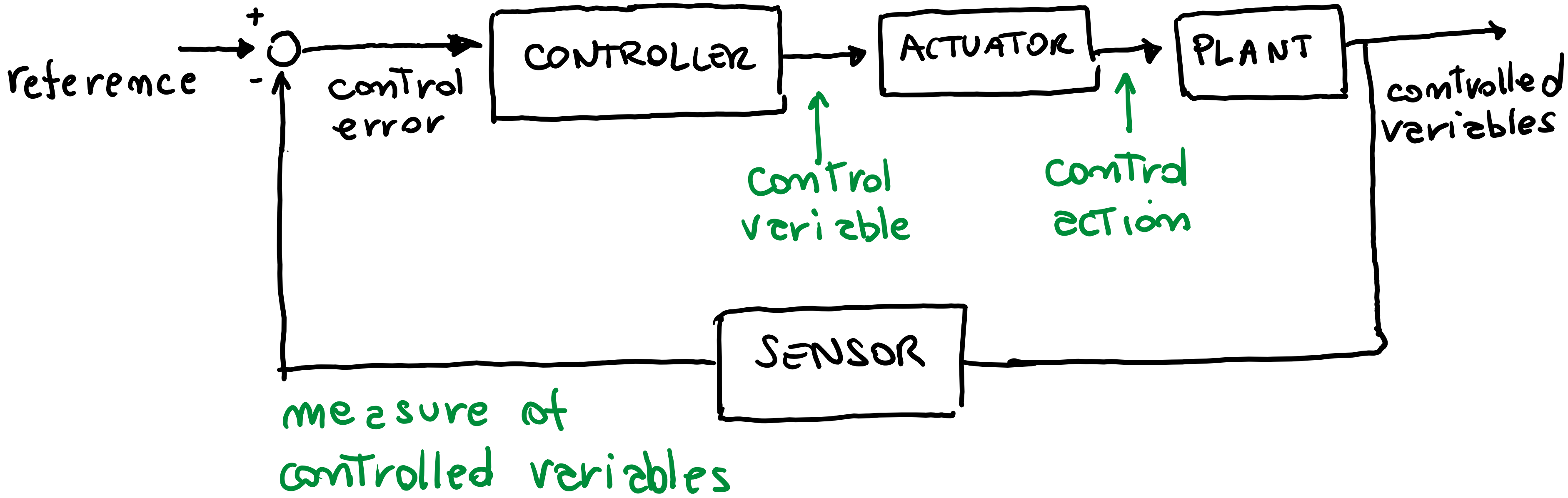
Online mapping can be used for locomotion



B3-Signal processing for robotics

Technological sketch of a closed loop control system

- Robot controllers are, in the computer era, implemented on **digital** machines



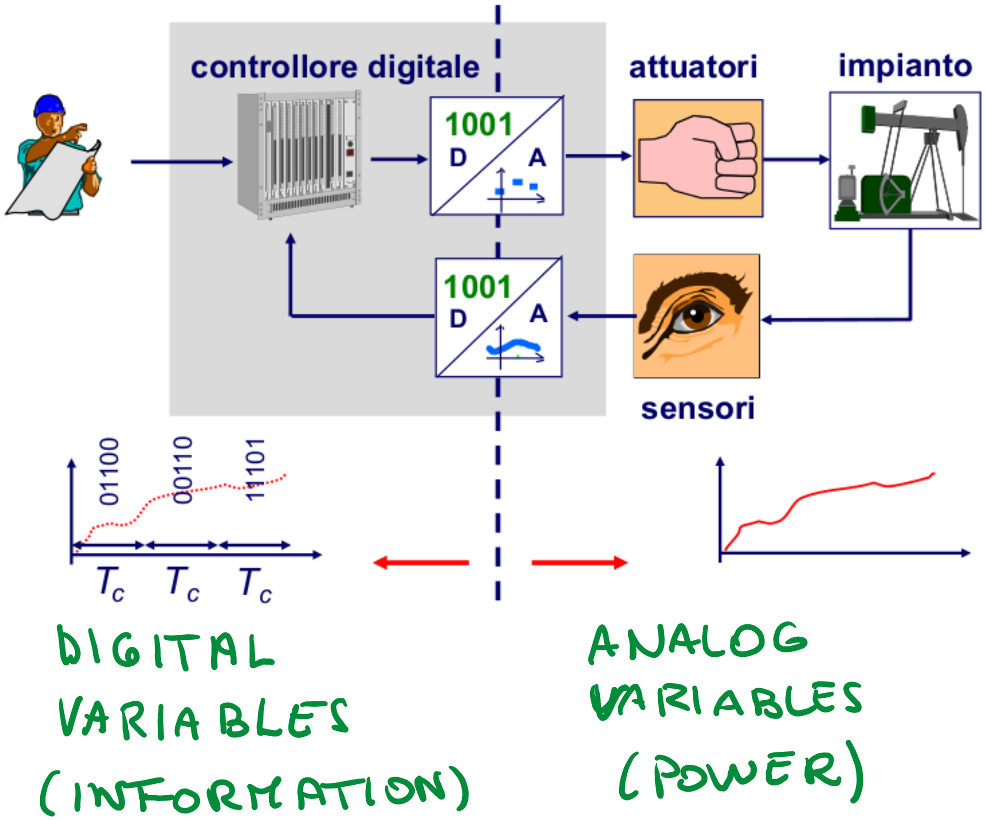
- The digital implementation of the controller implies that it works at **low** power, therefore the control signal must be **amplified** before being applied to the actuators

- The actuator converts an informative (low power) signal into a high power signal, making the control signal compatible with the plant input.

- The controlled variables are measured via sensors. They convert the physical quantity in a low power signal readable from the controller (i.e. electrical).

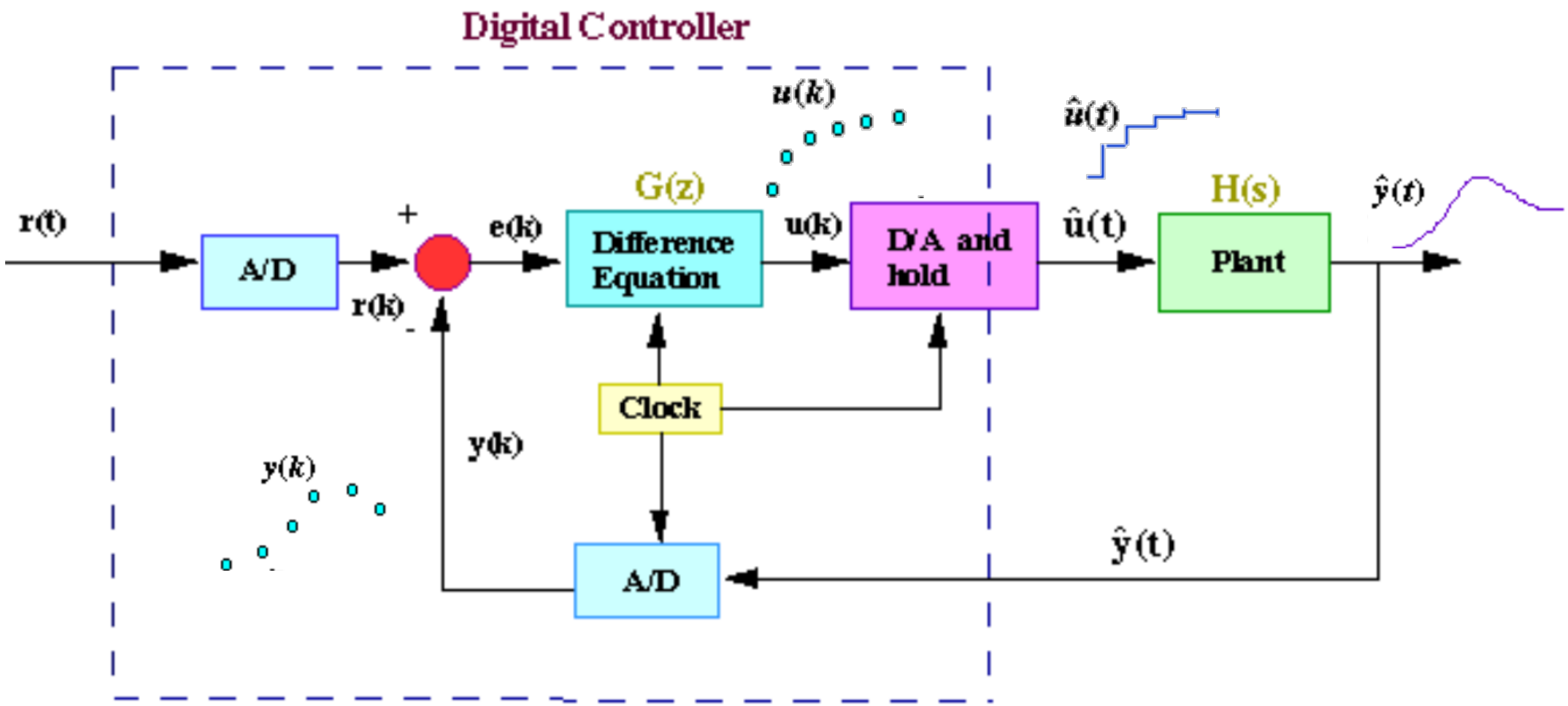
Computer Controlled Systems

- A Computer Controlled Systems comprises two fundamental actors in the general representation of a closed loop system: an A-D converter and a D-A converter, that are placed nearby the controller.



- They are synchronized with the controller via a clock signal of period T_s called **sampling time**

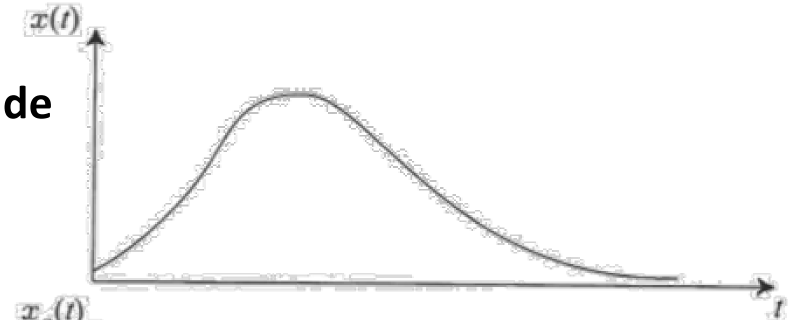
Signals



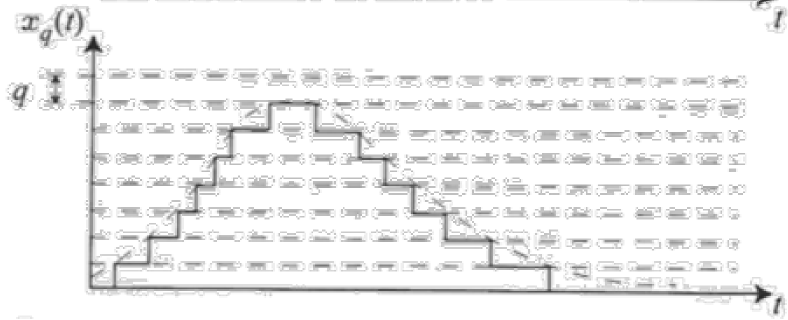
- The evolution of the controller happens at discrete time intervals (spaced by T_s),
- There are some instants in which the data are read from the A-D converter (attached to the sensor) and some instants in which the data are written to the D-A converter (attached to the actuator). Such instants are usually called **sampling instants**.

Signals

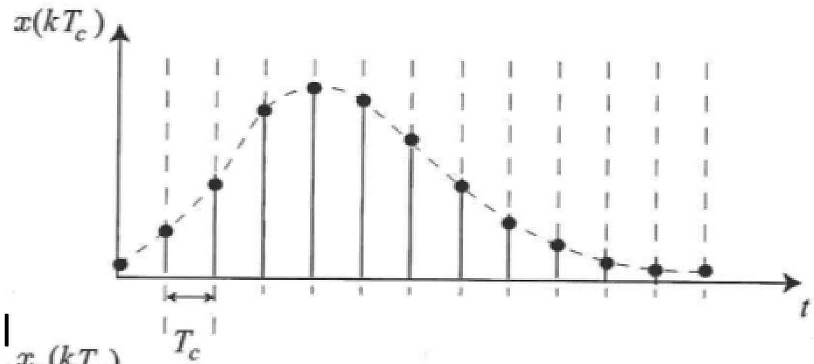
- **Analog signals**: vary **continuously** in their **magnitude** and with **time**, are called continuous time signals.



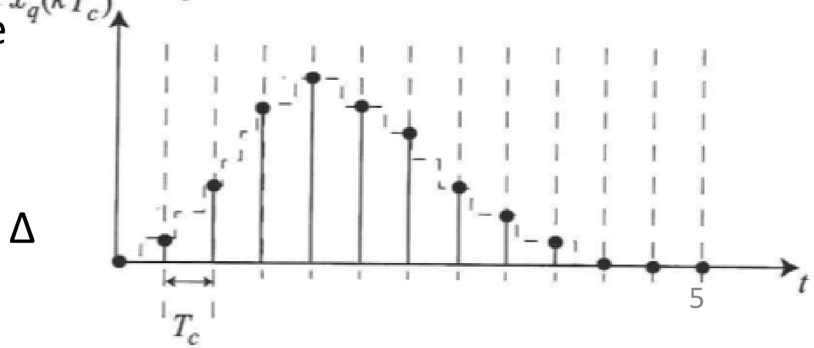
- **Quantized signals**: can assume only a limited number of values, can be represented by N bits (with N bit you can describe 2^N discrete levels/binary numbers). The minimum variation is called the quantization level q



- **Sampled signals**: are analog signals evaluated only at specific time instants separated by the sampling time T_s : $x(t) \Rightarrow x(kT_s)$, are also called **discrete** time signals (they have continously varying amplitude)



- **Digital signals**: a digital signal is a quantized signal that it is sampled (i.e. it varies only at discete time intervals equally spaced by T_s)



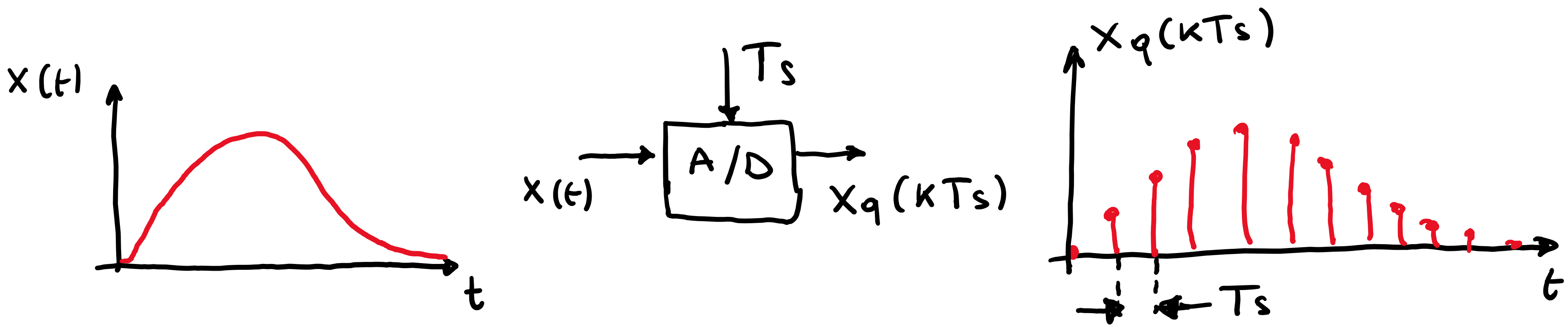
The number of bits N depends on the output range Δ and the quantization level q: $N = \log_2 (\Delta/q)$

Analog to Digital converter (A/D): sampling and quantization

- **Sampling** converts a time-varying voltage signal into a discrete-time signal, a **sequence** of real numbers.

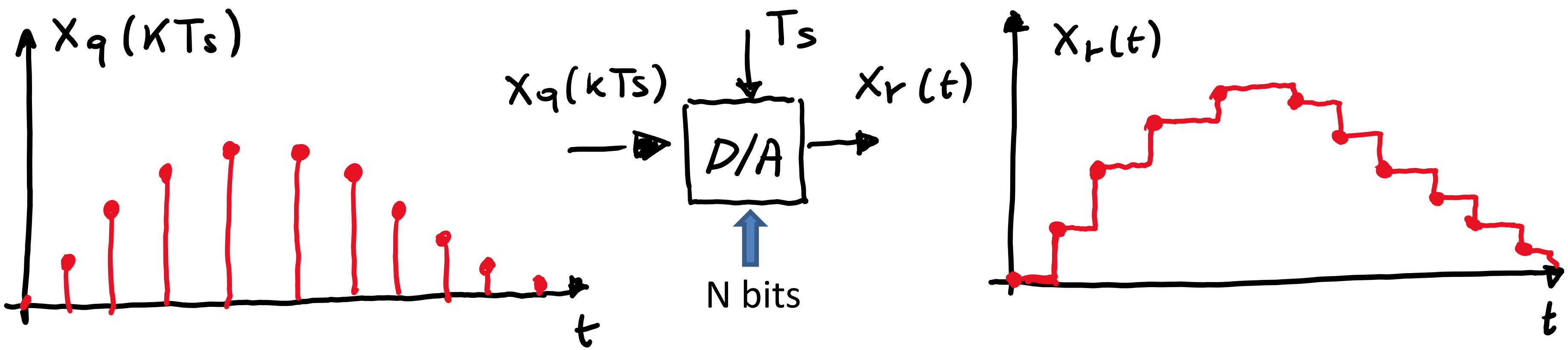
- **Quantization** replaces each real number with an approximation from a **finite** set of values.

- A/D converter receives in input an **analog signal** x(t), performs both quantization and sampling with a period T_s, giving in output a **digital signal** $x_q(kT_s)$ codified by mean of a sequence of bits



Digital to Analog (D/A) converter: reconstruction

- The inverse transformation, performed by the D/A converter implies the **reconstruction** of the analog signal $x_r(t)$ starting from the sequence of samples of the digital signal $x_q(kT_s)$
- This is realized inside the D/A by mean of the Zero Order Hold(ZOH) that maintains **constant** the input received at the instant $t=kT_s$ along the intervals $kT_s \leq t \leq (k+1)T_s$

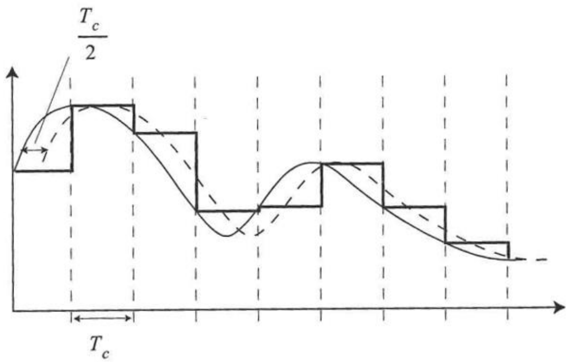


- Quantization, sampling and reconstruction are **approximations** that affect the control system
- controller digital implementation advantages:
  - increased flexibility
  - digital signals are inhereintly more **robust** than analog signals to be transmitted

Digital implementation issues: delay and loss of phase margin

- The most important impact of implementing a control system digitally is the **delay** associated with the **hold** in the sampling phase.

- We can see that the average of the reconstructed signal (dashed line) is an approximation of the original signal delayed by $T_s/2$

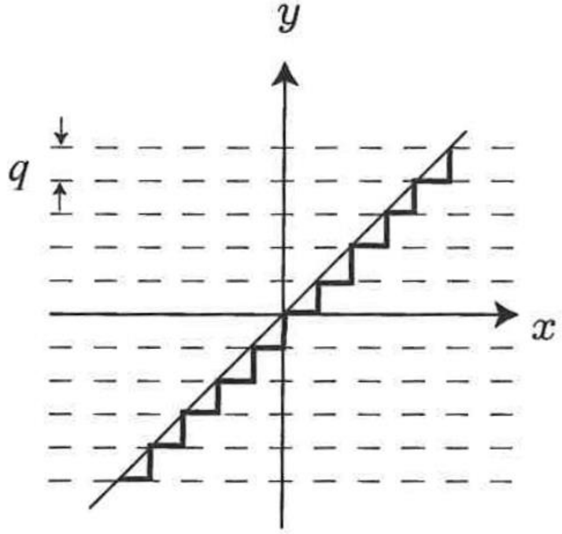


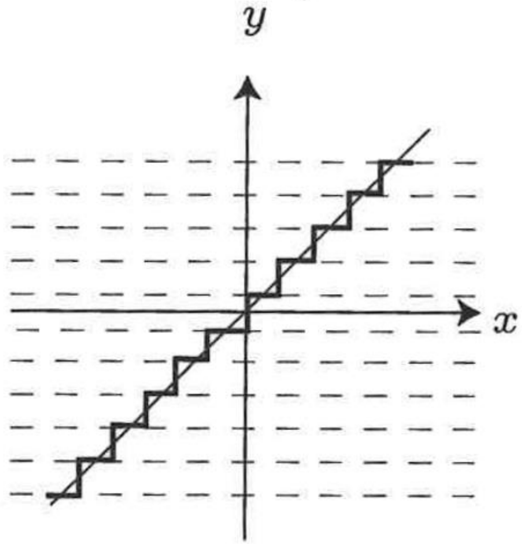
- A delay in any feedback system degrades its **damping** and **stability** because it causes a loss of **phase margin** (evaluated at the cross over frequency ω_c)

- In the specific, a time delay of $T_s/2$ translates into a phase delay $\Delta\Phi=-\omega T_s/2$

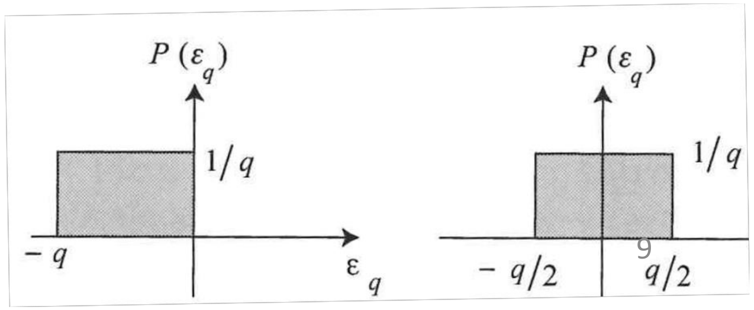
Digital implementation issues: quantization error

- quantizing a sequence of numbers produces a sequence of quantization errors which is sometimes modeled as an additive random signal called **quantization noise**
- due to quantization two values of the analog signal that differ of a quantity lower than the quantization level q, **cannot be discriminated**
- quantization can be implemented by truncation (a) or rounding (b)





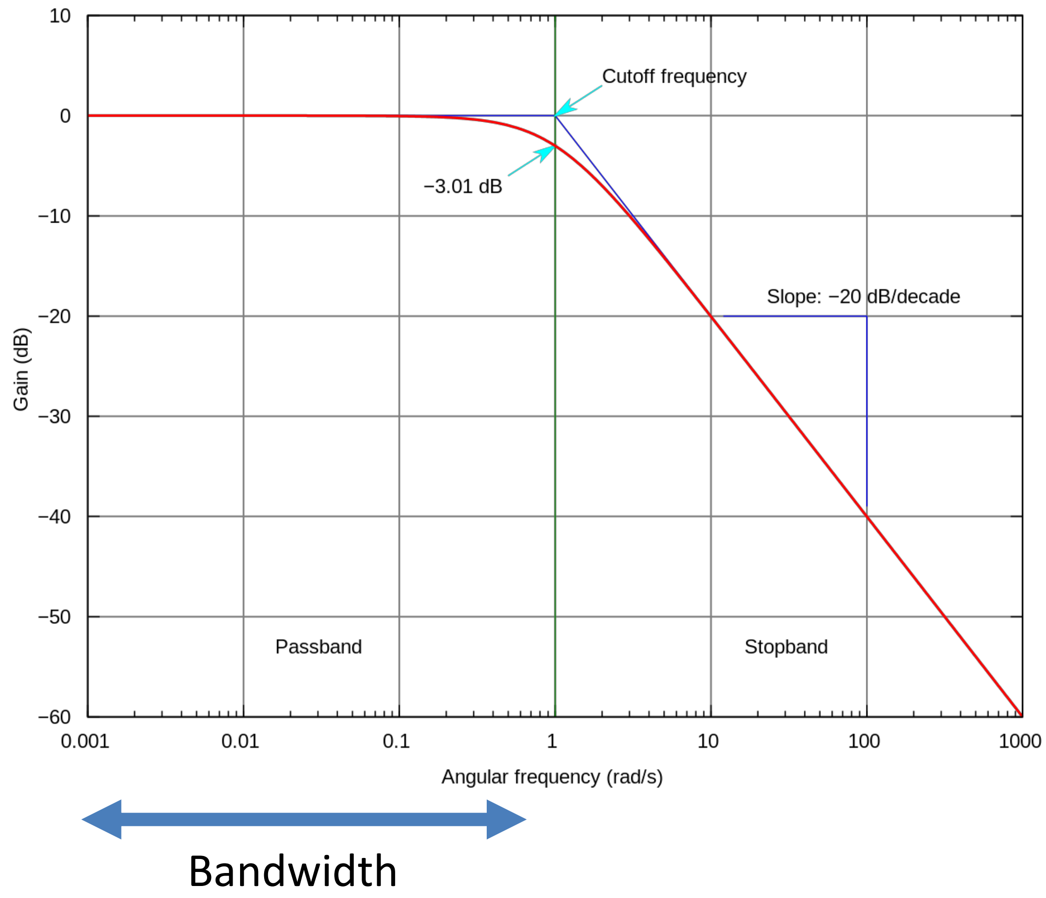
- Quantization noise can be modeled as addictive **white** noise ε_q uniformly distributed with constant probability density $P(\varepsilon_q)$ equal to 1/q



Low-pass filter

- An ideal low-pass filter should:
  - Keep unchanged (in magnitude and phase) the signal at the frequency inside the bandwidth of the filter (cut-off frequency)
  - Attenuate massively the signal at the frequencies **beyond** the filter bandwidth

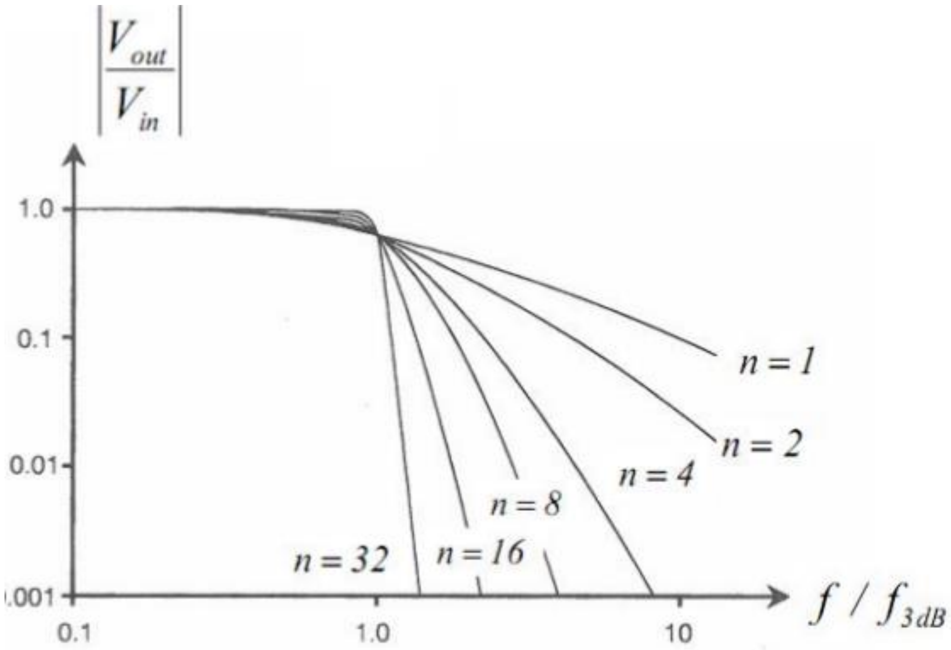
Bode diagram
of a low-pass filter



Butterworth filters

- the order of the filter (i.e. numbers of poles) determines how "sharp" is the frequency cut
- the price to pay to have more poles is an higher **phase delay**
- The higher the order, the bigger the **phase delay** close to the cut frequency

Example of higher order filter: Butterworth filter



Discrete implementation of a first order filter

Differential equation

$$y(t) + \tau \frac{dy}{dt}(t) = u(t) \Rightarrow$$

Continuous time Laplace Transfer function

$$Y(s)(1 + s\tau) = U(s) \Rightarrow \boxed{G(s) = \frac{1}{1+s\tau}}$$

1° order
(1 POLE)

$\Downarrow$

- Discretization with sampling time T_s => difference equation:

$$y(k) + \tau\left(\frac{y(k) - y(k-1)}{T_s}\right) = u(k)$$

$$y(k)\left(1 + \frac{\tau}{T_s}\right) = u(k) + \frac{\tau}{T_s}\, y(k-1)$$

$$y(k) = \frac{1}{1+\frac{\tau}{T_s}}\, u(k) + \frac{\tau/T_s}{1+\frac{\tau}{T_s}}\, y(k-1)$$

$$\boxed{y(k) = \beta\, u(k) + (1-\beta)\, y(k-1)} \qquad \beta = \frac{1}{1+\frac{\tau}{T_s}} = \frac{T_s}{T_s+\tau}$$

- Higher β means faster filter response and less filtering effect, when β is small we have a slower response (the influence of u(k) reflects slowly on the output y(k) and the settling time is higher)

Signal processing: mean (average) /moving mean (average)

- **arithmetic mean**: computed «a posteriori»: you need all data available to compute the mean

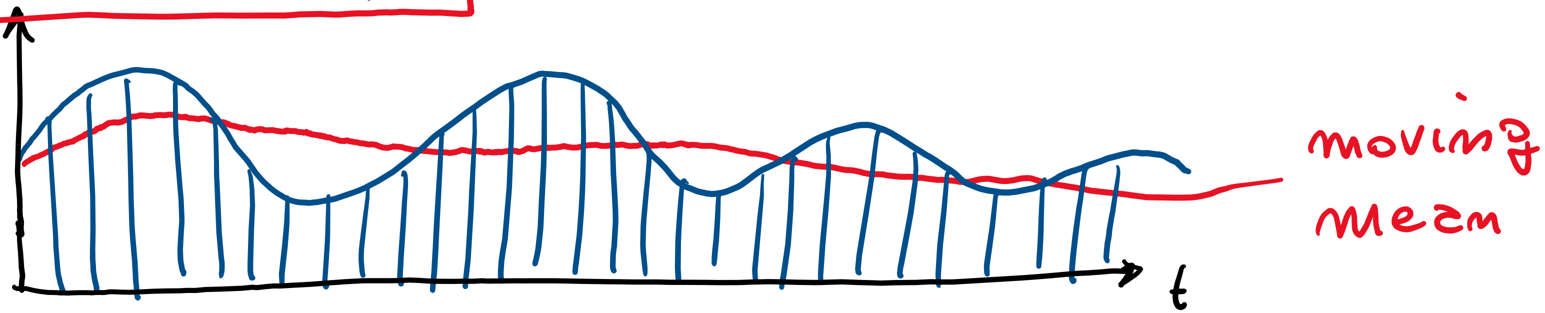
$$\boxed{\bar{X} = \frac{1}{m} \sum_{i=1}^{m} x_i}$$

- the sum could get very high values (overflow). To avoid overflow, usually in signal processing you use the **moving mean** using subsets (window) of the full data set.

- the first element of the moving mean is obtained by taking the average of the initial fixed subset of the number series.
- then the subset is modified by "shifting forward"; that is, excluding the first number of the series and including the next value in the subset.

$$\boxed{X(k) = \frac{1}{M} \sum_{i=k-M}^{k} x_i}$$

moving mean at k-th element with window M



- A moving mean is commonly used **smooth out** short-term fluctuations and highlight longer-term **trends** (e.g. like a low-pass filter but with gain different than 1)

Moving mean implementations

- To save memory a **ring buffer** can be used:

Buffer of k values

x_k	x_{k-1}	…	x_1	Step 1
x_{k+1}	x_k	…	x_2	Step 2
…	…	…	…	…
x_n	x_{n-1}	…	x_{n-k+1}	Step n-k+1

- Moving mean can be implemented also in a recursive way:

$$\bar{x}(k) = \frac{\bar{x}(k-1)(k-1) + x(k)}{k}$$

$$= \frac{\bar{x}(k-1)\,k - \bar{x}(k-1) + x(k)}{k}$$

new sample

$$\boxed{\bar{x}(k) = \bar{x}(k-1) + \frac{1}{k}\left(x(k) - \bar{x}(k-1)\right)}$$

moving average at previous sample