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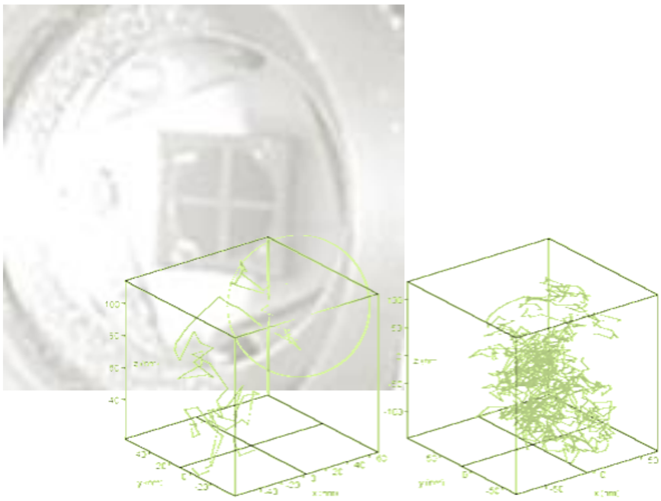
University of Freiburg

Lecture

Sensors

WS 2022/23



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Literature

1. Jacob Fraden: “Handbook of modern Sensors”

Download ebook from:

https://katalog.ub.uni-freiburg.de/opac/

then search

https://ebookcentral.proquest.com/lib/ubfreiburg/detail.action?docID=4178265

2. Gerald Urban: Lecture “Sensors” from WS 2021/22.

Download PDF from ILIAS

1. Data Acquisition (by J. Fraden)

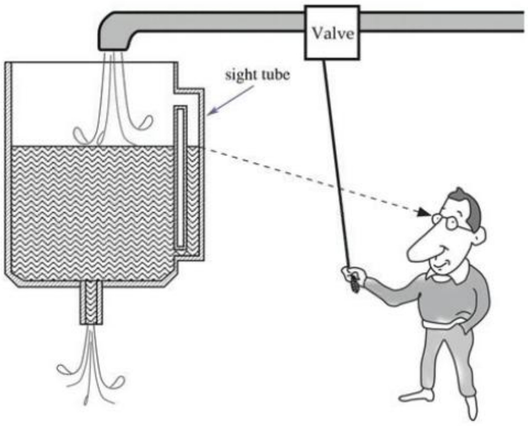
1.1 Sensors, Signals, and Systems

Additions by A. Rohrbach in green

A sensor is often defined as a "device that receives and responds to a signal or stimulus".

This definition is too broad…

Fig. 1.1 Level-Control System. Sight tube and operator's eye form a sensor—device that converts information into electrical signal



Better definition for sensor:

A sensor is a device that receives a stimulus and responds with an electrical signal.

Definition for stimulus

The stimulus is the quantity, property, or condition that is received and converted into electrical signal. Examples of stimuli are light intensity and wavelength, sound, force, acceleration, distance, rate of motion, and chemical composition.

A measurand has the same meaning as stimulus.

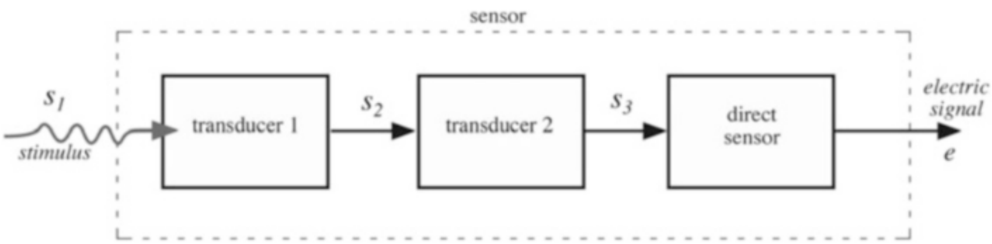


Fig. 1.2 Sensor may incorporate several transducers. Value s_1, s_2, etc. represent various types of energy. Direct sensor produces electrical output e

Other explanations and definitions for sensor:

- We may say: **a sensor is a translator of a generally nonelectrical value into an electrical value**. The **sensor's output signal** may be in form of voltage, current, or charge.
- The **output signal format** can be amplitude, polarity, frequency, phase, or digital code.
- A general property: **Any sensor is an energy converter.** Why: Any transmission of information requires transmission of energy.
- **Sensor and detector:** Both terms are synonyms and have the same meaning.

The term sensor should be distinguished from transducer:

- **Transducer**: converter of any one type of energy or property into another type of energy or property (e.g. a loudspeaker)
- **Sensor**: converts any one type of energy it into electrical signal.

Inset: English Wikipedia Definition (2022): A *sensor is a device, module, machine, or subsystem that detects events or changes in its environment and sends the information to other electronics, frequently a computer processor. Sensors are always used with other electronics.*

This is not true for e.g. a SARS-Cov2 rapid test, which does not need electronics! Unless we consider the electronic signal transfer from the eye to the brain….

In summary, there are **two types of sensors, direct and hybrid**:

- **A direct sensor** converts a stimulus into an electrical signal or modifies an externally supplied electrical signal
- **A hybrid sensor** (or simply—a sensor) in addition needs one or more transducers before a direct sensor can be employed to generate an electrical output.

A sensor does not function by itself; it is **always part of a larger system** that may incorporate many other detectors, signal conditioners, processors, memory devices, data recorders, and actuators (see Fig. 1.3)

An object equipped with sensors can be a car, space ship, animal or human, liquid, or gas.

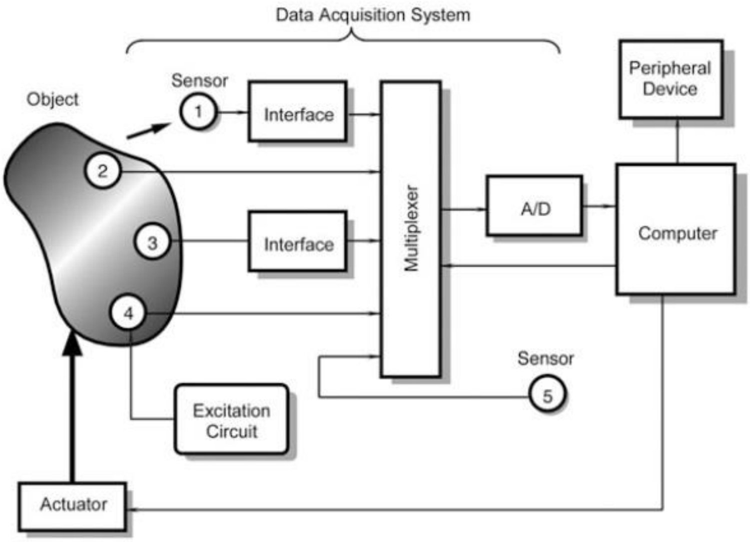


Fig. 1.3 Positions of sensors in data acquisition system. Sensor 1 is noncontact, sensors, 2 and 3 are passive, sensor 4 is active, and sensor 5 is internal to data acquisition system

- Some sensors (2, 3, and 4) are positioned directly on or inside the object. Sensor 1 perceives the object without a physical contact and is called a **noncontact sensor**.

- Sensors 1 and 3 cannot be directly connected to standard electronic circuits because of the **inappropriate output signal formats**, i.e. they require **interface devices** (signal conditioners) to produce a specific output format.
- Sensor 5 serves a different purpose: it monitors the internal conditions of the data acquisition system itself.
- Sensors 1, 2, 3, and 5 are **passive**: They generate electric signals without energy consumption from the electronic circuits.
- Sensor 4 is **active**: it requires an operating signal that is provided by an excitation circuit (e.g. current source). Example for active sensor: temperature-sensitive resistor (thermistor)
- A multiplexer (MUX) is a switch or a gate, connecting the sensors to analog-to-digital converters (A/D or ADC)

Example of a complex combination of various sensors, actuators, and indicating signals:

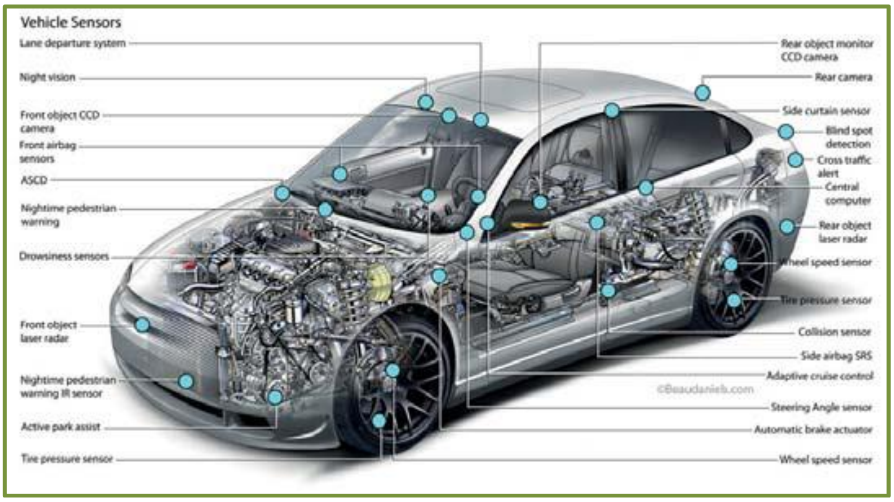
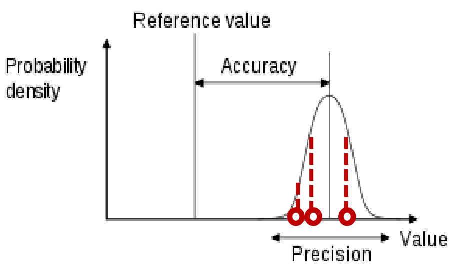


Fig. 1.4. Multiple sensors, actuators and warning signals are parts of a modern vehicle (Image: G.Urban)

Inset: How good should a sensor be?

- It should be sensitive to the measured property (e.g. SARS-Cov2 virus or e.g. blue light)
- It should be insensitive to any other property likely to be encountered in its application (e.g. insensitive to other viruses or to e.g. green light),
- It does not influence the measured property (difficult, since some energy is converted).
- It should have a high accuracy and precision:

Accuracy is the proximity of measurement results to the accepted value; **Precision** is the degree to which repeated (or reproducible) measurements under unchanged conditions show the same results.
Example: 3 measured values (see circles) with 3 different accuracies, 2 with the same precision and frequency (probability density)



1.2 Sensor classification

a) All sensors may be of two kinds: **passive and active:**

- A passive sensor does not need any additional energy source (e.g. photographic sensor using environmental light).
- An active sensor requires external power for operation, which is called an excitation signal (e.g. photographic sensor using flash light). That input signal is modified (modulated) by the sensor to produce the output signal.

b) Sensors can be classified into **absolute and relative** to a reference:

- An absolute sensor detects a stimulus in reference to an absolute physical scale that is independent on the measurement conditions (e.g. a pressure sensor measuring in vacuum at absolute zero).
- A relative sensor produces a signal that relates to some special case (e.g. a pressure sensor measuring relative to atmospheric pressure, which is non-zero).

c) A lists of various sensor characteristics and properties

Table 1.1 Sensor specifications

Sensitivity	Stimulus range (span)
Stability (short and long term)	Resolution
Accuracy	Selectivity
Speed of response	Environmental conditions
Overload characteristics	Linearity
Hysteresis	Dead band
Operating life	Output format
Cost, size, weight	Other

Table 1.2 Sensing element material

Inorganic	Organic
Conductor	Insulator
Semiconductor	Liquid gas or plasma
Biological substance	Other

Table 1.3 Conversion phenomena

Physical	Thermoelectric Photoelectric Photomagnetic Magnetoelectric Electromagnetic Thermoelastic Electroelastic Thermomagnetic Thermo-optic Photoelastic Other	Chemical	Chemical transformation Physical transformation Electrochemical process Spectroscopy Other
		Biological	Biochemical transformation Physical transformation Effect on test organism Spectroscopy Other

Table 1.4 Field of applications

Agriculture	Automotive
Civil engineering, construction	Domestic, appliances
Distribution, commerce, finance	Environment, meteorology, security
Energy, power	Information, telecommunication
Health, medicine	Marine
Manufacturing	Recreation, toys
Military	Space
Scientific measurement	Other
Transportation (excluding automotive)	

Table 1.5 Stimuli

<table>
<tr><th>Stimulus</th><th>Stimulus</th><th></th></tr>
<tr><td rowspan="3">Acoustic
Wave amplitude, phase
Spectrum polarization
Wave velocity
Other
Biological
Biomass (types, concentration states)
Other
Chemical
Components (identities, concentration, states)
Other
Electric
Charge, current
Potential, voltage
Electric field (amplitude, phase, polarization, spectrum)
Conductivity
Permittivity
Other
Magnetic
Magnetic field (amplitude, phase, polarization, spectrum)
Magnetic flux
Permeability
Other
Optical
Wave amplitude, phase, polarization, spectrum
Wave velocity
Refractive index
Emissivity, reflectivity, absorption
Other</td><td>Mechanical</td><td>Position (linear, angular)
Acceleration
Force
Stress, pressure
Strain
Mass, density
Moment, torque
Speed of flow, rate of mass transport
Shape, roughness, orientation
Stiffness, compliance
Viscosity
Crystallinity, structural integrity
Other</td></tr>
<tr><td>Radiation</td><td>Type
Energy
Intensity
Other</td></tr>
<tr><td>Thermal</td><td>Temperature
Flux
Specific heat
Thermal conductivity
Other</td></tr>
</table>

Table 1.6 SI basic units

Quantity	Name	Symbol	Defined by. . . (year established)
Length	meter	m	. . .the length of the path traveled by light in vacuum in 1/299,792,458 of a second. . . (1983)
Mass	kilogram	kg	. . .after a platinum-iridium prototype (1889)
Time	second	s	. . .the duration of 9,192,631,770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium-133 atom (1967)
Electric current	ampere	A	force equal to 2×10^{-7} N/m of length exerted on two parallel conductors in vacuum when they carry the current (1946)
Thermodynamic temperature	kelvin	K	The fraction 1/273.16 of the thermodynamic temperature of the triple point of water (1967)
Amount of substance	mole	mol	. . .the amount of substance which contains as many elementary entities as there are atoms in 0.012 kg of carbon 12 (1971)
Luminous intensity	candela	cd	. . .intensity in the perpendicular direction of a surface of 1/600,000 m^2 of a blackbody at temperature of freezing Pt under pressure of 101,325 N/m^2 (1967)
Plane angle	radian	rad	(supplemental unit)
Solid angle	steradian	sr	(supplemental unit)

2. Transfer functions (by J. Fraden)

Motivation – the sensor as a "black box"

Most of stimuli are not electrical. From its input to the output a sensor may perform several signal conversion steps before it produces and outputs an electrical signal.

Example: pressure inflicted on a fiber optic pressure sensor → results in strain in the fiber → causes deflection in its refractive index → changes the optical transmission and modulates the photon density → the photon flux is detected by a photodiode → and converted into electric current

The key goal of sensing can be investigated by Response Theory:

How can an unknown input stimulus be determined from the sensor's electric output?

Answer: determine and use the transfer functions of the sensor system

2.1 Mathematical models

An ideal or theoretical input–output (stimulus–response) relationship exists for every sensor.

If the input–output function is time invariant (does not change with time) it is called a (static) transfer function.

The electric output signal E is a function $f(\ldots)$ of the input signal (also stimulus or measurement quantity) s such that

$$E = f(s) \tag{2.1}$$

The transfer function $f(s)$ describes the measuring system of the sensor. If it is known, the inverse transfer function $f^{-1}() = F()$ can be found and used to obtain (compute) the value of stimulus s:

$$s = f^{-1}(E) = F(E) \tag{2.2}$$

Example: the transfer function of a thermo-anemometer—a sensor that measures mass flow of a fluid (or a gas). It can be modeled by a square root function $f(s)$ of the input airflow rate.

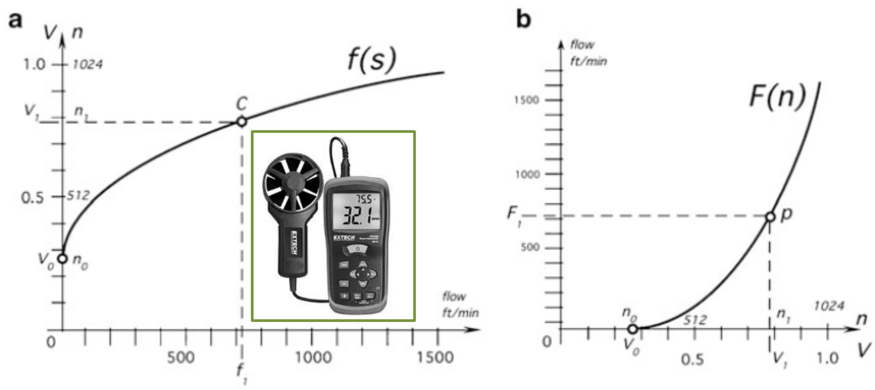


Fig. 2.1 Transfer function (**a**) and inverse transfer function (**b**) of thermo-anemometer

A hemispherical cup anemometer (1846)

Remark: Graphically, the inverse function can be obtained by a mirror reflection with respect to the axis y = x.

A physical or chemical law that forms a basis for the sensor's operation should be known!

Example: a linear resistive potentiometer that is used to sense the displacement d (stimulus). Ohm's law can be applied for computing the transfer function as illustrated in Fig. 8.1. In this case, the electric output E is the measured voltage $V = V_0 \cdot d/D$ with inverse transfer function provides the input

$$d = F(V) = \frac{D}{V_0} \cdot V \qquad (2.3)$$

where V_0 is the reference voltage and D is the maximum displacement (full scale); both being constants. By $f^{-1}(V) = F(V)$ we can compute displacement d from the measured voltage V.

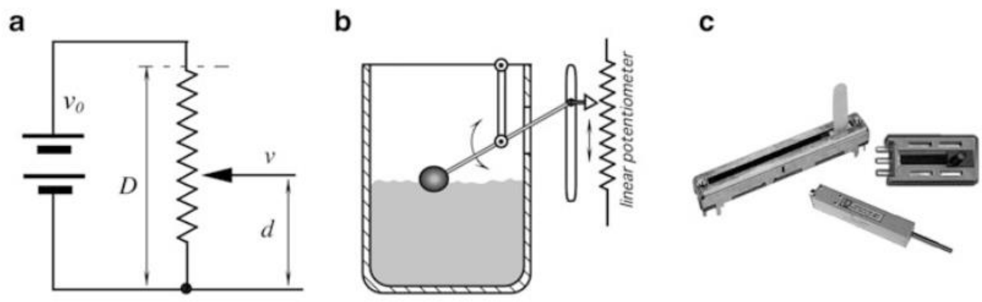


Fig. 8.1 Potentiometer as position sensor (**a**); fluid level sensor with float (**b**); linear potentiometers (**c**)

Functional approximations

Approximation is a selection of a suitable mathematical expression that can fit the experimental data as close as possible. The act of approximation can be seen as a curve fitting of the experimentally observed values into the approximating function.

The simplest model of a transfer function is linear: $E(s) = A + B \cdot s$ (2.4)

where the slope B of the linear function is called sensitivity. If the sensor response is E_0 for some known input stimulus s_0, can be rewritten in a more practical form

$$E(s) = E_0 + B \cdot (s - s_0) \qquad (2.5)$$

with $E(s = s_0) = E_0$. From this the inverse linear transfer function for computing the input stimulus from the output can be obtained

$$s(E) = \tfrac{1}{B}(E - E_0) + s_0 \qquad (2.6)$$

Most sensors are linear only for small ranges of inputs s, hence the transfer function can become nonlinear (e.g. logarithmic):

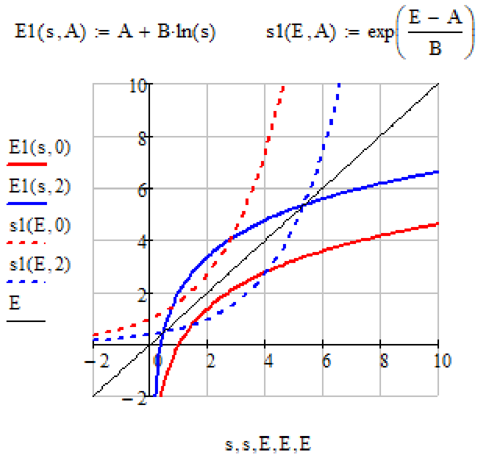
$$E(s) = B \cdot \ln(s / s_0) = A + B \cdot \ln(s) \quad (2.7) \qquad s(E) = s_0 \cdot \exp\left(\tfrac{1}{B} E\right) = \exp\left(\tfrac{1}{B}(E - A)\right) \quad (2.8)$$

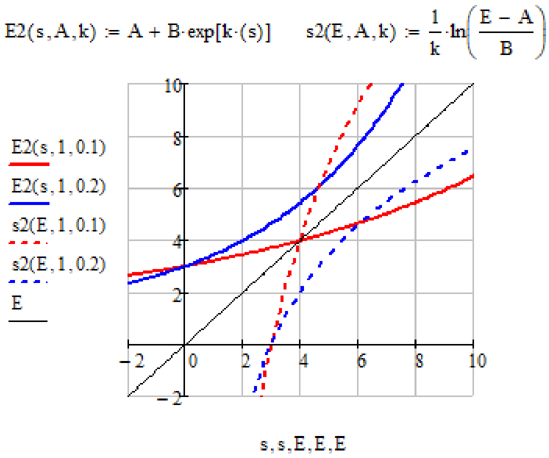
requiring 2 fit parameters B and $A = -B \cdot \ln(s_0)$ in this case.

The transfer function can become exponentially nonlinear:

$$E(s) = A + B \cdot \exp(k \cdot s) \quad (2.9) \qquad s(E) = \tfrac{1}{k} \ln\left(\tfrac{1}{B}(E - A)\right) \quad (2.10)$$

with 3 fit parameters A, B and k in this specific case. See the following examples:



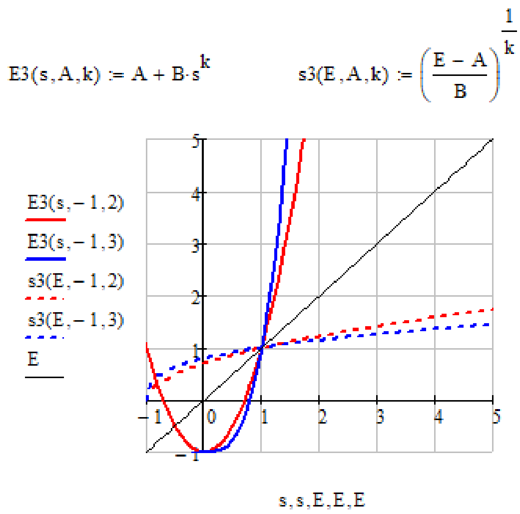


The (inverse) transfer function can become nonlinear according to a power law:

$$E(s) = A + B\cdot s^k \tag{2.11}$$

$$s(E) = \left(\tfrac{1}{B}(E-A)\right)^{1/k} \tag{2.12}$$

with again 3 fit parameters A, B and k in this specific case. See the example on the right.



The sensitivity S of a sensor

is again obtained by the varying slope $S(s) = \frac{\partial}{\partial s}E(s)$ of the output curve, which is for the logarithmic, exponential and power law case as follows

$\frac{\partial}{\partial s}E(s) = B/s$ (2.13) or $\frac{\partial}{\partial s}E(s) = B\cdot k\cdot \exp(k\cdot s)$ (2.14) or $\frac{\partial}{\partial s}E(s) = B\cdot k\cdot s^{k-1}$ (2.15)

Self-test: for which input ranges are the 3 nonlinear sensors above most sensitive?

A sensor with a chain of transducers

As shown in Fig.1.2 a sensor signal $E_{tot}(s)$ can be the result of several transducers, where the output of the first transducer $E_1(s)$ is the input the second one $E_2(E_1(s))$ and so on.

$$\begin{aligned} E_{tot}(s) &= E_1(s)\circ E_2(s)\circ E_3(s) \\ &= E_3\left(E_2\left(E_1(s)\right)\right) \end{aligned} \tag{2.16}$$

It is necessary that input and output signals have the same dimension (units) or the same format!