## *Robotics 1*

# Robot components:
## Proprioceptive sensors

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# Properties of measurement systems - 1

- accuracy

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

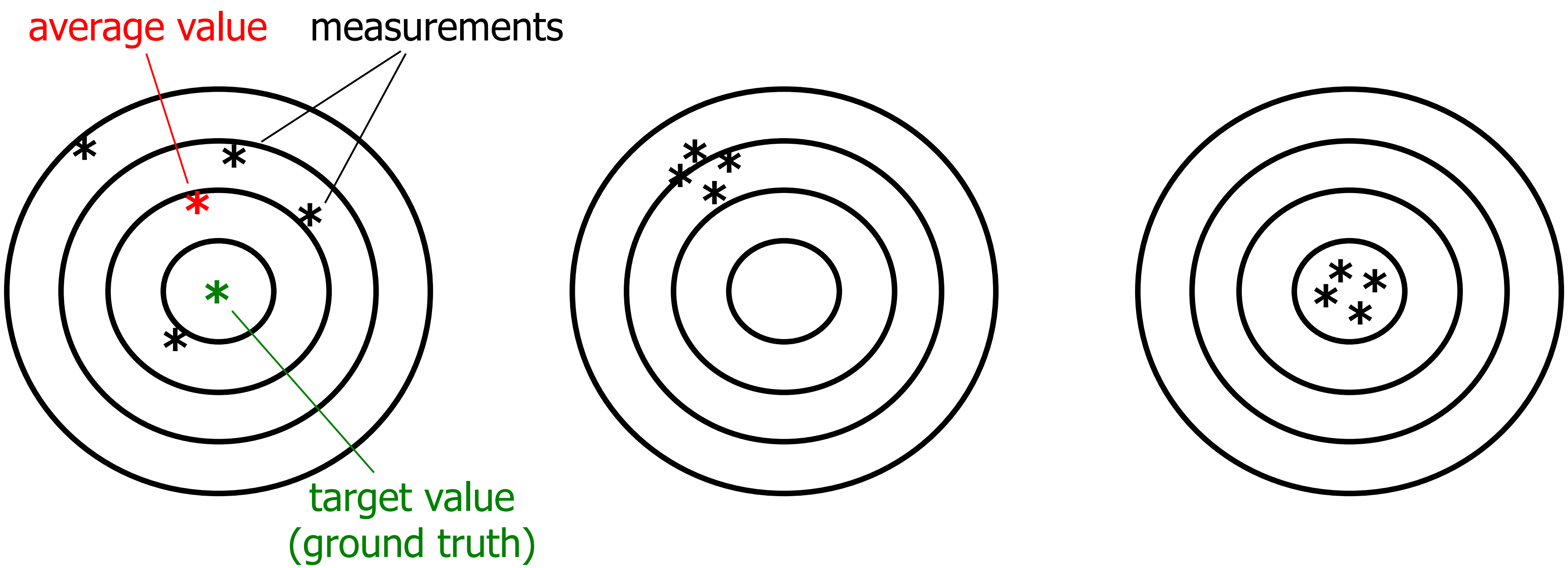
- repeatability

  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 on 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

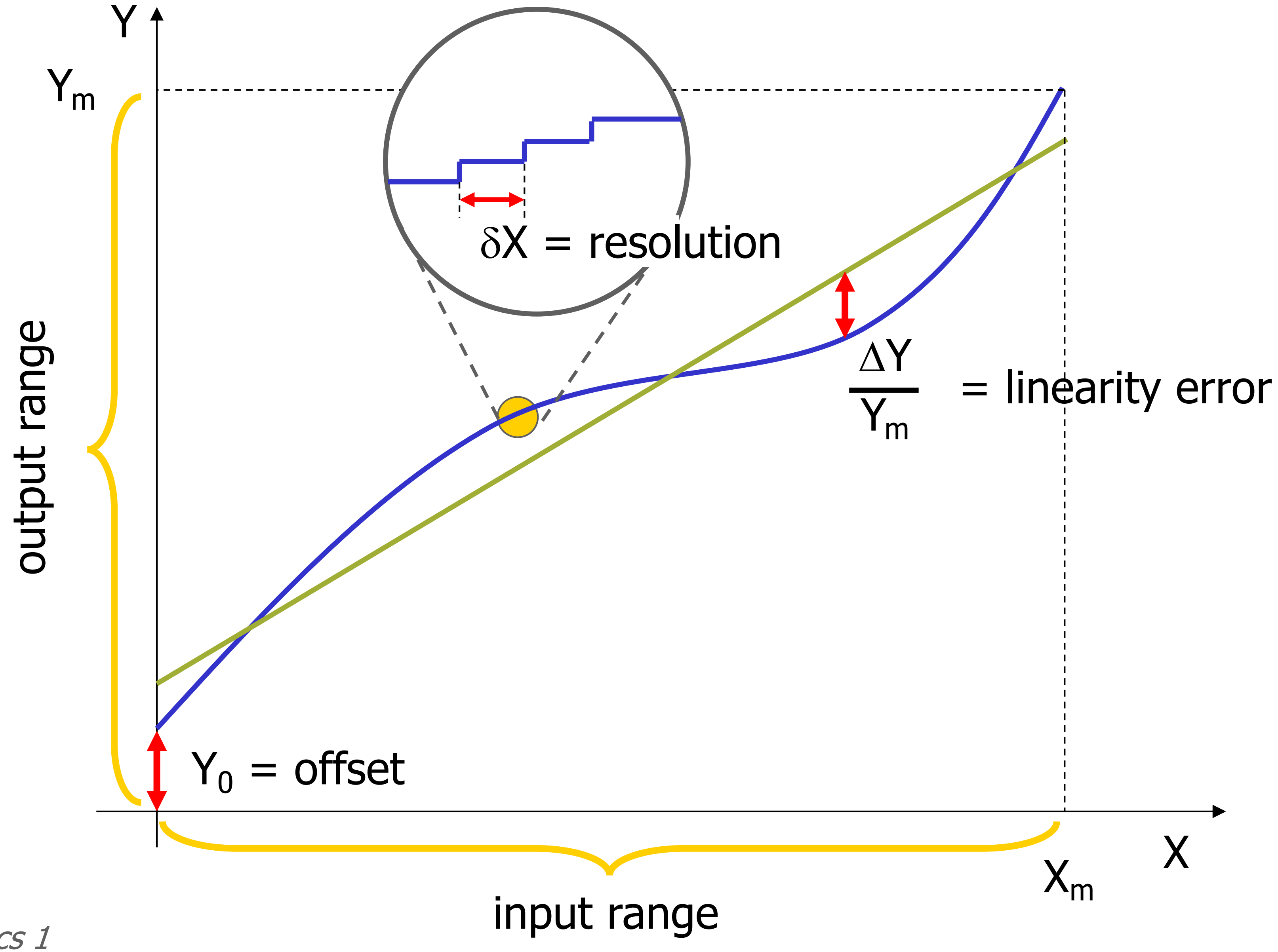
  - sometimes not zero after some operation cycles, due to hysteresis

- resolution error

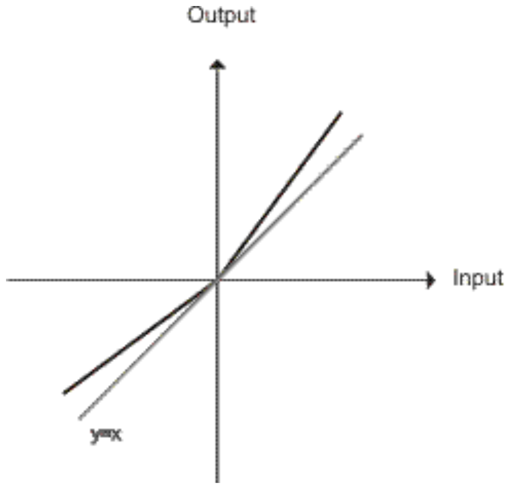
  maximum variation of the input quantity producing no variation of the measured output

  - in absolute value or in % of the input range

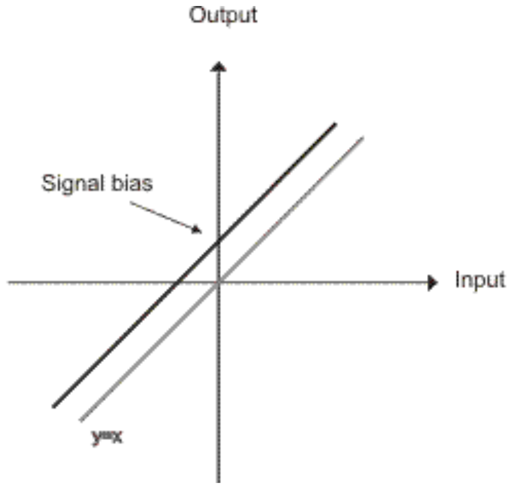
# Linearity, Offset, Resolution



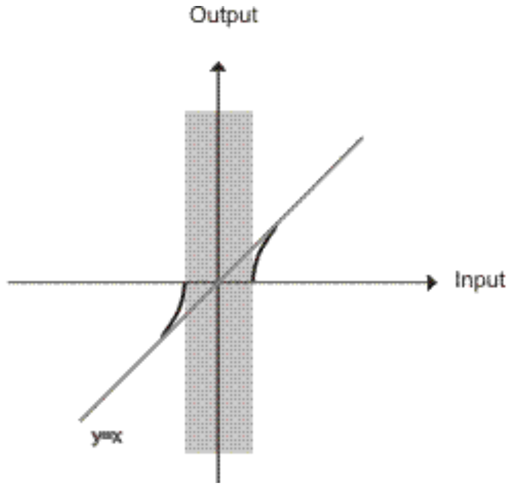
# Sensor measurements
## some non-idealities



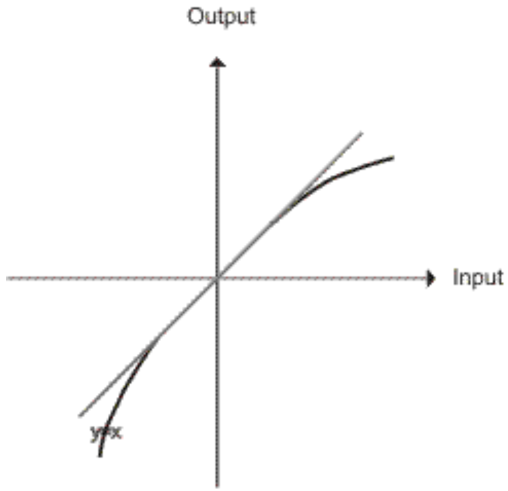
Asymmetry



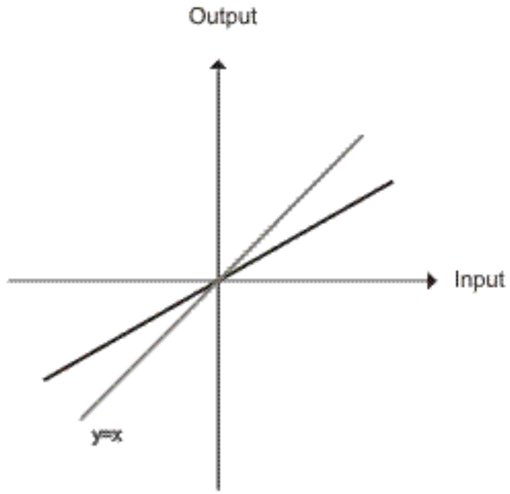
Bias



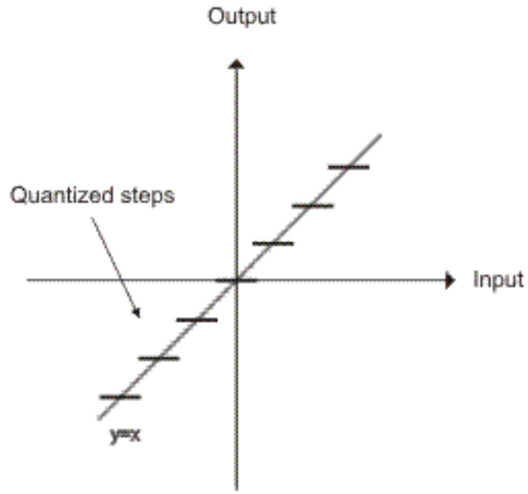
Dead zone



Nonlinearity



Scaling factor



Quantization

# Keywords on measurements

- data acquisition (in time): signal, sampling, frequency content (spectrum), bandwidth
- disturbance, noise (white, color), S/N (power) ratio, filtering
- random variables, distribution, mean, variance, covariance and correlation/independence of signals
- mean (average, expected value): off-line, on-line (recursive)
- recursive mean: moving, weighted (forgetting), adaptive
- estimation error and measurement error
- Kalman Filter: recursive mean that minimizes the variance of the estimation error (optimal for linear dynamic systems)
- Low-Pass Filter: RC, Butterworth, Bessel, Chebyshev, …
- causal and non-causal filters for the derivative(s) of a signal

# Classes of sensors for robots

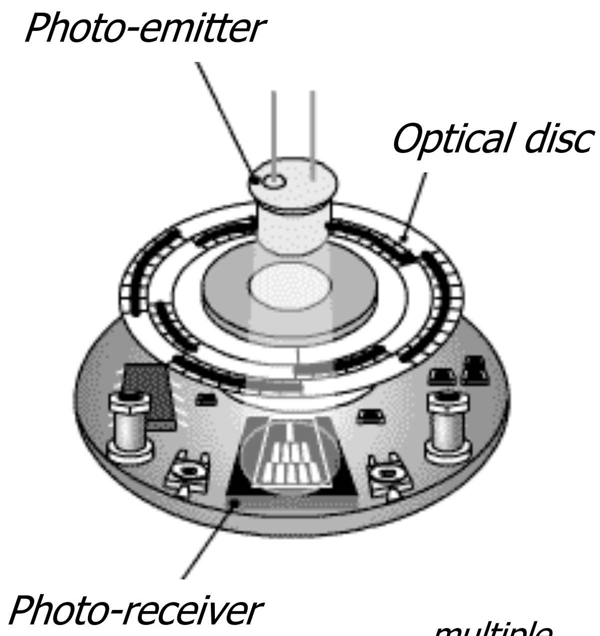
- proprioceptive sensors measure the internal state of the robot (position and velocity of joints, but also torque at joints or acceleration of links)
  - kinematic calibration, identification of dynamic parameters, control
- exteroceptive sensors measure/characterize robot interaction with the environment, 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

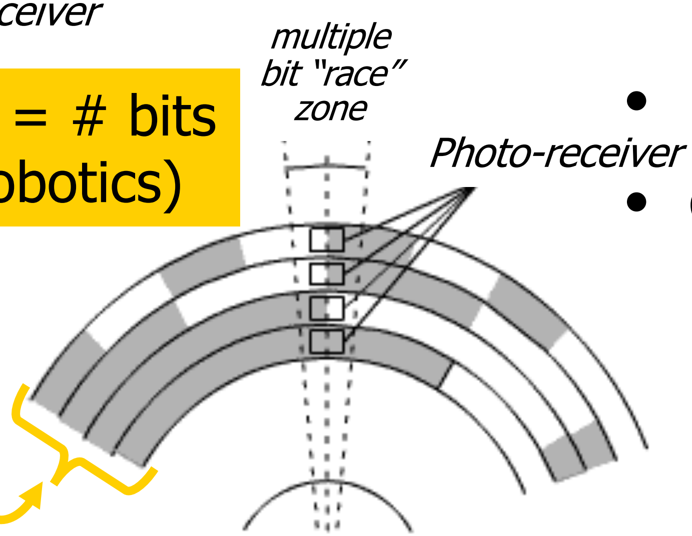
- provide an electrical signal proportional to the displacement (linear or angular) of a mechanical part with respect to a reference position
- linear displacements: potentiometers, linear variable-differential transformers (LVDT), inductosyns
- angular displacements: potentiometers, resolvers, syncros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

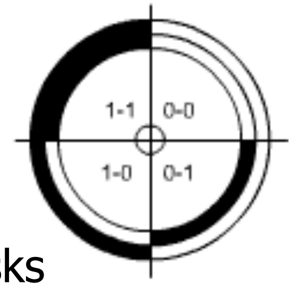



- rotating optical disk, with alternate transparent and opaque sectors on multiple concentric tracks
- (infrared) light beams are emitted by leds and sensed by photo-receivers
- light pulses are converted into electrical pulses, electronically processed and transmitted in output
- resolution = $360^{\circ}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

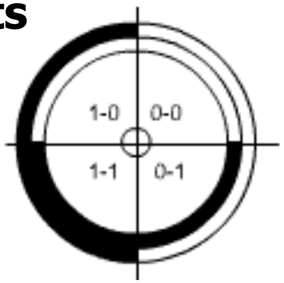
# Absolute encoding

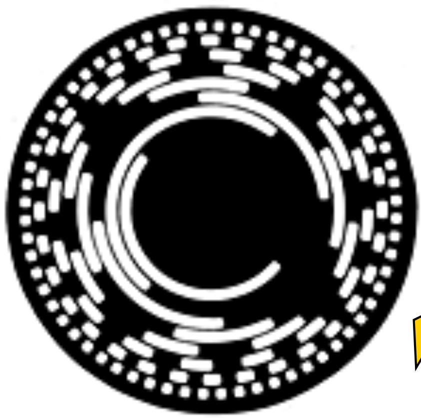
binary coding



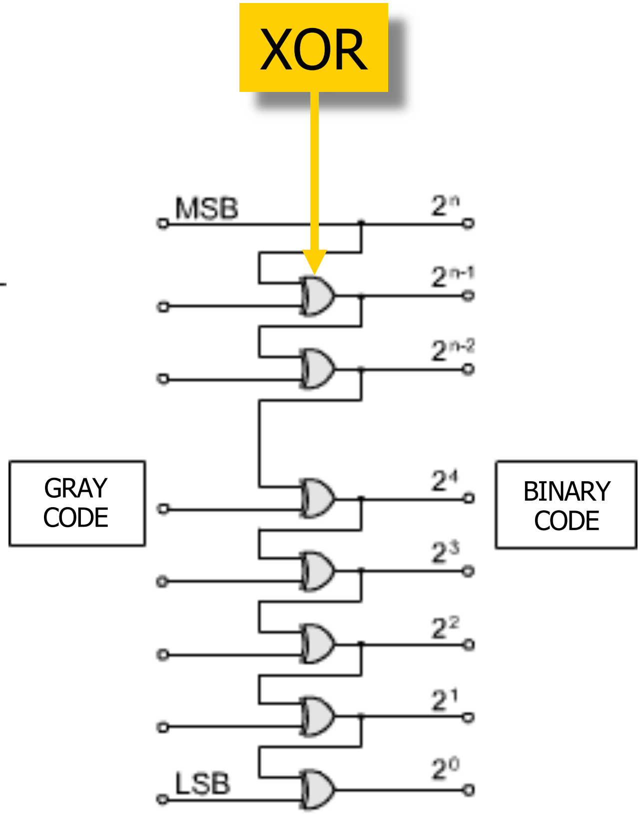

optical disks with **2 bits**

Gray coding



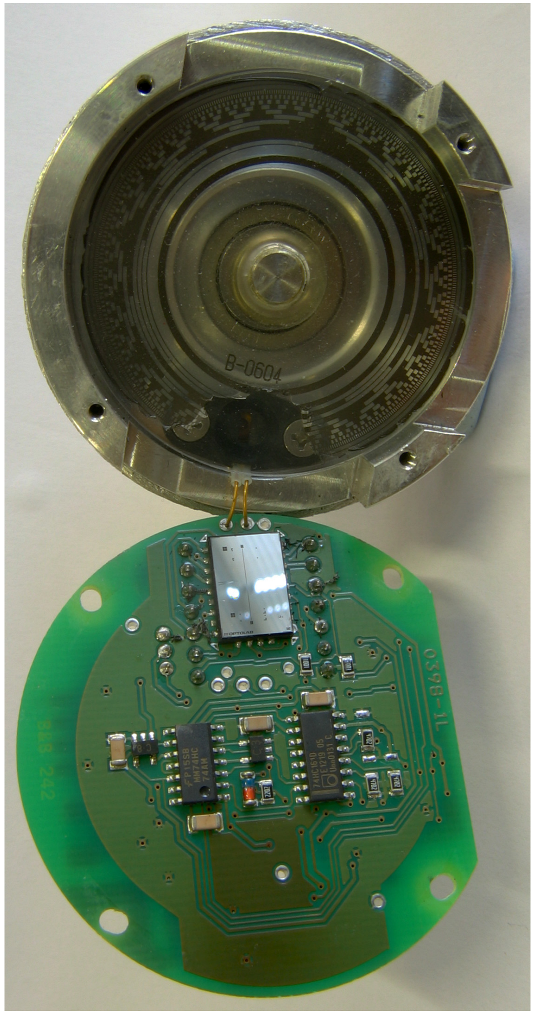
**8-bit** Gray-coded absolute encoder




| 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

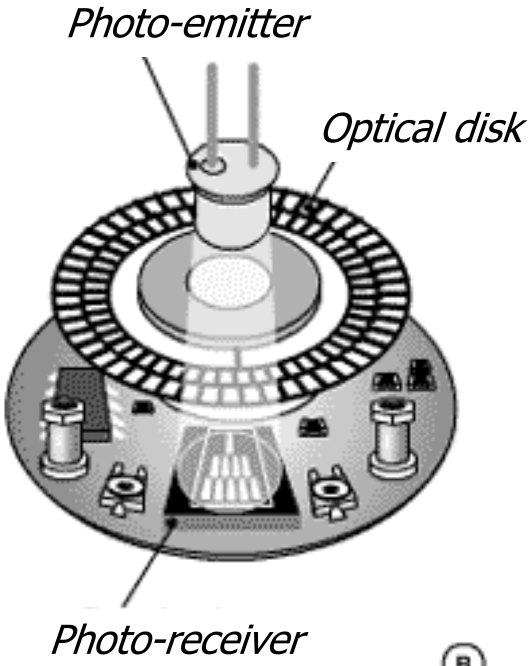
- ready to measure at start (no "homing")
- two modes for permanent operation
  - when switching off the drive, position parameters are saved on a flash memory (and brakes activated)
  - battery for the absolute encoder is always active, and measures position even when the drive is off
  - data memory > 20 years
- single-turn or multi-turn versions, e.g.
  - 13-bit single-turn has $2^{13} = 8192$ steps per revolution (resolution = $0.044^{\circ}$)
  - 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

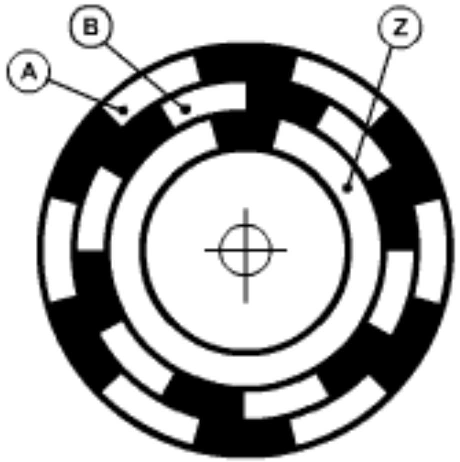
round flange

multi-turn

# Incremental encoders




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

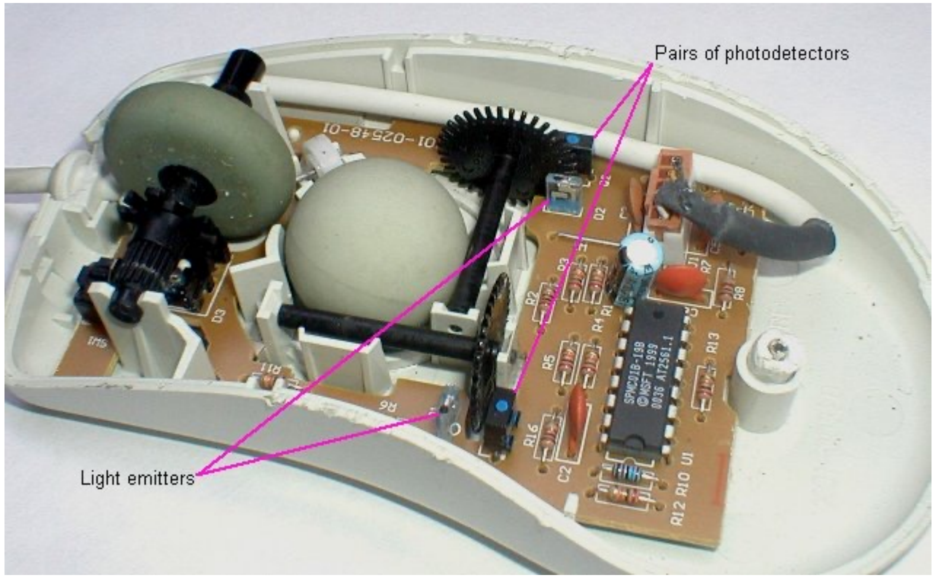



*The three tracks on an optical disk (here $N_e = 6$)*

- 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

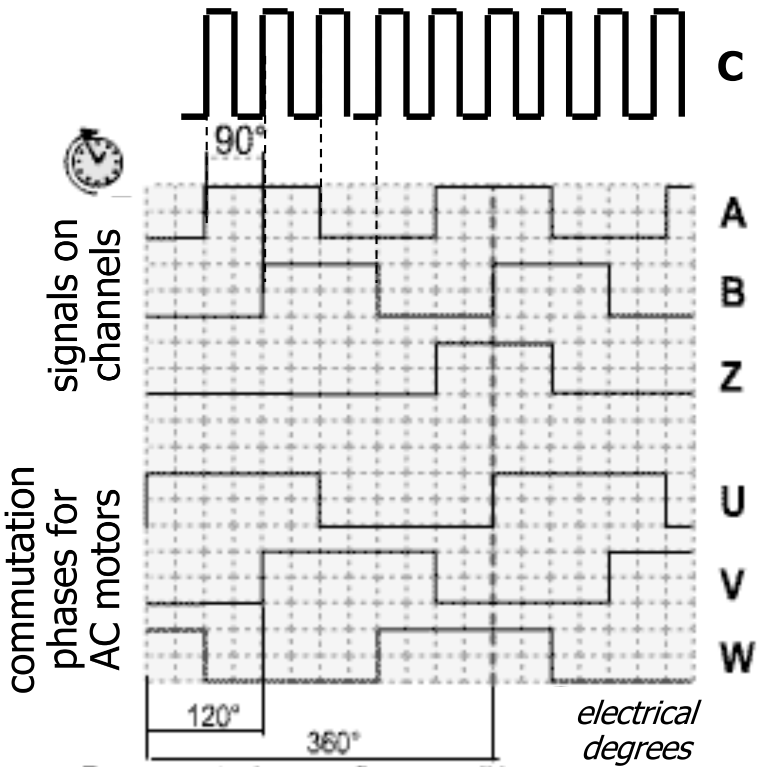
- two (cheap) incremental encoders inside a (old fashioned) mouse



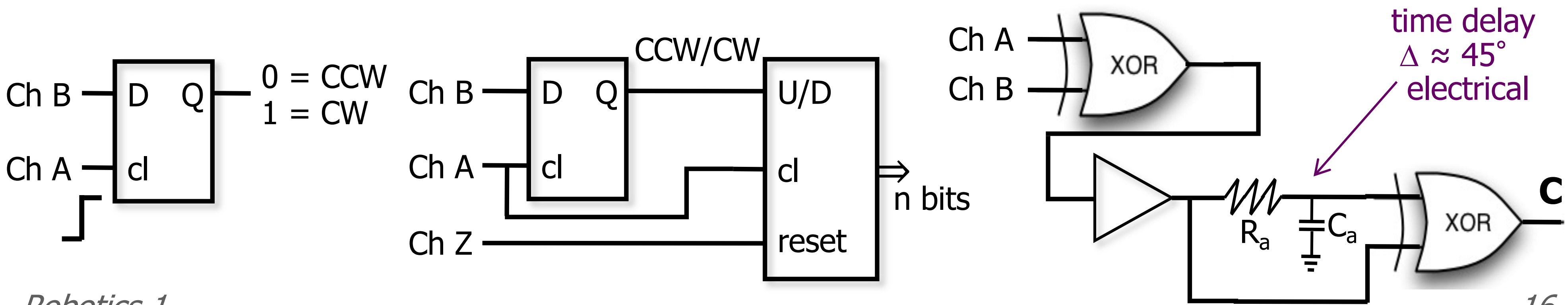

- a OMRON incremental encoder with 2000 pulses/turn


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

# Signal processing

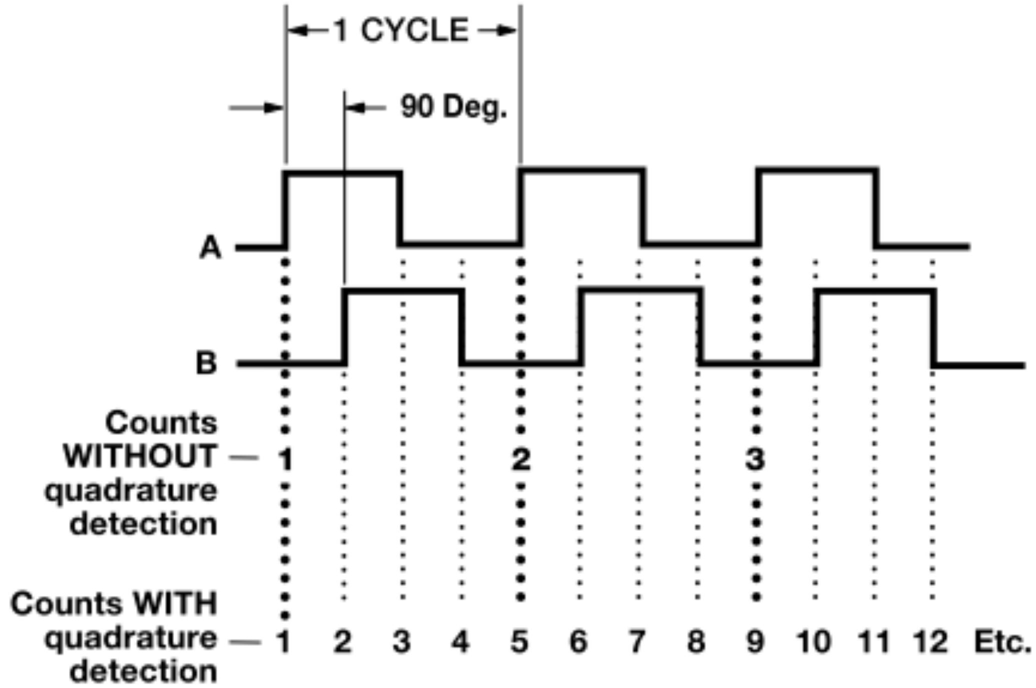



- "fractions of a cycle" of each pulse train are measured in "electrical degrees"
- $1^\circ$ electrical = $1^\circ$ mechanical/$N_e$
  $360^\circ$ mechanical = 1 turn
- signals are fed in a digital counter, with a D-type flip-flop to sense direction + reset
- to improve resolution ($4\times$), the leading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



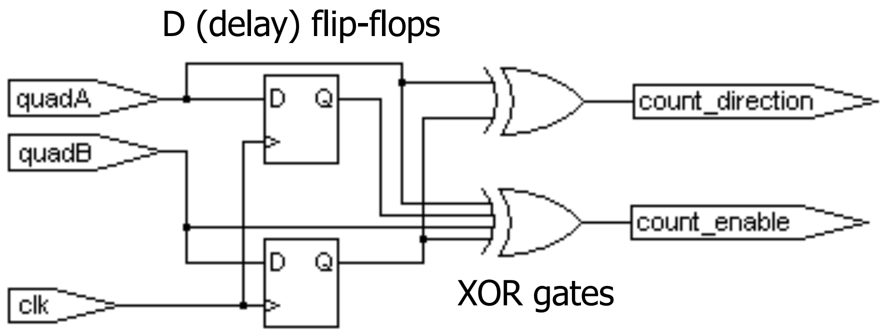
# Count multiplication

## example of quadrature detection

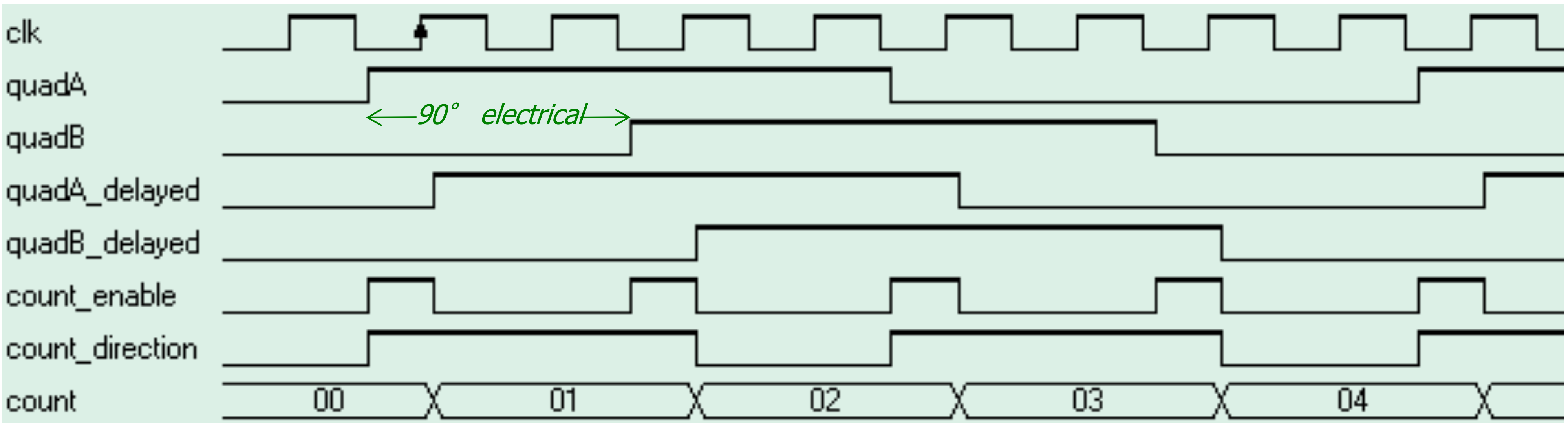



- an incremental encoder with $N_e = 2000$ (electrical) cycles provides a count of $N = 8000$ pulses/turn after electronic multiplication
- its final resolution is (mechanical) $360^\circ/8000 = .045^\circ$ ($= 0^\circ\ 2'\ 42''$)
- needs a 13-bit counter to cover a full turn without reset ($2^{13} =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

# Quadrature detection in incremental encoders
## a more complete implementation

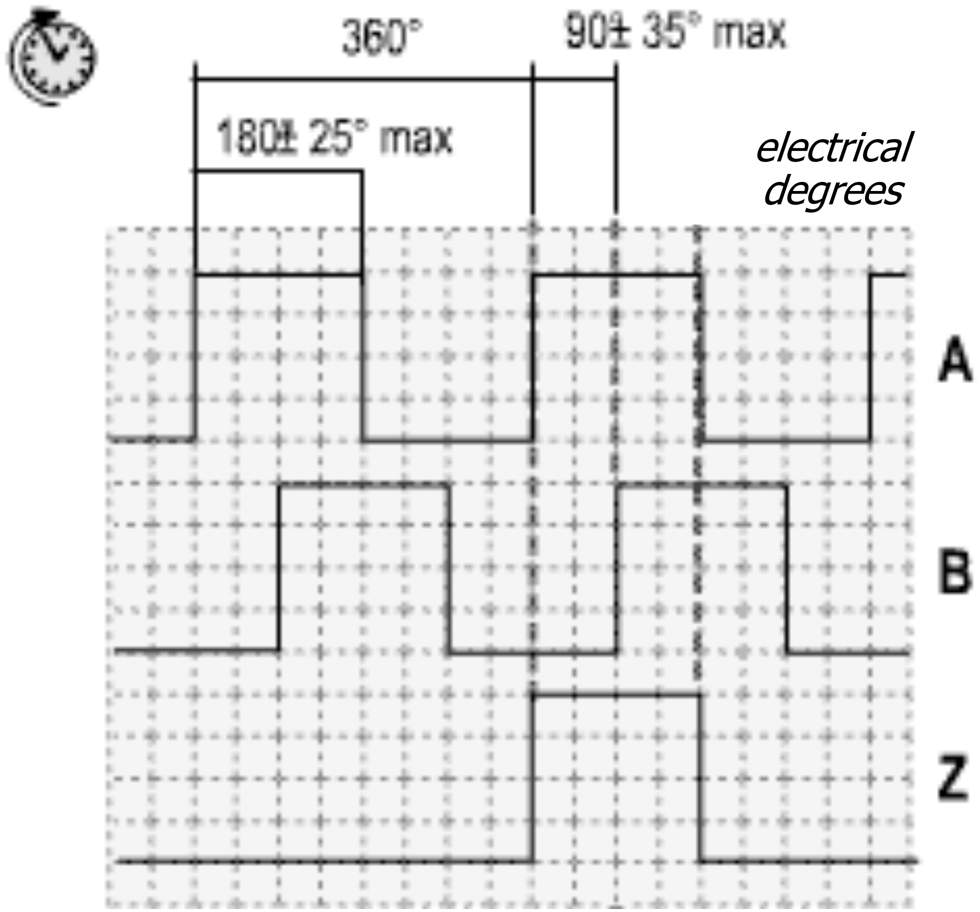



NOTE: since in practice A and B signals may **not** be synchronous to the clock signal, two extra D flip-flops per input should be used to avoid meta-stable states in the counters




- 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

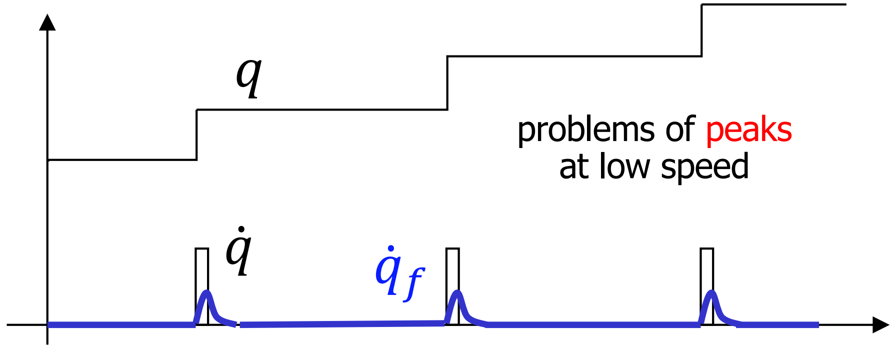


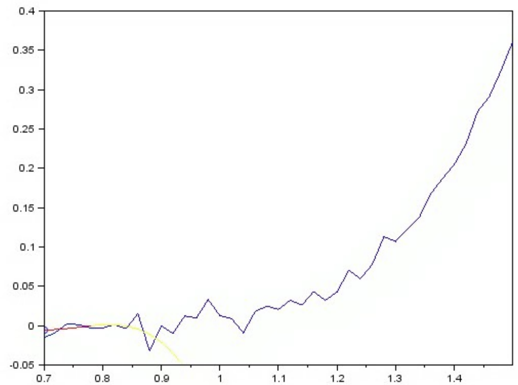

...apart from quantization errors

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

# Indirect measure of velocity

- numerical differentiation of digital measures of position
  - to be realized online with Backward Differentiation Formulas (BDFs)
  - 1-step BDF (Euler): $\dot{q}_k = \dot{q}(kT) = \dfrac{1}{T}(q_k - q_{k-1}) \;\Leftrightarrow\; \dot{q}_k = \dfrac{\Delta q_k}{T} \;\Leftarrow$ directly from incremental encoder
  - 4-step BDF: $\dot{q}_k = \dfrac{1}{T}\left(\dfrac{25}{12}q_k - 4q_{k-1} + 3q_{k-2} - \dfrac{4}{3}q_{k-3} + \dfrac{1}{4}q_{k-4}\right)$
- 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 online 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

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

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

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

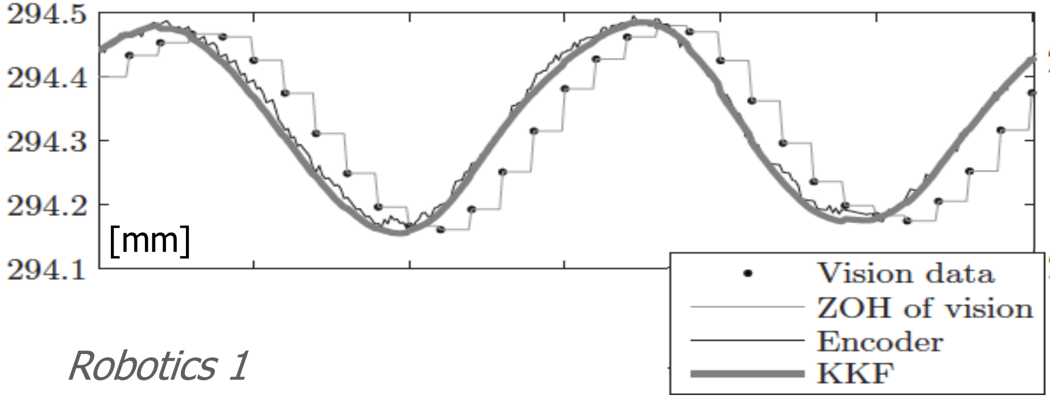
unmeasured velocity

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

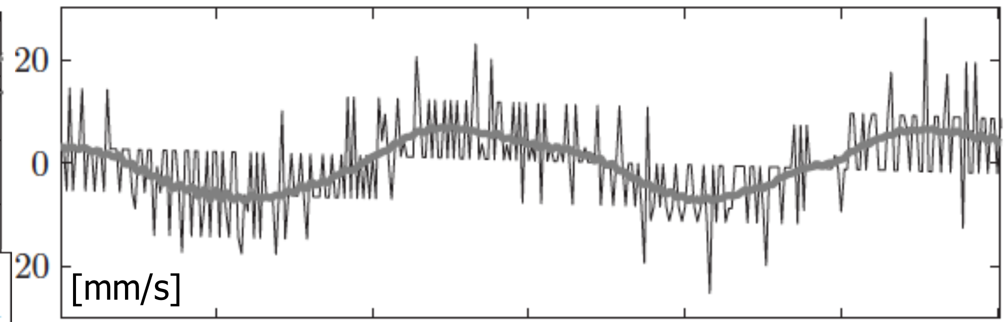
$$\hat{\boldsymbol{\xi}}(k) = \underbrace{\begin{pmatrix} 1 & T \\ 0 & 1 \end{pmatrix} \hat{\boldsymbol{\xi}}(k-1)}_{\text{(a priori) prediction}} + \boldsymbol{K}_k \underbrace{\left( z(k) - \begin{pmatrix} 1 & 0 \end{pmatrix} \begin{pmatrix} 1 & T \\ 0 & 1 \end{pmatrix} \hat{\boldsymbol{\xi}}(k-1)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

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

position measure and its filtered version



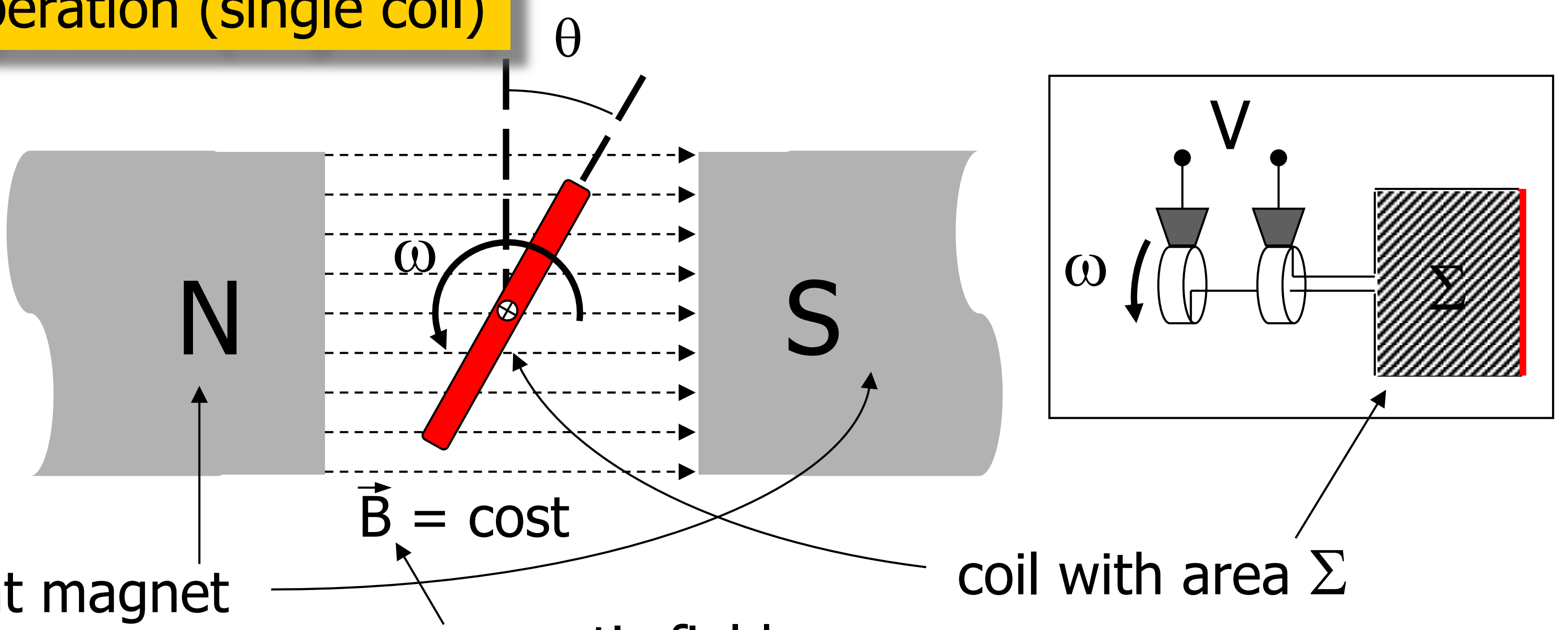

numerical velocity and its filtered estimate



# Velocity sensor: Tachometer

## always mounted on the (electrical) motor axis

principle of operation (single coil)




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

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

amplitude $V \propto \omega$

$\Rightarrow$ to reduce ripples, use m coils rotated regularly by 180°/m

# 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)

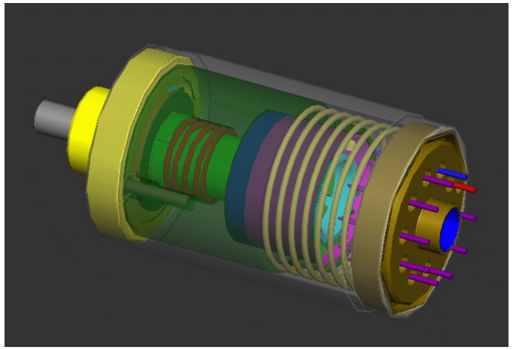
**B-Series Specifications**

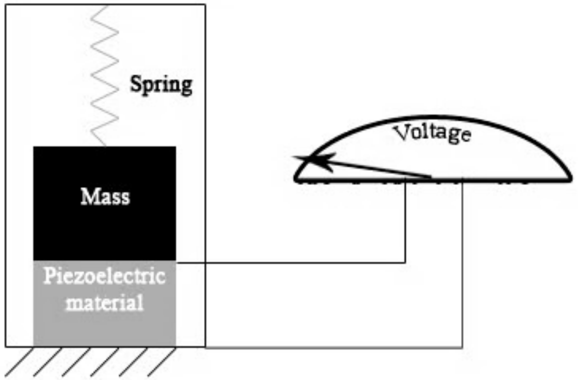
| Model Number | Mounting | Weight (approx) | Inertia (approx) oz-in.-sec$^2$ | V/1,000 RPM | RPM (max) | Driving Torque (max) | Arm R (ohms dy-namic) | Arm Ind (h) |
|---|---|---|---|---|---|---|---|---|
| SA-740B-1* | Face | 4.0 oz | $2.27 \times 10^{-4}$ | 20.8 V | 8,000 | 0.25 oz-in. | 1000 | 0.56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

1.75 mNm (as a load)

# Accelerometers

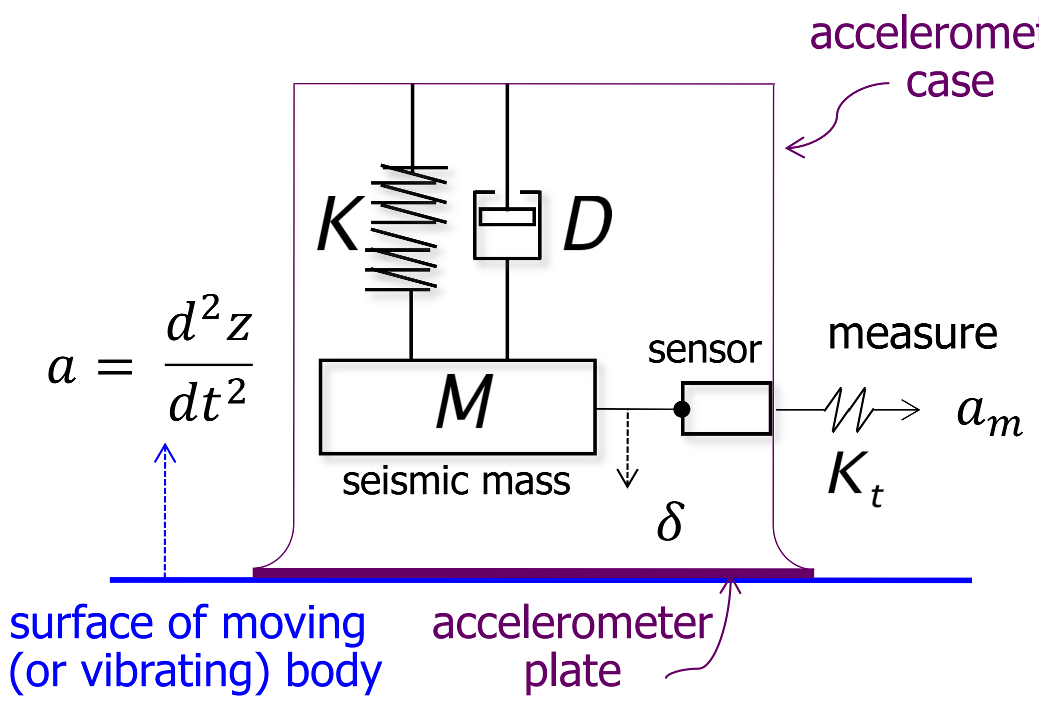
- measure of linear acceleration based on inertial forces (no "touch")
  - units: [m/s²] or gravitational acceleration [g] (non-SI unit: 1g ≈ 9.81 m/s²)
- different principles for converting mechanical motion in an electrical signal
  - piezoelectric: piezoceramics (PZT) or crystals (quartz), better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

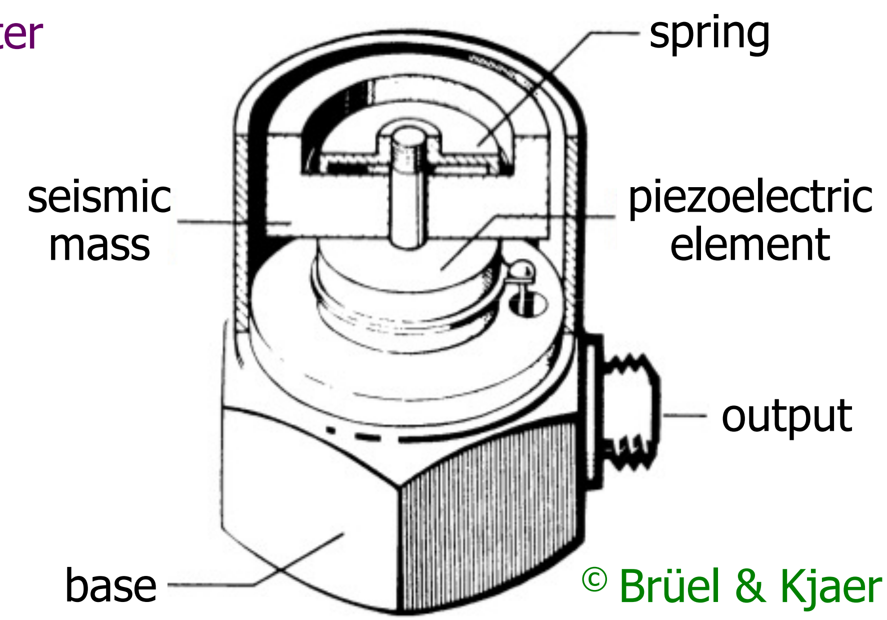





animation of measurement principle in a piezoelectric accelerometer

# Operation principle
## seismic accelerometer




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

$$a_m = K_t\delta$$

by Laplace transform

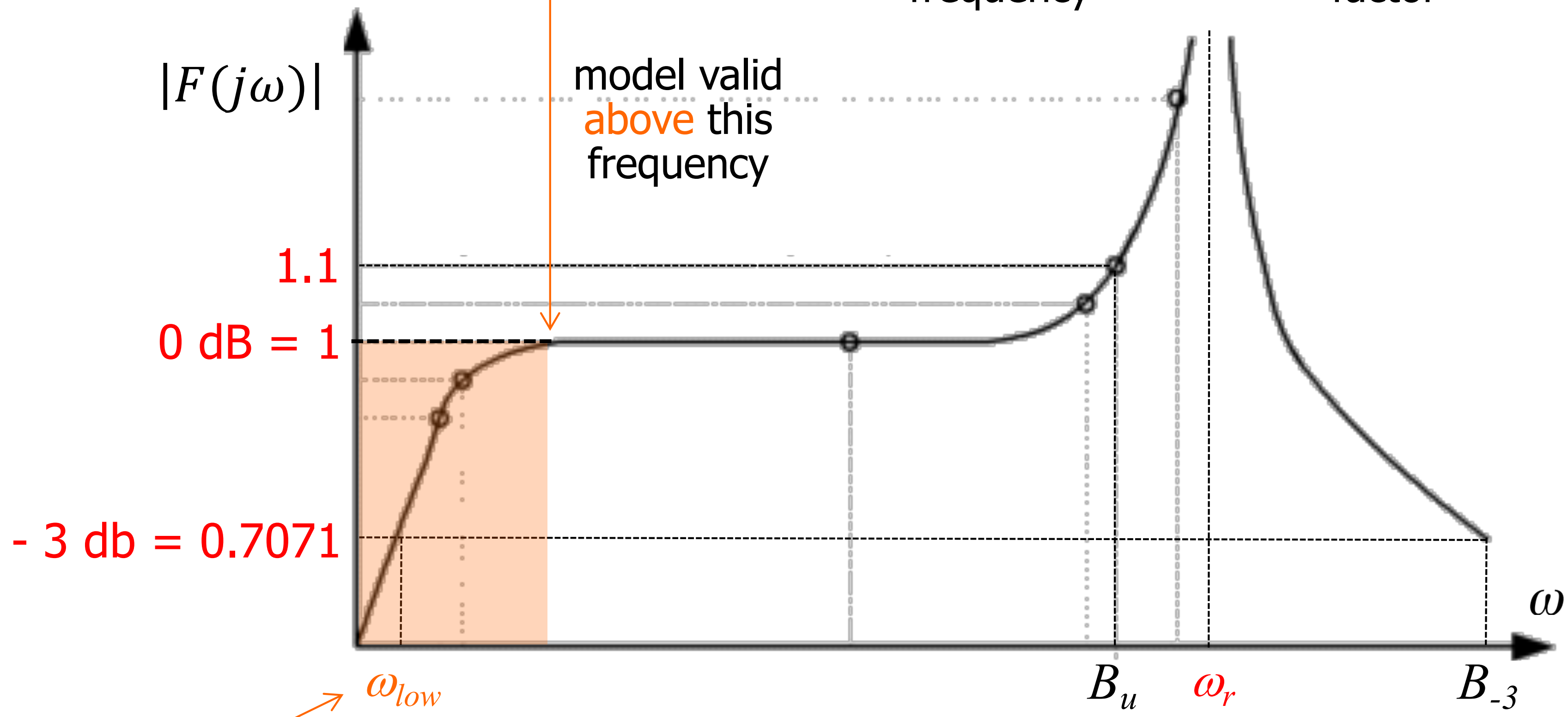
$$\frac{A_m(s)}{A(s)} = K_t \frac{M}{Ms^2 + Ds + K} = \frac{K_t}{s^2+(D/M)s+(K/M)}$$

# Frequency characteristics
## of a piezoelectric accelerometer

$$F(s) = \frac{A_m(s)}{A(s)} = \frac{K_t}{s^2+(D/M)s+(K/M)} \qquad \omega_r = \sqrt{K/M} \qquad \zeta = \frac{D}{2}\sqrt{1/KM}$$

resonance frequency

damping factor



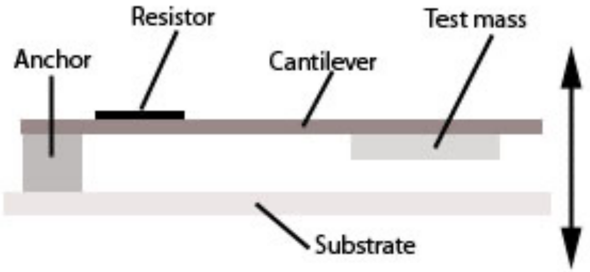

low frequency limit of piezoelectric use (≤ 1 Hz)

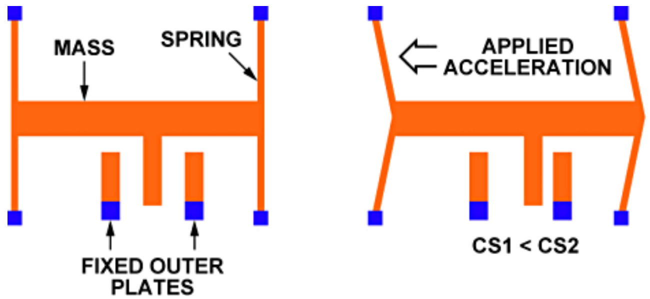
useful bandwidth $B_u \approx 0.3\omega_r$ for 10% error

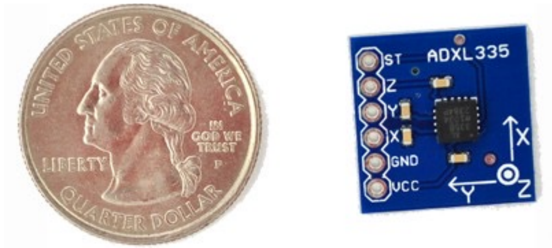
bandwidth

# MEMS accelerometers

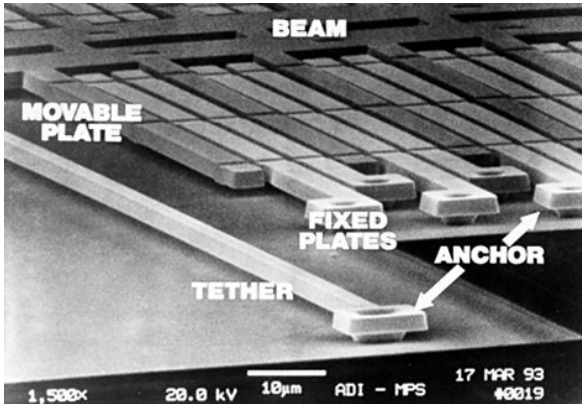
- very simple MEMS (a cantilever beam with a test mass, with damping from the residual gas sealed in the device), single- or tri-axial, very small and light
- cross-couplings among acceleration sensing directions should be limited ≤ 3%

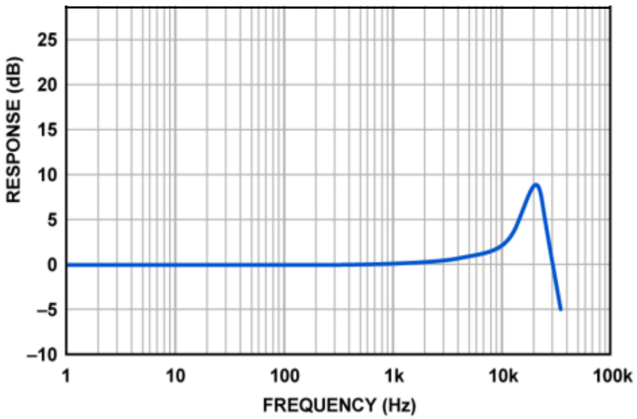


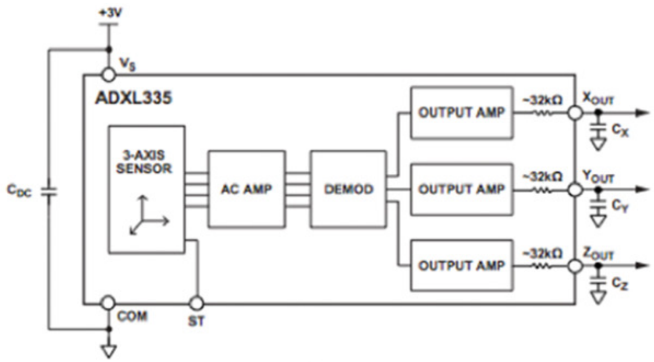



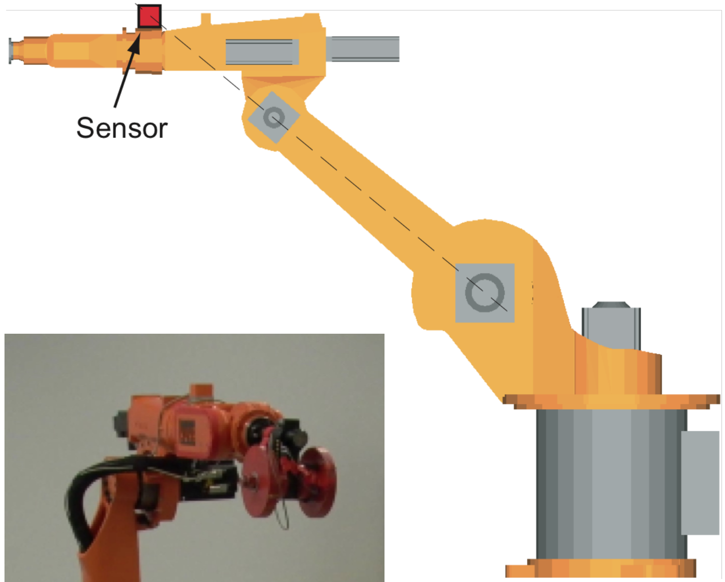

ADXL335 3-axis, small, low power, ±3g, with signal conditioned voltage outputs

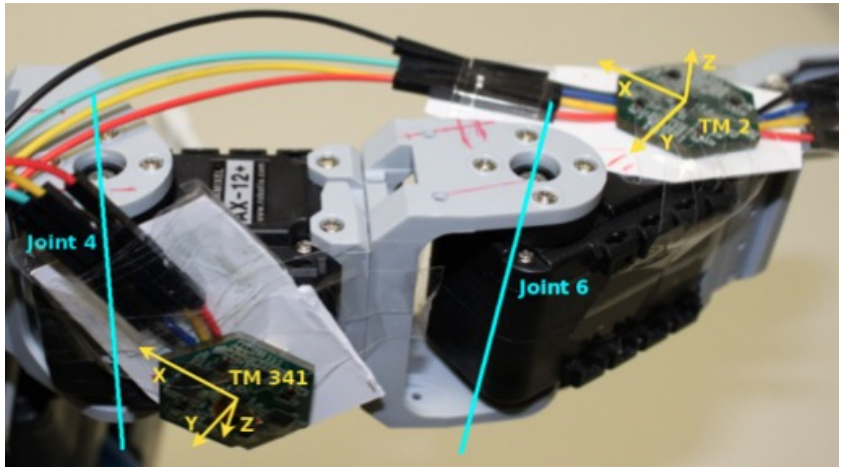


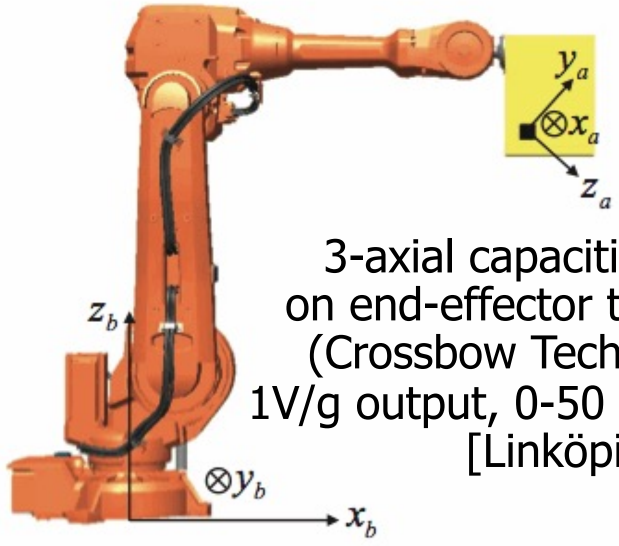
# Mounting accelerometers on robots




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, $\pm 2°$ align error) [Linköping, 2012]