Robotics 1

Robot components:
Proprioceptive sensors

Prof. Alessandro De Luca

DIPARTIMENTO DI INGEGNERIA INFORMATICA
AUTOMATICA E GESTIONALE ANTONIO RUBERTI

SAPIENZA
UNIVERSITÀ DI ROMA

Properties of measurement systems - 1

- accuracy

  agreement of measured values with a given reference standard (e.g., ideal characteristics)

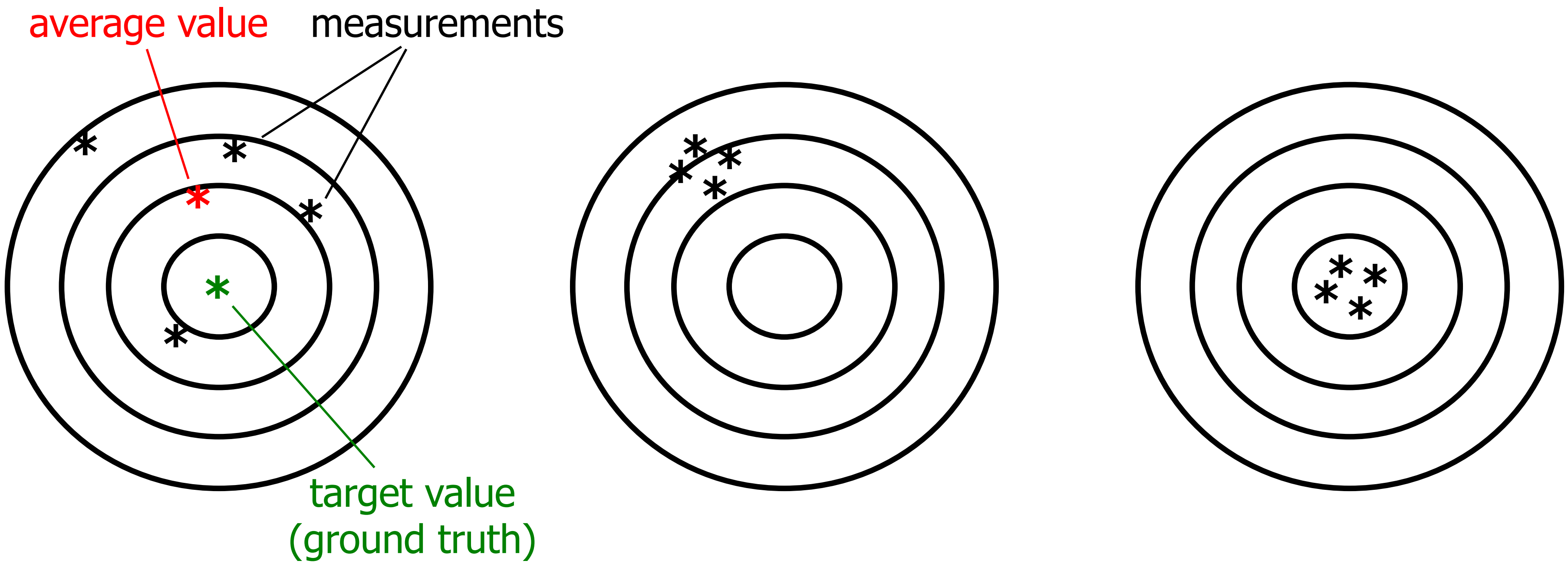
- repeatability

  capability of reproducing as output similar measured values over consecutive measurements of the same constant input quantity

- stability

  capability of keeping the same measuring characteristics over time/temperature (similar to accuracy, but in the long run)

Accuracy and Repeatability



low accuracy
low repeatability

low accuracy
high repeatability

high accuracy
high repeatability

better components!

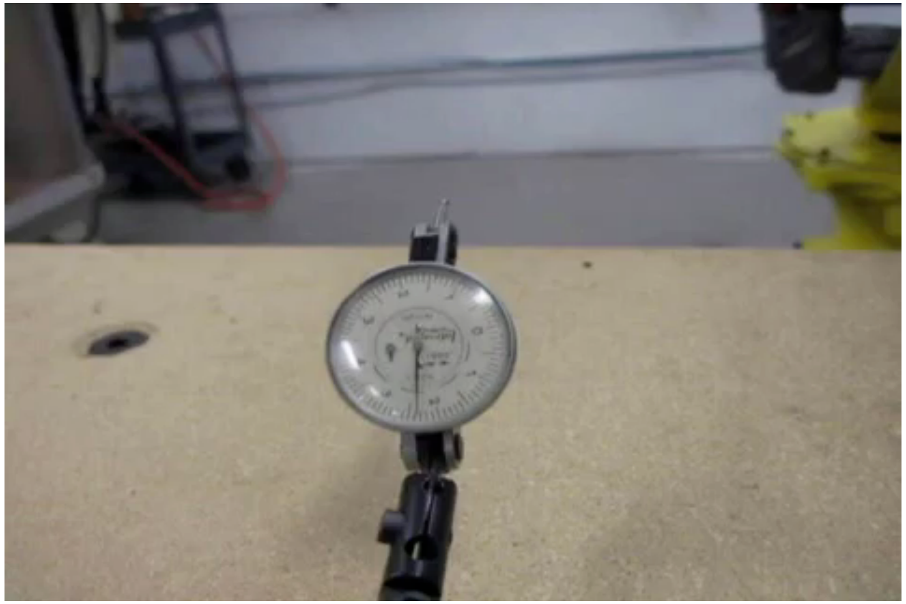
calibration!

Accuracy and Repeatability
in robotics

- accuracy is how close a robot can come to a given point in its workspace
  - depends on machining accuracy in construction/assembly of the robot, flexibility effects of the links, gear backlash, payload changes, round-off errors in control computations, ...
  - can be improved by (kinematic) **calibration**
- repeatability is how close a robot can return to a previously taught point
  - depends only the robot controller/measurement resolution

video

- both may vary in different areas of the robot workspace
  - standard ISO 9283 defines conditions for assessing robot performance
  - limited to static situations (recently, interest also in dynamic motion)
  - robot manufacturers usually provide only data on "repeatability"



simple test on repeatability of a Fanuc ArcMate100i robot (1.3 m reach)

Properties of measurement systems - 2

- linearity error

  maximum deviation of the measured output from the straight line that best fits the real characteristics

  - as % of the output (measurement) range

- offset error

  value of the measured output for zero input

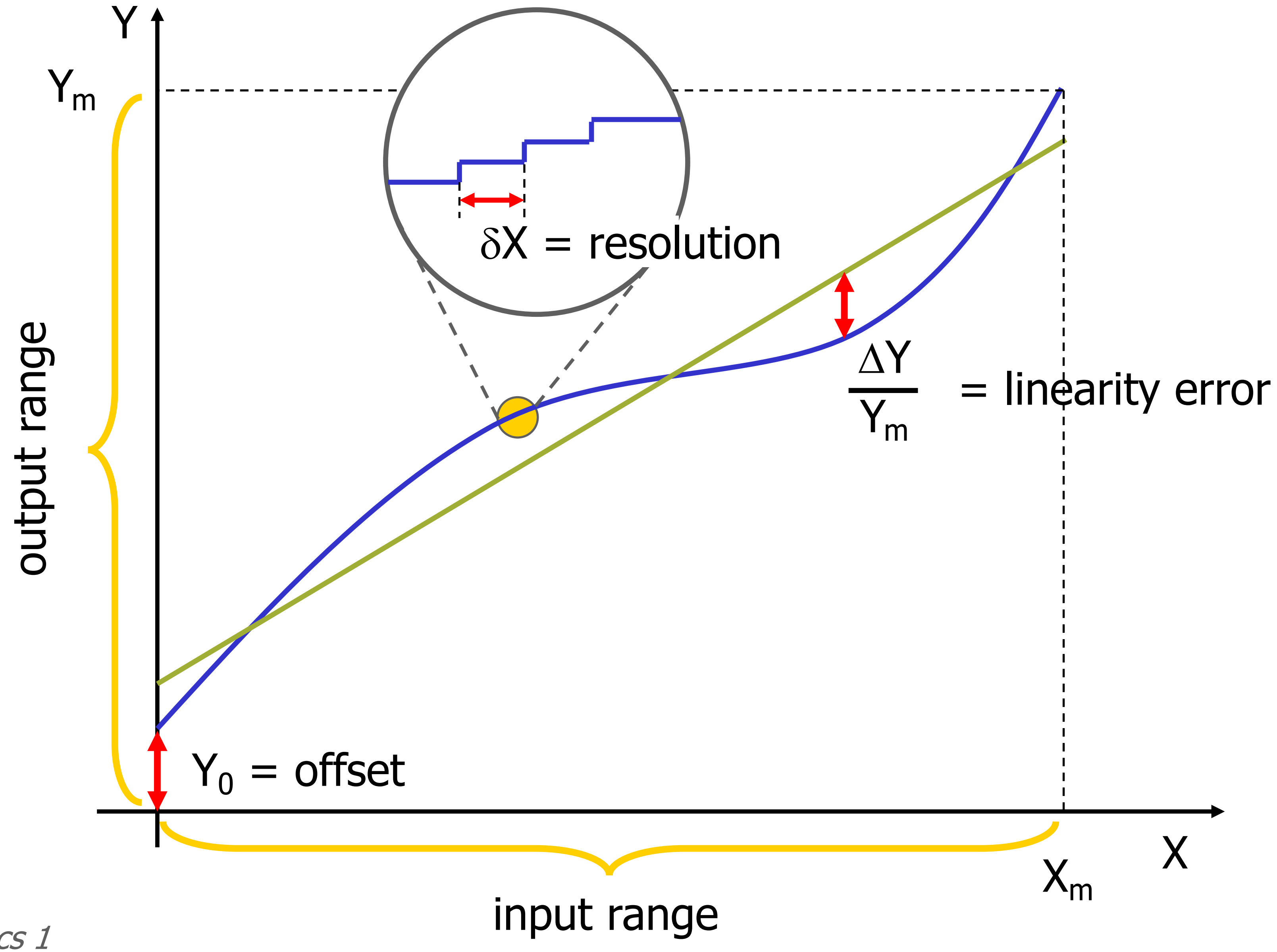
  - sometimes not zero after an operation cycle, due to hysteresis

- resolution error

  maximum variation of the input quantity producing no variation of the measured output

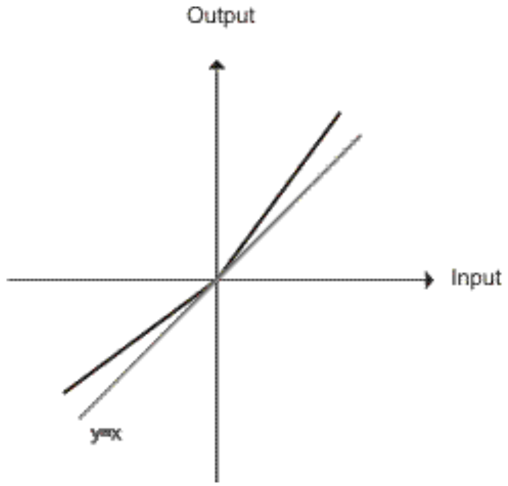
  - in absolute value or in % of the input range

Linearity, Offset, Resolution

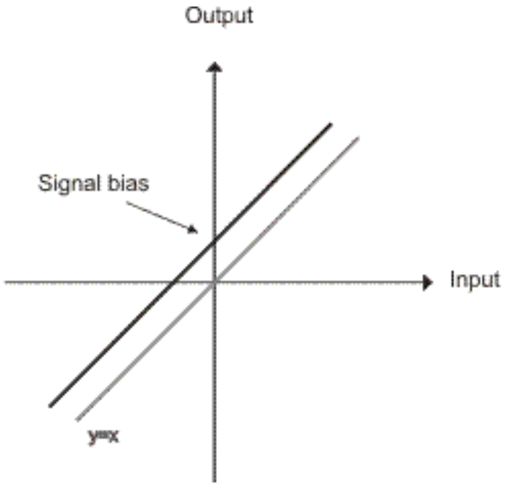


Sensor measurements

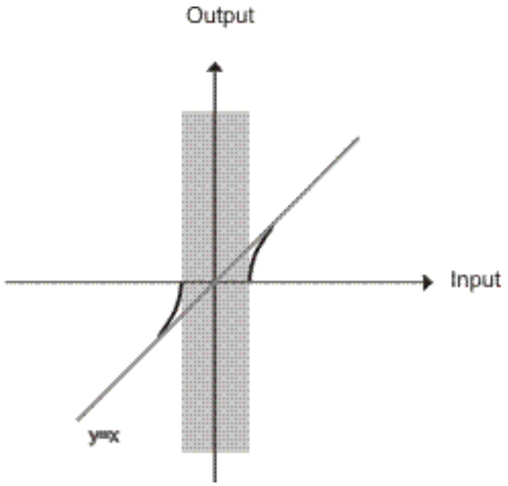
some non-idealities



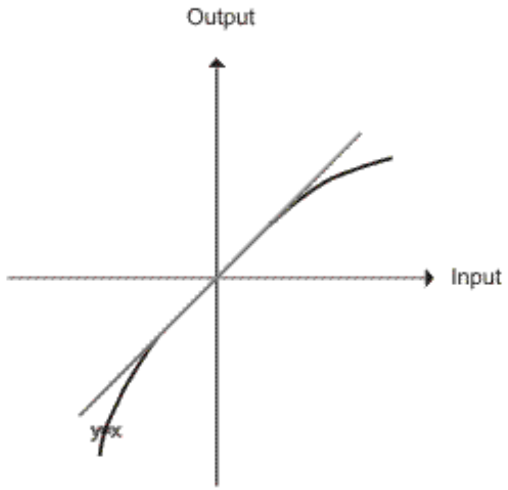
Asymmetry



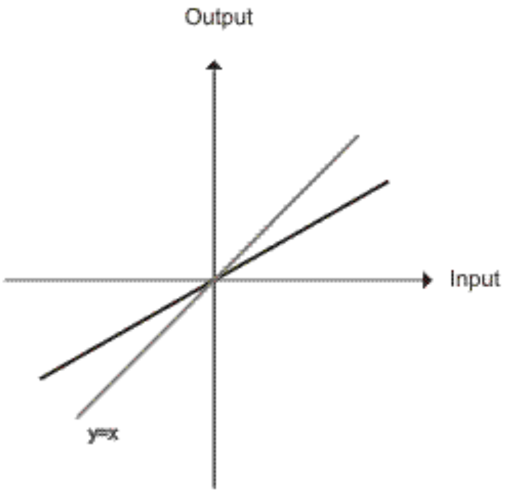
Bias



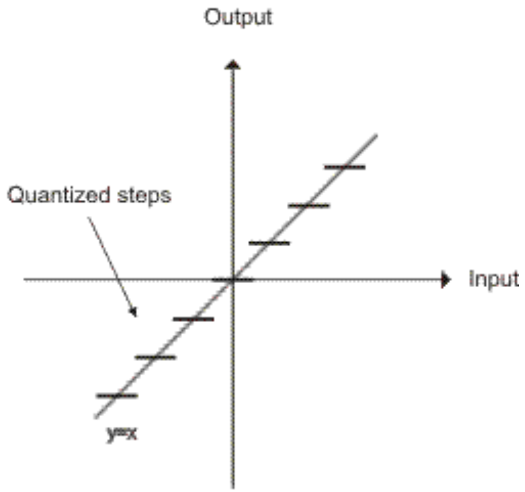
Dead zone



Nonlinearity



Scaling factor



Quantization

Classes of sensors for robots

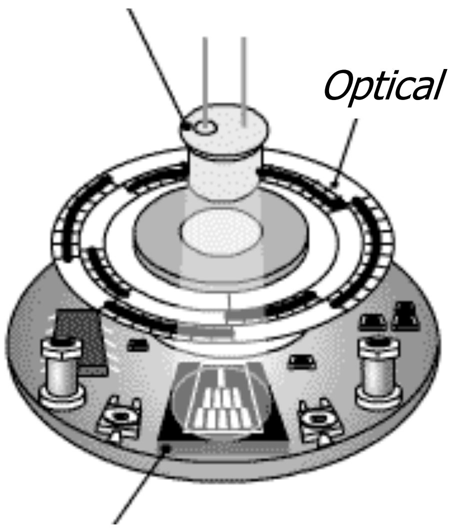
- proprioceptive sensors measure the internal state of the robot (position and velocity of joints, but also torque at joints or acceleration of links)
  - kinematic calibration, identification of dynamic parameters, control
- exteroceptive sensors measure/characterize robot interaction with the environment, enhancing its autonomy (forces/torques, proximity, vision, but also sensors for sound, smoke, humidity, …)
  - control of interaction with the environment, obstacle avoidance in the workspace, presence of objects to be grasped, …
  - mobile-base robots: localization in a map, navigation in unknown environments, …

Position sensors

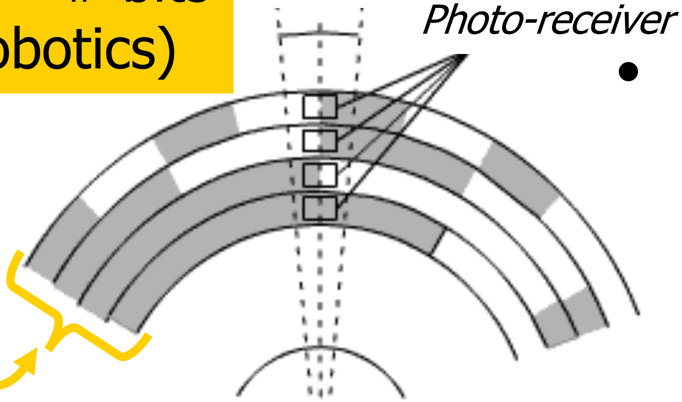
- provide an electrical signal proportional to the displacement (linear or angular) of a mechanical part with respect to a reference position
- linear displacements: potentiometers, linear variable-differential transformers (LVDT), inductosyns
- angular displacements: potentiometers, resolvers, syncros (all analog devices with A/D conversion), optical **encoders (digital)**, Hall sensors, ...

the most used in robotics, since also linear displacements are obtained through rotating motors and suitable transmissions

Absolute encoders



N_t = # tracks = # bits (min 12 in robotics)

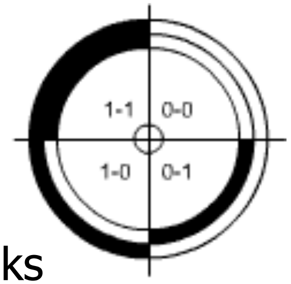


- rotating optical disk, with alternate transparent and opaque sectors on multiple concentric tracks
- (infrared) light beams are emitted by leds and sensed by photo-receivers
- light pulses are converted into electrical pulses, electronically processed and transmitted in output
- resolution = $360^\circ / 2^{N_t}$
- digital encoding of absolute position

when the optical disk is rotating fast, the use of binary coding may lead to (large) reading errors, in correspondence to multiple transitions of bits

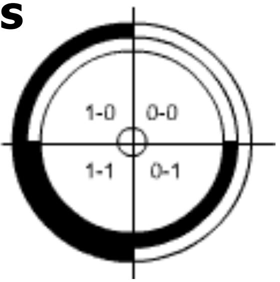
Absolute encoding

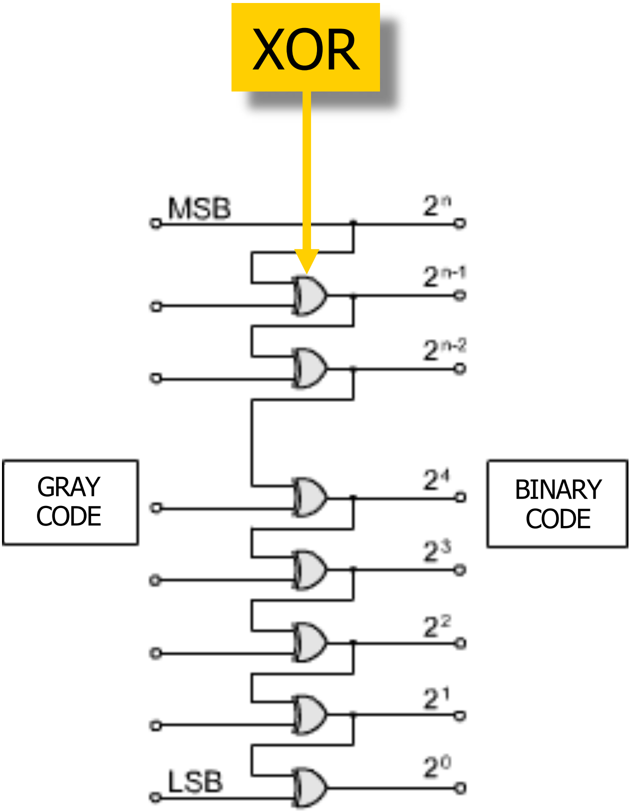
binary coding



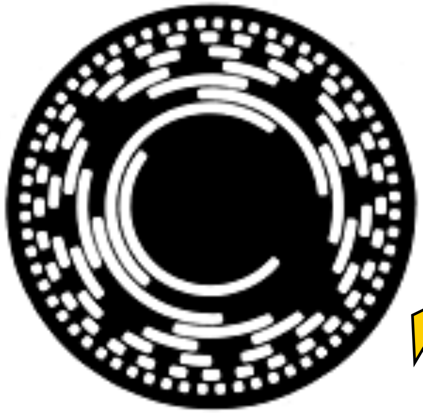
optical disks with **2 bits**

Gray coding





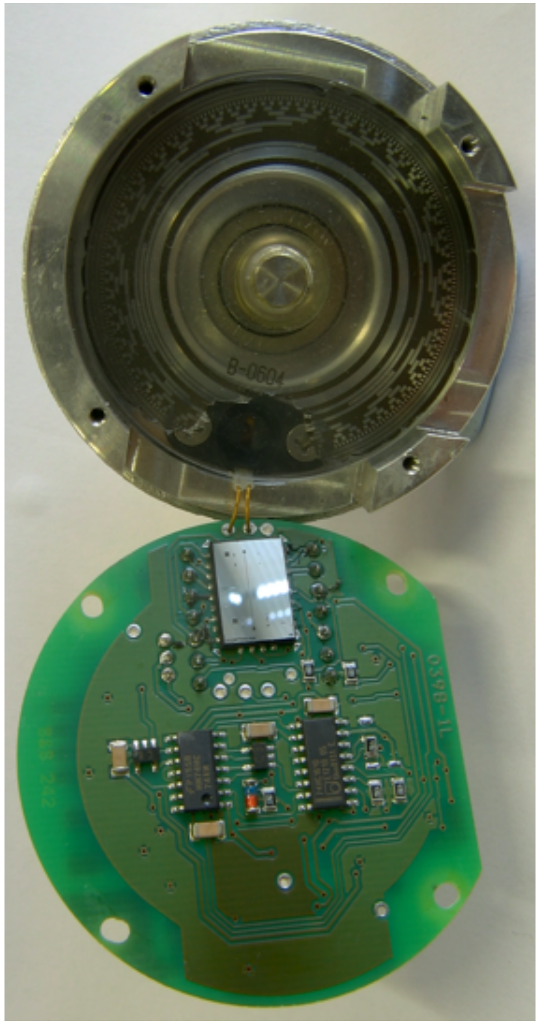
DECIMAL	BINARY	GRAY
0	0000	0000
1	0001	0001
2	0010	0011
3	0011	0010
4	0100	0110
5	0101	0111
6	0110	0101
7	0111	0100
8	1000	1100
9	1001	1101
10	1010	1111
11	1011	1110
12	1100	1010
13	1101	1011
14	1110	1001
15	1111	1000



8-bit Gray-coded absolute encoder

adjacent codes differ by just one bit

Use of absolute encoders



13-bit absolute encoder opened: Gray-coded disk and electronics

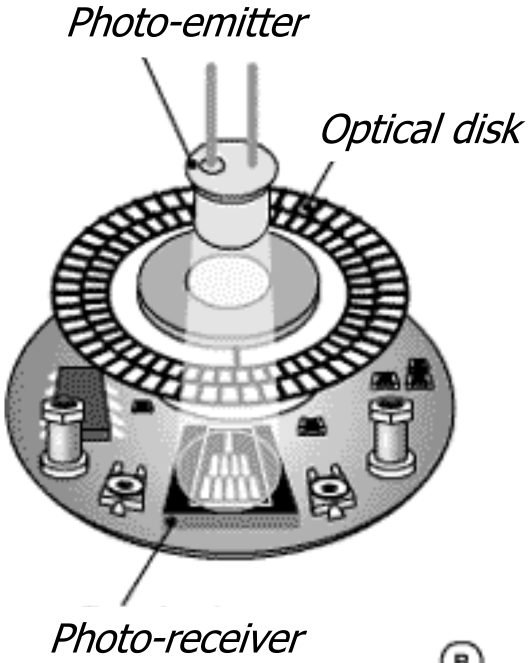
- ready to measure at start (no "homing")
- two modes for permanent operation
  - when switching off the drive, position parameters are saved on a flash memory (and brakes activated)
  - battery for the absolute encoder is always active, and measures position even when the drive is off
  - data memory > 20 years
- single-turn or multi-turn versions, e.g.
  - 13-bit single-turn has $2^{13} = 8192$ steps per revolution (resolution = 0.044°)
  - 29-bit multi-turn has 8192 steps/revolution + counts up to $2^{16} = 65536$ revolutions
- aluminum case with possible interface to field bus systems (e.g., CANopen or PROFIBUS)
- typical supply 5/28V DC @1.2 W

hollow shaft

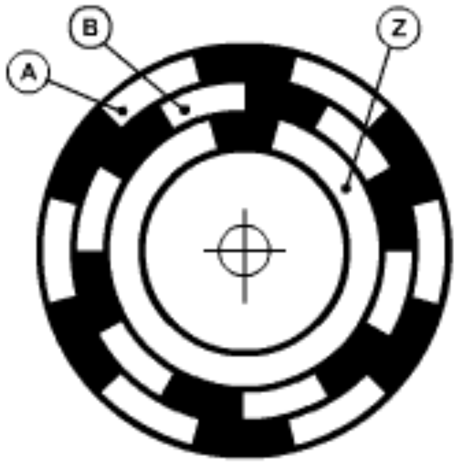
round flange

multi-turn

Incremental encoders



- optical rotating disk with three tracks, alternating transparent and opaque areas: measures incremental angular displacements by counting trains of N_e pulses ("counts") per turn ($N_e = 100 \div 5000$)

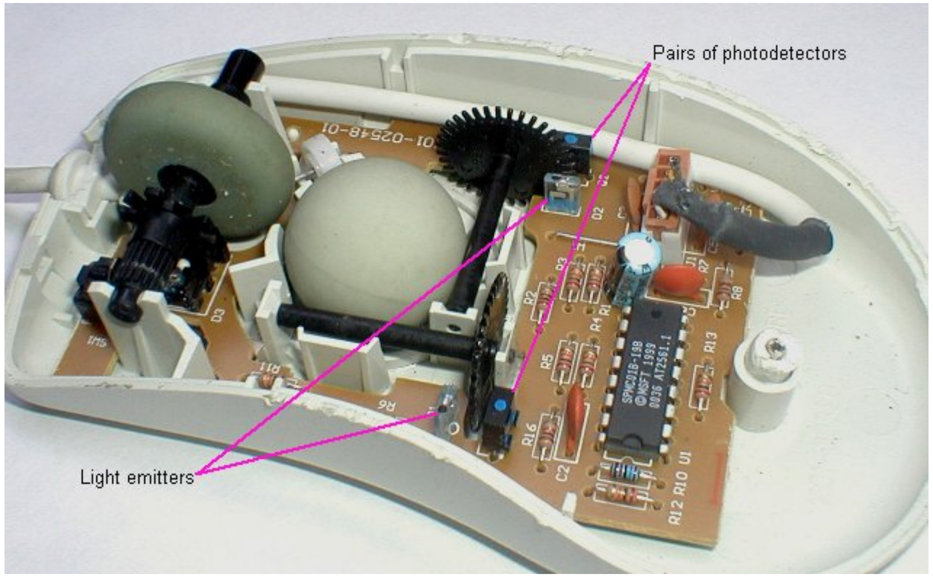


The three tracks on an optical disk (here $N_e = 6$)

- the two A and B tracks (channels) are in quadrature (phase shift of 90° electrical), allowing to detect the direction of rotation
- a third track Z is used to define the "0" reference position, with a reset of the counter (needs "homing" at start)
- some encoders provide as output also the three phases needed for the switching circuit of brushless motors

Incremental encoders

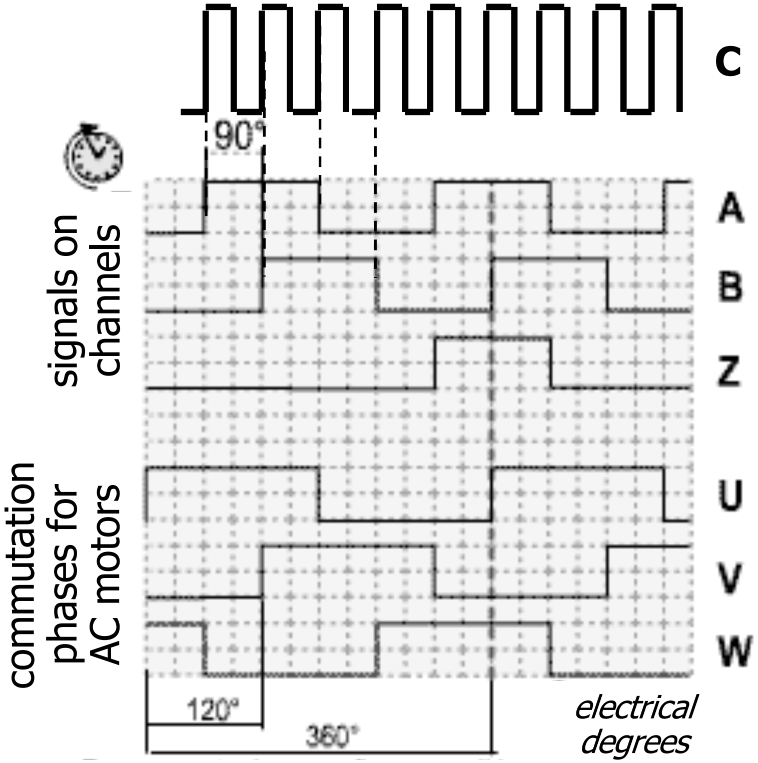
- two (cheap) incremental encoders inside a mouse



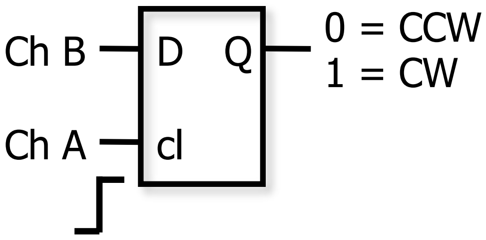
- a OMRON incremental encoder with 2000 pulses/turn

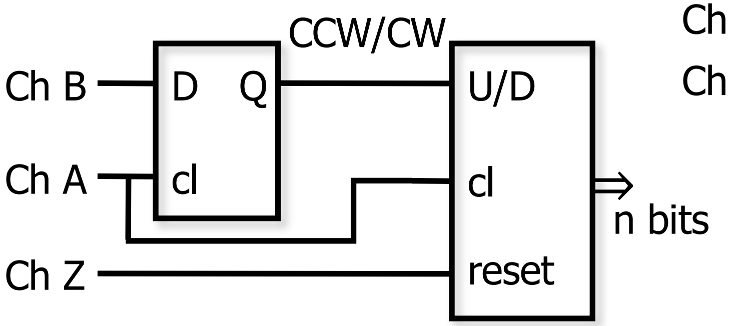
diameter ∅ 40 mm
mass m ≈ 100 g
inertia $J = 1 \cdot 10^{-6}$ kg m^2

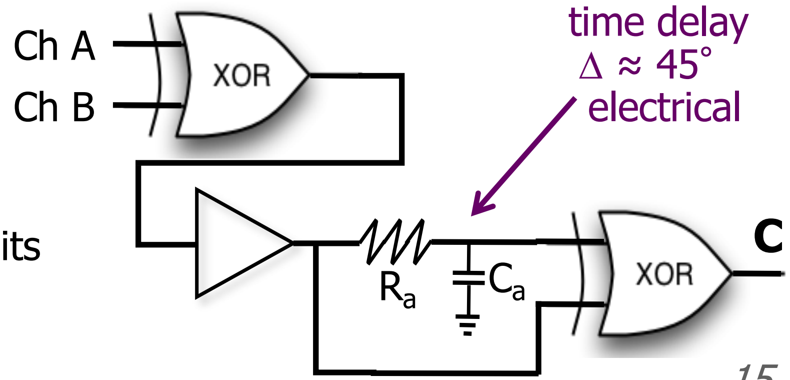
Signal processing



- "fractions of a cycle" of each pulse train are measured in "electrical degrees"
- 1° electrical = 1° mechanical/N_e
  360° mechanical = 1 turn
- signals are fed in a digital counter, with a D-type flip-flop to sense direction + reset
- to improve resolution (4 ×), the leading and trailing edges of signals A and B are used
- the sequence of pulses C will clock now the counter (increments or decrements)

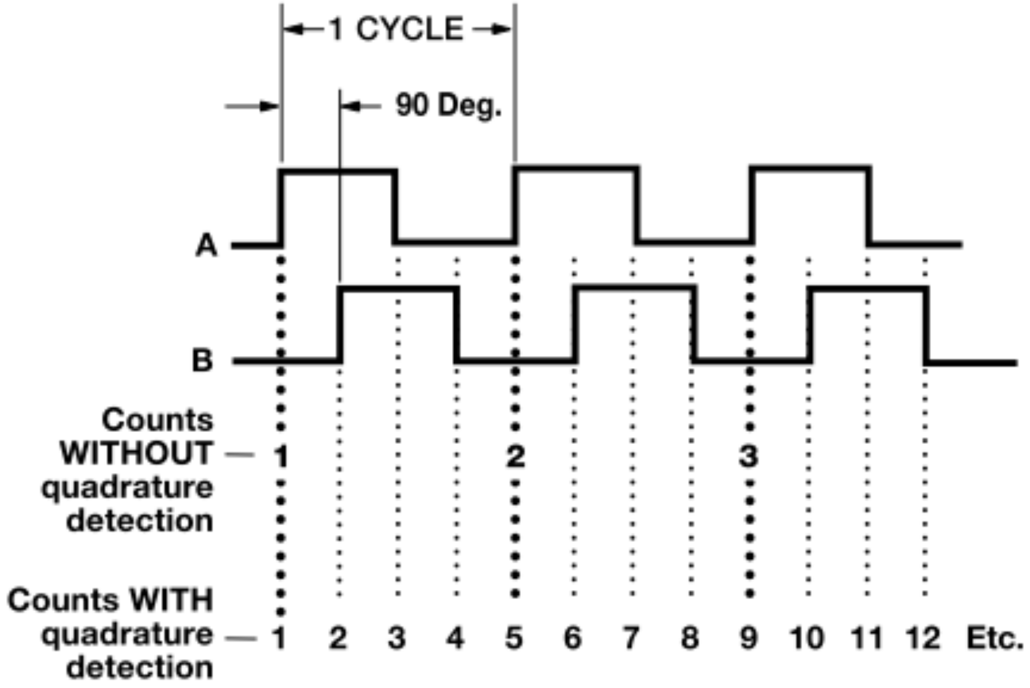






Count multiplication

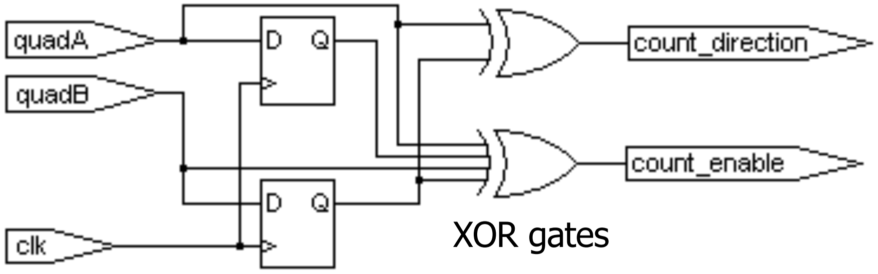
example of quadrature detection



- an incremental encoder with $N_e = 2000$ (electrical) cycles provides a count of $N = 8000$ pulses/turn after electronic multiplication
- its final resolution is (mechanical) $360^\circ/8000 = .045^\circ$ ($= 0^\circ\ 2'\ 42''$)
- needs a 13-bit counter to cover a full turn without reset ($2^{13} = 8192$)

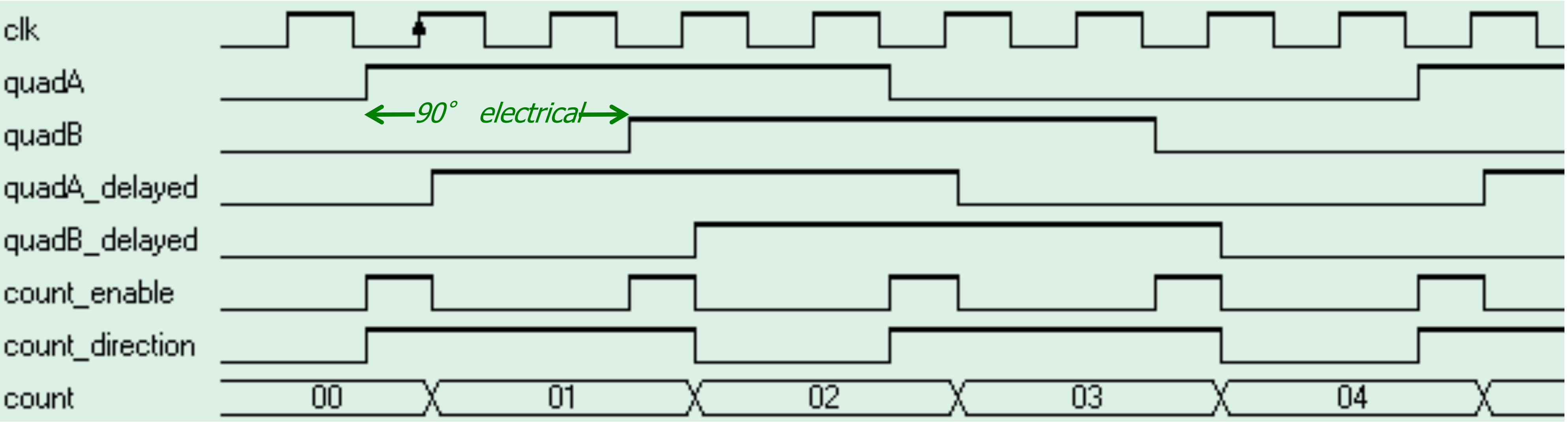
Quadrature detection in incremental encoders

a more complete implementation


D (delay) flip-flops

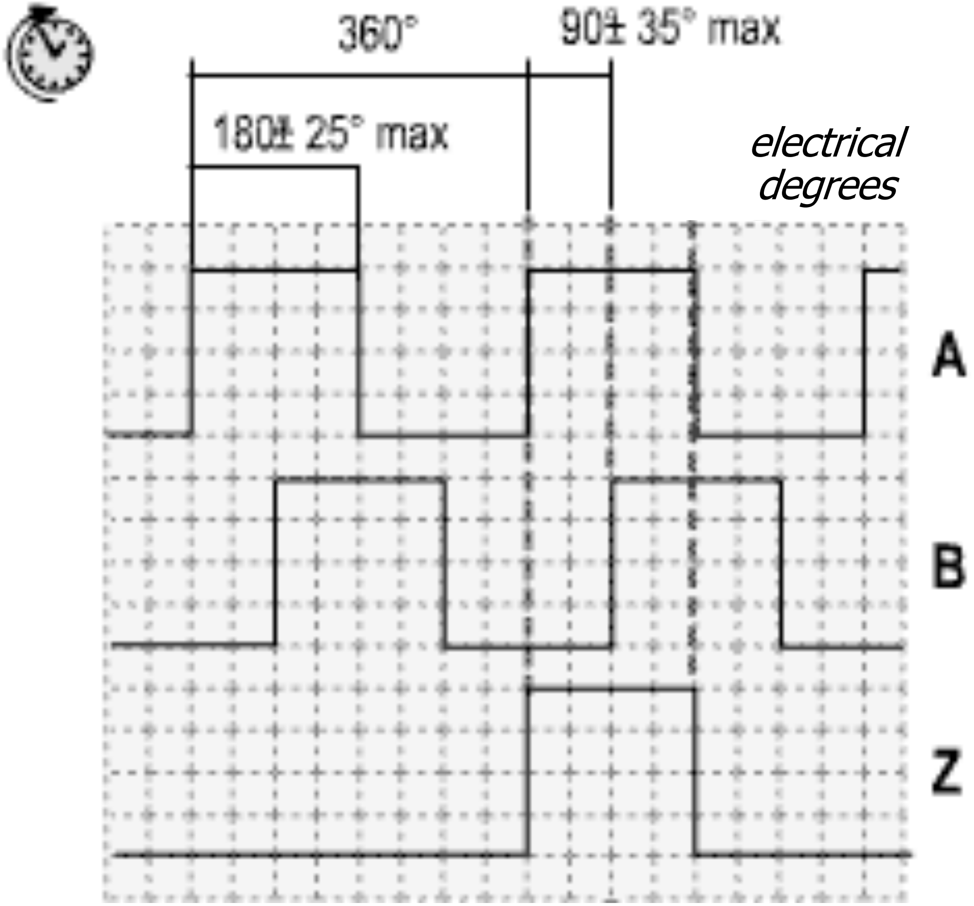
XOR gates

NOTE: since in practice A and B signals may
not be synchronous to the clock signal,
two extra D flip-flops per input should be used
to avoid meta-stable states in the counters



- it is assumed that an oversampling clock "clk" (e.g., as provided by a FPGA) is available, which is faster than the two quadrature signals A and B
- the digital count output will have a resolution multiplied by 4

Accuracy in incremental encoders



...apart from quantization errors

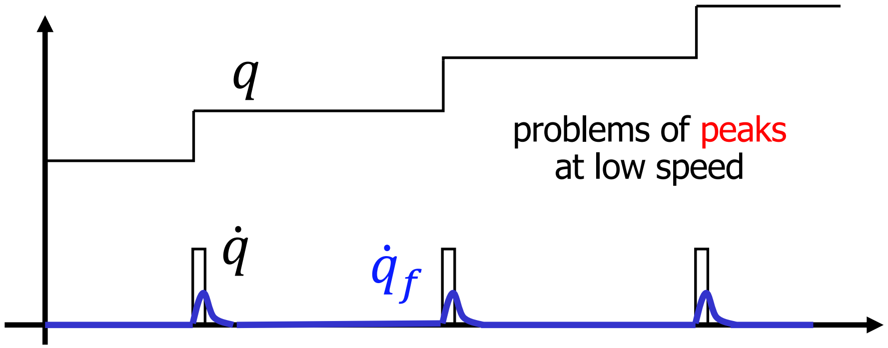
- division error: maximum displacement between two consecutive leading/trailing edges, typically within max ± 25° electrical
- the phase shift of the two channels, nominally equal to 90° electrical, is typically within max ± 35° electrical (quadrature error)

Indirect measure of velocity

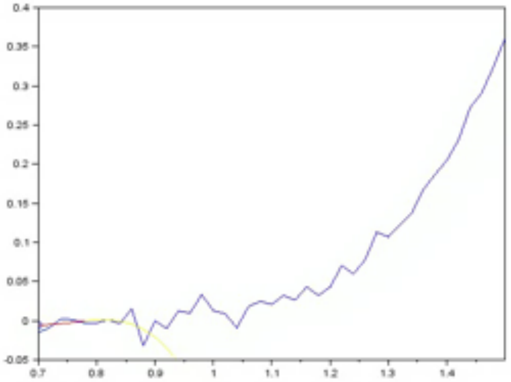
- numerical differentiation of digital measures of position
  - to be realized on line with Backward Differentiation Formulas (BDFs)
  - 1-step BDF (Euler): $\dot{q}_k = \dot{q}(kT) = \dfrac{1}{T}(q_k - q_{k-1}) \iff \dot{q}_k = \dfrac{\Delta q_k}{T} \Longleftarrow$
  - 4-step BDF: $\dot{q}_k = \dfrac{1}{T}\left(\dfrac{25}{12}q_k - 4q_{k-1} + 3q_{k-2} - \dfrac{4}{3}q_{k-3} + \dfrac{1}{4}q_{k-4}\right)$

directly
from
incremental
encoder

- convolution filtering is needed because of noise and position quantization
  - use of non-causal filters (e.g., Savitzky-Golay) helps, but introduces delays
- Kalman filter for on line state estimation (optimal, assuming Gaussian noise)



problems of peaks
at low speed



animation of Savitzky-Golay filter
with cubic polynomials

Kinematic Kalman Filter
for velocity estimation

motion and sensing discrete-time model for estimation

$$\boldsymbol{\xi}(k) = \begin{pmatrix}1 & T\\ 0 & 1\end{pmatrix}\boldsymbol{\xi}(k-1) + \boldsymbol{\mu}$$

$$z(k) = \begin{pmatrix}1 & 0\end{pmatrix}\boldsymbol{\xi}(k) + \nu$$

noisy position measure (encoder output)

zero mean Gaussian noises with (co)variances $\boldsymbol{Q}$ (a matrix) and R

T = sampling time

$$\boldsymbol{\xi}(k) = \left(x(k)\ \dot{x}(k)\right)^T$$

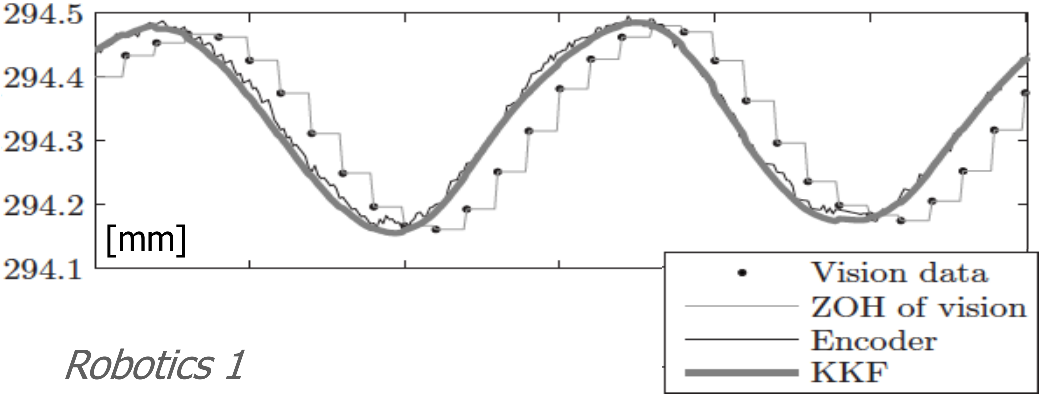
actual state

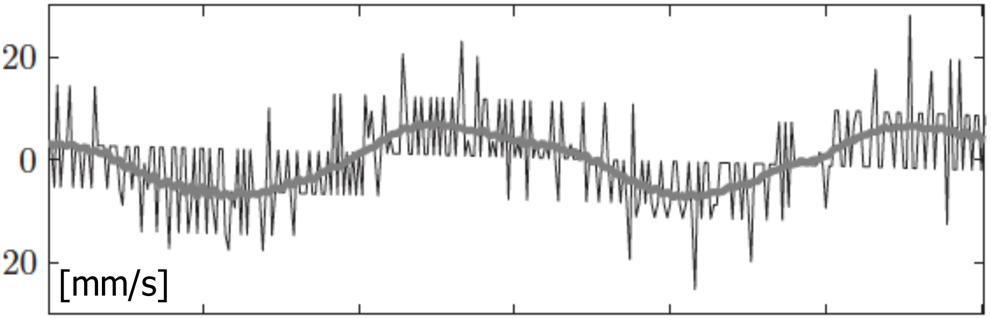
unmeasured velocity

design a (linear) Kalman filter providing an estimate $\hat{\boldsymbol{\xi}}(k)$ of the model state

$$\hat{\boldsymbol{\xi}}(k) = \underbrace{\begin{pmatrix}1 & T\\ 0 & 1\end{pmatrix}\hat{\boldsymbol{\xi}}(k-1)}_{\text{(a priori) }\textbf{prediction}} + \boldsymbol{K}_k \underbrace{\left(z(k) - \begin{pmatrix}1 & 0\end{pmatrix}\begin{pmatrix}1 & T\\ 0 & 1\end{pmatrix}\hat{\boldsymbol{\xi}}(k-1)\right)}_{\textbf{correction}\text{ (based on the measured output)}}$$

using the optimal Kalman gain $\boldsymbol{K}_k$

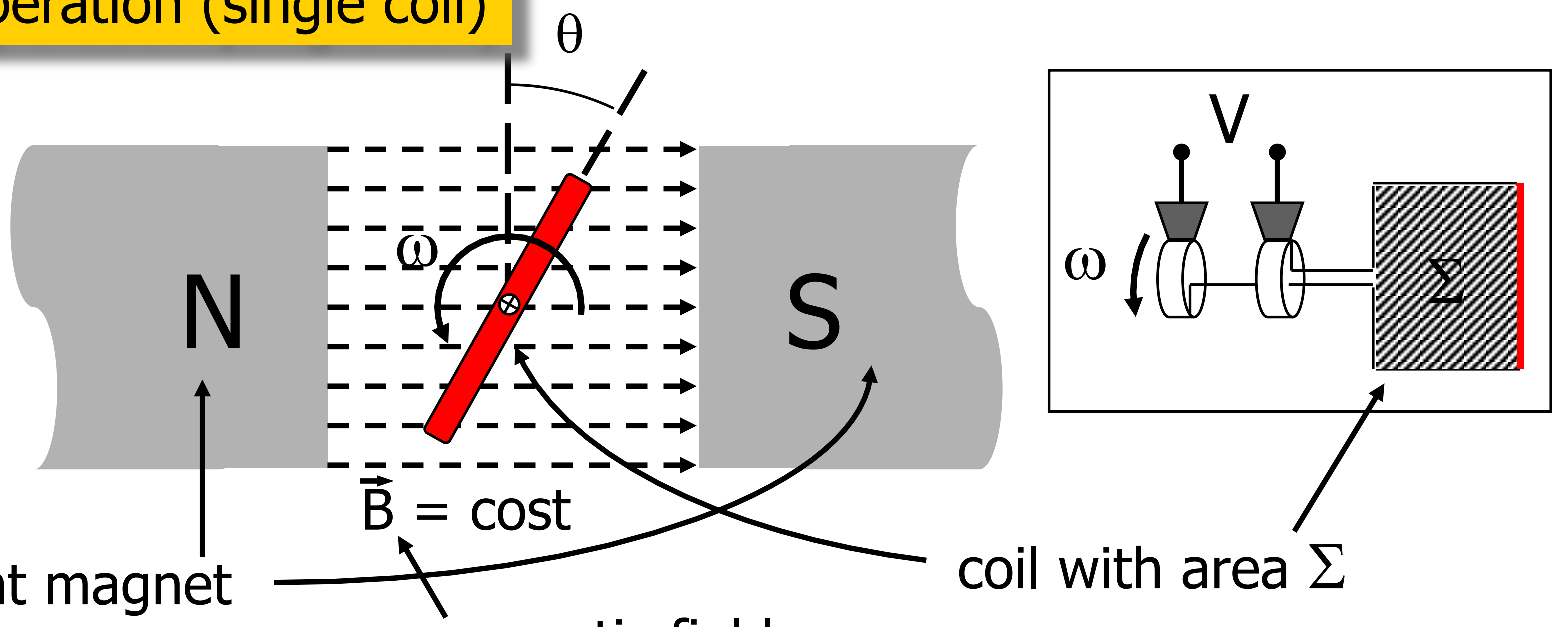

position measure and its filtered version


numerical velocity and its filtered estimate

Velocity sensor: Tachometer

always mounted on the (electrical) motor axis

principle of operation (single coil)



permanent magnet

coil with area Σ

magnetic field:

flux through the coil is $\Phi(\vec{B}) = |\vec{B}|\Sigma \cos\theta = |\vec{B}|\Sigma \cos\omega t$

$$V = -\,d\Phi/dt = |\vec{B}|\Sigma\,\omega \sin\omega t$$

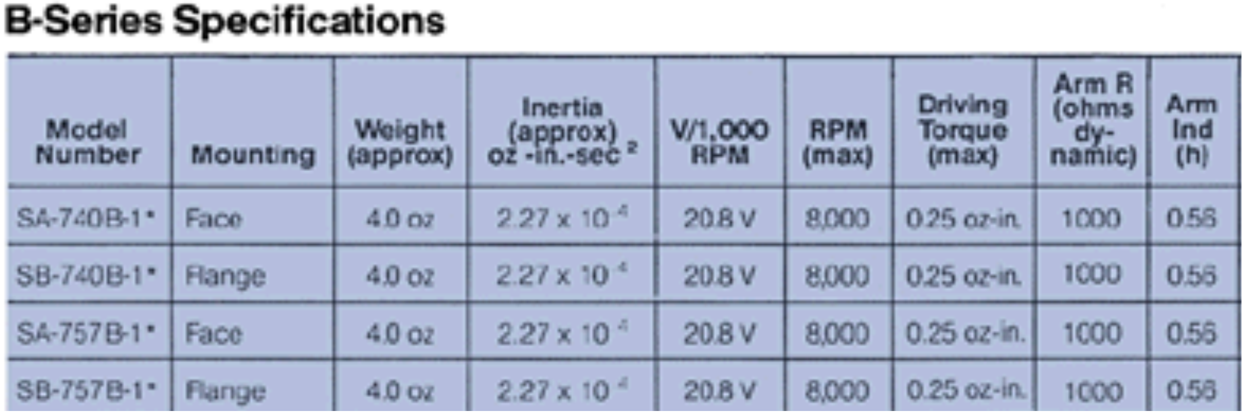
⇒ to reduce ripples, use m coils
rotated regularly by 180°/m

amplitude $V \propto \omega$

DC tachometer

an example

- Servo-Tek Tach Generator (B series)
- bi-directional
- output voltage 11÷24 V @1000 RPM
- low ripple: < 3% peak-to-peak of DC value (with 72 KHz filter)
- weight = 113 g, diameter = 2.9 cm
- linearity error < 0.1% (at any speed)
- stability 0.1% (w.r.t. temperature)



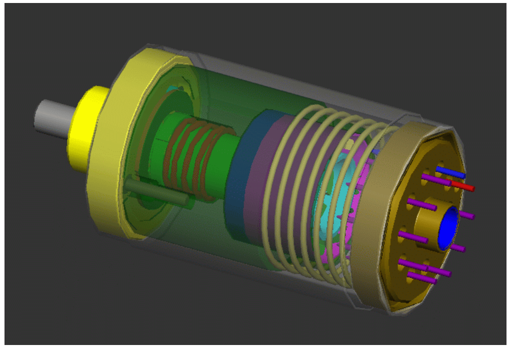
B-Series Specifications

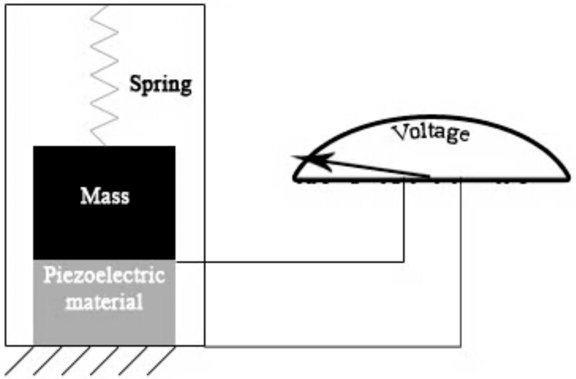
Model Number	Mounting	Weight (approx)	Inertia (approx) oz -in.-sec ^{2}	V/1,000 RPM	RPM (max)	Driving Torque (max)	Arm R (ohms dy-namic)	Arm Ind (h)
SA-740B-1*	Face	4.0 oz	2.27×10^{-4}	20.8 V	8,000	0.25 oz-in.	1000	0.56
SB-740B-1*	Flange	4.0 oz	2.27×10^{-4}	20.8 V	8,000	0.25 oz-in.	1000	0.56
SA-757B-1*	Face	4.0 oz	2.27×10^{-4}	20.8 V	8,000	0.25 oz-in.	1000	0.56
SB-757B-1*	Flange	4.0 oz	2.27×10^{-4}	20.8 V	8,000	0.25 oz-in.	1000	0.56

↑ 1.75 mNm (as a load)

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)
- different principles for converting mechanical motion in an electrical signal
  - piezoelectric: piezoceramics (PZT) or crystals (quartz), better linearity & stability, wide dynamic range up to high frequencies, no moving parts, no power needed
  - piezoresistive: for high-shocks, measures also static acceleration (g_0), needs supply
  - capacitive: silicon micro-machined sensing element, superior in static to low frequency range, can be operated in servo mode, cheap but limited resolution
  - modern solution: small MEMS (Micro Electro-Mechanical Systems)
- multiple applications: from vibration analysis to long range navigation



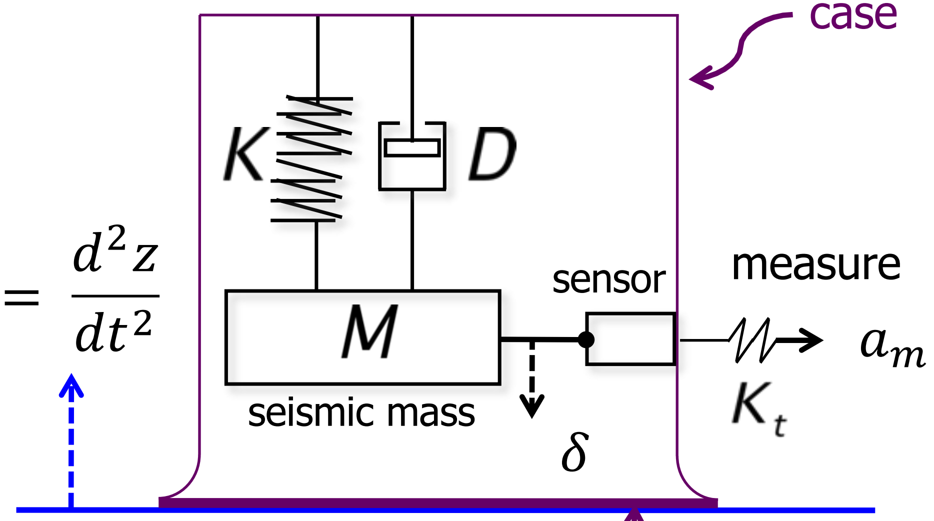


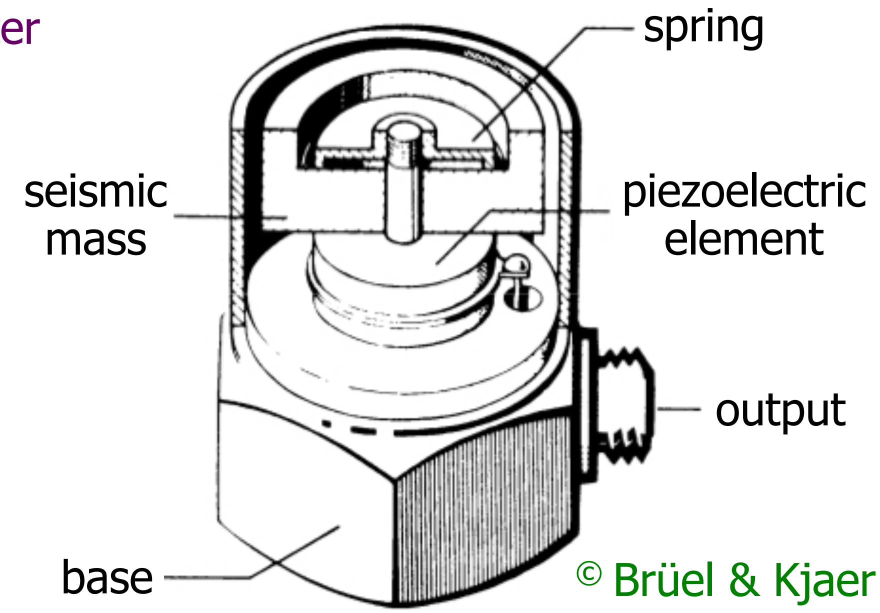
animation of measurement principle in a piezoelectric accelerometer

Operation principle

seismic accelerometer

$$a = \frac{d^2 z}{dt^2}$$





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$$Ma = M\ddot{\delta} + D\dot{\delta} + K\delta$$

$$a_m = K_t \delta$$

$$\xrightarrow[\text{transform}]{\text{by Laplace}}$$

$$\frac{A_m(s)}{A(s)} = K_t \frac{M}{Ms^2 + Ds + K}$$

$$= \frac{K_t}{s^2 + (D/M)s + (K/M)}$$

Frequency characteristics

of a piezoelectric accelerometer

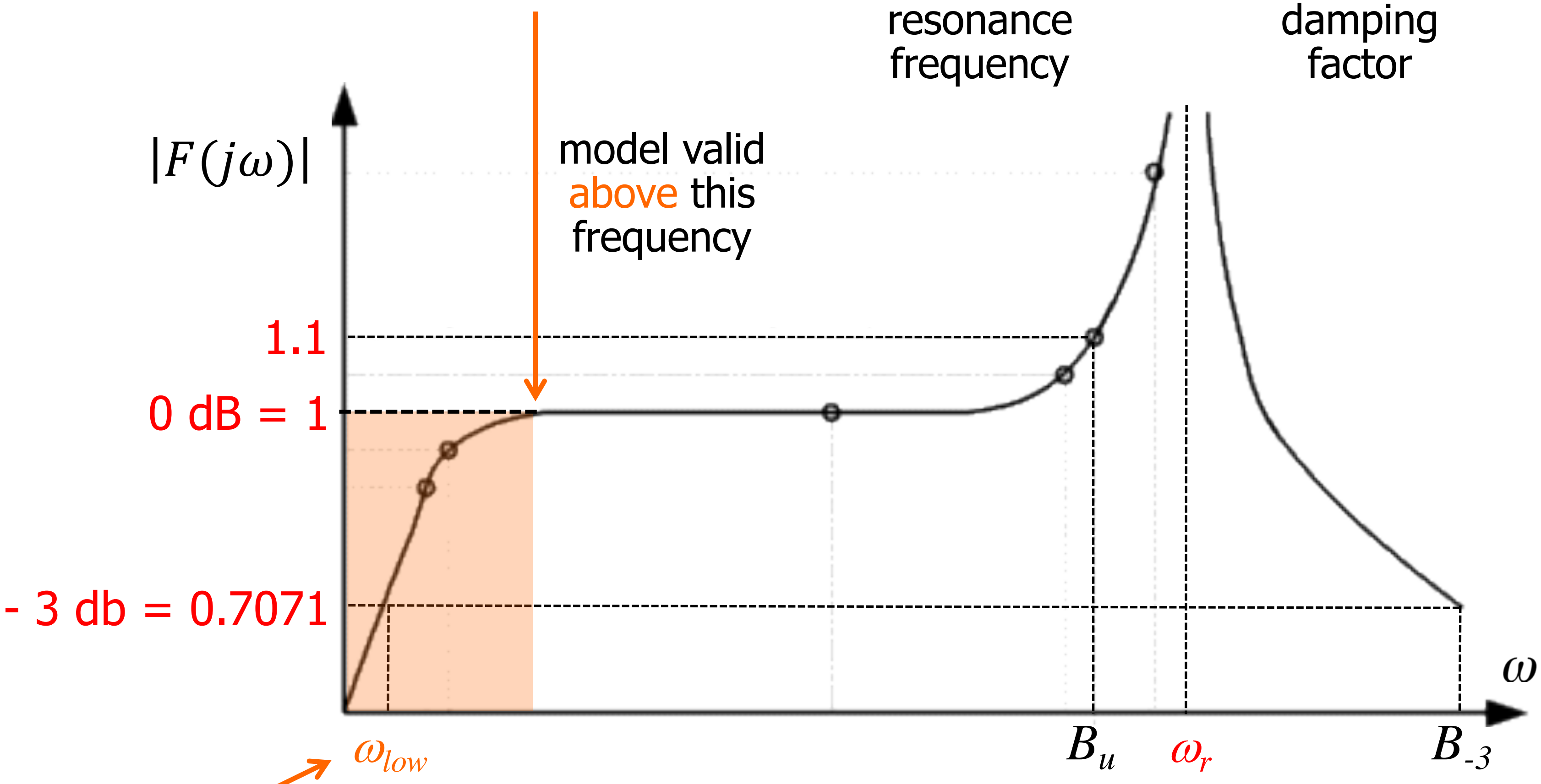
$$F(s) = \frac{A_m(s)}{A(s)} = \frac{K_t}{s^2+(D/M)s+(K/M)}$$

$$\omega_r = \sqrt{K/M}$$

resonance frequency

$$\zeta = \frac{D}{2}\sqrt{1/KM}$$

damping factor



model valid above this frequency

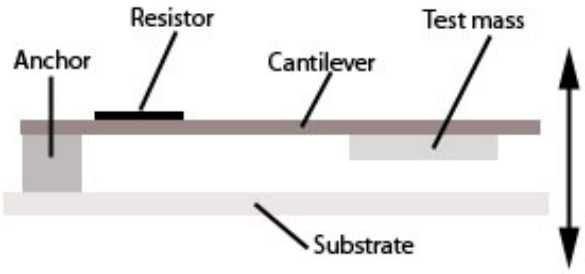
low frequency limit of piezoelectric use (≤ 1 Hz)

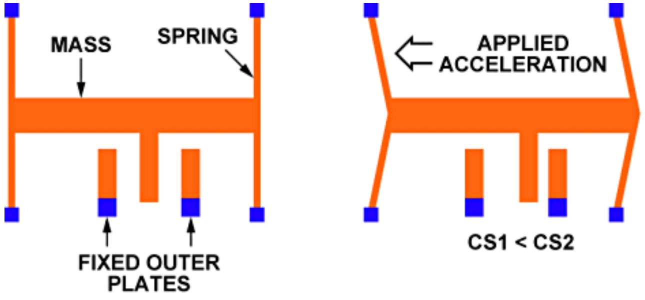
useful bandwidth $B_u \approx 0.3\omega_r$ for 10% error

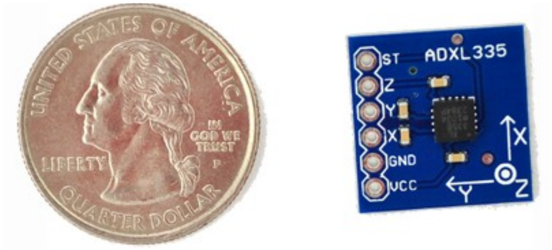
bandwidth

MEMS accelerometers

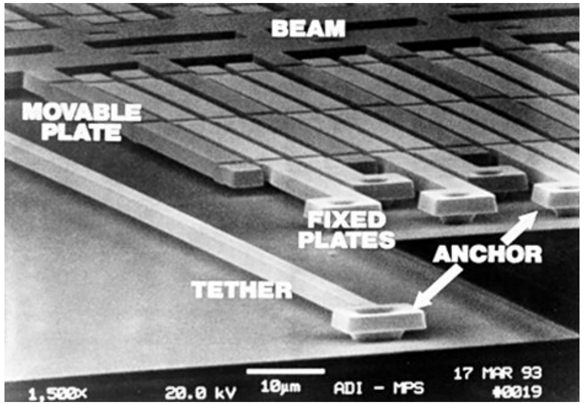
- very simple MEMS (a cantilever beam with a test mass, with damping from the residual gas sealed in the device), single- or tri-axial, very small and light
- cross-couplings among acceleration sensing directions should be limited ≤ 3%

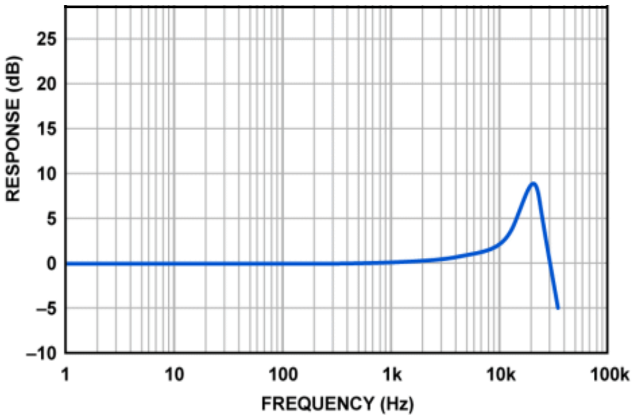


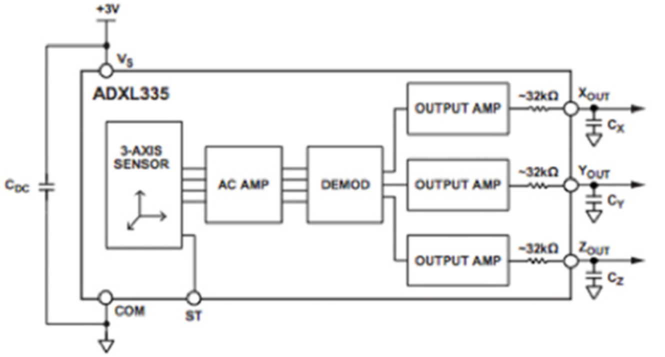




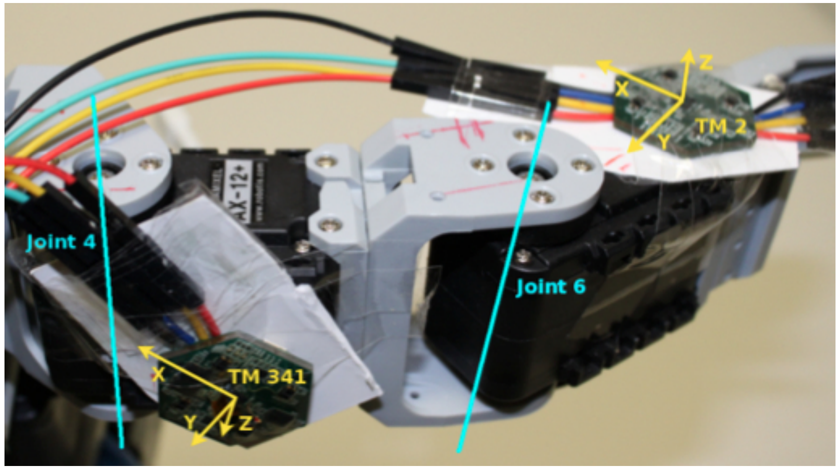
ADXL335 3-axis, small, low power, ±3g, with signal conditioned voltage outputs



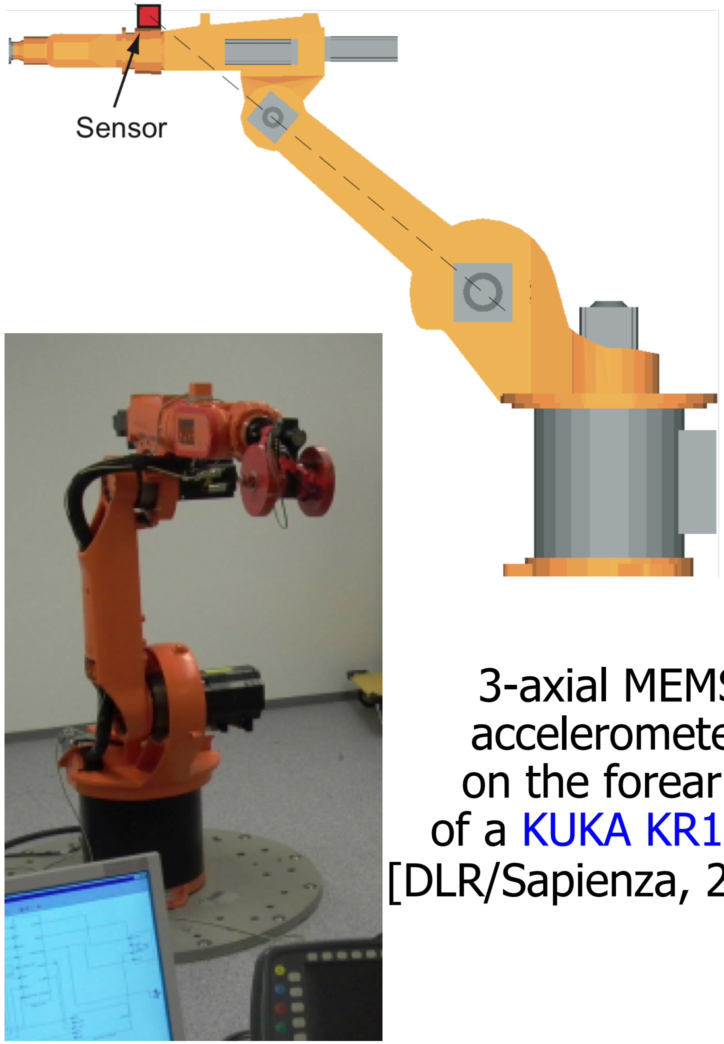




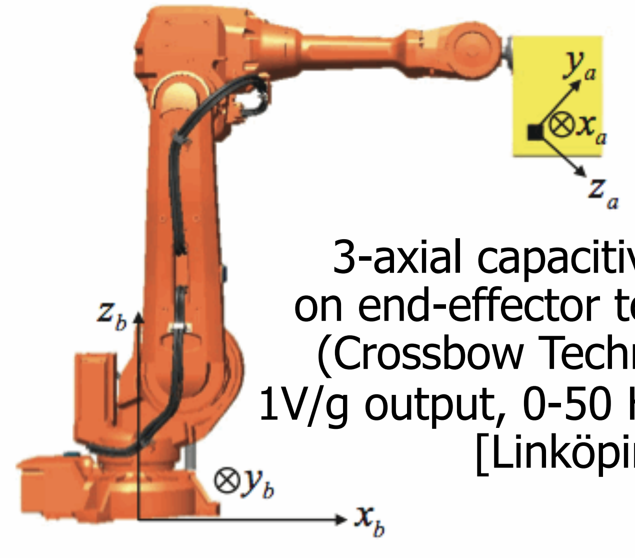
Mounting accelerometers on robots



Bosch BMA 150 3-axial accelerometers integrated in two larger Tactile Modules on the links of a Bioloid humanoid left arm [TUM, 2011]



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



3-axial capacitive accelerometer on end-effector tool of an ABB robot (Crossbow Technology: 2g range, 1V/g output, 0-50 Hz, ±2° align error) [Linköping, 2012]