Cours de Bases de la Robotique
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1. Introduction
   MB: Introduction à robots parallèles.

2. Bases Théoriques
   MB: Cinématique
   HB: Jacobien, Dynamique

3. Composants
   MB: Contrôle, Interfaces
   HB: Capteurs, Actionneurs

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Today's program

- Definitions, Classifications (linear, absolute, incremental, ...)
- Position sensors:
  - Inductive, Eddy Current
  - Encoders (linear, rotary, optical, potentiometer)
  - Strain Gauges, Jauge de déformation
  - Position Sensitive Detector (PSD)
  - Capacitive
  - Linear-Variable Differential Transformer (LVDT)
- Force sensors:
  - Strain gauges, Jauges de contraintes
  - Displacement free force sensors
  - Multi DOF sensors

Just like an actuator, a sensor is basically a transducer from one form of energy to another.

Input power
\[\text{e.g. mechanical}\]

Output power
\[\text{e.g. electrical}\]

Losses
\[\text{Disturbances, noise}\]

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Proprioception – Exteroception

- **Proprioception**: In order to know the robot's configuration: position, angle, velocity, acceleration or force. Reference within robot (or body) itself
- **Exteroception**: Vision from the task, taking external reference. Position, orientation, mass, vision. (Vision is a huge topic of its own, not treated in this lecture)

Proprioception – Exteroception

- **Notion importante en biomécanique**
  - Exemple: Travail avec paraplégique: Problème d'absence de proprioception.
  - Le paraplégique ne perçoit ni la position ni la charge (force) de ses membres.
  - Nécessité de regarder ses membres, miroir, entendre les moteurs de l'exosquelette...

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Cours Bases de la Robotique

3.1 Capteurs pour la robotique

**Sensors**

Focus: General, industrial, medical robotics

Sensing for mobile, flying robotics & autonomous vehicles would be a lecture by itself
Sensors: Classification criteria

- what is the measurand?
  - Position (distance)
  - Velocity, acceleration
  - Angle, Rotational Speed, inclination
  - Force, Torque
  - Pressure, stress (normal, shear...)
  - Temperature, humidity
  - Noise, vibrations
  - Electric/Magnetic field
  - etc.

- What physical principle for the transducer from measurand to electronic signal?
  - Mechanical
    - optical (interferometry, intensity, triangulation, t.o.f., etc.), infrared, acoustical, capacitive, inductive, eddy currents, hall effect
    - piezo: piezoelectric, piezoresistive dilatation (thermal), ...

Sensors: Classification criteria

- Measurand
- Physical principle
- Metrological principles:
  - absolute vs. incremental (relative)
  - differential
  - averaging vs. local
  - Indirect measurement: nulling.

Example Nulling principle:
Precision scale Mettler Toledo

- Principle: Compensate weight with voice coil force
- zero position measrmt.only
- Advantage: the sensor may be highly nonlinear!
- It just must detect the sweep through zero with high repetitivity & sensitivity

What is a sensor?

A sensor is a transducer ...

It transforms a physical variable to be measured (the "measurand") into an electrical signal (the "output") to be treated by a data acquisition system.

Ideally only one way, no noise, no cross coupling from other physical variables (such as e.g. temperature)
Signal Conditioning

The first stage of signal conditioning is considered part of the sensor.

The raw electrical signal is often very weak. Signal processing (ampl., signal extraction) as close as possible to measurand (why?)

Transfer Function

The functional relationship between physical input signal and electrical output signal.

\[
\text{Bandwidth} = \frac{1}{\text{T}_{\text{sp}} + 3\tau}
\]

Définitions de base

- Résolution: Resolution
- Sensibilité: Sensitivity
- Fidélité = répétabilité: Repeatability (rel. accuracy)
- Justesse: Trueness (abs. accuracy)
- Répétable et juste = précision: True and repeatable = precise

Sensitivity

is the relationship indicating how much output you get per unit input. Also called "gain". 

Slope of the input-output curve

Resolution

The resolution is defined as the minimum detectable measurand change.

Répétabilité vs. Justesse

True – (rel.) Accuracy

Resolution – Accuracy (applies to sensors & actuators)

The resolution is the smallest displacement: achievable or measurable.

the Trueness, "absolute accuracy" is the deviation of the mean of the actual output from the true value.

Good repeatability: "relative accuracy" is how much scatter when repeating a measurement.

Good repeatability and good trueness result in good precision.
**Nonlinearity**: Maximum deviation of the slope from a linear transfer function over the specified dynamic range.

**Linearity**: When the sensitivity is constant, i.e., independent from the measured value, the input-output function will be linear.

**Dynamic Range**: The limits within which the input (measurand) can vary while avoiding output saturation. If the dynamic range is exceeded, we reach saturation. The output signal can either saturate or take meaningless values (wrap-arounds etc.; beware, e.g., for angular measurements!) Ariane V crash: 8-bit, 16 bit problem!!!

**Hysteresis**: A sensor may give a different reading for the same quantity depending on the direction of approach.

**Drift**: – Phénomène lent – Le plus souvent due au changement de température – Peut aussi être résultat du vieillissement d’un capteur

**Position Sensor Errors**:

**Abbe error** - is the linear positional error caused by the axis of measurement being offset from the axis of displacement. This error is avoid by measurement system coaxial with displacement to be measured.

**Typical precisions in robotics**

- Conventional robotics (industrial): 100 - 10 μm
- Precision robotics (micro-assembly): 10 - 1 μm (machine tools)
- High precision robotics: 1 - 0.001 μm (micro-robotics)
One nanometer is very small!

- 1 nanometer = 10 Angstrom (Å)
- 1 nanometer = ca. 4 atomic radii
- A 40 mm steel rod will expand 480 nm for a temperature change of 1 degree
- A 40 mm steel rod in length and 6 mm in diameter will bend 6 nm on its own weight

Récapitulation: Un bon capteur sera:

- Linéaire
- Faible bruit (Bon rapport Signal-Bruit)
- Réponse rapide
- Haute bande passante
- Grande plage de mesure combiné avec haute résolution
  (*High Dynamic Range*)
- Haute sensibilité
- Haute précision
- Faibles dérives
- Faible hystérésis
- Découpé de paramètres autres que la grandeur mesurée

The most obvious position sensor:

A simple potentiometer (rotational or linear)

Advantages:
- Low-cost
- No processing electronics
- Linear, instantaneous

Drawbacks:
- Not contact-free
- Output signal can be noisy
- Wear
- Thermal drift

Position, velocity, acceleration, angle, rotational speed/accel.

<table>
<thead>
<tr>
<th>Sensor Type</th>
<th>Advantages</th>
<th>Drawbacks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accelerometer</td>
<td>Capacitive displacement sensor</td>
<td>May be fragile</td>
</tr>
<tr>
<td>Gravimeter</td>
<td>Gravimetric (electrical, opt. MEMS)</td>
<td>May be fragile</td>
</tr>
<tr>
<td>Inclinometer</td>
<td>Integrated circuit (piezo) sensor</td>
<td>May be fragile</td>
</tr>
<tr>
<td>Gyroscope (Mechanical, opt., MEMS)</td>
<td>Laser ranging device</td>
<td>May be fragile</td>
</tr>
<tr>
<td>Laser surface velocity</td>
<td>Laser angular velocity</td>
<td>May be fragile</td>
</tr>
<tr>
<td>Odometer</td>
<td>Linear encoder</td>
<td>May be fragile</td>
</tr>
<tr>
<td>Photodiode sensor</td>
<td>Linear (rotational) variable differential</td>
<td>May be fragile</td>
</tr>
<tr>
<td>Position sensor</td>
<td>Transformer</td>
<td>May be fragile</td>
</tr>
<tr>
<td>Rate sensor</td>
<td>Tachometer</td>
<td>May be fragile</td>
</tr>
<tr>
<td>Rate sensor</td>
<td>Variable reluctance sensor</td>
<td>May be fragile</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

Systematic and random errors

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Influencing parameters</th>
<th>Improvement by</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurement</td>
<td>Accuracy, linearity</td>
<td>Calibration</td>
</tr>
<tr>
<td>Resolution</td>
<td>Accuracy, linearity</td>
<td>Signal processing</td>
</tr>
<tr>
<td>Stability</td>
<td>Accuracy, linearity</td>
<td>Control</td>
</tr>
<tr>
<td>Precision</td>
<td>Accuracy, linearity</td>
<td>Model fitting</td>
</tr>
<tr>
<td>Uniformity</td>
<td>Accuracy, linearity</td>
<td>Measurement</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>Accuracy, linearity</td>
<td>Sensor</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>Accuracy, linearity</td>
<td>Electronics</td>
</tr>
<tr>
<td>Resolution</td>
<td>Accuracy, linearity</td>
<td>Drivers</td>
</tr>
<tr>
<td>Uniformity</td>
<td>Accuracy, linearity</td>
<td>Preload</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>Accuracy, linearity</td>
<td>Compensation</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>Accuracy, linearity</td>
<td>Stiffness</td>
</tr>
<tr>
<td>Resolution</td>
<td>Accuracy, linearity</td>
<td>Load force</td>
</tr>
<tr>
<td>Random drift</td>
<td>Temperature, thermal expansion coefficient</td>
<td>Material selection, temperature control, mechanical design</td>
</tr>
<tr>
<td>Friction</td>
<td>Material selection, lubrication</td>
<td>Stiff mechanism, frictionless mechanisms</td>
</tr>
<tr>
<td>Vibration, noise</td>
<td>Resonance frequency</td>
<td>Stiff mechanisms, low mass (high resonance frequency), elimination of sources' vibration, damping, vibration filtering (isolation table)</td>
</tr>
</tbody>
</table>

Analog Potentiometer

Example:

100° ± 1°
Assuming ±10 mV noise.

What is the expected maximal resolution?

20 Volts / 20 mVolts = 1000 steps
[10 bits = 1024 steps]

ie. resolution of 1000 / 1024 = 0.97°
Not good and not sufficient
Main principles for position sensors
- Inductive (Electromagnetic)
  - "true" inductive
  - Eddy current
  - Resolvers, LVDT (Lin. var. diff. transformer)
  - Hall effect sensors
- Capacitive (Electrostatic)
- Optical (incl. infrared)
  - Interferometer
  - Incremental (relative)
  - Absolute encoder
  - PSD (Photo Sensitive Diode) Intensity, Triangulation
- Time of flight

Inductive Sensor
typ. ca 10-100 kHz
- Measures the inductance of a ferromagnetic target, which changes in function of the distance from sensor.
- Can be very accurate. Problem in case of tangential motion of target (typical: Rotating machinery)
  - What is really measured, is the magnetic homogeneity of the material. Accurate, if averaging over a large surface.

Inductive Sensor
typ. 10-100 kHz
- Large choice of commercial products, for every price, range, accuracy
- Good averaging out of small target defects
- Dirt resistant
- Low measurement range (mm range)
- Target must be ferromagnetic and homogenous within the measurement volume

Eddy Current Sensor
typ. ca 50 kHz – Mhz-range
- Now we measure not the imaginary part, but the real part of the impedance
- In practice, every sensor is a combination of both effects!
- Now non-ferromagnetic, but conducting target possible!
  - This is much less restrictive than the inductive principle.
    - Large choice of commercial products
    - Now also sensitive to inhomogeneities in conductivity
    - Low range

Simple structure: Easy to adapt to harsh environments (hot, UHV, corrosive, liquid)
- Little effect of temperature: Has been made for T up to 500 °C
- UHV compatibility!
  - In these cases not PCB, but screen printing on Alumine substrate, Ag–Pd conductors

Incremental Encoders
- Measurement of angles or distance by increments
- Most common: Optical rules
- Increments on glass disc or rule: Typically 20 µ
- Electronic counter

- Relative sensor! Has to be calibrated (referenced) on power up
Optical Encoders (working principle)

How to discriminate the direction?

Direction detection: Signals in “quadrature” : 90° phase shift

Encoders (signal conditioning)

Comparator with hysteresis

The resolution is multiplied by 4!

Enhancing the resolution of an optical encoder

Problem: Light source (LEDs) too large with respect to the pitch
Solution: Use a fixed Mask with the same pitch!

Encoders (working principle)

The masks are shifted by ¼ of pitch (direction detection)
The LEDs’ relative position doesn’t matter any more.
Example of a quadrature counter
Size : 24 bits

If a 1000 pitch incremental rotational encoder is used:

\[ \text{Resolution} = \frac{360°}{1000 \times 4} = 0.08 \degree. \]

For a size of 24 bits,

\[ \text{Size}_{\text{max}} \text{ of counter} = 2^{24} \text{ bits} \]

\[ \text{Angle}_{\text{max}} = 0.08 \times 2^{24} = 3728 \text{ turns}. \]

If the motor turns a screw with a step of 1 mm,

\[ \text{Distance}_{\text{max}} = 3728 \times 1 \text{ mm} = 3728 \text{ m}. \]

To count this distance,

 Use of a quadrature counter

Incremental Encoder

Absolute Encoder

Rotary encoders

Rotary encoders (maxon motor)

Absolute position

Only 1 bit changes between subsequent position with the Gray code.
Rotary encoders

Absolute code wheel (3 bits)

Absolute code wheel (16 bits)

LVDT: Linear Variable Differential Transformer

Differential measurement principles:
- Very robust to temperature change, supply voltage fluctuations etc.
- No electronics at sensor itself, very robust, large operating temp. Range (used in Industry & Airplanes)

RVDVT, a special type of the more general Resolver

Basic resolvers are two-pole resolvers, meaning that the angular information is the mechanical angle of the rotor. They give the absolute angle position. Multipole resolvers have 2p poles (p pole pairs), and thus can deliver p cycles in one rotation of the rotor; the electrical angle is p times the mechanical angle. Some types of resolvers include both types, with the 2-pole windings used for absolute position and the multipole windings for accurate position. Two-pole resolvers can usually reach angular accuracy up to about ±5 ″, whereas a multipole resolver can provide better accuracy, up to ±10 ″ for 16-pole resolvers, to as low 1″ for 128-pole resolvers.

Resolvers: Example from Bomatec catalogue (Tamagawa)

Example Admotec Zurich

Le Rotasyn utilise un entrefer constant sur le rail avec un volant diamanté à l'axialité et aux changements magnétiques parfaits. Il peut être directement connecté à des convertisseurs resolver-numérique (RDC en anglais) classiques.
High resolution over large range:

The dynamic range is limited by the signal to noise ratio

<table>
<thead>
<tr>
<th>resolution</th>
<th>range</th>
<th>noise</th>
<th># bits</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 µm</td>
<td>1 nm</td>
<td>100</td>
<td>6.10</td>
</tr>
<tr>
<td>1 mm</td>
<td>1 mm</td>
<td>100</td>
<td>8.62</td>
</tr>
<tr>
<td>1 cm</td>
<td>1 cm</td>
<td>100</td>
<td>10.98</td>
</tr>
<tr>
<td>1 m</td>
<td>1 m</td>
<td>100</td>
<td>13.21</td>
</tr>
</tbody>
</table>

When nm resolution has to be measured on several millimeters, incremental sensors and counters must be selected.

Strain gauges = Jauge de contrainte as position sensor

The strain \( \varepsilon = \frac{\Delta L}{L} \) is defined as deformation. \( \Delta L \).

Strain gauges can be used as position sensors.

A incident light (e.g. laser beam) generates photocurrents in a PIN junction. The collected current provide the position information.

Position sensors (Position Sensitive Detector - PSD)

Resolution (few µm)

Moderate range (a few mm)

Reduce size

Cost effective

Position sensors (capacitive)

The capacity changes with electrode distances and/or surfaces.

\[ C = \varepsilon \times \frac{S}{x} \]

Free high resolution (pm)

Short range (100-500 µm)

Bulky (cm)

Expensive (sensor and electronics)
Sensors (Linear-Variable-Differential-Transformer, LVDT)

High resolution (10-20 nm)
Moderate range (few mm)
Moderate cost

Sensors used in the « TWICE » Exoskeleton

Hall effect angular position sensor

6 Fr/piece

Load cell from CHF 20.- scale

CHF 5.-

High-end sensors: Baumer, Kistler, LEM…

Baumer (Frauenfeld)
Encoders: Example
- Lenord + Bauer « Drehgeber »
  up to 100'000 rpm (200 kHz)

Linear encoders
- Industrial products
  - Robust, reliable
  - Rather compact
  - Moderate cost
  - Resolution up to 5 nm

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High-end sensors: Baumer, Kistler, LEM
- Kistler (Winterthur) force, torque, accelerometers, pressure
- Baumer (Frauenfeld) position, angle, acceleration, inductive, laser, ultrasonic etc.
- LEM (Geneva) electrical current

Metrology: Coordinate Measurement Machine (CMM)
- Principle
- Housing for good temperature homogeneity
- 3D touch probe

Metrology: 3D touch probe
- Repeatability in one point: 5 nm
- Accuracy within the volume: < 30 nm
- Probe diameter: 1 mm down to 0.125 mm

Un micro-robot équipé d’un AFM
- Scanner AFM

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Mesure de position par AFM

10 µm

Optical Position Sensors

Exemple de Start-up EPFL

Laser interferometer

The reference scale is the wavelength of a laser beam. Interferences with a reference beam creates nodes every \( \lambda/4 \) (typically 160 nm).

Fringe counter (nodes): typ. 160 nm
Interpolation (amplitude): typ. 0.16 nm (1'000 node)

Multi axis configuration

Some examples of laser interferometers

SIOS ZYGO

RENISHAW

Other example

Deflection sensors for Local Measurements

STM Tunneling Beam Deflection Interferometry Capacitance Piezoresistance Piezomodterny
### Force Sensors

**Multi-DoF sensor (6 dof wrist, Bejczy)**

### FSR  Force Sensing Resistors

- Semi-conductive paste (containing graphite particles) sandwiched between polymer layers, deposited by screen printing.
- Invented in the 1980ies by Mick Fleetwood looking for sensors for his drums...
- Robust, low cost, good sensitivity, but limited precision (around 10%).
- MW to kW @ 100 kN/cm

### Application in Biomedical Technology:

- Foot sensor
- Presence sensor in car seats
- etc.

### Force sensor, principle

\[ F = K \cdot \Delta x \]

*A force sensor (load cell) is basically an elastic body and a position sensor.*
A force sensor (load cell) is basically an elastic body and a position sensor. The deformation can be measured with strain gauges.

The strain $e$ is proportional to the deformation $\Delta x$.

Strain gauges are often used as position sensors.

Stack piezo cantilevers: flexure

Sensitivity: $K = F/\Delta x$.

High sensitivity means low stiffness (small $K$). It is generally a problem for high accuracy manipulation.
Different types of strain gauge technology

- Base
- Cantilever Beam
- Force Centering Ball
- Amplification Circuit
- Lead Frame SIL

Commercial products: Millinewton (Sensile), SensorOne

Piezoelectric transducers:

- Piezo as an actuator: charge $\rightarrow$ strain $\rightarrow$ stress
- Piezo as a sensor: stress $\rightarrow$ strain $\rightarrow$ charge

Piezoelectric materials:
- Quartz (weak)
- Salt (very weak)
- Polycrystalline ferroelectric ceramics:
  - BaTiO$_3$
  - Lead Zirconate Titanate (PZT)

Basic mechanism:
- Stress $\rightarrow$ strain $\rightarrow$ charge
  - Also charge $\rightarrow$ strain (actuator)
  - Complex geometry (polarization direction, strain tensor, shear...)
  - Small displacements, high forces, high voltages ($\mu$m to tens of $\mu$m for cm size PZT, 100s of V)</lth>
  - Nonlinearity, hysteresis
  - Ceramics $\rightarrow$ brittle $\rightarrow$ prestress

Mechatronics technology
- 2-dof friction drive «LINROT» for translation and rotation
- 6-dof force sensor
- For extended bandwidth
- Compensation of friction and inertia
- Signal conditioning electronics already integrated
Accelerometers, Gyroscopes

**IMU for Inertial Measurement Unit**

- MEMS-fabricated
- Detection of motion of proof-mass
- Detection:
  - capacitive
  - optic (laser)
  - piezoelectric/piezoresistive
  - others
- Applications:
  - crash detection
  - motion analysis
  - smartphone
  - games etc.

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Detection of orientation

- gyrocompass
- magnetic compass
- Optical gyroscopes (precise, expensive)
- MEMS: Out-of-plane oscillation

Together with accelerometers:

**“IMU” Inertial Measurement Unit**

**Applications:**
- Mobile robotics
- Biomedical
- Drones etc.

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Problème des mesures inertielles:

Position & Orientation s’obtiennent après une double intégration

Repère zéro?

Compléter avec GPS, SLAM*, utilisation de la gravitation et de repères pour l’initialisation & la recalibration

*SLAM: Simultaneous Localization And Mapping

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Exemple d’une start-up EPFL qui exploite les capteurs IMU MEMS:

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Force sensing in surgical telemanipulators

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Pièces d’horlogerie...
Force Sensor for Knee Surgery:

Example: Technology choice (PCB) leads to new sensor: Transverse Flux Sensor

Transverse Flux Sensor
- Excitation frequ. 20 kHz to 3 MHz depending on electric & magnetic properties of target material
- Potential for high precision since there is averaging over large target area. Unaffected by low frequ. & static fields.

2D diamagnetic vibration sensor
- Electrostatic actuators for nulling

2D accelerometer with a 4-segment photodiode