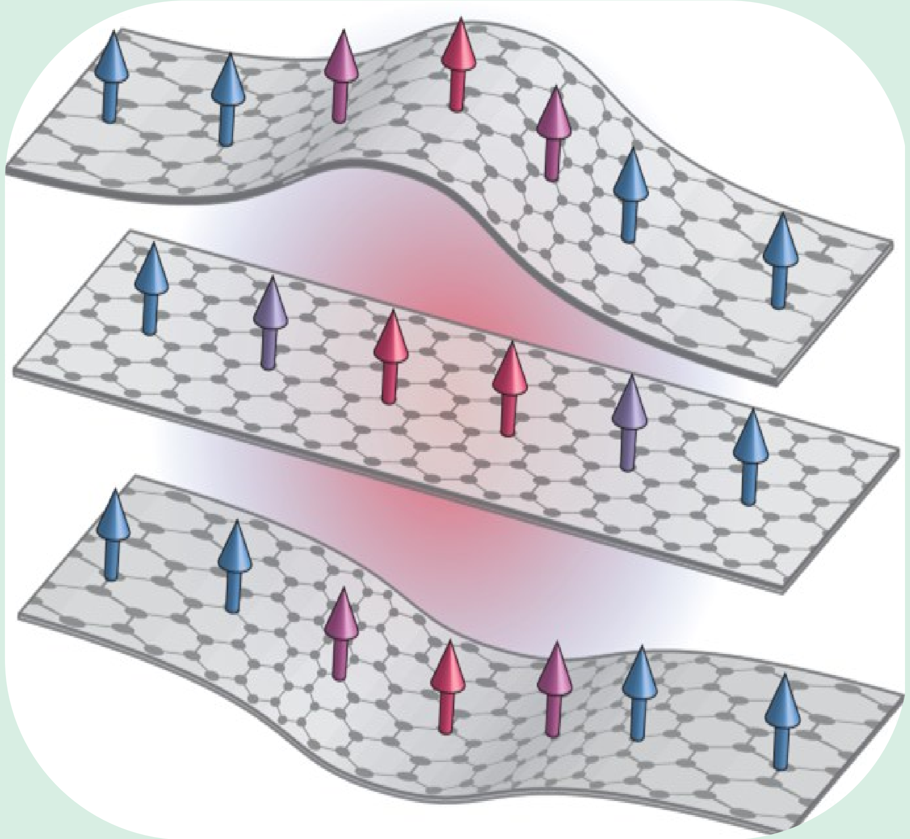
Physics behind sensing technologies

Master's Degree in Physics

Academic Year 2025-2026



Useful info

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Course contents and slides:

https://polysense.poliba.it/index.php/physics-behind-sensing-technologies/

Suggested textbook

J. Fraden – Handbook of Modern Sensors – Physics Designs and Applications, Springer.

Syllabus

1. Data Acquisition.

Sensors, Signals, and Systems. Sensor Classification. Units of Measurements.

2. Transfer Functions.

Mathematical Models. Calibration. Computation of Parameters. Computation of a Stimulus.

3. Sensor Characteristics.

Span (Full-Scale Input). Full-Scale Output. Accuracy. Calibration Error. Hysteresis. Nonlinearity. Saturation. Repeatability. Dead Band. Resolution. Special Properties. Output Impedance. Output Format. Excitation. Dynamic Characteristics. Dynamic Models of Sensor Elements. Environmental Factors. Reliability. Application Characteristics. Uncertainty.

Syllabus

4. Physical Principles of Sensing.

Electric Charges, Fields, and Potentials. Capacitance. Magnetism. Induction. Resistance. Piezoelectric Effect. Pyroelectric Effect. Hall Effect. Thermoelectric Effects. Sound Waves. Temperature and Thermal Properties of Materials. Heat Transfer.

5. Sensing of Physical Quantities.

Displacement. Velocity and acceleration. Force and strain. Pressure sensors. Humidity and moisture sensors. Temperature sensors.

6. Laboratory activities.

Chapter 1

Data acquisition and sensing systems

1.1 Sensors, Signals, and Systems

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

This definition is broad. In fact, it is so broad that it covers almost everything from a human eye to a trigger in a pistol.

This world is divided into natural and man-made objects.

The natural sensors, like those found in living organisms, usually respond with signals having electrochemical characteristics (i.e., the nerve fibers).

In man-made devices, information is also transmitted and processed in electrical form, through the transport of electrons.

1.1 Sensors, Signals, and Systems

A narrower definition of a sensor, may be phrased as:

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

The term stimulus represents the quantity, property, or condition that is received and converted into electrical signal, either voltage, current or charge.

Examples of stimuli are light intensity and wavelength, sound, force, acceleration, distance, rate of motion, and chemical composition.

When we say "electrical," we mean a signal which can be channeled, amplified, and modified by electronic devices.

1.1 Sensors, Signals, and Systems

Any sensor is an energy converter, as they all deal with energy transfer between the object of measurement to the sensor. The process of sensing is a particular case of information transfer, thus the sensor's performance must be assessed only as part of a data acquisition system.

Any transmission of information requires transmission of energy. A special case is when the net energy flow is zero, and that also carries information about existence of that particular situation.

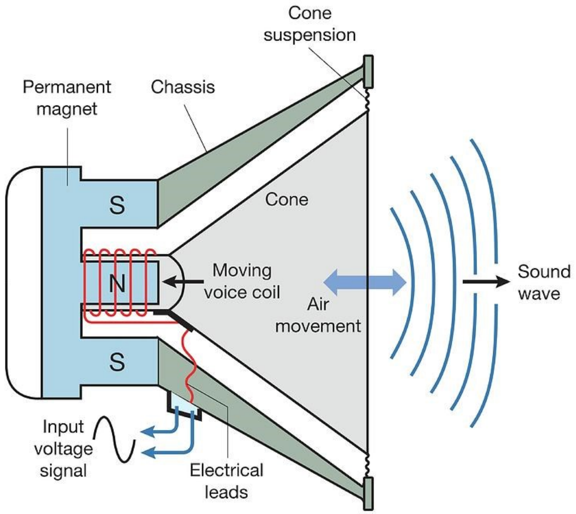
For example, an infrared radiation sensor will produce a positive voltage when the object is warmer than the sensor (infrared flux is flowing to the sensor), and a negative voltage when the object is cooler than the sensor (infrared flux flows from the sensor to the object). When the sensor and the object are at the same temperature, the flux is zero and the output voltage is zero. This carries a message that the temperatures are equal to one another.

1.1 Sensors, Signals, and Systems

The term sensor and term detector are typically used as synonyms. However, detector is more often used to stress qualitative rather than quantitative nature of measurement.

The term sensor is distinguished from transducer. The latter is a converter of any one type of energy or property into another type of energy or property, whereas the former converts it into electrical signal.

An example of a transducer is a loudspeaker which converts an electrical signal into a variable magnetic field and, subsequently, into acoustic waves.



1.1 Sensors, Signals, and Systems

Transducers may be used as actuators in various systems. An actuator may be described as opposite to a sensor as it converts electrical signal into generally nonelectrical energy.

Transducers may be parts of a hybrid or complex sensor.

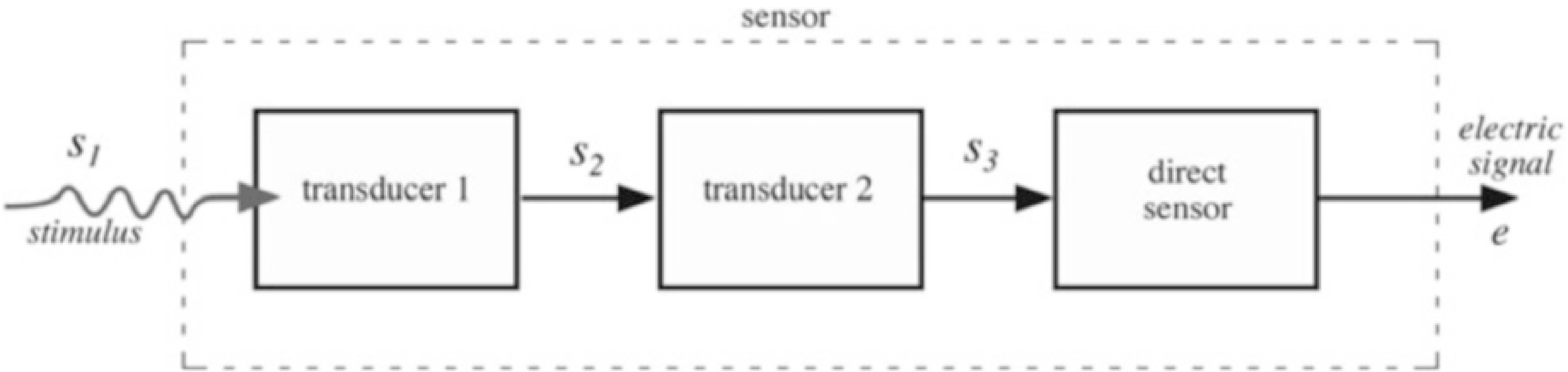
For example, a chemical sensor may comprise two parts: the first part converts energy of an exothermal chemical reaction into heat (transducer) and another part, a thermopile, converts heat into an electrical output signal. The combination of the two makes a hybrid chemical sensor, a device which produces electrical signal in response to a chemical reagent.

This suggests that many sensors incorporate at least one direct-type sensor and possibly a number of transducers. The direct sensors are those that employ certain physical effects to make a direct energy conversion into a generation or modulation of an electrical signal.

1.1 Sensors, Signals, and Systems

In general, we can define 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.



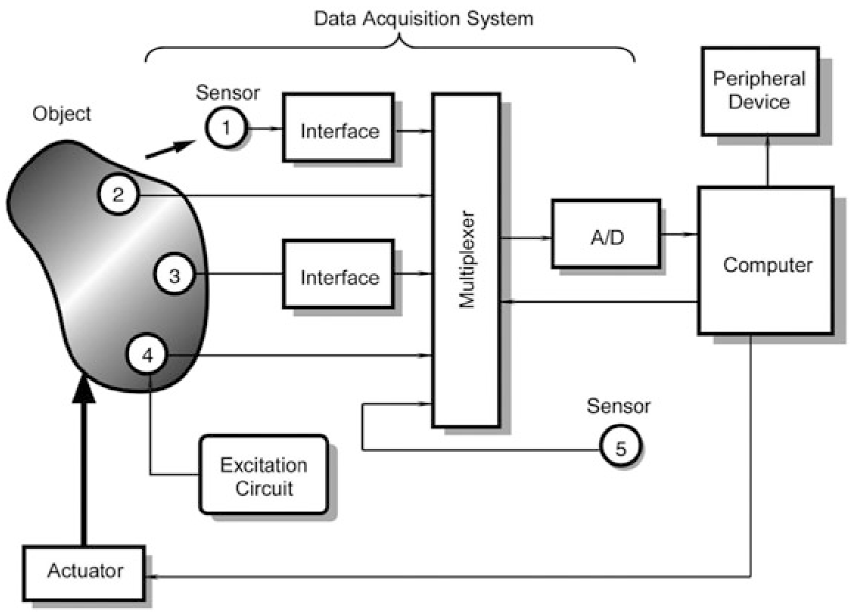
1.1 Sensors, Signals, and Systems

A sensor typically does not operate standalone, but it is always part of a larger system that may incorporate other detectors, signal conditioners, memory devices, data recorders, and actuators.

Data can be collected from an object by several sensors.

Some of them are positioned directly on or inside the object. Other sensors perceive the object without a physical contact and are called noncontact sensor.

Examples of such a sensor is a radiation detector and a TV camera.

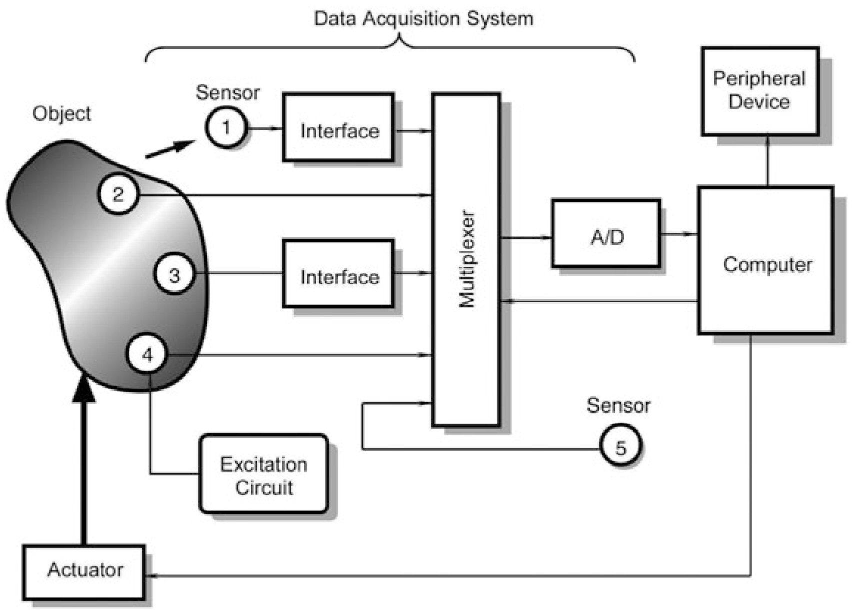


1.1 Sensors, Signals, and Systems

Moreover, some sensors cannot be directly connected to standard electronic circuits because of the inappropriate output signal formats. They require the use of interface devices (signal conditioners) to produce a specific output format.

Electrical signals from multiple sensors are fed into a multiplexer (MUX), which is a switch or a gate. Its function is to connect the sensors, one at a time, to an analog-to-digital converter (A/D or ADC) if a sensor produces an analog signal, or directly to a computer if a sensor produces signals in a digital format.

The computer controls a multiplexer and ADC for the appropriate timing. Also, it may send control signals to an actuator that acts on the object.



1.1 Sensors, Signals, and Systems

Example: car door monitoring arrangement.

Every door in a car is supplied with a sensor that detects the door position (open or closed). In most cars, the sensor is a simple electric switch.

Signals from all door switches go to the car's internal processor (one/zero).

The processor identifies which door is open (signal is zero) and sends an indicating message to the peripheral devices (a dashboard display and an audible alarm). A car driver (the actuator) gets the message and acts on the object (closes the door) and the sensor outputs the signal "one".

1.2 Sensor classification

Sensor classification schemes range from very simple to the complex. Depending on the classification purpose, different classification criteria may be selected. However, several practical ways to look at sensors exist.

- **Passive and active sensors**

A passive sensor does not need any additional energy source. It 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. *Examples: thermocouples, photodiodes*.

An active sensor requires external power for their operation, which is called an excitation signal. That signal is modified (modulated) by the sensor to produce the output signal. The active sensors sometimes are called parametric because their own properties change in response to an external stimulus and these properties can be subsequently converted into electric signals. *Examples: thermistors, resistive strain gauge*.

1.2 Sensor classification

- **Absolute and relative sensors**

An absolute sensor detects a stimulus in reference to an absolute physical scale that is independent on the measurement conditions. Examples of absolute sensors are thermistors, as their electrical resistance directly relates to the absolute temperature scale of Kelvin, or absolute pressure sensors, which produce signals in reference to an absolute zero on a pressure scale, i.e., the vacuum.

A relative sensor produces a signal that relates to some reference case. Examples of relative sensors are thermocouples producing electric voltage as function of a temperature gradient across the thermocouple wires. Thus, a thermocouple output signal cannot be assigned to a temperature without referencing to a selected baseline. A relative pressure sensor produces signal with respect to a selected baseline that is not zero pressure, for example, to the atmospheric pressure.

1.2 Sensor classification

- **Sensor's characteristics**

Another way to look at a sensor is to consider some of its properties that may be of a specific interest. These properties can be grouped as:

- sensor specifications (sensitivity, range, stability, resolution, accuracy, selectivity, speed of response etc.);
- sensing element material (inorganic, organic, conductor, insulator, semiconductor, liquid, gas or plasma etc.);
- conversion phenomena, which are mainly physical (thermoelectric, photoelectric, magnetoelectric, electromagnetic, thermoelastic, etc.) or chemical (chemical and physical transformation, electrochemical processes, etc.)
- stimuli (acoustic, electric, magnetic, optical, mechanical, thermal, etc.)

1.2 Sensor classification

Units of Measurements

Any physical or chemical measure must be related to a unit of measurements. The only exception are adimensional parameters and normalized scales. The base measurement system is known as SI which stands for French “Le Systéme International d’Unités”, which sets the basic units. All other physical quantities are derivatives of these base units.

Quantity	Name	Symbol
Length	meter	m
Mass	kilogram	kg
Time	second	s
Electric current	ampere	A
Thermodynamic temperature	kelvin	K
Amount of substance	mole	mol
Luminous intensity	candle	cd