



Robotics 1

Robot components: Proprioceptive sensors

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DIPARTIMENTO DI INGEGNERIA INFORMATICA
AUTOMATICA E GESTIONALE ANTONIO RUBERTI



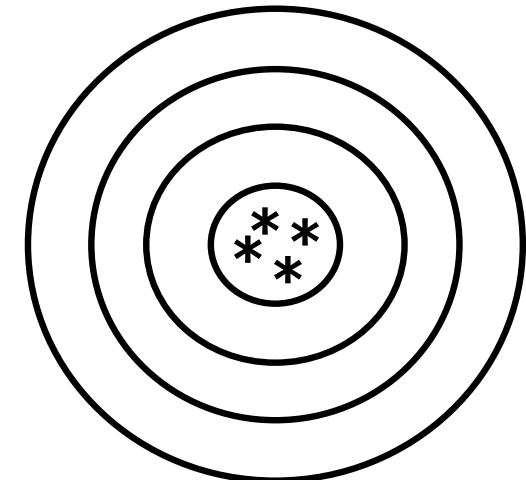
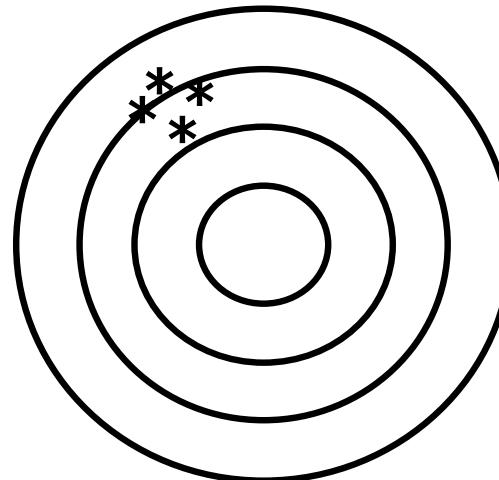
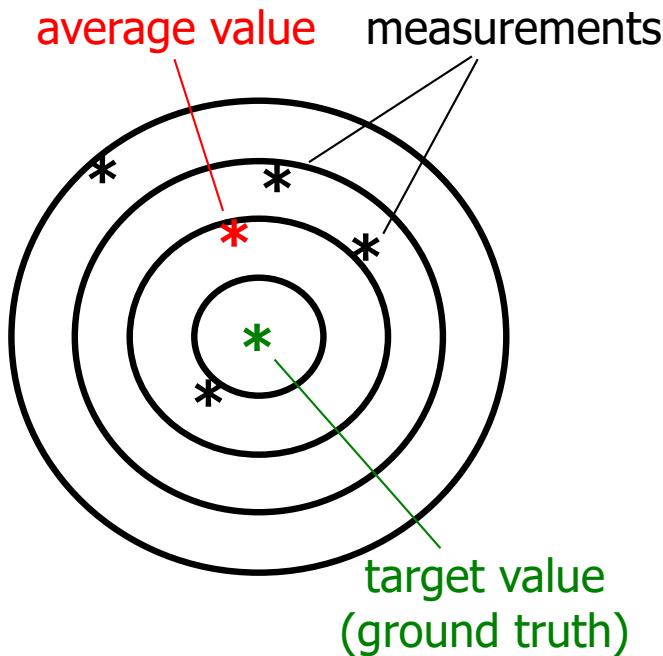


Properties of measurement systems - 1

- **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
- 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”

[video](#)



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

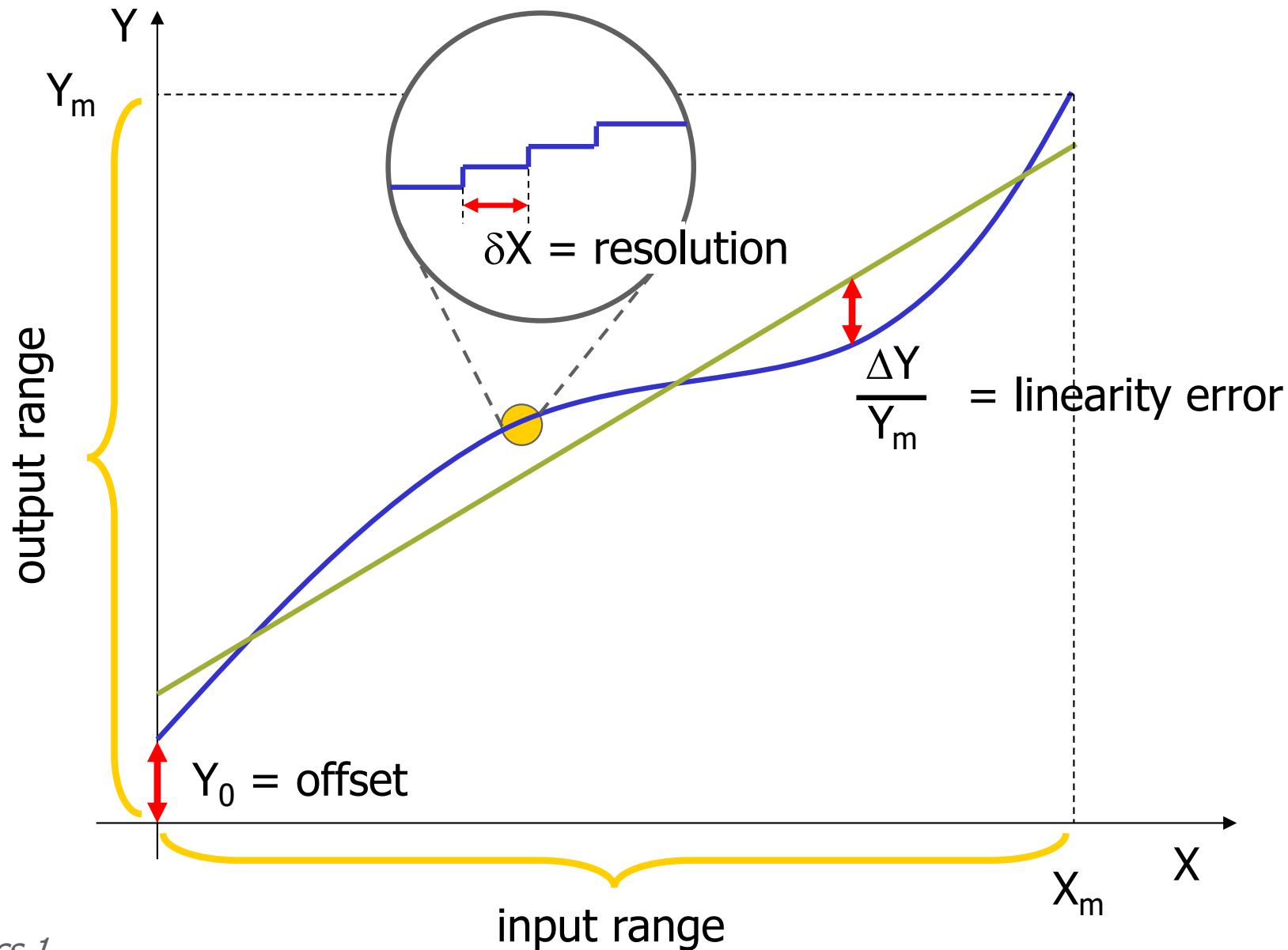


Properties of measurement systems - 2

- **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

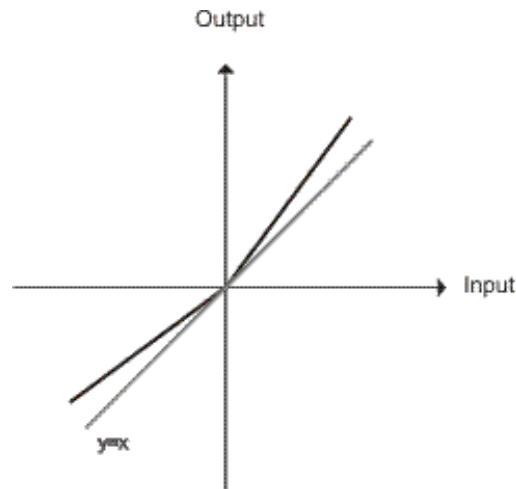


Linearity, Offset, Resolution

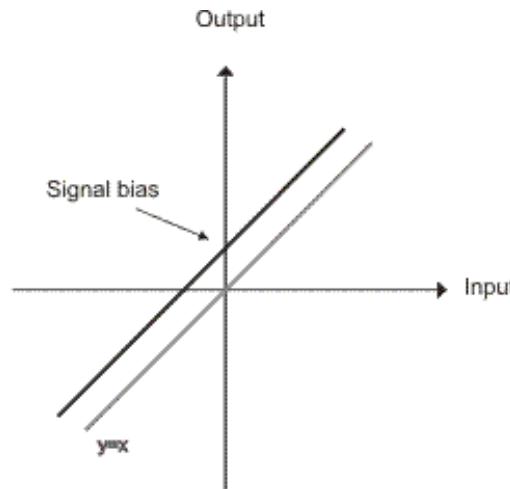




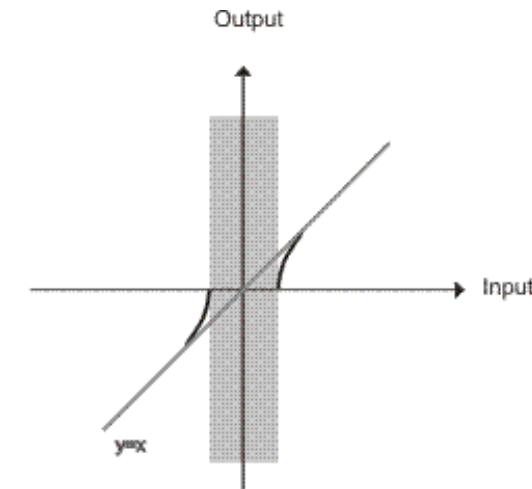
Sensor measurements some non-idealities



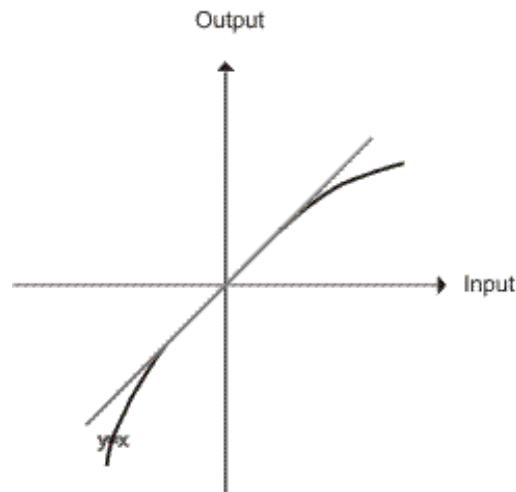
Asymmetry



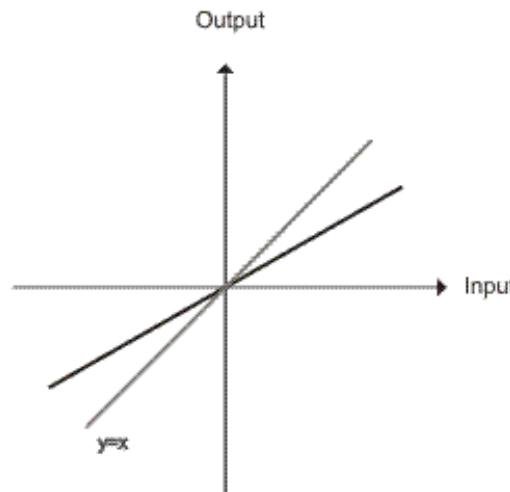
Bias



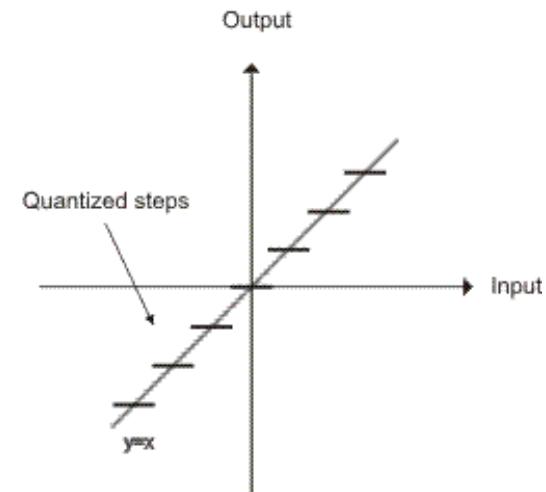
Dead zone



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

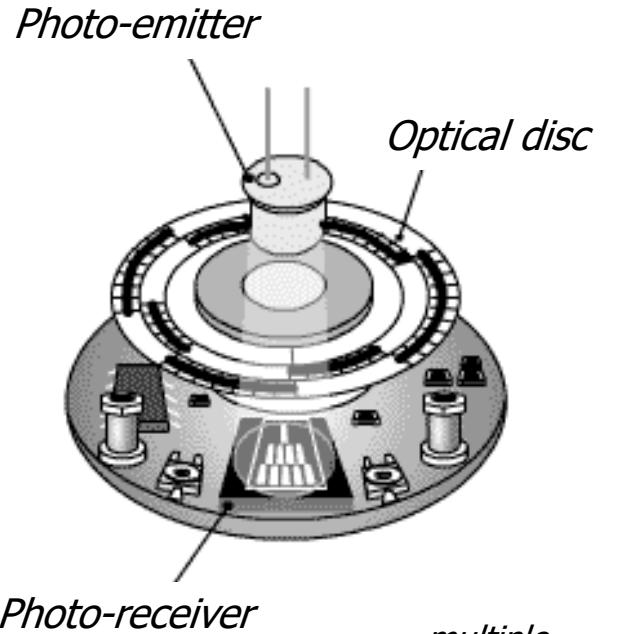
- provide an **electrical signal proportional to the displacement** (linear or angular) of a mechanical part with respect to a reference position
- **linear** displacements: potentiometers, linear variable-differential transformers (LVDT), inductosyns
- **angular** displacements: potentiometers, resolvers, 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



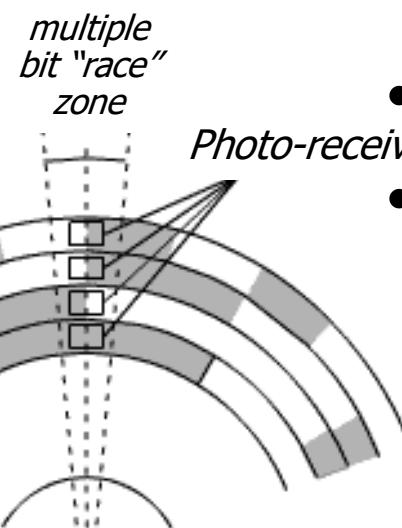


Absolute encoders



$$N_t = \# \text{ tracks} = \# \text{ bits}$$

(min 12 in robotics)

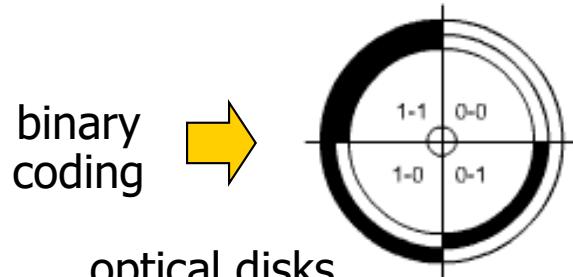


- rotating optical disk, with alternate transparent and opaque sectors on multiple concentric tracks
- (infrared) light beams are emitted by leds and sensed by photo-receivers
- light pulses are converted into electrical pulses, electronically processed and transmitted in output
- **resolution** = $360^\circ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

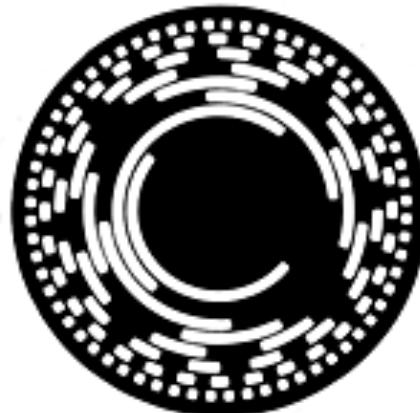
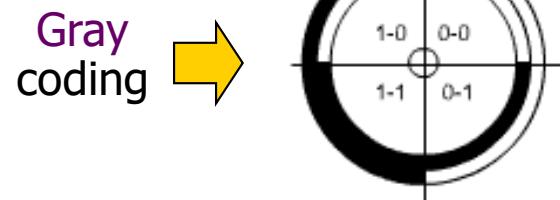
when the optical disk is rotating fast, the use of **binary coding** may lead to (large) reading errors, in correspondence to multiple transitions of bits



Absolute encoding

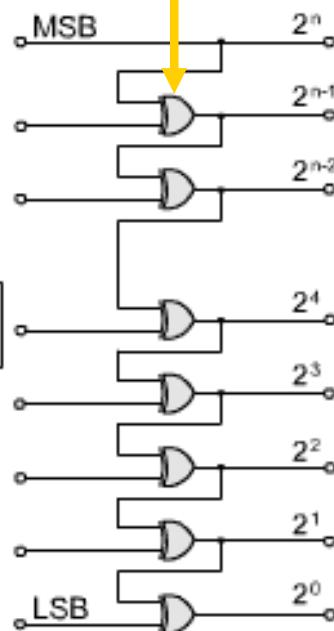


optical disks
with **2 bits**



GRAY
CODE

BINARY
CODE



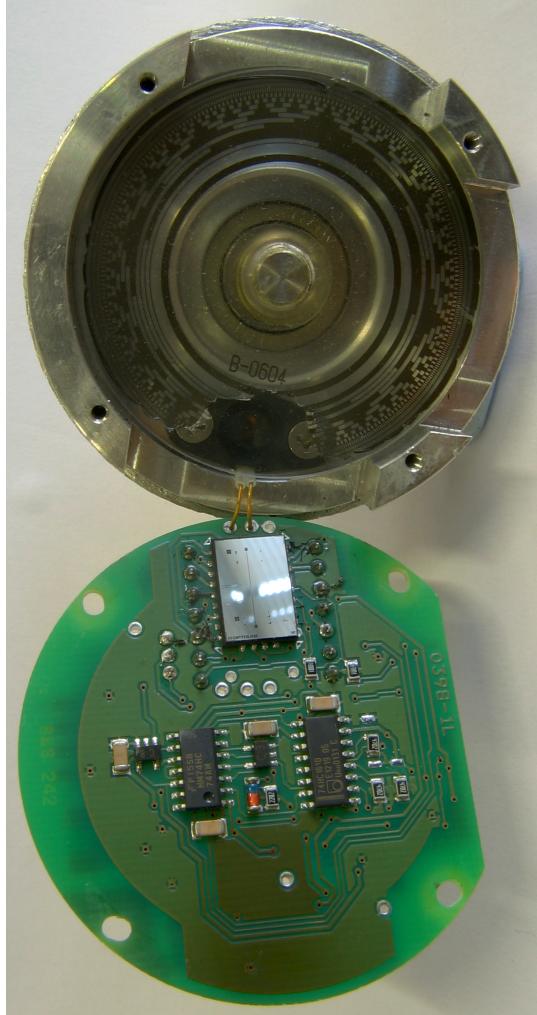
8-bit Gray-coded
absolute encoder

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

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



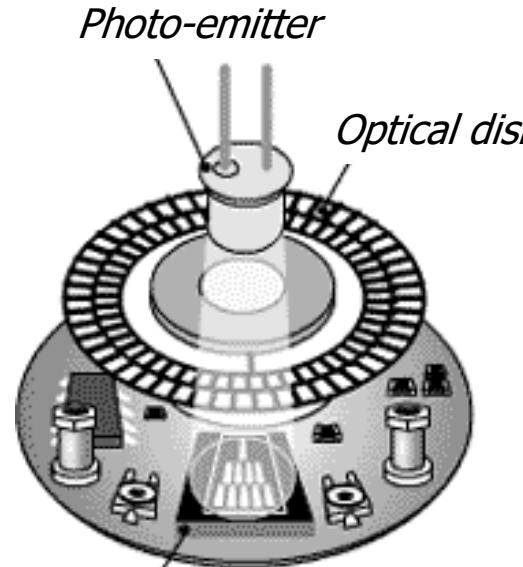
hollow shaft



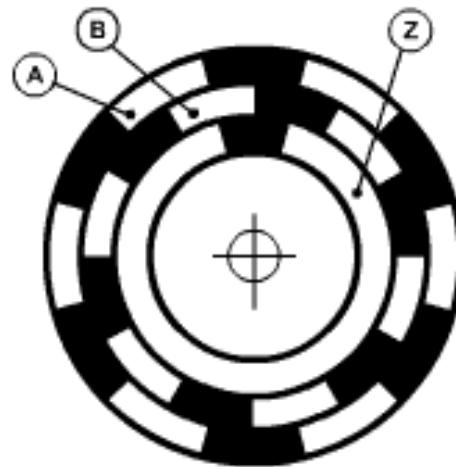
round flange



Incremental encoders



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

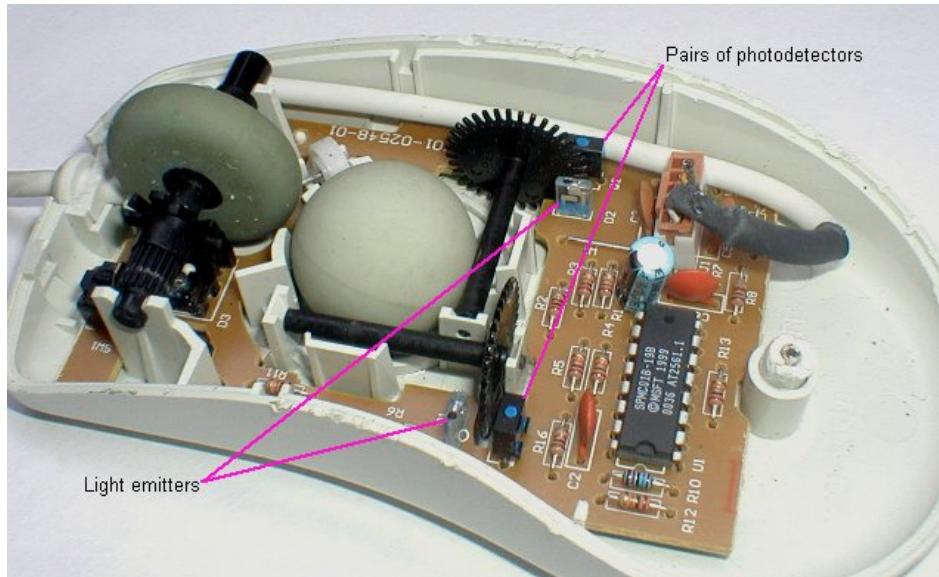


- optical rotating disk with three tracks, alternating transparent and opaque areas: measures **incremental** angular displacements by counting trains of N_e pulses ("counts") per turn ($N_e = 100 \div 5000$)
 - the two A and B tracks (**channels**) are in quadrature (phase shift of 90° electrical), 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

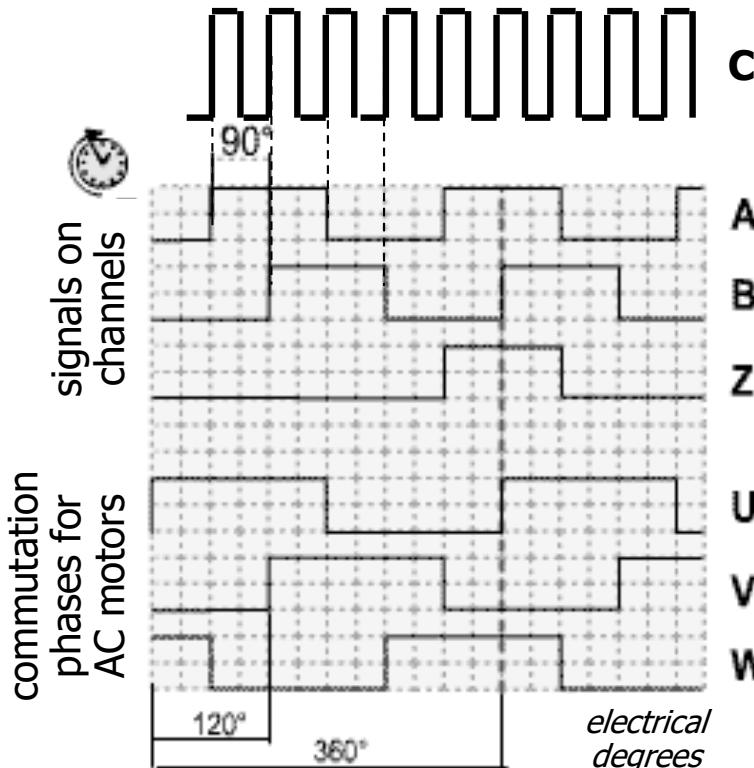
- two (cheap) incremental encoders inside a mouse
- a OMRON incremental encoder with 2000 pulses/turn



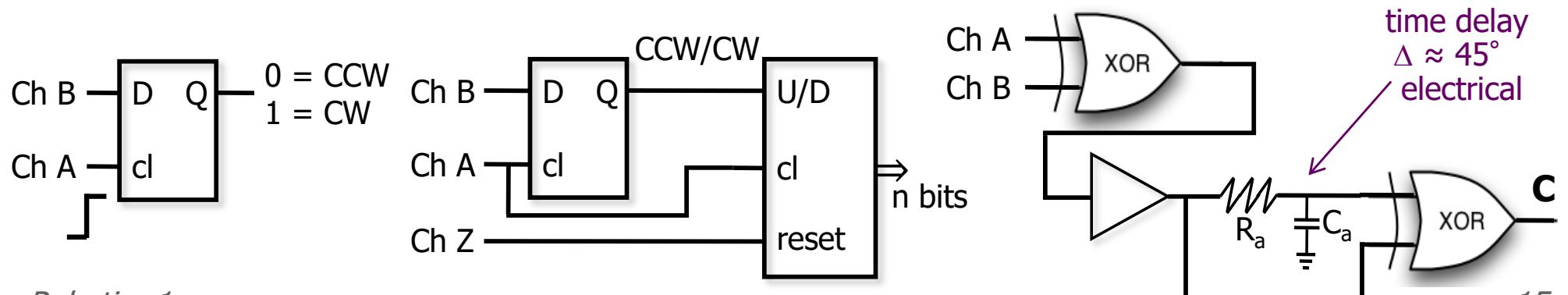
diameter \varnothing 40 mm
mass $m \approx 100$ g
inertia $J = 1 \cdot 10^{-6}$ kg m²



Signal processing



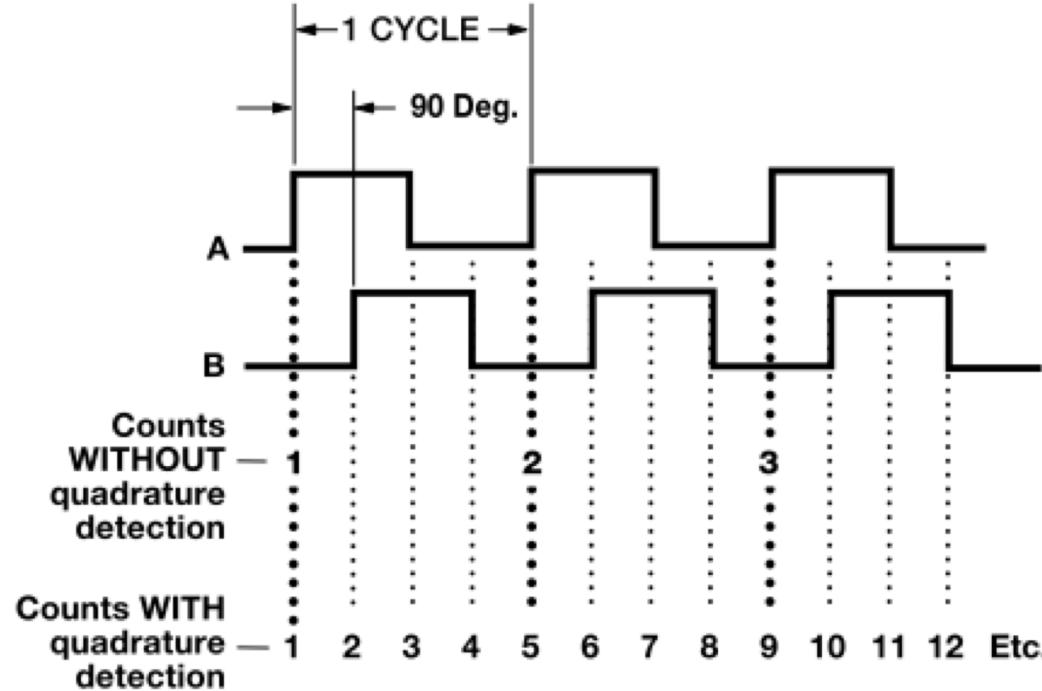
- “fractions of a cycle” of each pulse train are measured in “electrical degrees”
- $1^\circ \text{ electrical} = 1^\circ \text{ mechanical}/N_e$
 $360^\circ \text{ mechanical} = 1 \text{ turn}$
- signals are fed in a digital **counter**, with a **D-type** flip-flop to sense direction + **reset**
- to **improve resolution** ($4 \times$), 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

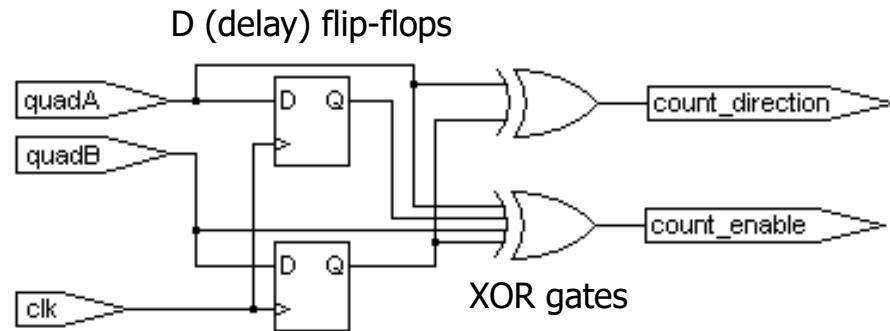


- an incremental encoder with $N_e = 2000$ (electrical) cycles provides a count of $N = 8000$ pulses/turn after electronic multiplication
- its final **resolution** is (mechanical) $360^\circ/8000 = .045^\circ$ ($= 0^\circ 2' 42''$)
- needs a 13-bit counter to cover a full turn without reset ($2^{13}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

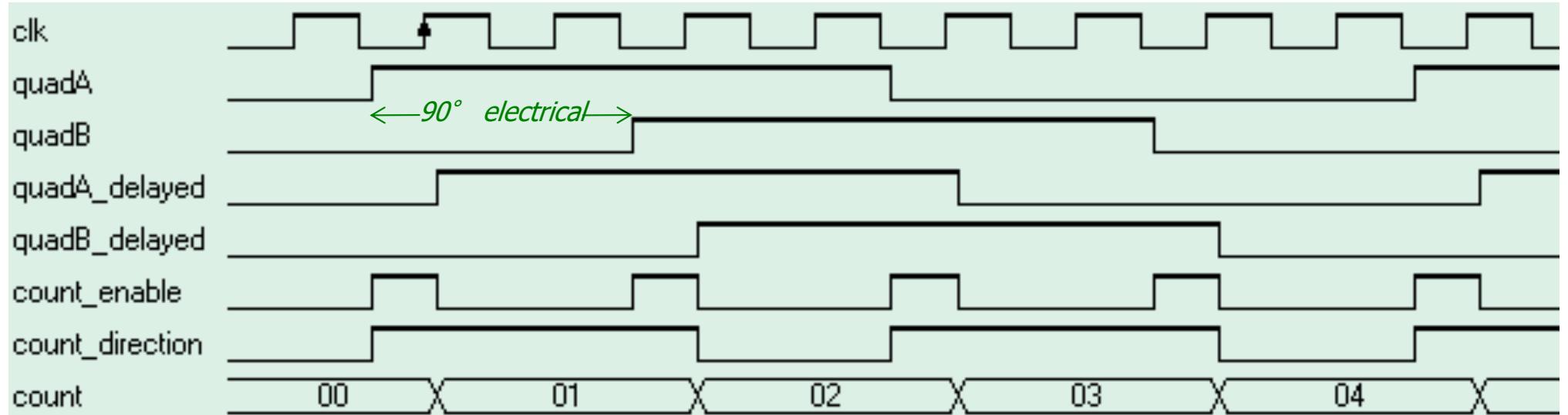


Quadrature detection in incremental encoders

a more complete implementation



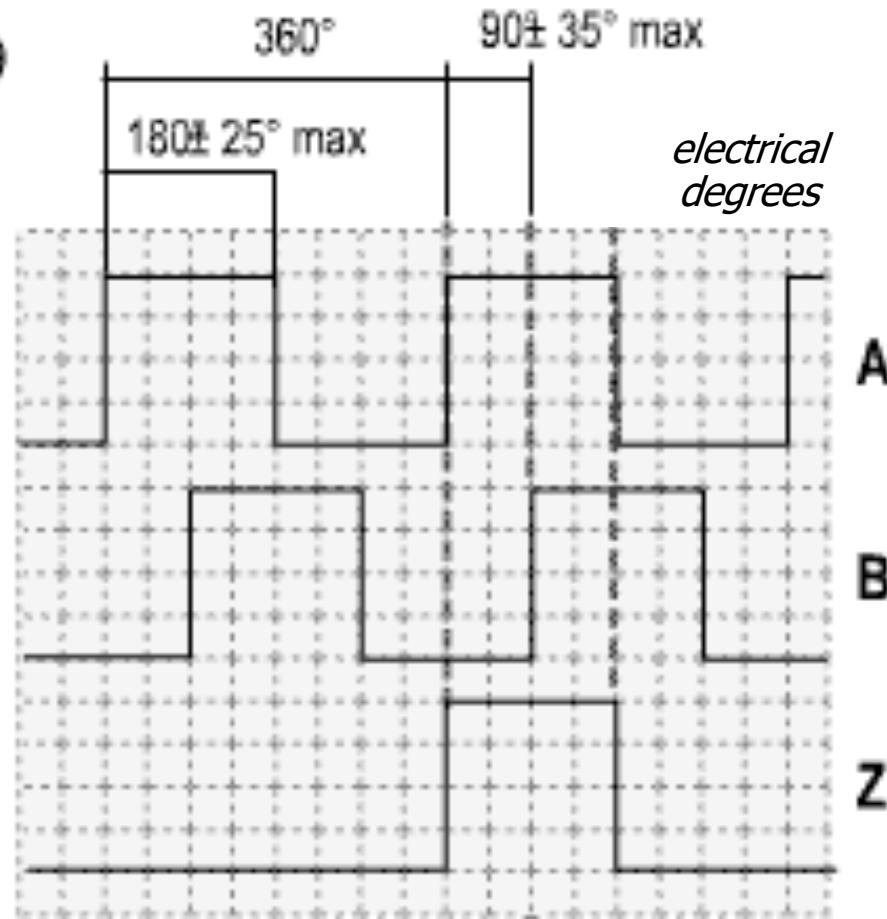
NOTE: since in practice A and B signals may **not** be synchronous to the clock signal, two extra D flip-flops per input should be used to avoid meta-stable states in the counters



- 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



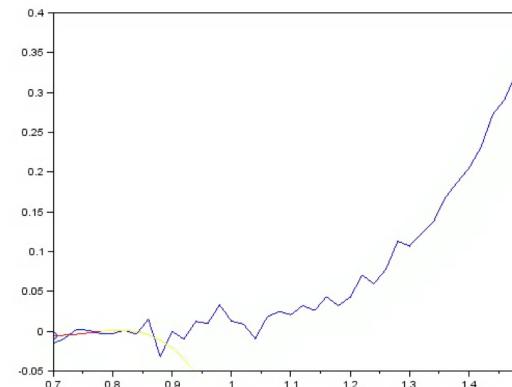
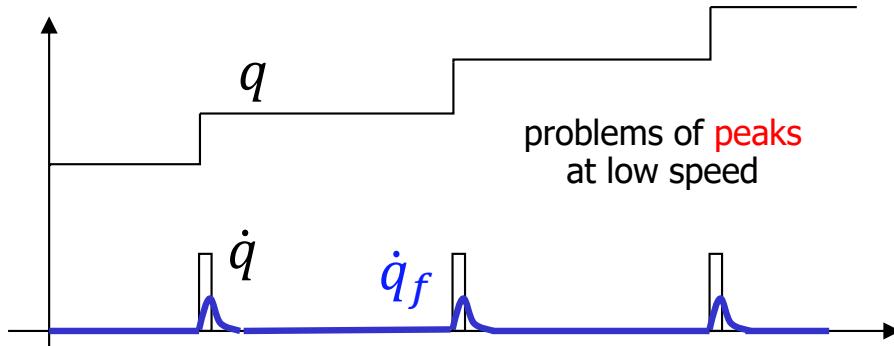
...apart from
quantization errors

- division error: maximum displacement between two consecutive leading/trailing edges, typically within max $\pm 25^\circ$ electrical
- the phase shift of the two channels, nominally equal to 90° electrical, is typically within max $\pm 35^\circ$ 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): $\dot{q}_k = \dot{q}(kT) = \frac{1}{T}(q_k - q_{k-1}) \Leftrightarrow \dot{q}_k = \frac{\Delta q_k}{T} \Leftarrow$ directly from incremental encoder
 - 4-step BDF: $\dot{q}_k = \frac{1}{T} \left(\frac{25}{12} q_k - 4q_{k-1} + 3q_{k-2} - \frac{4}{3} q_k + \frac{1}{4} q_{k-4} \right)$
- 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)



animation of Savitzky-Golay filter
with cubic polynomials



Kinematic Kalman Filter for velocity estimation

motion and
sensing
discrete-time
model for
estimation

noisy position measure
(encoder output)

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

zero mean
Gaussian noises
with (co)variances
 Q (a matrix) and R

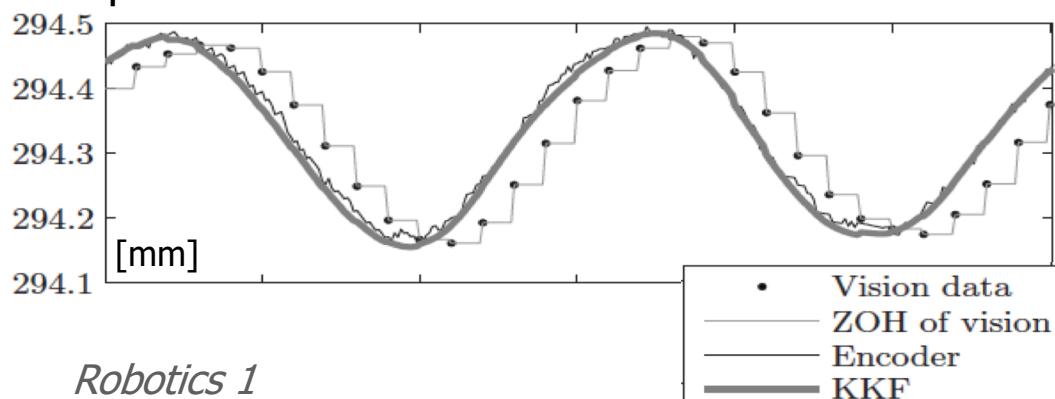
$$\begin{aligned}T &= \text{sampling time} \\ \xi(k) &= (x(k) \dot{x}(k))^T \\ \uparrow & \downarrow \\ \text{actual state} & \quad \text{unmeasured velocity}\end{aligned}$$

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

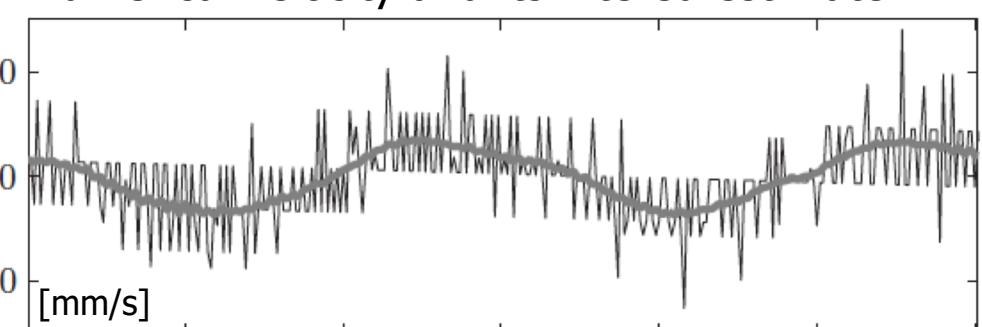
$$\hat{\xi}(k) = \underbrace{\begin{pmatrix} 1 & T \\ 0 & 1 \end{pmatrix} \hat{\xi}(k-1)}_{\text{(a priori) prediction}} + K_k \underbrace{\left(z(k) - \begin{pmatrix} 1 & 0 \end{pmatrix} \begin{pmatrix} 1 & T \\ 0 & 1 \end{pmatrix} \hat{\xi}(k-1) \right)}_{\text{correction (based on the measured output)}}$$

using the **optimal Kalman gain** K_k

position measure and its filtered version



numerical velocity and its filtered estimate

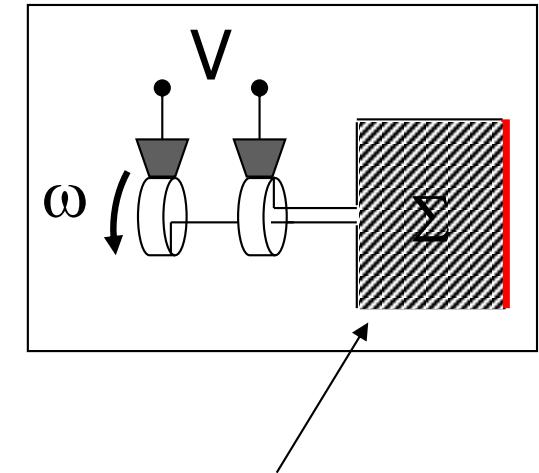
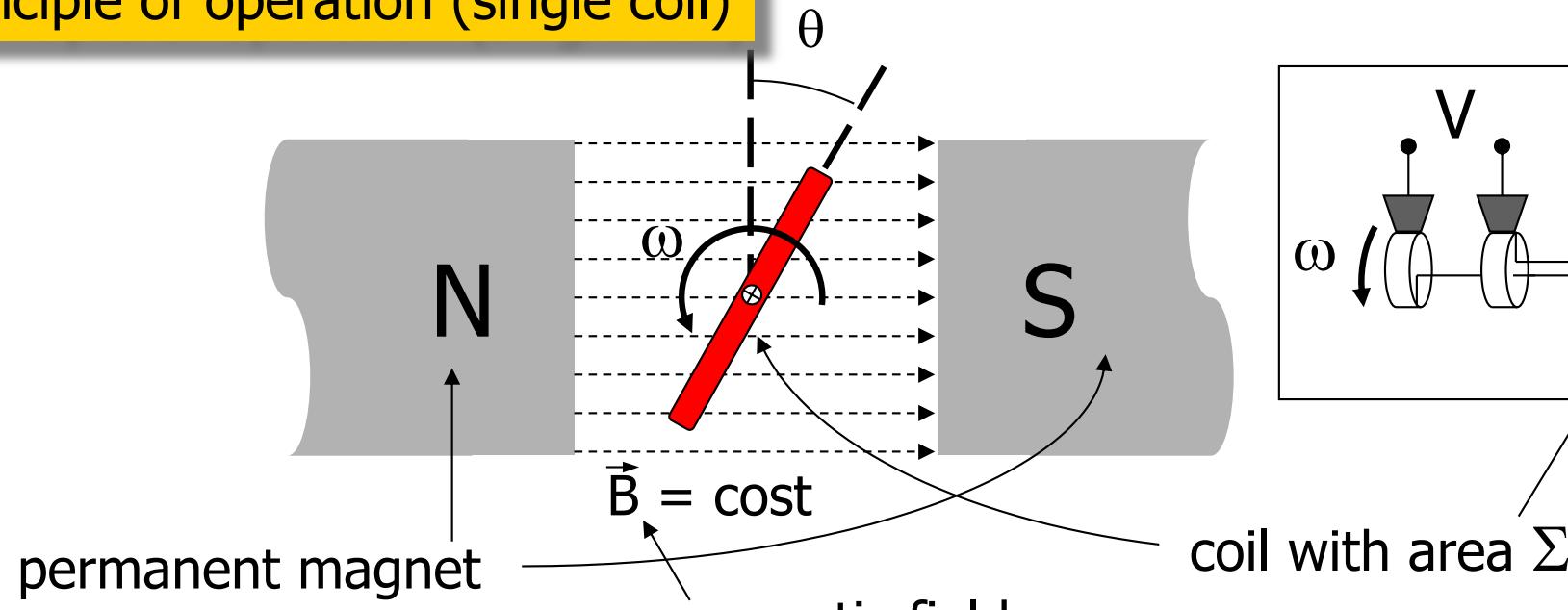




Velocity sensor: Tachometer

always mounted on the (electrical) motor axis

principle of operation (single coil)



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

amplitude $V \propto \omega$

⇒ to reduce ripples, use m coils rotated regularly by $180^\circ/m$



DC tachometer

an example



- **Servo-Tek Tach Generator (B series)**
- bi-directional
- output voltage $11 \div 24 \text{ V}$ @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 dynamic)	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

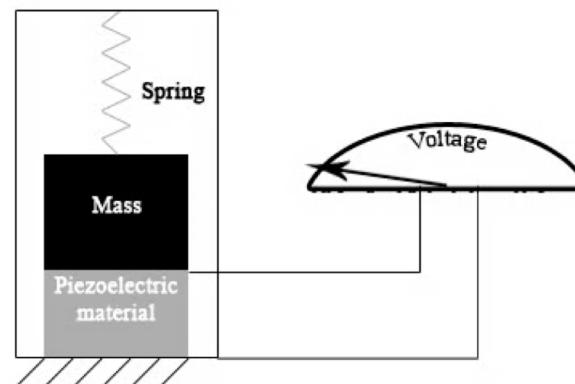
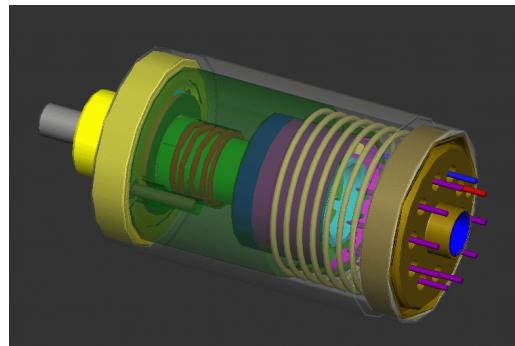


1.75 mNm (as a load)



Accelerometers

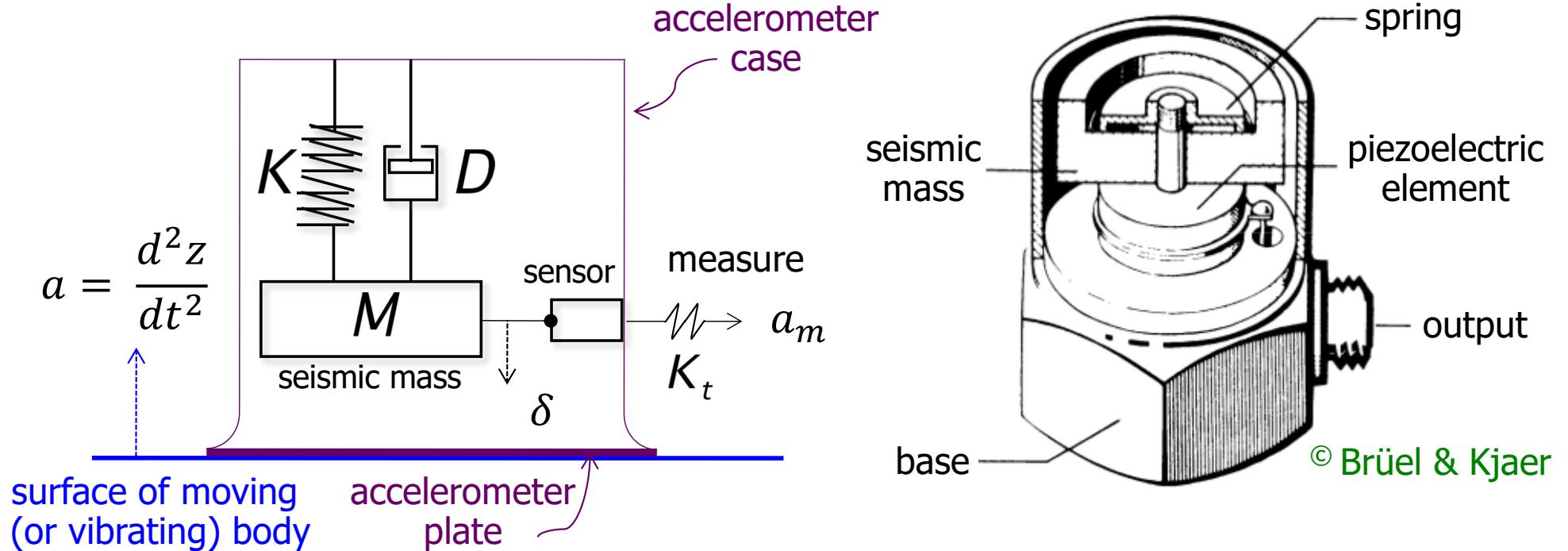
- measure of linear acceleration based on **inertial forces** (no “touch”)
 - units: [m/s²] or gravitational acceleration [g] (non-SI unit: 1g ≈ 9.81 m/s²)
- different principles for converting mechanical motion in an electrical signal
 - **piezoelectric**: piezoceramics (PZT) or crystals (quartz), better 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



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

$$a_m = K_t \delta$$

by Laplace transform →

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

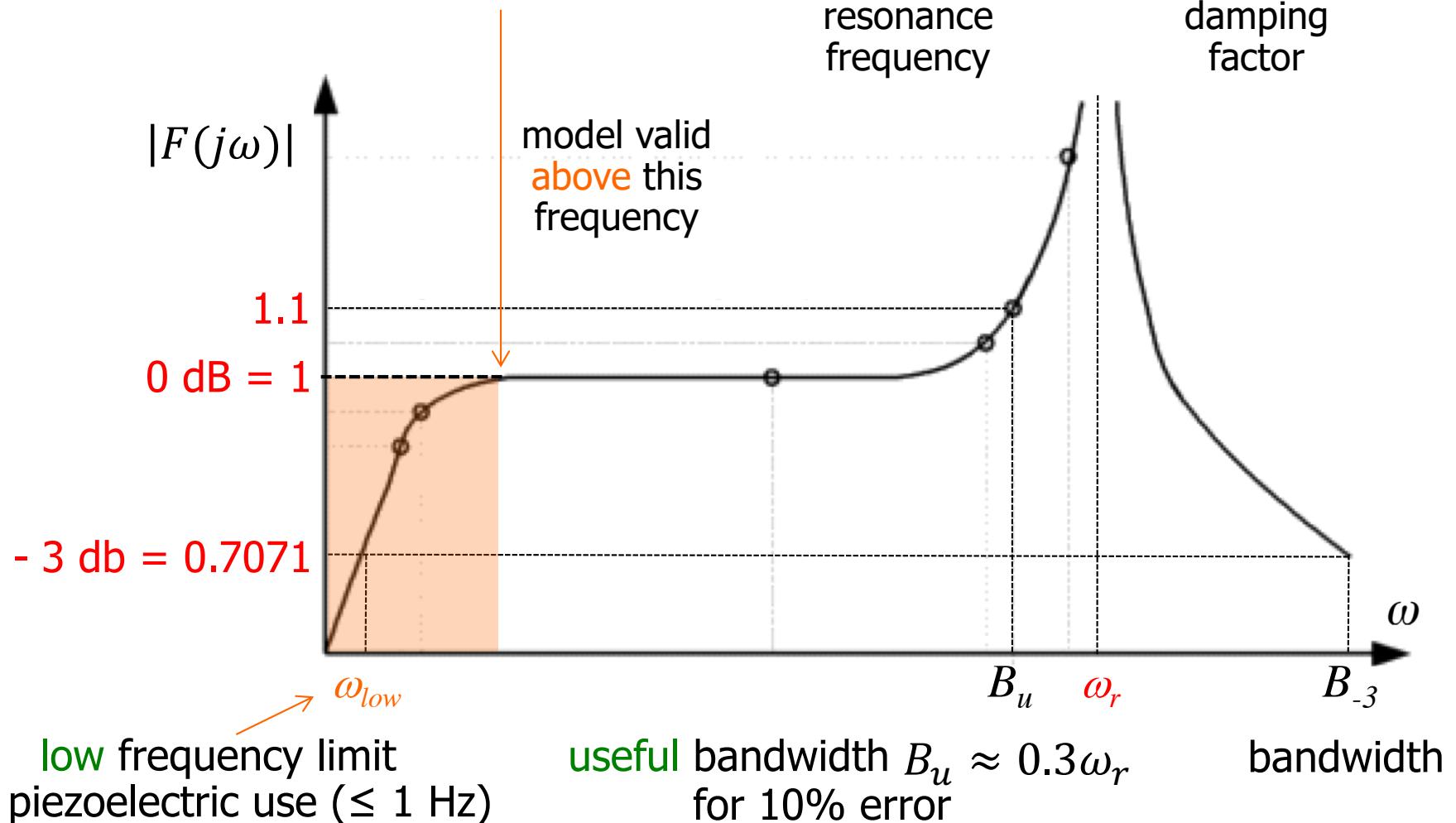
$$= \frac{K_t}{s^2 + (D/M)s + (K/M)}$$



Frequency characteristics of a piezoelectric accelerometer

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

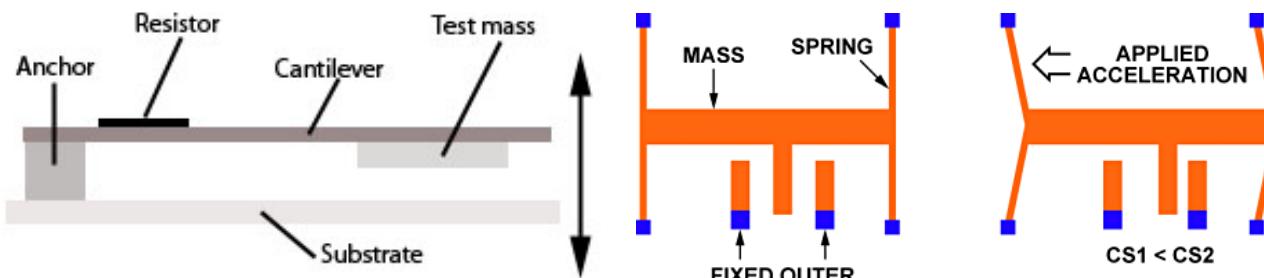
$$\omega_r = \sqrt{K/M} \quad \zeta = \frac{D}{2} \sqrt{1/KM}$$



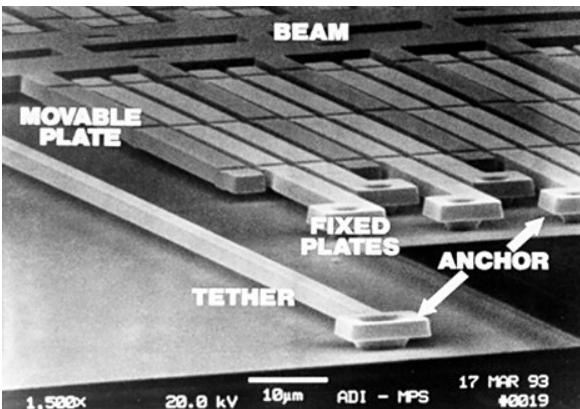
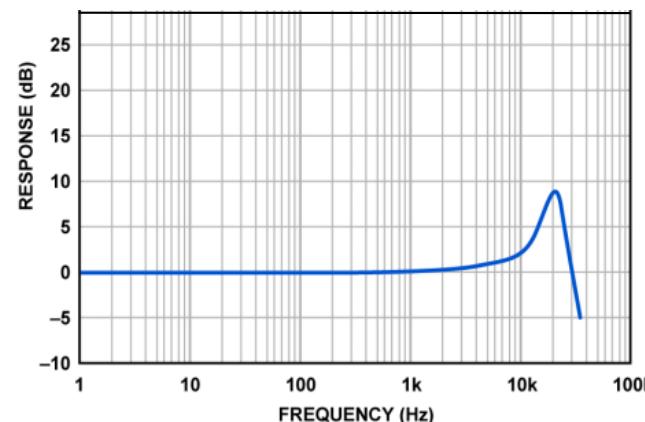
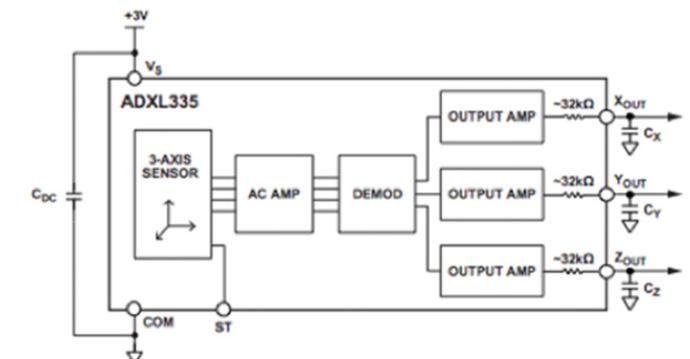


MEMS accelerometers

- 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 $\leq 3\%$



ADXL335 3-axis, small, low power, $\pm 3g$, with signal conditioned voltage outputs

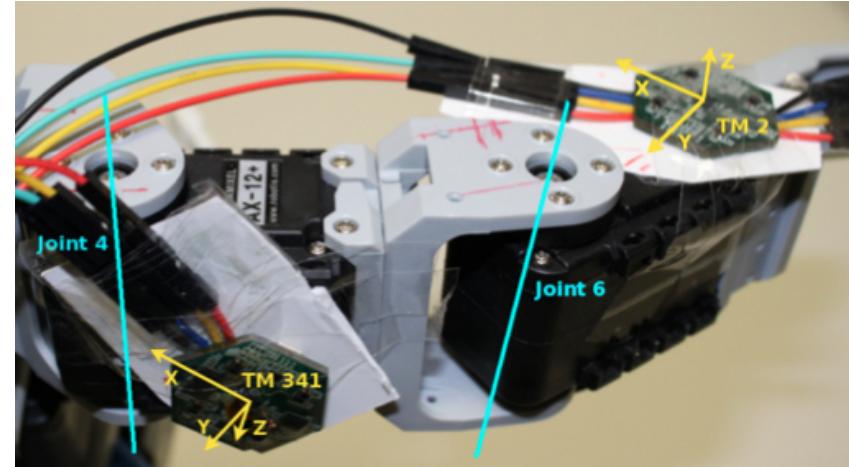
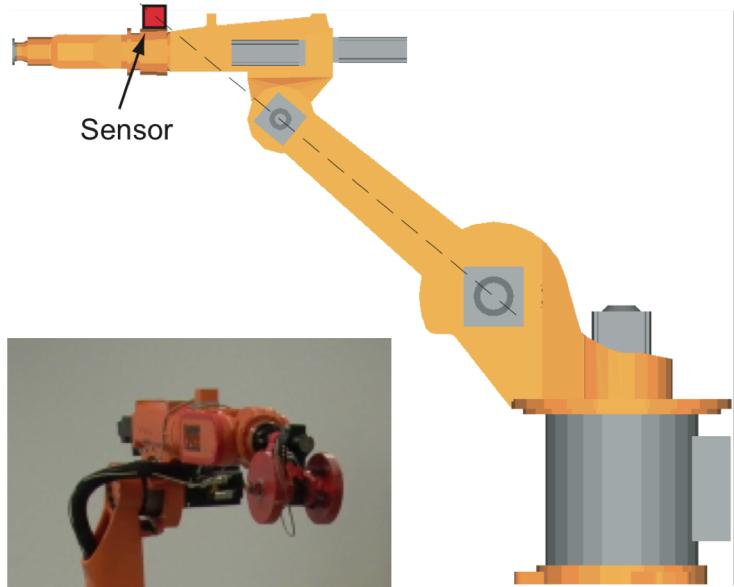




Mounting accelerometers on robots



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



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 capacitive accelerometer
on end-effector tool of an [ABB robot](#)
(Crossbow Technology: 2g range,
1V/g output, 0-50 Hz, $\pm 2^\circ$ align error)
[Linköping, 2012]