Advanced Measurement Systems & Sensors (0640732)

Lecture (2)

Sensor Characteristics

(Part One)

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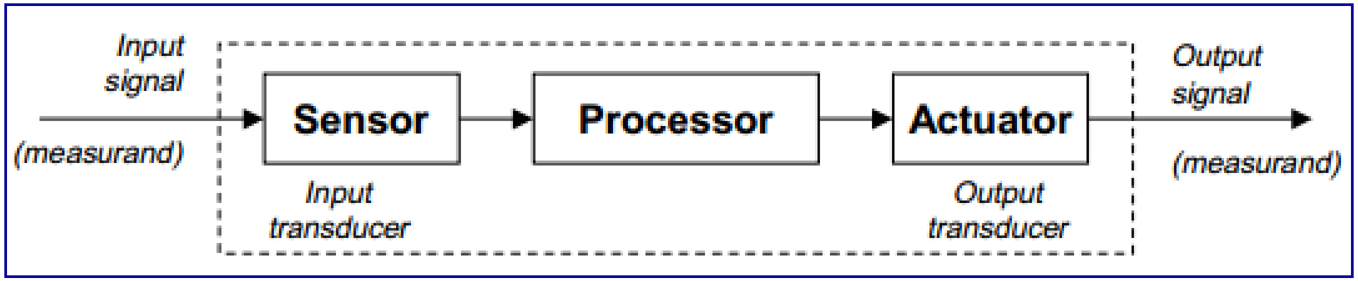
Sensors and Transducers:

What is a Transducer:

- A device that converts a signal from one physical form to a corresponding signal having a different physical form.
- Transducer is a converter of any one type of energy into another.
- Transducers may be used as actuators in various systems.
- An example of a transducer is a **loudspeaker**, which converts an electrical signal into a variable magnetic field (acoustic waves).

➢ **Physical form:** mechanical, thermal, magnetic, electric, optical, chemical…



➢ **Transducers:** sensors and actuators

➢ Sensor: an input transducer (i.e., a microphone)

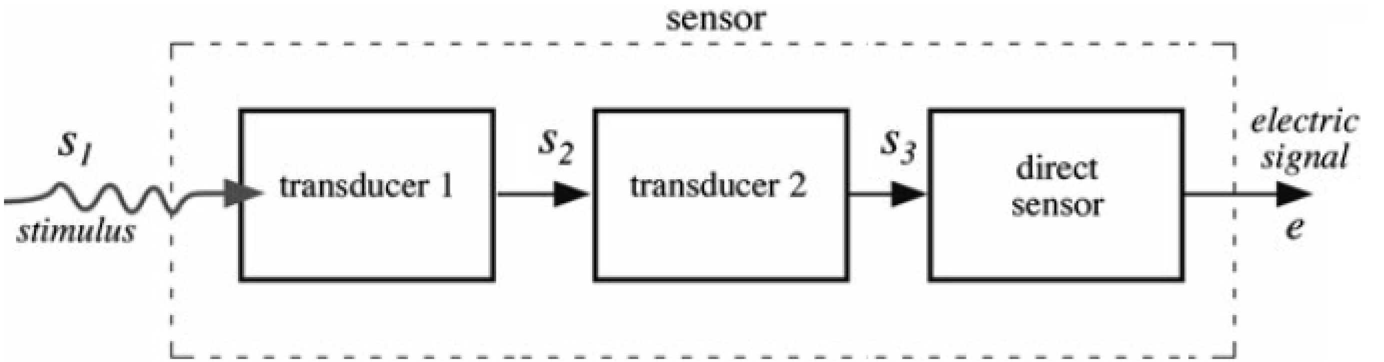
➢ Actuator: an output transducer (i.e., a loudspeaker)

What is a Sensor?

- A device that receives and responds to a signal or stimulus.
- The **sensor** converts any type of energy into electrical energy.
- It is a transducer whose purpose is to sense or detect some c/cs of its environs.
- It is a transducer used to detect a parameter in one form and report it in another form of energy.

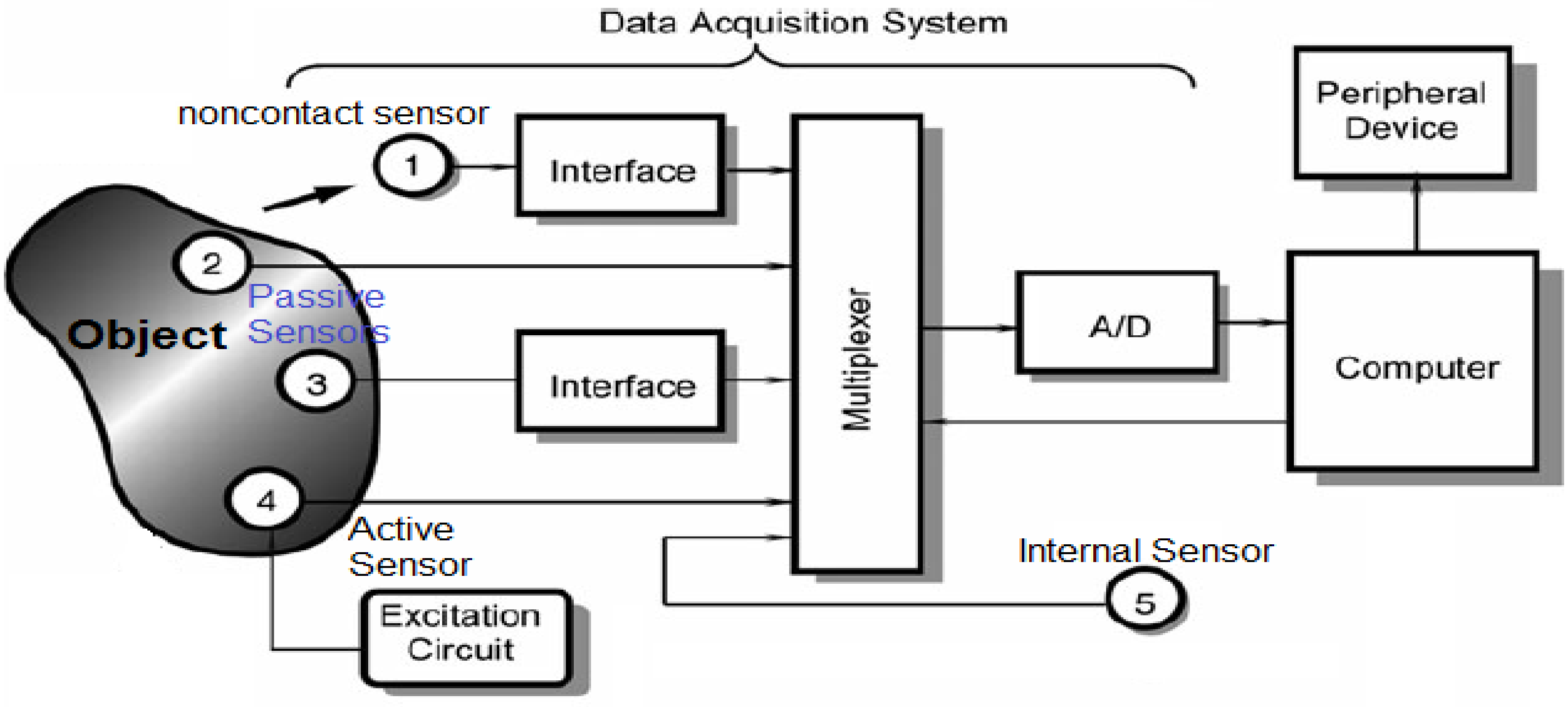
Example: A pressure sensor detects pressure (a mechanical form of energy) and converts it to electrical signal for display.

- A sensor is a device that receives a stimulus (measurand) and responds with an electrical signal.
- A sensor may have several energy conversion steps before it produces and outputs an electrical signal, since most of stimuli are not electrical.



- Any sensor is an energy converter.
- A sensor may incorporate several transducers (S1, S2, S3) are various types of
- energy. The last part is a direct sensor producing electrical output (e).
- Example: a **chemical sensor** produces electrical signal in response to a chemical reagent. The sensor may have two parts; the first one converts the energy of a chemical reaction into heat (transducer) and another part (a thermopile) converts heat into an electrical signal.
- There are two types of sensors;

1. **Direct sensor:** converts the measured variable into an electrical signal or modifies an electrical signal by using an appropriate physical effect.
2. **Complex sensor:** needs one or more transducers of energy before a direct sensor can be employed to generate an electrical output.



Sensor 1: Noncontact sensor, such as a radiation detector and a TV camera.

Sensors 1, 2, 3: are passive sensors positioned directly on or inside the object.

Sensor 4: Active sensor requires an operating signal, which is provided by an excitation circuit. Thermistor is an example, it a temperature-sensitive resistor. It needs a constant current source, which is an excitation circuit.

Sensor 5: is an internal sensor, monitors internal conditions of a data acquisition system itself.

Sensor Classification:

Different classification criteria may be selected.

All sensors may be of two kinds: passive and active.

1. **Passive sensor:** it does not need any additional energy source and directly generates an electric signal in response to an external stimulus. That is, the input stimulus energy is converted by the sensor into the output signal. Most of passive sensors are direct sensors as we defined them earlier.
   Example: a thermocouple, a photodiode, and a piezoelectric sensor.

2. **Active Sensor:** it requires external power for its operation, which is called an excitation signal. That signal is modified by the sensor to produce the output signal.
   Example: a thermistor is a temperature sensitive resistor. It does not generate any electric signal, but by passing an electric current through it (excitation signal) its resistance can be measured by detecting variations in current and/or voltage across the thermistor.

Sensor Classification:

Depending on the selected reference, sensors can be classified into absolute and relative.

1. **Absolute sensor:** it detects a stimulus in reference to an absolute physical scale that is independent of the measurement conditions.

   Examples:

- Thermistor is an absolute sensor, it is a temperature-sensitive resistor. Its electrical resistance directly relates to the absolute temperature scale of Kelvin.
- An absolute pressure sensor produces signal in reference to vacuum – an absolute zero on a pressure scale.

2. **Relative sensor:** it produces a signal that relates to some special case.

   Examples:

- Thermocouple is a relative sensor that produces an electric voltage, which is a function of a temperature gradient across the thermocouple wires. The sensor output signal cannot be related to any particular temperature without referencing to a known baseline.
- A relative pressure sensor produces signal with respect to a selected baseline that is not zero pressure, for example, to the atmospheric pressure.

Sensor Classification:

Sensors can be classified depending some of its properties that may be of a specific interest.

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

Sensor Material

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

Detection means used in sensors

Biological
Chemical
Electric, magnetic or electromagnetic wave
Heat, temperature
Mechanical displacement or wave
Radioactivity, radiation

Sensor Classification:

Conversion Phenomena

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

Field of Applications

Civil engineering, Distribution, commerce, finance Energy, power Health, medicine Manufacturing Military Scientific measurement Transportation	Domestic, appliances Environment, meteorology, security Information, telecommunication Marine Recreation, toys Space Other

Sensor Classification:

Stimulus

Acoustic	Wave amplitude, phase, polarization Spectrum Wave velocity
Biological	Biomass (types, concentration, states) Other
Chemical	Components (identities, concentration, states) Other
Electric	Charge, current Potential, voltage Electric field (amplitude, phase, polarization, Conductivity Permittivity
Magnetic	Magnetic field (amplitude, phase, polarization, Magnetic flux Permeability
Optical	Wave amplitude, phase, polarization, spectrum Wave velocity Refractive index Emissivity, reflectivity, absorption

Mechanical	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
Radiation	Type Energy Intensity
Thermal	Temperature Flux Specific heat Thermal conductivity

Units of Measurements:

The base measurement system is known as SI, which stands for Le Syste´me International d'Unite´s in French:

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} newton per meter 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 newton per m^2 (1967)
Plane angle	Radian	rad	(supplemental unit)
Solid angle	Steradian	sr	(supplemental unit)

Sensor characteristics:

Static characteristics:

The properties of the system after all transient effects have settled to their final or steady state:

- ✓ Accuracy
- ✓ Discrimination
- ✓ Precision
- ✓ Errors
- ✓ Drift
- ✓ Sensitivity
- ✓ Linearity
- ✓ Hystheresis (backslash)

Dynamic characteristics:

The properties of the system transient response to an input:

- ➢ Zero order systems
- ➢ First order systems
- ➢ Second order systems

Accuracy and Resolution:

Accuracy: is the capacity of a measuring instrument to give RESULTS close to the TRUE VALUE of the measured quantity.

- Accuracy is related to the bias of a set of measurements
- Accuracy is measured by the absolute and relative errors

$$\text{ABSOLUTE ERROR} = \text{RESULT} - \text{TRUE VALUE}$$

$$\text{RELATIVE ERROR} = \frac{\text{ABSOLUTE ERROR}}{\text{TRUE VALUE}}$$

Resolution (Discrimination): is the minimal change of the input necessary to produce a detectable change at the output.

- When the increment is from zero, it is called **Threshold**.

Precision:

Precision: is the capacity of a measuring instrument to give the same reading when repetitively measuring the same quantity under the same prescribed conditions.

- Precision implies agreement between successive readings, NOT closeness to the true value
- Precision is related to the variance of a set of measurements.
- Precision is a necessary but not sufficient condition for accuracy.

Two terms closely related to precision Repeatability and Reproducibility.

Repeatability: is the precision of a set of measurements taken over a short time interval

Reproducibility: is the precision of a set of measurements BUT:

- ✓ taken over a long time interval or
- ✓ Performed by different operators or
- ✓ with different instruments or
- ✓ in different laboratories

Accuracy and Errors:

Systematic errors: Result from a variety of factors

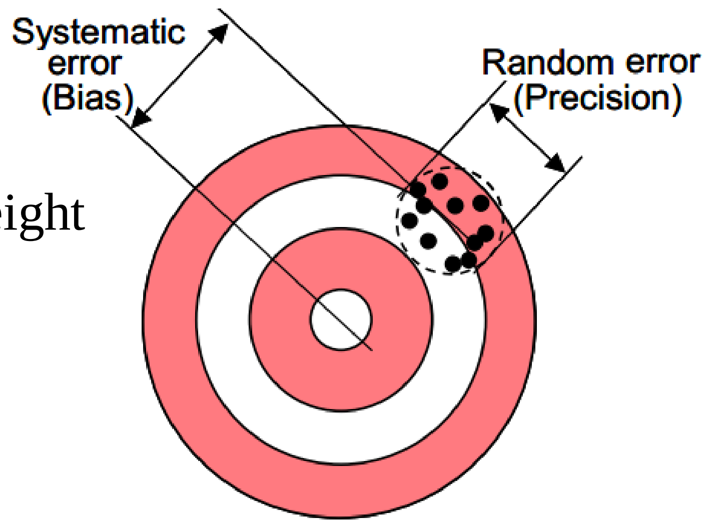
- ✓ Interfering or modifying variables (i.e., temperature)
- ✓ Drift (i.e., changes in chemical structure or mechanical stresses)
- ✓ The measurement process changes the measurand (i.e., loading errors)
- ✓ The transmission process changes the signal (i.e., attenuation)
- ✓ Human observers (i.e., parallax errors)

Systematic errors can be corrected with compensation methods (i.e., feedback, filtering)

Random errors (NOISE):

A signal that carries no information.

- ➢ Sources of randomness:
  - ✓ Repeatability of the measurand itself (i.e., height of a rough surface)
  - ✓ Environmental noise (i.e., background noise picked by a microphone)
  - ✓ Transmission noise (i.e., 60Hz hum)
- ➢ Signal to noise ratio (SNR) should be >>1



Other Static Characteristics:

Input range: The maximum and minimum value of the physical variable that can be measured (i.e., -40F/100F in a thermometer)

Output range: can be defined similarly

Sensitivity: The slope of the calibration curve. An ideal sensor will have a large and constant sensitivity.

- A nonlinear transfer function exhibits different sensitivities at different points, in this case the sensitivity is defined as a first derivative of the transfer function:

$$\text{sensitivity} = b_i(s_i) = \frac{dS(s_i)}{ds} \approx \frac{\Delta S_i}{\Delta s_i}$$

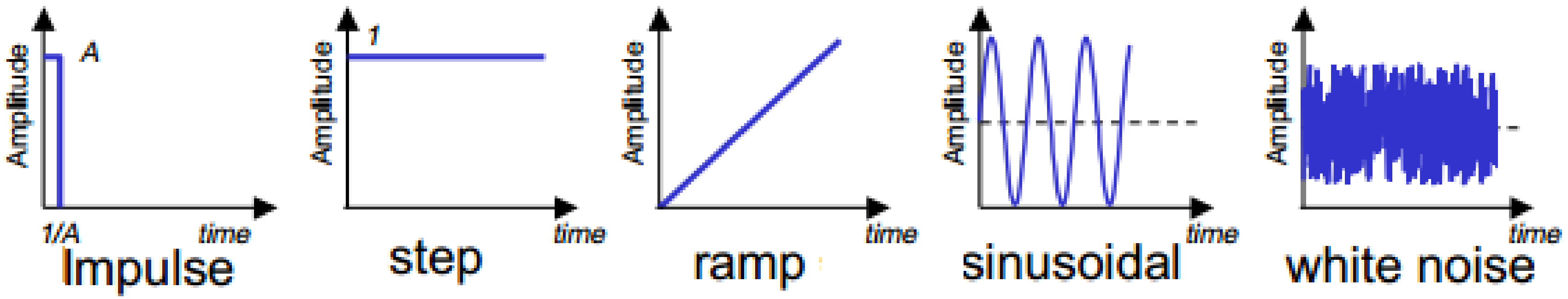
Linearity: The closeness of the calibration curve to a specified straight line (i.e., theoretical behavior, least-squares fit)

Hysteresis: The difference between two output values that correspond to the same input depending on the trajectory followed by the sensor (i.e., magnetization in ferromagnetic materials)

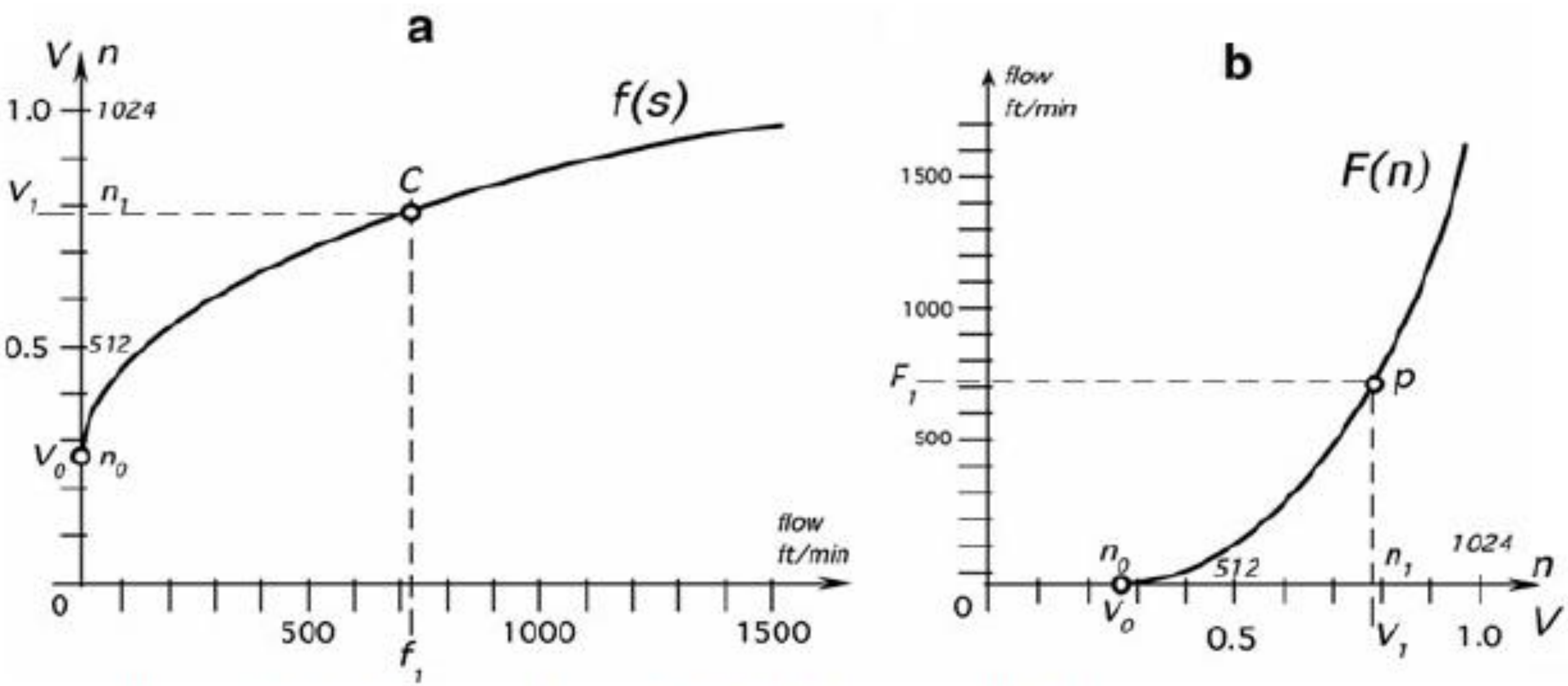
Backslash: hysteresis caused by looseness in a mechanical joint

Dynamic Characteristics:

- The sensor response to a variable input is different from that exhibited when the input signals are constant (the latter is described by the static characteristics)
- The reason for dynamic characteristics is the presence of energy-storing elements:
  - Inertial: masses, inductances
  - Capacitances: electrical, thermal
- Dynamic characteristics are determined by analyzing the response of the sensor to a family of variable input waveforms:



1. Sensor Transfer Function:



Transfer function (a) and inverse transfer function (b) of a thermo-anemometer

- The transfer function represents the relation between stimulus (s) and response electrical signal (S) produced by the sensor. This relation can be written as S= f(s).
- Normally, stimulus (s) is unknown while the output signal S is measured. An inverse $f^{-1}(S)$ of the transfer function is required to compute the stimulus from the sensor's measured response (S).

Mathematical Model:

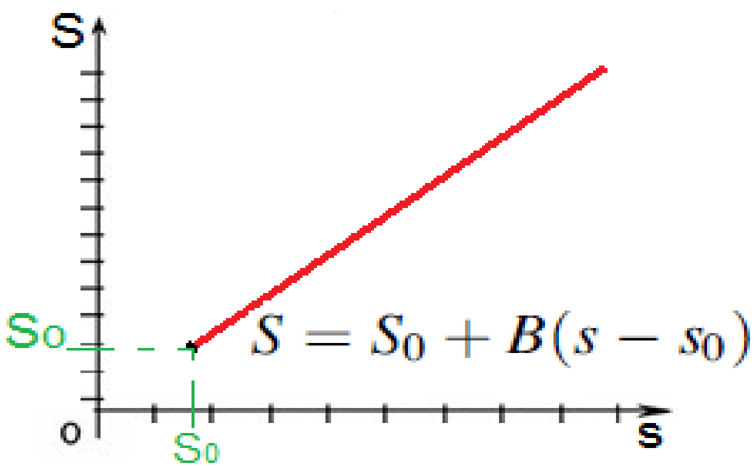
Example: A linear resistive potentiometer is used for sensing displacement (d). Ohm's law can be applied to compute the transfer function of the sensor. The response (S) is the measured voltage (v) and the inverse transfer function F(S) can be given as;

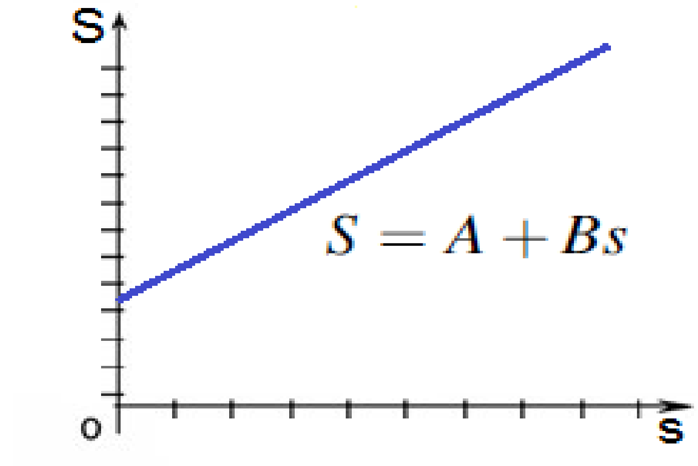
$$\text{Displacement (d)} = \frac{v}{E} D$$

where; E is the reference voltage and D is the maximum displacement (full scale); both are constants.

From this function we can compute displacement (d) from the measured voltage (v).

Functional Approximations:





- The simplest transfer function is linear, and is given by:

$$S = A + Bs$$

It represents a straight line with intercept A, and slope B, which is called **sensitivity**, since the larger B the greater the influence of the stimulus).

- In many cases, it is required to reference the sensor not to **zero** but to some more practical input reference value (s_0). If the sensor response (S_0) is known for that input reference, the above equation can be rewritten as;

$$S = S_0 + B(s - s_0)$$

- The above represent linear approximation of a nonlinear sensor's response.

Sensors with nonlinearity:

In many cases, when nonlinearity cannot be ignored, the transfer function can be approximated by a multitude of linear mathematical functions;

1. Logarithmic function:

$$S = A + B \ln s$$

$$s = e^{\frac{S-A}{B}}$$

2. Exponential function:

$$S = Ae^{ks}$$

$$s = \frac{1}{k} \ln \frac{S}{A}$$

3. Power function:

$$S = A + Bs^{k}$$

$$s = \sqrt[k]{\frac{S-A}{B}}$$

where A, B are parameters and k is the power factor.

Polynomial Approximations:
A sensor may have such a transfer function that none of the above functional approximations would fit sufficiently well. In this case, a polynomial approximation, that is a power series, can be applied.

Example:

$$S = Ae^{ks}$$

The above exponential function can be approximately calculated by a third order polynomial by dropping all the higher terms of its series expansion:

$$S = Ae^{ks} \approx A\left(1 + ks + \frac{k^2}{2!}s^2 + \frac{k^3}{3!}s^3\right)$$

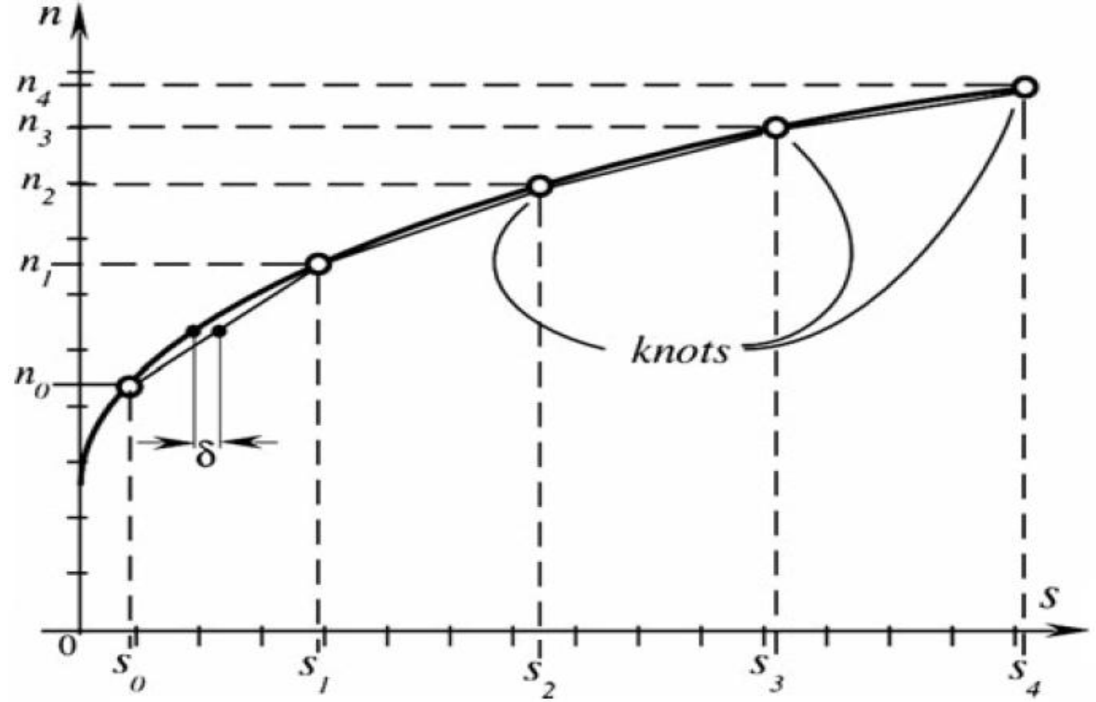
In many cases it is sufficient to investigate approximation of a sensor's response by the 2nd and 3rd degree polynomials that can be expressed as;

$$S = a_2 s^2 + b_2 s + c_2$$

$$S = a_3 s^3 + b_3 s^2 + c_3 s + d_3$$

Linear Piecewise Approximation:

- The idea is to break up a nonlinear transfer function of any shape into sections and consider each such section being linear. Curved segments between the sample points (knots) are replaced with straight line segments.



- An error of a piecewise approximation can be characterized by a maximum deviation (δ) of the approximation lines from the real curve.
- The knots do not need to be equally spaced. They should be closer to each other where a nonlinearity is high and farther apart where a nonlinearity is small.
- The spline interpolation method is using a different 3rd order polynomial interpolation between the selected experimental points called knots.

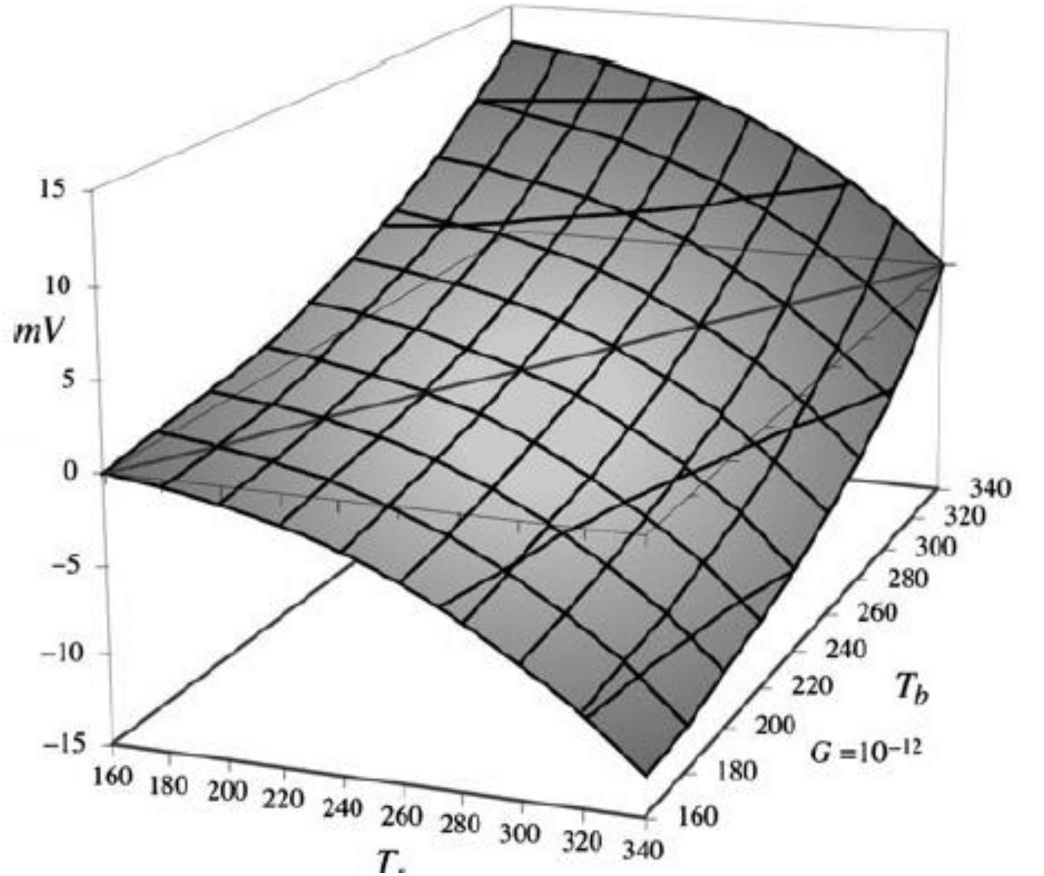
Multidimensional Transfer Functions:

A transfer function may be a function of more than one variable when the sensor's output is dependent on more than one input stimulus.

Example: Humidity sensor output depends on two input variables; relative humidity and temperature.

Example: The transfer function of a thermal radiation (infrared) sensor has two parts; the absolute Temperature (Tb), and the absolute temperature (Ts) of the sensor's surface (measured by a separate temperature sensor. The output voltage (V) is nonlinear and proportional to the difference;

$$V = G\left(T_b^4 - T_s^4\right)$$



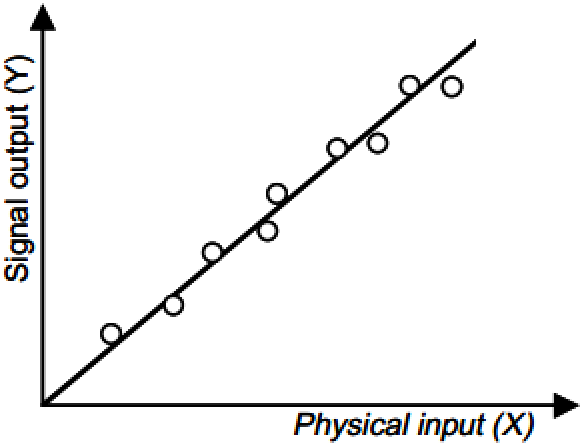
2. Sensor Calibration:

- In language;
  Calibrate means “to check, adjust, or determine by comparison with a standard”.
  Calibration is a “comparison between measurements”.

Sensor Calibration is the relationship between the physical measurement variable (X) and the signal variable (S)

- A sensor or instrument is calibrated by applying a number of KNOWN physical inputs and recording the response of the system.

- The purpose of the calibration is to find the unknown coefficients (parameters) of the sensor transfer function so that the fully defined function can be employed during the measurement process to compute any stimulus in the desirable range, not only at the points used during the calibration.



Calibration Methods:

Calibration of a sensor can be done in several possible ways, some of which are;

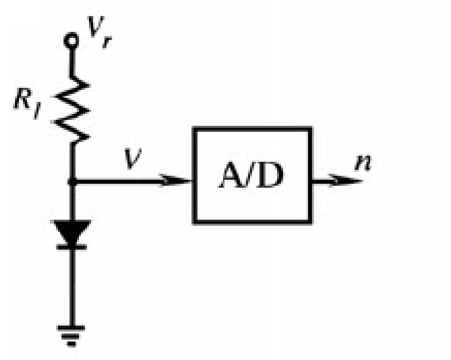
1. Calculation of the transfer function or its approximation to fit the selected calibration points (curve fitting by computing coefficients of a selected approximation).
2. Adjustment of the data acquisition system to modify the measured data by making them to fit into a normalized or "ideal" transfer function. An example is scaling of the acquired data.
3. Modification of the sensor' properties to fit the predetermined transfer function.
4. Creating a sensor-specific reference device with matching properties at particular calibrating points.

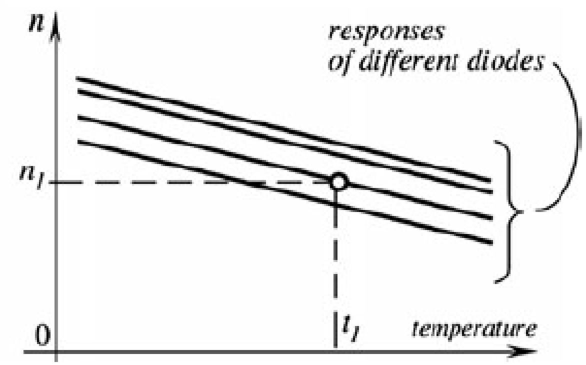
Example: Three methods of calibrating a thermistor (temperature sensitive resistor) is given in Page 22 of Reference 1.

Computation of Transfer Function Parameters:

Example: A forward-biased semiconductor p–n junction is used as a temperature sensor, its transfer function is linear;

$$n = n_1 + B(t - t_1)$$





At first calibrating temperature t_1, the output is n_1. After subjecting the sensor to the second calibrating temperature t_2, the output is n_2

$$n_2 = n_1 + B(t_2 - t_1)$$

$$\text{the sensitivity (slope)} = B = \frac{n_2 - n_1}{t_2 - t_1}$$

After calibration is done, temperature can be computed from

$$t = t_1 + \frac{(n - n_1)}{B}$$

Computation of Transfer Function Parameters:

Example: For nonlinear transfer functions, calibration at one data point may be sufficient only in some rare cases, but often two and more input–output pairs would be required. When a 2nd or a 3rd degree polynomial transfer functions are employed, respectively 3 and 4 calibrating pairs are required.

For a 3rd order polynomial;

$$S = as^3 + bs^2 + cs + d$$

- To find four parameters (a, b, c, and d), four calibrating i/o pairs are required:

$$S_1 = as_1^3 + bs_1^2 + cs_1 + d$$
$$S_2 = as_2^3 + bs_2^2 + cs_2 + d$$
$$S_3 = as_3^3 + bs_3^2 + cs_3 + d$$
$$S_4 = as_4^3 + bs_4^2 + cs_4 + d$$

- To solve this system, first one computes the determinants of the systems:

$$\Delta = \left(\frac{s_1^2 - s_2^2}{s_1 - s_2} - \frac{s_1^2 - s_4^2}{s_1 - s_4}\right)\left(\frac{s_1^3 - s_2^3}{s_1 - s_2} - \frac{s_1^3 - s_3^3}{s_1 - s_3}\right) - \left(\frac{s_1^2 - s_2^2}{s_1 - s_2} - \frac{s_1^2 - s_3^2}{s_1 - s_3}\right)\left(\frac{s_1^3 - s_2^3}{s_1 - s_2} - \frac{s_1^3 - s_4^3}{s_1 - s_4}\right)$$

$$\Delta_a = \left(\frac{s_1^2 - s_2^2}{s_1 - s_2} - \frac{s_1^2 - s_4^2}{s_1 - s_4}\right)\left(\frac{S_1 - S_2}{s_1 - s_2} - \frac{S_1 - S_3}{s_1 - s_3}\right) - \left(\frac{s_1^2 - s_2^2}{s_1 - s_2} - \frac{s_1^2 - s_3^2}{s_1 - s_3}\right)\left(\frac{S_1 - S_2}{s_1 - s_2} - \frac{S_1 - S_4}{s_1 - s_4}\right)$$

$$\Delta_b = \left(\frac{s_1^3 - s_2^3}{s_1 - s_2} - \frac{s_1^3 - s_3^3}{s_1 - s_3}\right)\left(\frac{S_1 - S_2}{s_1 - s_2} - \frac{S_1 - S_4}{s_1 - s_4}\right) - \left(\frac{s_1^3 - s_2^3}{s_1 - s_2} - \frac{s_1^3 - s_4^3}{s_1 - s_4}\right)\left(\frac{S_1 - S_2}{s_1 - s_2} - \frac{S_1 - S_3}{s_1 - s_3}\right)$$

- Then, the polynomial coefficients are calculated as;

$$a = \frac{\Delta_a}{\Delta}; \quad b = \frac{\Delta_b}{\Delta};$$

$$c = \frac{1}{s_1 - s_4}\left[S_1 - S_4 - a\left(s_1^3 - s_4^3\right) - b\left(s_1^2 - s_4^2\right)\right];$$

$$d = S_1 - as_1^3 - bs_1^2 - cs_1$$

Linear Regression Formula:

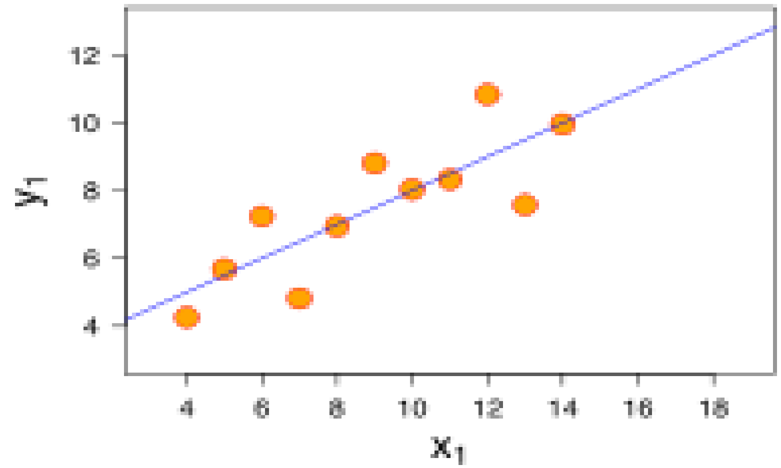
Simple linear regression is a way to describe a relationship between two variables through an equation of a straight line, called line of best fit, that most closely models this relationship.

The following formula is used:

$$y = A + Bx$$

where

$$B = \frac{\sum_{i=1}^{n} x_i y_i - n\bar{x}\bar{y}}{\sum_{i=1}^{n} x_i^2 - n\bar{x}^2} \quad \text{and} \quad A = \bar{y} - B\bar{x}$$



Example: consider the given experimental data. The regression equation is a linear equation, we need to solve for A and B. Computations are shown below;

No.	x_i	y_i	$(x_i - \bar{x})$	$(y_i - \bar{y})$	$(x_i - \bar{x})^2$	$(y_i - \bar{y})^2$	$(x_i - \bar{x})(y_i - \bar{y})$
1	95	85	17	8	289	64	136
2	85	95	7	18	49	324	126
3	80	70	2	-7	4	49	-14
4	70	65	-8	-12	64	144	96
5	60	70	-18	-7	324	49	126
Sum	390	385			730	630	470
Mean	78	77					

$B = \Sigma [(x_i - \bar{x})(y_i - \bar{y})] / \Sigma [(x_i - \bar{x})^2]$	$A = \bar{y} - B * \bar{x}$
$B = 470/730 = 0.644$	$A = 77 - (0.644)(78) = 26.768$

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