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
  - Target value (ground truth)

- High accuracy
- High repeatability
  - Average value

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”

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

\[ Y = \text{output range} \]

\[ Y_0 = \text{offset} \]

\[ \delta X = \text{resolution} \]

\[ \frac{\Delta Y}{Y_m} = \text{linearity error} \]
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

- 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
- \[ \text{resolution} = \frac{360^\circ}{2^{N_t}} \]
- 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

\[ N_t = \# \text{ tracks} = \# \text{ bits} \] (min 12 in robotics)
Absolute encoding

Binary coding

Gray coding

Optical disks with 2 bits

XOR

Gray-coded absolute encoder

<table>
<thead>
<tr>
<th>DECIMAL</th>
<th>BINARY</th>
<th>GRAY</th>
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<tr>
<td>15</td>
<td>1111</td>
<td>1000</td>
</tr>
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</table>
Use of absolute encoders

- 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
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 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 $\phi \approx 40 \text{ mm}$
- mass $m \approx 100 \text{ g}$
- inertia $J = 1 \cdot 10^{-6} \text{ kg m}^2$
“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)

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Ch B  D  Q  cl  0 = CCW  1 = CW
Ch A

CCW/CW

U/D
cl
reset

Ch A
U/D

Ch B
cl

n bits

Ch Z
reset

XOR

time delay Δ ≈ 45° electrical

C
Count multiplication
equivalent 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) $360°/8000 = .045° (= 0° 2’ 42’’)$
- 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 metastable 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

- **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 $90^\circ$ electrical, is typically within max $\pm 35^\circ$ electrical (quadrature error)

...apart from quantization errors
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): \( \dot{q}_k = \dot{q}(kT) = \frac{1}{T} (q_k - q_{k-1}) \iff \dot{q}_k = \frac{\Delta q_k}{T} \)
  - 4-step BDF: \( \dot{q}_k = \frac{1}{T} \left( \frac{25}{12} q_k - 4q_{k-1} + 3q_{k-2} - \frac{4}{3} q_{k-3} + \frac{1}{4} q_{k-4} \right) \)

- **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](image)
Kinematic Kalman Filter for velocity estimation

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

\[T = \text{sampling time}\]

\[\xi(k) = (x(k) \dot{x}(k))^T\]

- Noisy position measure (encoder output)
- Zero mean Gaussian noises with (co)variances (a matrix) and \(R\)
- Motion and sensing discrete-time model for estimation

Design a (linear) Kalman filter providing an estimate \(\hat{\xi}(k)\) of the model state using the optimal Kalman gain \(K_k\)

- (a priori) prediction
- Correction (based on the measured output)

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

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

\[
V = -\frac{d\Phi}{dt} = |\vec{B}| \Sigma \omega \sin \omega t
\]

amplitude \( V \propto \omega \)

⇒ 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 $11 \div 24 \text{ V @}1000 \text{ RPM}$
- 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

<table>
<thead>
<tr>
<th>Model Number</th>
<th>Mounting</th>
<th>Weight (approx)</th>
<th>Inertia (approx)</th>
<th>$V/1,000$ RPM</th>
<th>RPM (max)</th>
<th>Driving Torque (max)</th>
<th>Arm R (ohms dynamic)</th>
<th>Arm Ind (h)</th>
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</thead>
<tbody>
<tr>
<td>SA-740B-1*</td>
<td>Face</td>
<td>4.0 oz</td>
<td>$2.27 \times 10^{-4}$</td>
<td>20.8 V</td>
<td>8,000</td>
<td>0.25 oz-in.</td>
<td>1000</td>
<td>0.55</td>
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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 (g₀), 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

\[ a = \frac{d^2 z}{dt^2} \]  

surface of moving (or vibrating) body
accelerometer plate

\[ M \ddot{a} = M \ddot{\delta} + D \dot{\delta} + K \delta \]

by Laplace transform

\[ a_m = K_t \delta \]

\[ \frac{A_m(s)}{A(s)} = K_t \frac{M}{M s^2 + D s + K} \]

\[ = \frac{K_t}{s^2 + \left(\frac{D}{M}\right)s + \left(\frac{K}{M}\right)} \]

Robotics 1
Frequency characteristics of a piezoelectric accelerometer

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

\[ \omega_r = \sqrt{\frac{K}{M}} \quad \zeta = \frac{D}{2} \sqrt{\frac{1}{KM}} \]

- 3 dB = 0.7071
0 dB = 1

\( \omega_{low} \)
low frequency limit of piezoelectric use (≤ 1 Hz)

useful bandwidth \( B_u \) for 10% error \( \approx 0.3\omega_r \)

model valid above this frequency

robotics spectrum
resonance frequency
bandwidth

\( |F(j\omega)| \)
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

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]

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