64-424
Intelligent Robotics

https://tams.informatik.uni-hamburg.de/lectures/2018ws/vorlesung/ir

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Technical Aspects of Multimodal Systems

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Outline

1. Organization
2. Motivation

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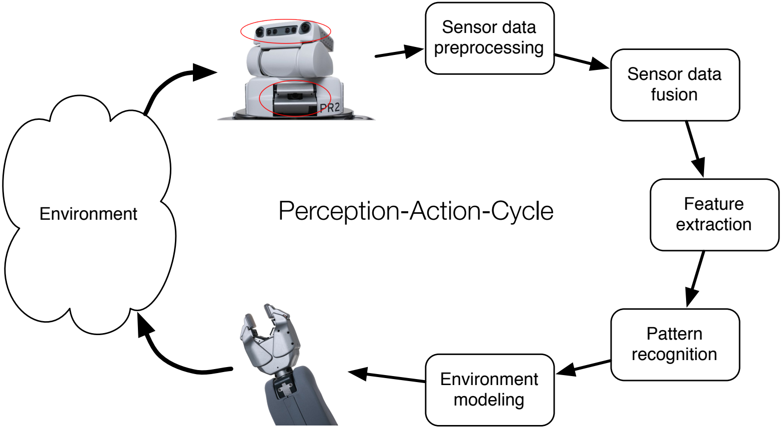
2. Motivation

Sensors in robotics: Perception

- Sensors are crucial to the development of intelligent robotic systems
- Sensor data provides an abstract perception of the environment
- The Perception-Action-Cycle represents the control loop
  1. Sensing of the environment
  2. "Intelligent" processing of obtained data
  3. Execution of an action
- The cycle is crucial to the implementation of interactive, adaptive and situation-based behavior

Perception-Action-Cycle: Overview



Perception-Action-Cycle

1. **Data acquisition:** Sampling of analog/digital signals output from sensor devices
2. **Data (pre-)processing:** Filtering, normalization and/or scaling, etc., of acquired data
3. **Data fusion:** Combination/fusion of multi-modal and redundant sensor data leading to robust measurements, reduced uncertainty and an increase in information
4. **Feature extraction:** Extraction of features representing a mathematical model of the sensed environment in order to approximate the natural human perception

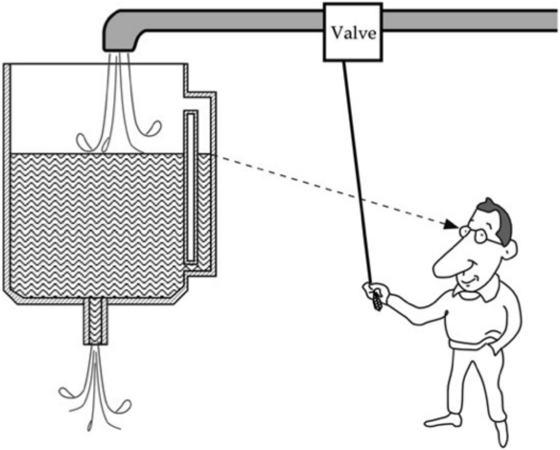
Perception-Action-Cycle (cont.)

5. **Pattern recognition:** Extracted features are searched for patterns in order to classify the data
6. **Environment modeling:** Successfully classified patterns are used to model the environment of the robotic system

... ...

n. **Action:** Based on the model of the environment sets of goal-oriented actions are executed manipulating the environment (using robotic arms, grippers, wheels, etc.)

A Sensor - A Simple Example

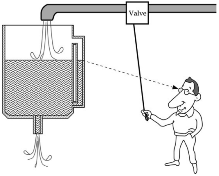


What is a sensor?

The sensor in the example consists of two parts:

- The water level indicator
- The human eye

⇒ Perception of the level indicator results in a signal to the brain



Definition

A sensor is a unit, which

- receives a signal or stimulus
- and reacts to it

Natural and physical sensors

Natural sensors:

- A reaction is an electrochemical signal on neural pathways
- Examples: Auditory sense, visual sense, tactile sense, ...

Physical sensors:

Definition

A physical sensor is a unit, which

- receives a signal or stimulus
- and reacts to it with an *electrical signal*

Input signal

- A physical sensor converts a (generally) non-electrical signal into an electrical one
- This signal is referred to as the stimulus

Definition

A stimulus is a

- quantity,
- characteristic or
- state,

which is perceived and converted into an electrical signal

Output signal

- The output signal can be
  - a voltage,
  - a current or
  - a charge
- Furthermore, the signal can be distinguished by
  - amplitude,
  - frequency or
  - phase

Taxonomy

- Intrinsic sensors:
  Provide data about the *internal system state*
- Extrinsic sensors:
  Provide data about the *environment*

- Active sensors:
  Modify *applied electrical signal* in response to the change of the stimulus
- Passive sensors:
  Create an electrical signal in response to the change of the stimulus (conversion of the stimulus)

Further classification

Physical sensors can also be classified by:

- Type of stimulus
- Characteristics, specification and parameters
- Type of stimulus detection
- Conversion of stimulus to output signal
- Sensor material
- Field of application
- ...

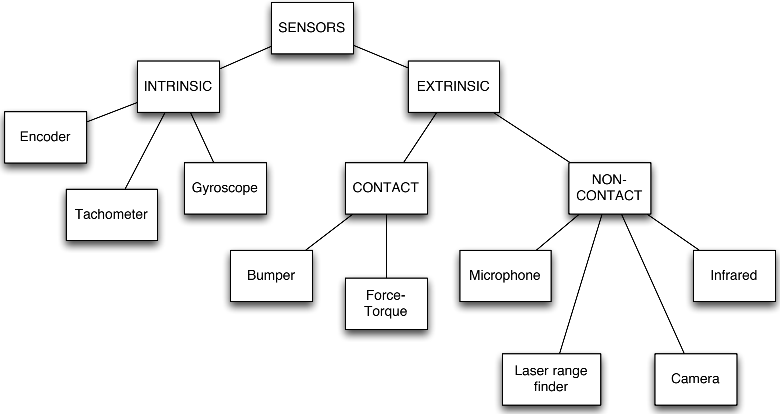
Sensor examples

- **Intrinsic sensors:**
- **Extrinsic sensors (force/pressure):**
- **Extrinsic sensors (distance):**
- **Visual sensors:**

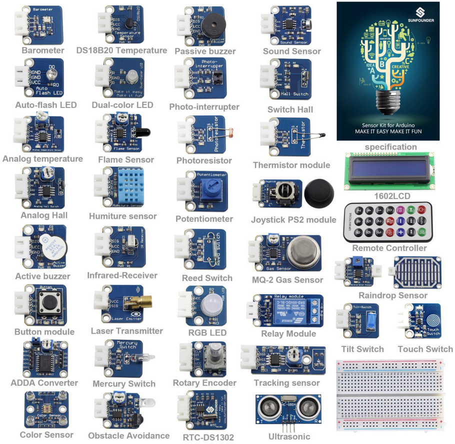
Sensor examples

- **Intrinsic sensors:**
  Encoder (incremental/absolute), accelerometer, gyroscope, ...
- **Extrinsic sensors (force/pressure):**
  Strain gauge, force-torque sensor, piezoelectric sensor, ...
- **Extrinsic sensors (distance):**
  Sonar sensor, infrared sensor, laser range finder, ...
- **Visual sensors:**
  Linear camera, CCD-/CMOS-camera, stereo vision cameras, omnidirectional vision camera, ...

Classification example



Sensor Examples



https://www.robotshop.com/media/files/images2/37-modules-sensor-kit-arduino-v2-desc-includes.jpg

Sensor Examples

https://www.techspurts.com/a-drone-will-be-in-charge-of-driving-your-autonomous-car-if-its-sensors-break-down/

Measurement with sensors

- Measurement results have to be *reliable* (within specification)
- Important scientific criterion: *Reproducibility* of measurements
- Scientific statements have to be comparable
- Statements must be *quantitative* and based on measurements
- Measurement result consists of:
  - Numerical value
  - Measuring unit
- Additionally: Declaration of measurement accuracy

Measurement errors

No measurement process yields an entirely accurate result!

Measurement deviation (Measurement error)

Systematic deviation ("systematic error"):

- Deviation is caused by the sensor itself
- For example: wrong calibration, persistent sources of interference like friction, etc.
- Elimination is possible, but requires elaborate examination of the error source

Random deviation ("random or stochastic error"):

- Deviation is caused by inevitable, external interference
- Repeated measurements yield different results
- Individual results fluctuate around a mean value

Error declaration

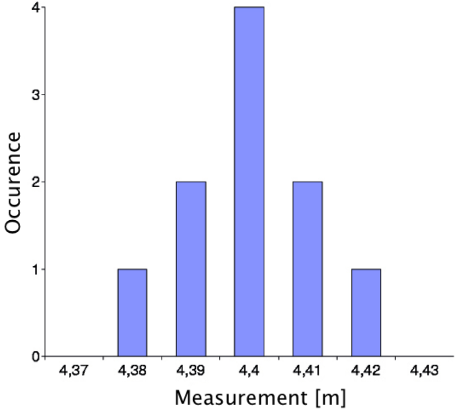
- Measurements are always afflicted with uncertainty
- **Example:** Distance measurement
  - Distance to an object is measured 10 times $(x_1, ..., x_{10})$

Individual measurement results:				
$4,40\ m$	$4,40\ m$	$4,38\ m$	$4,41\ m$	$4,42\ m$
$4,39\ m$	$4,40\ m$	$4,39\ m$	$4,40\ m$	$4,41\ m$

- Due to random deviation individual measurement results x_i vary

Error declaration (cont.)

Measurements can be illustrated in a histogram:



Mean value

The mean value $\bar{x}$ of the individual measurements x_i is determined as follows:

$$\bar{x} = \frac{1}{N} \sum_{i=1}^{N} x_i$$

- The mean value is also called arithmetic average or best estimate for the true value μ
- μ is the *mean* or *expected value* of the set of all possible measurement values (population)

Absolute and relative error

Measurement deviation can be specified in two different ways

- Absolute measurement deviation ("Absolute error"):
  The absolute error Δx_i of a **single** measurement x_i equals the deviation from the mean value $\bar{x}$ of all N measurements $\{x_n | n \in \{1 \ldots N\}\}$ of a measurement series
  - The unit is equal to that of the measured value
  - $\Delta x_i = |x_i - \bar{x}|$
- Relative measurement deviation ("Relative error"):
  The relative error $\Delta x_{i\,\mathrm{rel}}$ is the relation between absolute error Δx_i and the mean value $\bar{x}$
  - Has no dimension, often specified as a percentage (%)
  - $\Delta x_{i\,\mathrm{rel}} = \frac{\Delta x_i}{\bar{x}_i}$

Variance of a measurement series

- How far are the measurement samples spread out?

The *distribution* of single measurement values x_i around the arithmetic mean $\bar{x}$ is represented by the variance of a measurement series [1]

$$s^2 = (\Delta x)^2 = \frac{1}{N-1} \sum_{i=1}^{N} (\Delta x_i)^2$$

$$= \frac{1}{N-1} \sum_{i=1}^{N} (x_i - \bar{x})^2$$

Standard deviation of a measurement series

Similar to the variance, the positive square root of the variance - called the standard deviation - is another representation of the dispersion of measurement values x_i around the mean value $\bar{x}$

$$s = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(x_i - \bar{x})^2}$$

- The standard deviation is also known as the mean error of a single measurement
- In contrast to the variance the standard deviation carries the same unit as the measurement samples

Standard deviation of the mean

- The true mean value (μ) of the population is unknown

The standard deviation of the mean value, also error of the mean value, is determined as follows

$$s_{\bar{x}} = \sqrt{\frac{1}{N(N-1)} \sum_{i=1}^{N} (x_i - \bar{x})^2} = \frac{\Delta x}{\sqrt{N}} = \frac{s}{\sqrt{N}}$$

$s_{\bar{x}}$ is the deviation of the mean values of individual measurement series ($\bar{x}$) from the true mean value μ

Measurement result

- The variance and standard deviation of a measurement series show us the spread from the mean of the series
- The standard deviation of the mean gives us the spread from the true mean μ

With the above in mind we can expect a measurement sample to be given by

$$x = (\bar{x} \pm s_{\bar{x}} \pm s)\,[Unit]$$

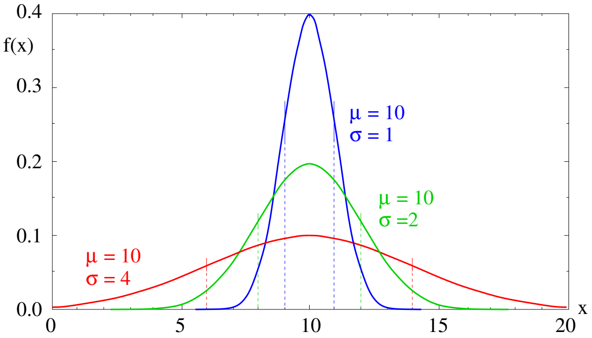
Normal distribution

- For $N \to \infty$ a discrete distribution of a measurement series turns into a continuous distribution
- With $N \to \infty$ we can assume $\bar{x} \to \mu$ and $s \to \sigma$, resulting in the density function of a normal distribution (*Gaussian distribution*)

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}}\, e^{-\frac{(x-\mu)^2}{2\sigma^2}}$$

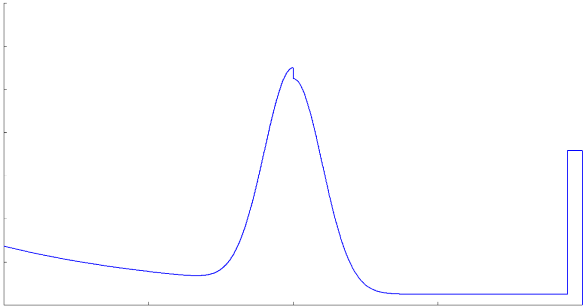
- The measurements of a physical/technical quantity X are *usually* assumed to be normally distributed

Normal distribution (cont.)



$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}}$$

Many measurements are not actually normally distributed



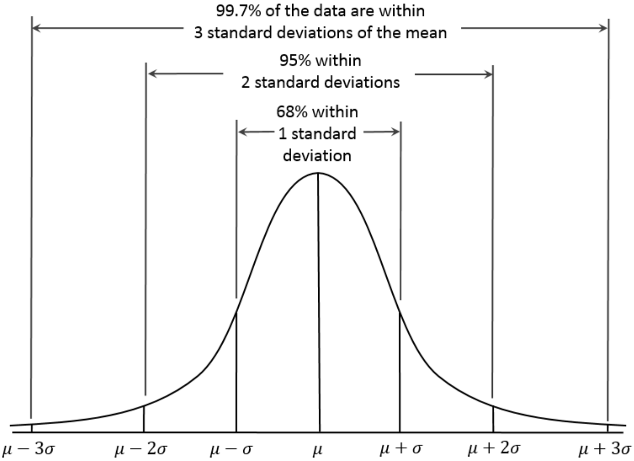
A model for measurements of distances might account for

- stochastic noise
- disturbances before target
- noise floor
- max-range artifacts

Confidence interval

- Interval around a determined mean value of a measurement series that is said to contain other samples of the series with a given probability (confidence)
- A confidence interval of σ ($s_{\bar{x}}$) is said to contain 68.27 % of the population samples
- Extended to 2σ ($2s_{\bar{x}}$) the interval covers 95.45 % of the population
- 3σ ($3s_{\bar{x}}$) is said to contain 99.73 % of the population

Confidence interval (cont.)



Full scale input/output

- The dynamic range of measurable stimulus levels is defined as the full scale input (span) of the sensor
  - An input signal (stimulus) outside of the specified range may result in a strong falsification of the output signal ...
  - ...or damage the sensor (e.g. thermistor)
- Similarly to the range of the stimulus the full scale output defines the range of output electrical signal

Accuracy

- Manufacturers always provide a specification of accuracy for the given range of the output signal
- With physical sensors accuracy really means inaccuracy
- Often the inaccuracy is given in the form of a relative error
- Sometimes the manufacturer provides data about *systematic* errors (determined through calibration)
- The specification of inaccuracy subsumes the effects various sources of error

Resolution

- The resolution is the smallest possible change of the stimulus that is detected by the sensor
- **Examples:** Potentiometer (resistance), laser range finder (distance), ...
- The resolution may vary over the entire range of the input signal
- The resolution of digital output is defined by the number of bits
- A sensor is said to have a *continuous* or *infinitesimal* resolution if it does not have distinct resolution steps in the output signal
- Resolution is bound by the noise floor

Decision Task: Purchase a Scale

- Option A: 0-120$\pm$1 kg, displays 0.1 kg
- Option B: 0-150$\pm$0.1 kg, displays 1 kg
- Option C: 0-100$\pm$0.1 kg, displays 0.01 kg

- Range
- Accuracy
- Resolution

Sensor characteristics

- A sensor may feed the stimulus through several conversion stages until it emits an electrical output signal
- **Example:** Pressure on a fibre-optic sensor
  1. Fiber strain $\rightarrow$ change of refractive index
  2. Change of optical transmission properties
  3. Photon flux detection
  4. Conversion into electrical output signal
- We consider the sensor a **"black box"** and look at the relation between the stimulus and the output signal

Transfer function

- The transfer function of a sensor represents the relation between stimulus and output signal
- Each sensor has an ideal/theoretical relation between the stimulus and output signal

Definition

The ideal relation between stimulus and output signal of a sensor is characterized by the transfer function

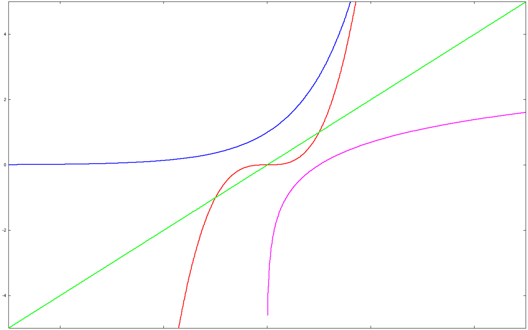
$$S = f(s)$$

- S represents the true value of the stimulus s

Transfer function (cont.)

Possible transfer functions are

- Linear —
  $$S = a + k \cdot s$$
- Logarithmic —
  $$S = a + k \cdot \ln s$$
- Exponential —
  $$S = a \cdot e^{ks}$$
- Polynomial —
  $$S = a_0 + a_1 \cdot s^k$$



Approximation of a transfer function

Measurement of a relation between two quantities x and y

- **Linear relation** $\rightarrow$ Linear regression (e.g. least-squares fit)
- **Non-linear relation**
  - Linearization followed by linear regression (e.g. logarithmic function)
  - Least-squares fit through numerical optimization techniques
- To reduce the statistical error an adequate number of measurements should be acquired

Interlude - Approximation vs. Interpolation

A measurement series should be approximated using the simplest possible function $f(x)$

- Approximation:
  The function $f(x)$ shows a very good representation of the value pairs (x_i, y_i) (e.g. least-squares fit)
  - $f(x_i) = y_i$ **does not** need to be valid
- Interpolation:
  The function $f(x)$ shows an exact representation of the value pairs
  - $f(x_i) = y_i; \quad i = 1, 2, \dots, n$ **must** be valid

Real transfer function

- **Problem:** Unlike the ideal transfer function the real transfer function is usually neither linear nor monotonic
- The ideal relation between stimulus and output signal is generally affected by
  - manufacturing tolerances,
  - material defects,
  - environmental influences,
  - wear and tear,
  - ...
- **Nevertheless:** Each sensor should work within the specified precision

Real transfer function (cont.)

- $S = f_{ideal}(s)$: The ideal transfer function
- $\pm\Delta$: Maximum deviation from the ideal transfer function
- $\pm\delta$: Actual deviation from the ideal transfer function

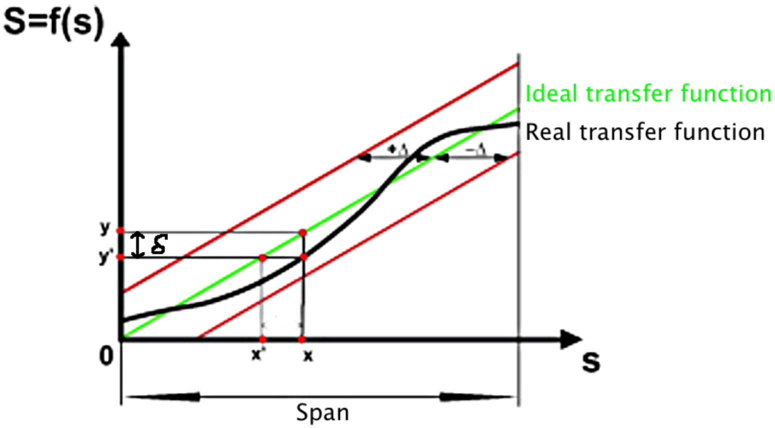
Definition

The physical relation between stimulus and output signal of a sensor is characterized by the real transfer function

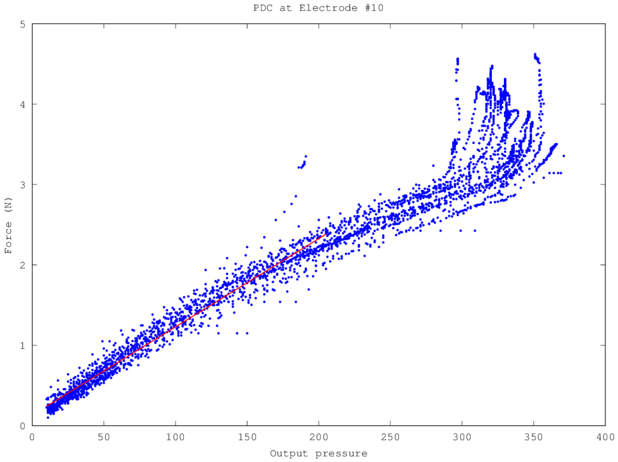
$$S' = f_{real}(s) = f_{ideal}(s) \pm \delta \qquad \delta \leq \Delta$$

- S' represents the measured value of the stimulus s

Real transfer function (cont.)



Real transfer function (cont.)



Calibration error

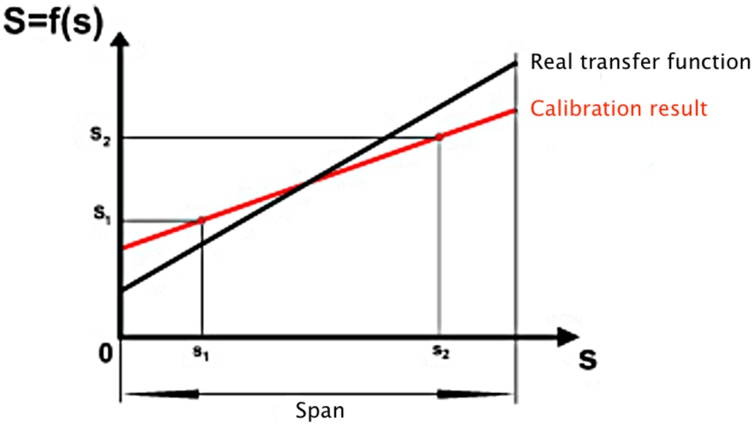
A calibration problem

- According to specification a sensor has a linear transfer function
- However, manufacturing tolerances lead to different slopes

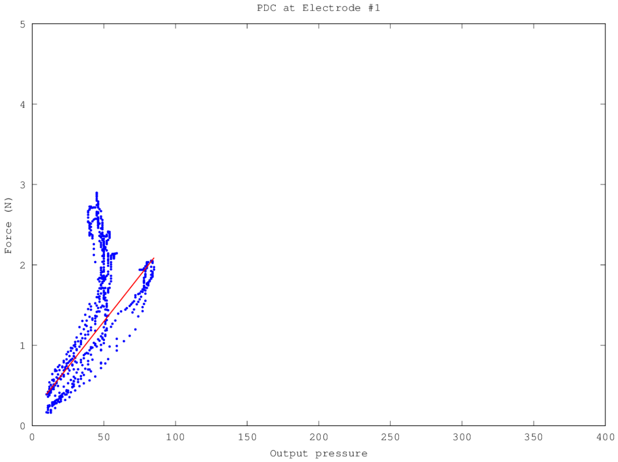
A calibration procedure

- The manufacturer determines the slope through:
  - Application of multiple stimuli $s_1, \ldots, s_n$ to the sensor
  - Measurement of the corresponding output signals $S_1, \ldots S_n$
  - Calculation of the slope based on the obtained value pairs
- *Caution:* Due to measurement errors, the slope may deviate from the real one if the pool of measured value pairs is chosen too small

Calibration error (cont.)



Calibration error (cont.)



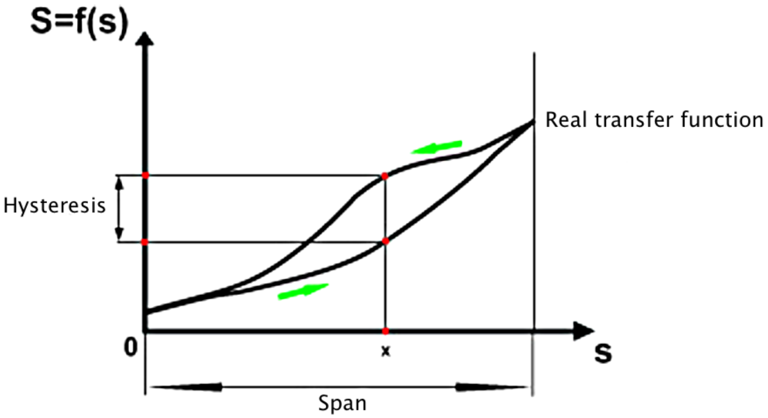
Hysteresis error

- Some sensors output different signals if the stimulus value is being approached from opposing directions of the range
- This deviation is called the hysteresis error

$$\lim_{\substack{\varepsilon\to 0,\\ \varepsilon>0}} f(s+\varepsilon) \neq \lim_{\substack{\varepsilon\to 0,\\ \varepsilon<0}} f(s+\varepsilon)$$

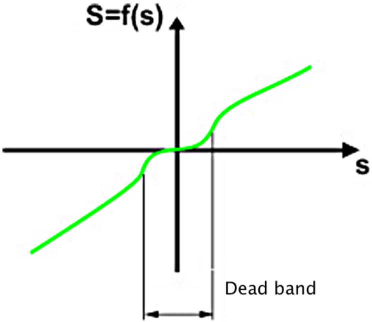
- **Examples:** Temperature sensor, displacement sensor, ...

Hysteresis error (cont.)



Dead band

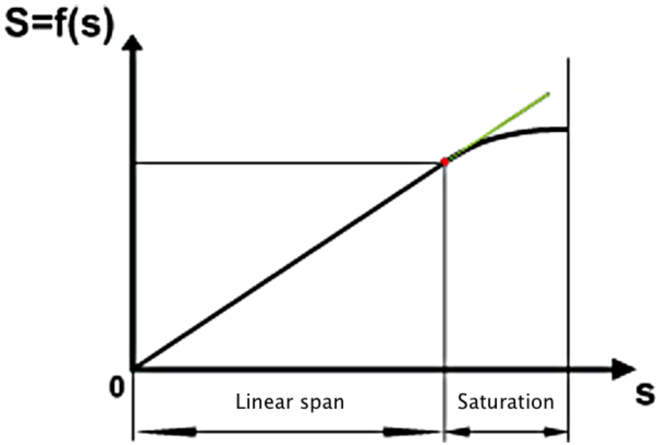
The dead band of a sensor is defined as insensitivity within a coherent range of the input signal (usually close to 0), resulting in the output of the same signal for that range



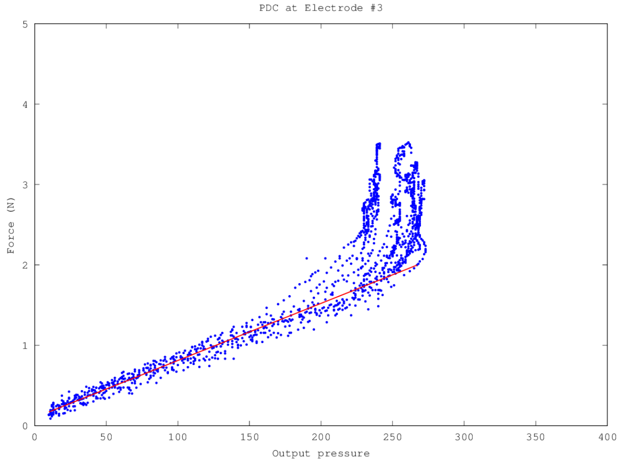
Saturation

- Every sensor has a limited operating range, the *full scale input*
- Many sensors have a linear transfer function
- However, from a certain stimulus value on the output becomes non-linear
- This effect is called saturation

Saturation (cont.)



Saturation (cont.)



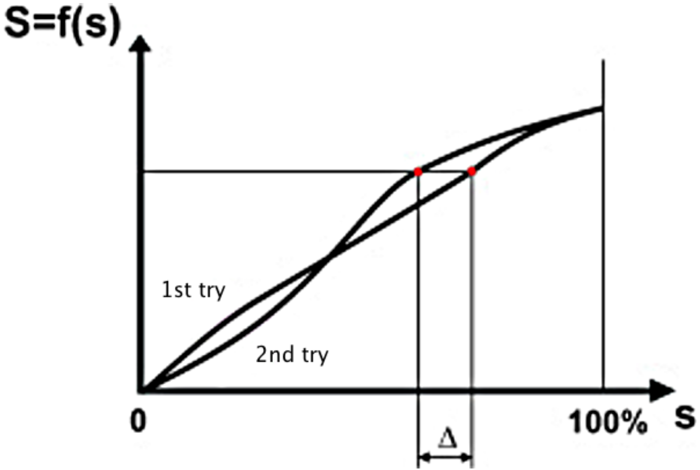
Repeatability error

- A sensor may produce different output values under the same conditions
- This type of error is called repeatability error

- A repeatability error is usually determined as: Maximum distance Δ of two output signals for the same stimulus value
- Repeatability is specified in relation to the full scale input

$$\delta_r = \frac{\Delta}{FSI} \cdot 100\%$$

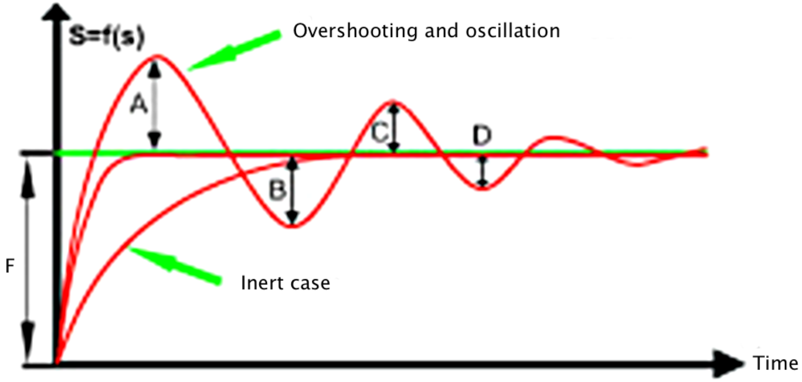
Repeatability (cont.)



Dynamic characteristics

- Under static conditions previously mentioned characteristics are enough to fully specify a particular sensor
- However, variation of the stimulus introduces time-dependency
- **Reason:** The sensor does not always provide an immediate response to the stimulus
- Therefore, a sensor does not always immediately output a signal corresponding to the stimulus
- Such effects are called the dynamic characteristics of a sensor
- The associated errors are called dynamic errors

Dynamic characteristics (cont.)



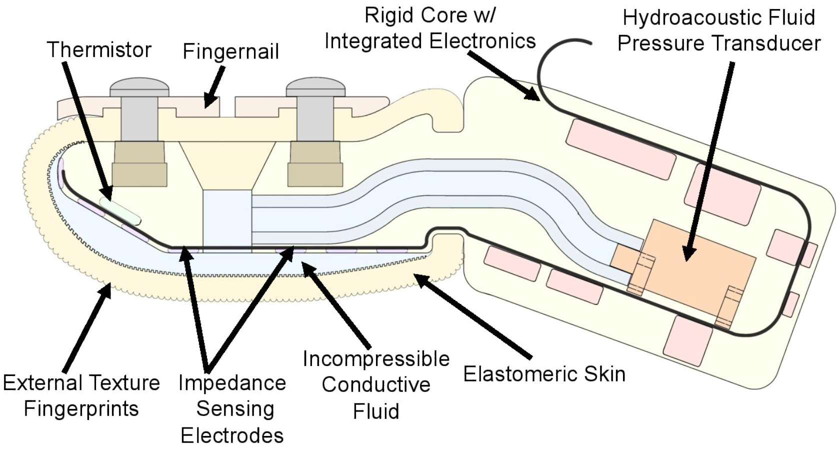
Further sensor characteristics

- Reliability, e.g. *mean time between failure* (MTBF)
- Certain properties relevant to the field of application:
  - Design
  - Weight
  - Form factor
  - Price
  - ...

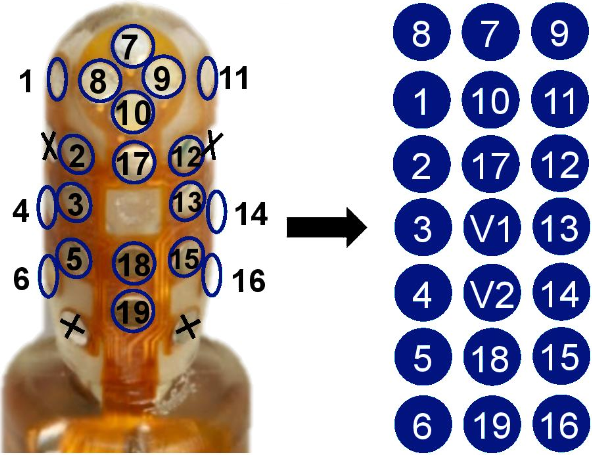
Environmental factors

- Ambient temperature (minimum and maximum)
- Ambient air humidity (minimum and maximum)
- Short- and long-term stability (drift)
- Static and dynamic changes of electromagnetic fields, gravitational forces, vibration, radiation etc.
- Self-heating (e.g. due to flow of current)

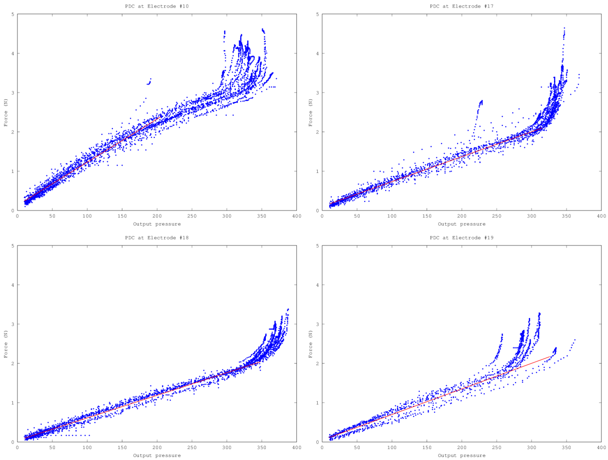
The BioTac sensor



The BioTac sensor



The BioTac sensor



Datasheet Example

- Commercial available sensor typically come with a datasheet
- It specifies sensor errors, transferfunctions, etc.
- Normally these values are correct, but some vendors "improve" their hardware in the datasheet
- Example
  - OPT 3001 Ambient Light Sensor
  - http://www.ti.com/lit/ds/symlink/opt3001.pdf