Chapter 1: Fundamental Principles of Sensors

1.1 Definitions

The physical quantity being measured:

Displacement;

Temperature;

Pressure, etc.

Is designated as the measurand and is represented by m.

$$s = f(m)$$

s is the output quantity or response of the sensor;

m is the input quantity or excitation.

The measurement of s must make it possible to know the value of m (fig.1).

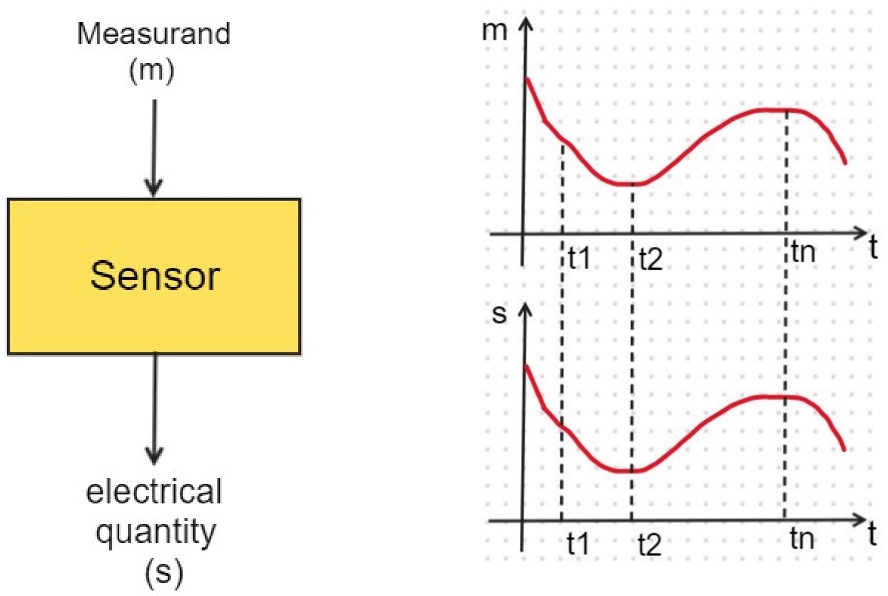


Fig.1 Example of evolution of a measurand m

and the corresponding response s of the sensor.

The relation $s = F(m)$ results in its theoretical form from the physical laws which govern the operation of the sensor, and in its numerical expression from its construction (geometry, dimensions), the materials which constitute it and possibly from its environment and its mode of use (temperature, power supply).

For every sensor the relation $s = F(m)$ in its numerically exploitable form is explained by calibration.

For a set of values of m known with precision, the corresponding values of s are measured, which makes it possible to plot the calibration curve (fig.2a).

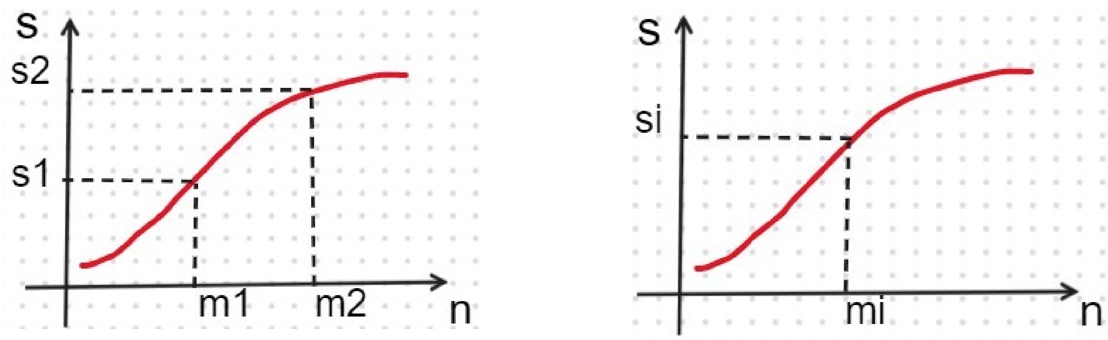


Fig.2 Calibration curve of a sensor: a) its establishment from the known values of the measurand m, b) its exploitation, from the measured values of the response s of the sensor; to any measured value of s, we can associate a value of m which determines it.

For reasons of ease of use, we strive to make the sensor so that it establishes a linear relationship between the variations Δs of the output quantity and Δm of the input quantity:

$$\Delta s = S. \Delta m$$

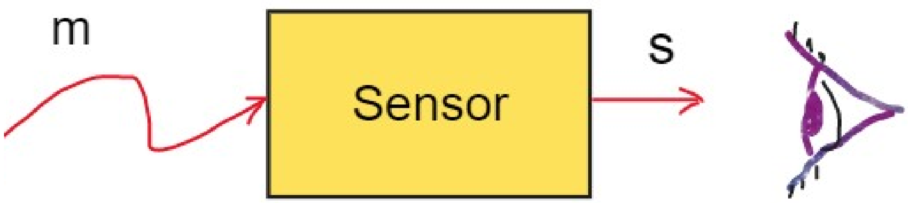
S is the sensitivity of the sensor.

One of the important problems in the design and use of a sensor is the constancy of its sensitivity S which must depend as little as possible:

- Of the value of m (linearity) and its frequency variation (bandwidth).
- Of time (ageing).

• Of the action of other physical quantities in its environment which are not the subject of the measurement and which are referred to as influence quantities.

As an electrical element, the sensor presents itself, seen from its output,



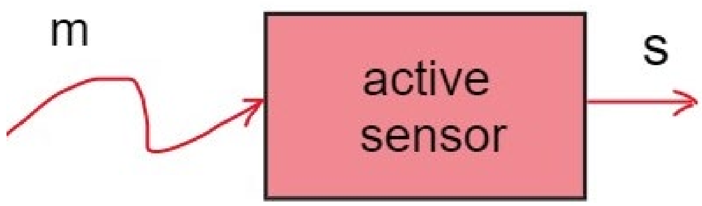
either as a generator, s then being a load, a voltage or a current and it is then an active sensor;

or either as an impedance, s then being a resistance, an inductance or a capacitance: the sensor is then said to be passive.

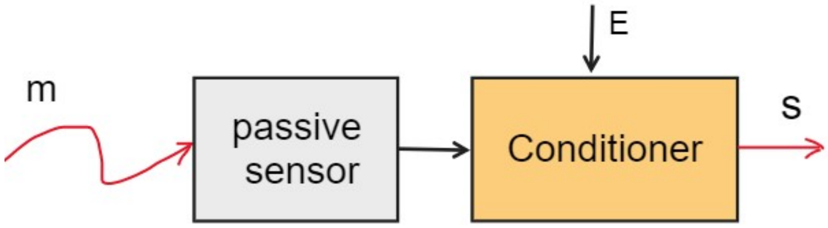
This distinction between active and passive sensors based on their equivalent electrical diagram reflects a fundamental difference in the very nature of the physical phenomena involved.

The electrical signal is the variable part of the current or voltage which carries the information related to the measurand: amplitude and frequency of the signal must be unambiguously related to the amplitude and frequency of the measurand.

An active sensor which is a source, directly delivers an electrical signal;



The same is not true of a passive sensor whose impedance variations are only measurable by the modifications of the current or of the voltage which they cause in a circuit which is also supplied by an external source.



The electric circuit necessarily associated with a passive sensor constitutes its conditioner, and it is the whole of the sensor and its conditioner which is the source of the electric signal.

1.2 Active Sensors

Operating as a generator, an active sensor is generally based in principle on a physical effect which ensures the conversion into electrical energy of the form of energy specific to the measurand:

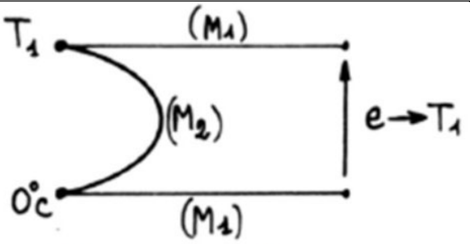
thermal, mechanical or radiant energy.

The most important of these effects are listed in Table 1.

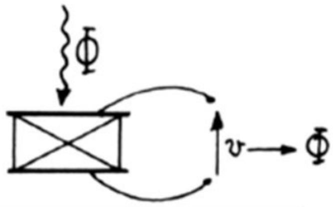
Measurand	Effect used	Output quantity
Temperature	*Thermoelectricity*	*Voltage*
Optical radiation flux	*Pyroelectricity* *Photoemission* *Photovoltaic effect* *Photoelectromagnetic effect*	*Charge* *Current* *Voltage* *Voltage*
Strength **Pressure** **Acceleration**	*Piezoelectricity*	*Charge*
Speed	*Electromagnetic induction*	*Voltage*
Position	*Hall effect*	*Voltage*

Table1. Active sensors: basic physical principles.

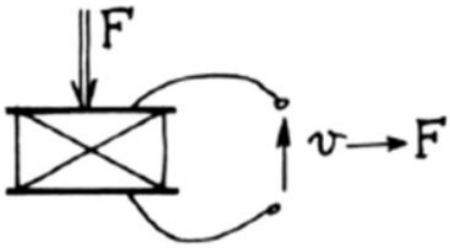
Thermoelectric effect

A circuit formed by two conductors (M_1 and M_2) of different chemical nature whose junctions are at temperatures T_1 and T_2 is the seat of an electromotive force $e(T_1,T_2)$. Application: determination from the measurement of e of an unknown temperature T_1 when T_2 is known (0 degrees for example).	 Thermoelectricity

Pyroelectric effect

Some so-called pyroelectric crystals have a spontaneous electrical polarization which depends on their temperature; they carry on the surface electric charges of opposite signs on the opposite faces. Application: A radiation flux absorbed by a Pyroelectric Crystal raises its temperature which leads to a modification of its polarization which is measurable by the variation of the voltage at the terminals of an associated capacitor.	 Pyroelectricity

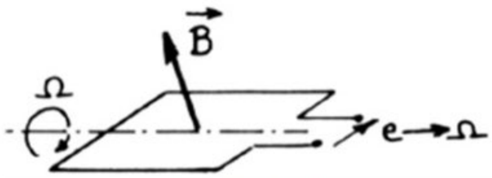
Piezoelectric effect

The application of a force and more generally of a mechanical constraint to certain so-called piezoelectric materials, quartz for example, leads to a deformation which causes the appearance of equal electric charges and opposite signs on the opposite faces. Application: measurement of force or related quantities (pressure, acceleration) from the voltage which appears between the two faces of the piezoelectric element.	 Piezoelectricity

Electromagnetic induction effect

When a conductor moves in a fixed induction field, it is the seat of an emf proportional to the flow cut per unit of time, therefore to its speed of movement.

Application: The measurement of the emf. of induction makes it possible to know the speed of movement which is at its origin.

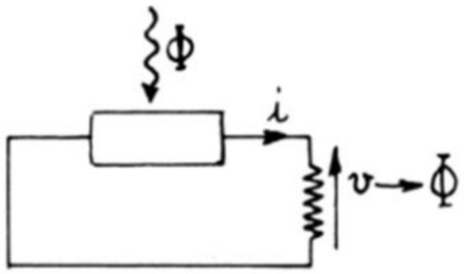


Electromagnetic induction

Photoelectric effects

There are several of them, which differ in their manifestations but which have a common origin in the release of electrical charges in matter under the influence of light or more generally electromagnetic radiation, the wavelength of which is less than a value threshold, characteristic of the material.

Applications: the photoelectric effects which make it possible to obtain a current or a voltage which is a function of the illumination of a target are the basis of methods for measuring photometric quantities on the one hand, and they ensure on the other hand the transposition into an electrical signal of information for which light can be the vehicle.



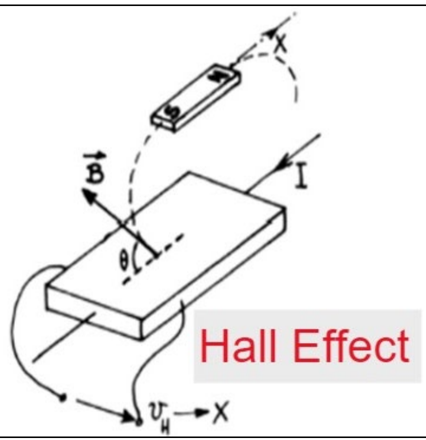
Photoelectricity

Hall effect

A material, generally semiconductor and in the form of a wafer, is traversed by a current I and subjected to an induction B making an angle θ with the current. It appears, in the direction perpendicular to the induction and to the current, a voltage VH which has the expression:

$$VH = KH.I.B.sin\theta$$

where KH depends on the material and the dimensions of the wafer.
Application: a magnet attached to the object whose position we want to know determines the values of B and θ at the level of the wafer: the voltage VH which in this way is a function of the position of the object therefore ensures an electrical translation.



Note: Sensors based on the Hall effect can be classified as active sensors since the information is linked to an emf. ; however, they are not energy converters because it is the source of the current I and not the measurand that delivers the energy linked to the signal.

1.3 Passive Sensors

These are impedances, where one determining parameter of which, is sensitive to the measurand. In the literal expression of an impedance there are terms related to:

- On the one hand to its geometry and its dimensions,

- On the other hand to the electrical properties of the materials: resistivity ρ, magnetic permeability μ, dielectric constant ϵ.

The impedance variation can therefore be due to the action of the measurand:

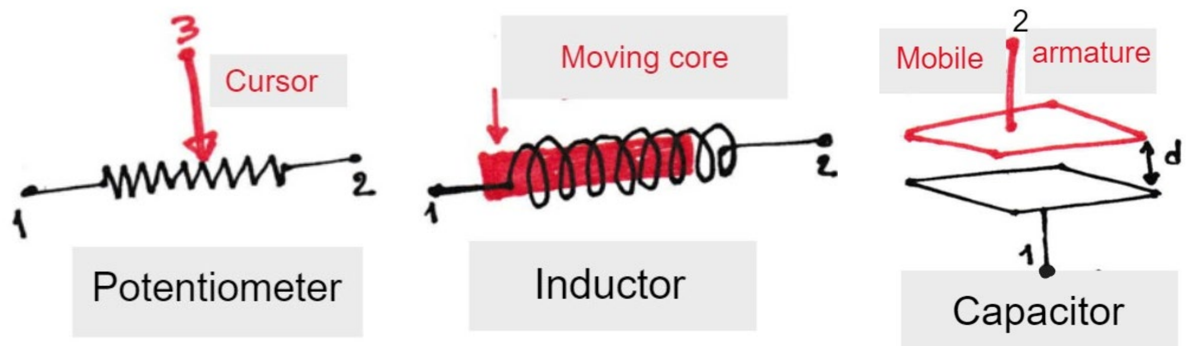
• Either on the geometric or dimensional characteristics,

• Or on the electrical properties of materials,

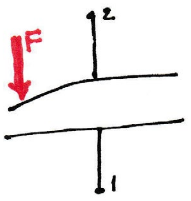
• Or more rarely on both simultaneously.

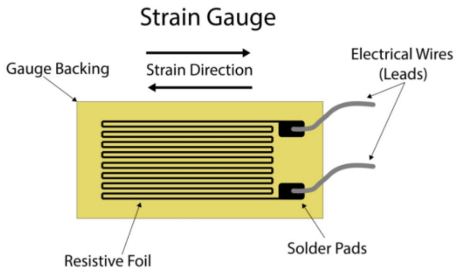
The geometric or dimensional parameters of the impedance can vary if the sensor comprises either a mobile element or a deformable element.

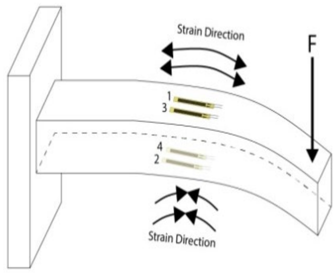
In the first case, each position of the mobile element corresponds to a value of the impedance and the measurement thereof makes it possible to know the position, this is the principle of a large number of position and displacement sensors. : Potentiometer, moving core inductor, moving armature capacitor.



In the second case, the deformation results from forces - or quantities related thereto (pressure, acceleration) - applied either directly or indirectly to the sensor: armature of a capacitor subjected to differential pressure, extensometer gauge rigidly linked to a constrained structure.







The change in impedance caused by the deformation of the sensor is linked to the forces to which the latter or the intermediate structure is subjected and it ensures an electrical translation thereof.

The electrical properties of materials, depending on their nature, can be sensitive to various physical quantities:

temperature, light, pressure, humidity, etc.

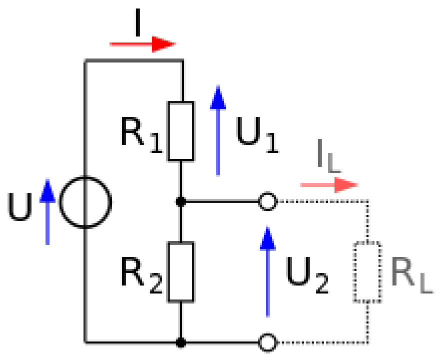
The following table gives an overview of the various measurands likely to modify the electrical properties of materials used for the production of passive sensors.

Measurand	**Sensitive electrical characteristics**	**Types of materials used**
Temperature	*Resistivity*	*Metals: platinum, nickel, copper, semiconductors.*
Very low temperatures	*Dielectric constant*	*Glasses*
Optical radiation flux	*Resistivity*	*Semiconductors*
Deformation	*Resistivity* *Magnetic permeability*	*Nickel alloys, doped silicon.* *Ferromagnetic alloys*
Position (magnet)	*Resistivity*	*Magneto-resistant materials: bismuth, indium antimony*
Humidity	*Resistivity* *Dielectric constant*	*Lithium chloride.* *Alumina, polymers*
Level	*Dielectric constant*	*Insulating liquids*

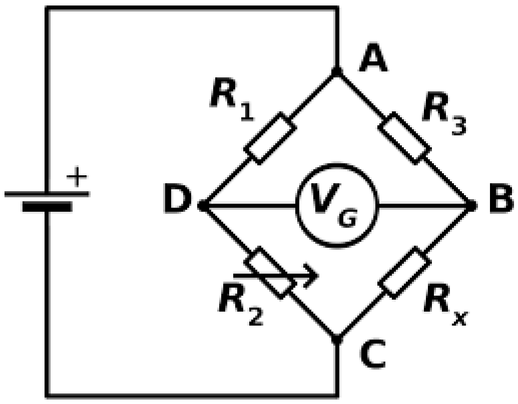
Passive sensors: physical principles and materials.

The impedance of a passive sensor and its variations can only be measured by integrating the sensor into an electrical circuit, which is powered and constitutes its conditioner. The most used types of conditioners are:

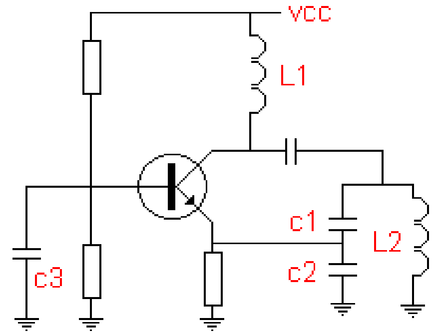
• The potentiometric assembly (circuit), which is a series association of a source, the sensor and an impedance which may or may not be of the same type.



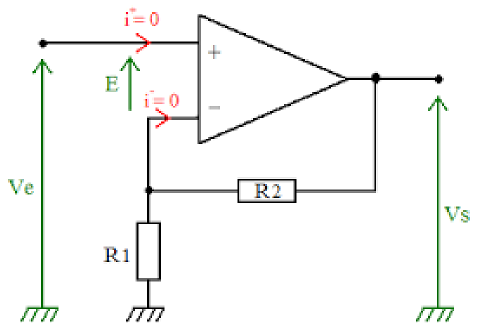
• The impedance bridge whose balance enables the impedance of the sensor to be determined or whose unbalance is a measurement of the variation of this impedance.



• The oscillating circuit which contains the impedance of the sensor and which is part of an oscillator whose frequency it fixes.



• The operational amplifier whose sensor impedance is one of the determining elements of its gain.

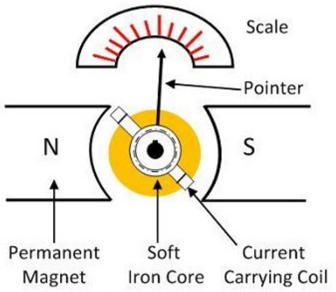


Note: the choice of conditioner is an important step in the production of a measurement system (chapter 3).

1.4 The Measurement Chain

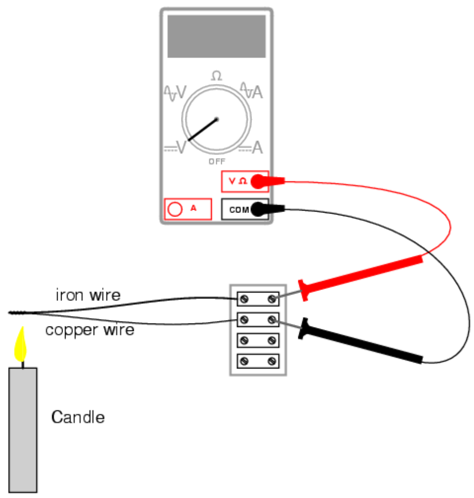
The measurement chain is made up of all the devices, including the sensor, making it possible under the best conditions to accurately determine the value of the measurand.
At the input of the chain, the sensor subjected to the action of the measurand allows, directly if it is active or by means of its conditioner if it is passive, to inject into the chain the electrical signal, support of information related to the measurand.
At the output of the chain, the electrical signal that it has processed and converted into a form that makes it possible to directly read the sought value of the measurand:

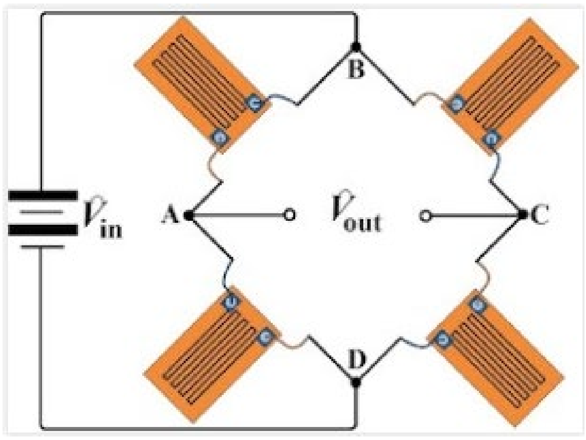
• Deflection of a pointer by a moving coil;
• Graphical or oscillographic analog recording;
• Display or print a number.



It is the calibration of the measurement chain as a whole which makes it possible to attribute to each indication at the output the corresponding value of the measurand acting at the input.
In its simplest form, the measurement chain can be reduced to the sensor, and its possible conditioner, associated with a reading device:

• Thermocouple and voltmeter;
• Strain gauge placed in a Wheatstone bridge, with a galvanometer or a voltmeter as a reading instrument.





But often the practical conditions of measurement lead to the introduction in the chain of functional blocks intended to optimize the acquisition and the processing of the signal:

• Linearization circuits of the signal delivered by the sensor;

• Instrumentation or isolation amplifier intended to reduce parasitic common mode voltages;

• Multiplexer, programmable instrumentation amplifier, blocking sampler, analog-digital converter when the information must be processed by computer (fig.1);

• Voltage-current or voltage-frequency converter when the signal must be transmitted remotely by cable (fig.2).

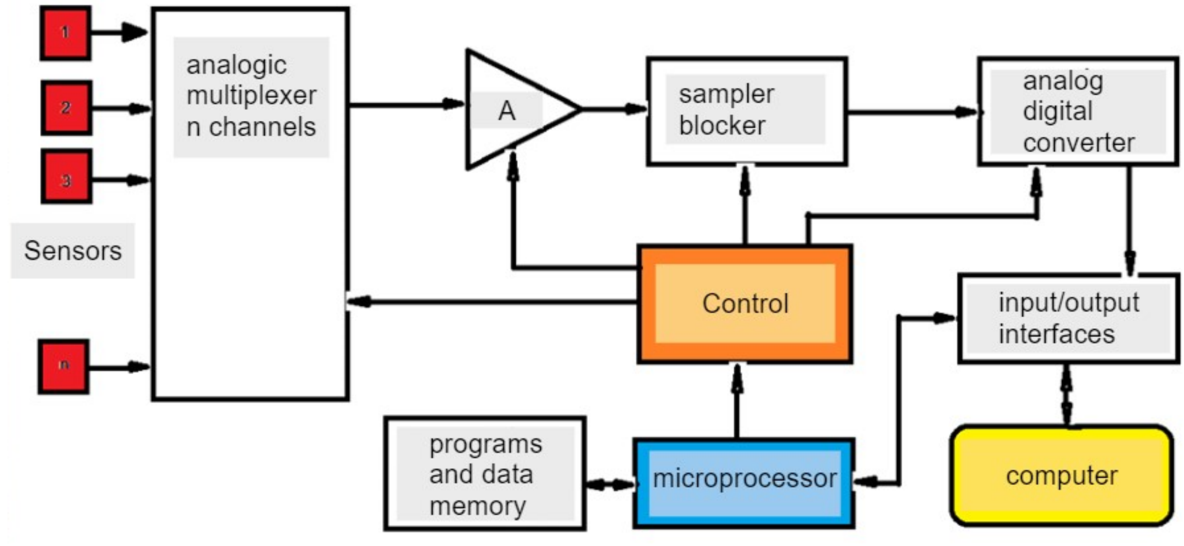


Fig.1: Measurement chain controlled by microprocessor.

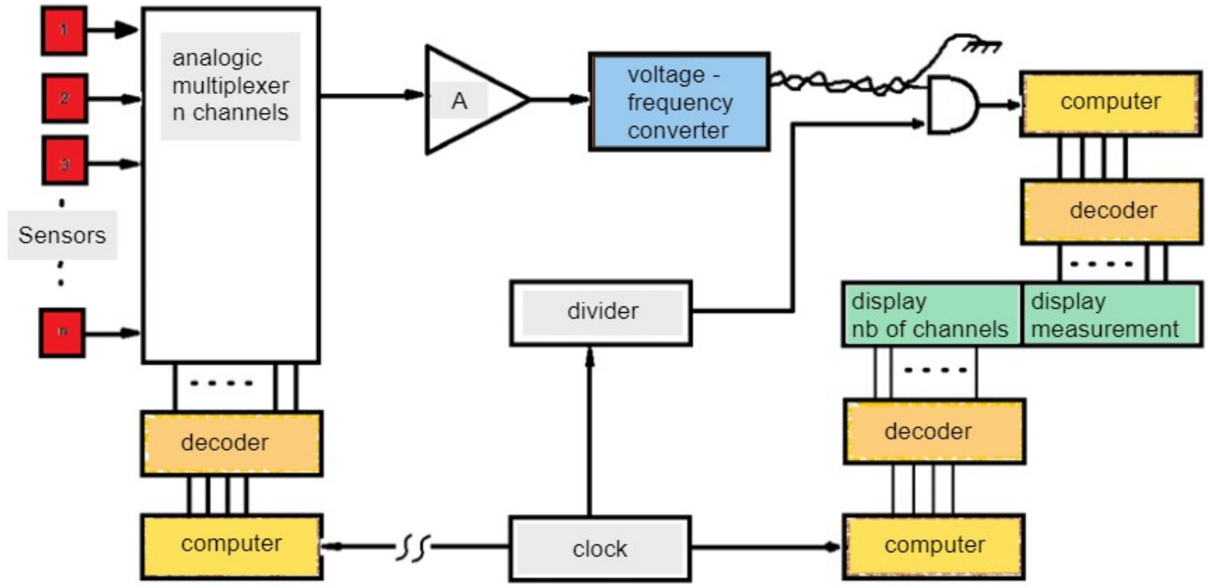


Fig.2 : Measurement chain with voltage-frequency conversion of signals allowing their two-wire transmission.

1.5 Integrated Sensors

An integrated sensor is a component produced using microelectronics techniques and which groups together on a silicon substrate the sensor, the test body (if any), and electronic signal conditioning circuits.

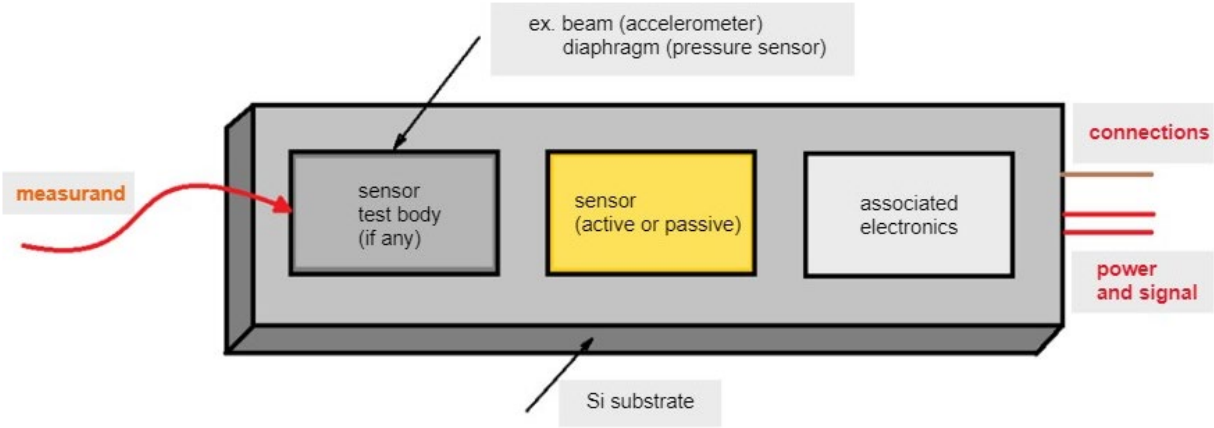


Fig.3: General structure of an integrated sensor.

Integration brings multiple benefits:

• Miniaturization;

• Cost reduction through mass production;

• Increased reliability by removing numerous soldered connections;

• Improved interchangeability;

• Better protection against parasites;

• The signal being conditioned at the source.

The use of silicon however imposes a limitation of the range of use from -50°C to 150°C approximately.

The sensor itself generally takes advantage of the sensitivity of silicon to various physical quantities.

Examples of silicon-based sensors:

• Thermometric resistors

• Strain gauges

• Photocapacities

• Hall effect pads

• Photodiodes and phototransistors

• Nuclear detection diodes

• Thermometric transistors

• ISFET (sensitive ion)

• GASFET (sensitive gas)

The sensor can also be made by depositing on the silicon substrate a thin film of a material more appropriate than silicon to the measurand considered but compatible with the integrated circuit manufacturing process:

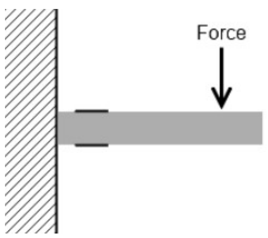
• Piezoelectric ZnO

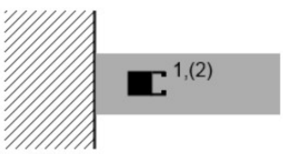
• Magnetoresistant InSb (indium antimonide)

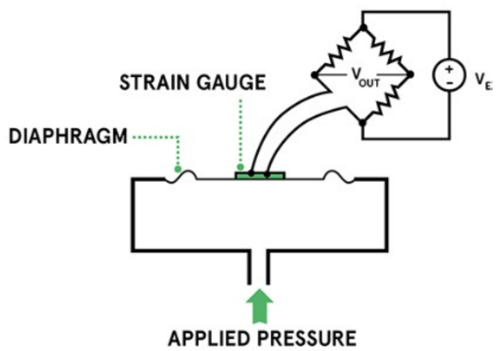
• Hygroscopic polymers (moisture)

• Thermoelectric couple (Bi/Sb)

The deformation of the test body under the action of the measurand (acceleration for the beam, pressure for the diaphragm) can be converted into an electrical signal by means of a bridge of piezoresistive gauges implanted in suitable zones, or by means of a deposit of piezoelectric ZnO undergoing stress under the action of the deformation of the test body.







The electronic circuits associated with the sensor are made according to conventional techniques for manufacturing ICs, they include, depending on the case:

- Thermal compensation circuits
- Linearization
- Amplification
- Transmission by voltage-frequency or voltage-current conversion.
- DTC type registers (charge-coupled device), for storing and transferring information.

1.6 Smart Sensors

The smart sensor refers to the measurement assembly of a physical quantity made up of two parts:

• A measurement chain controlled by microprocessor;

• A two-way communication interface.

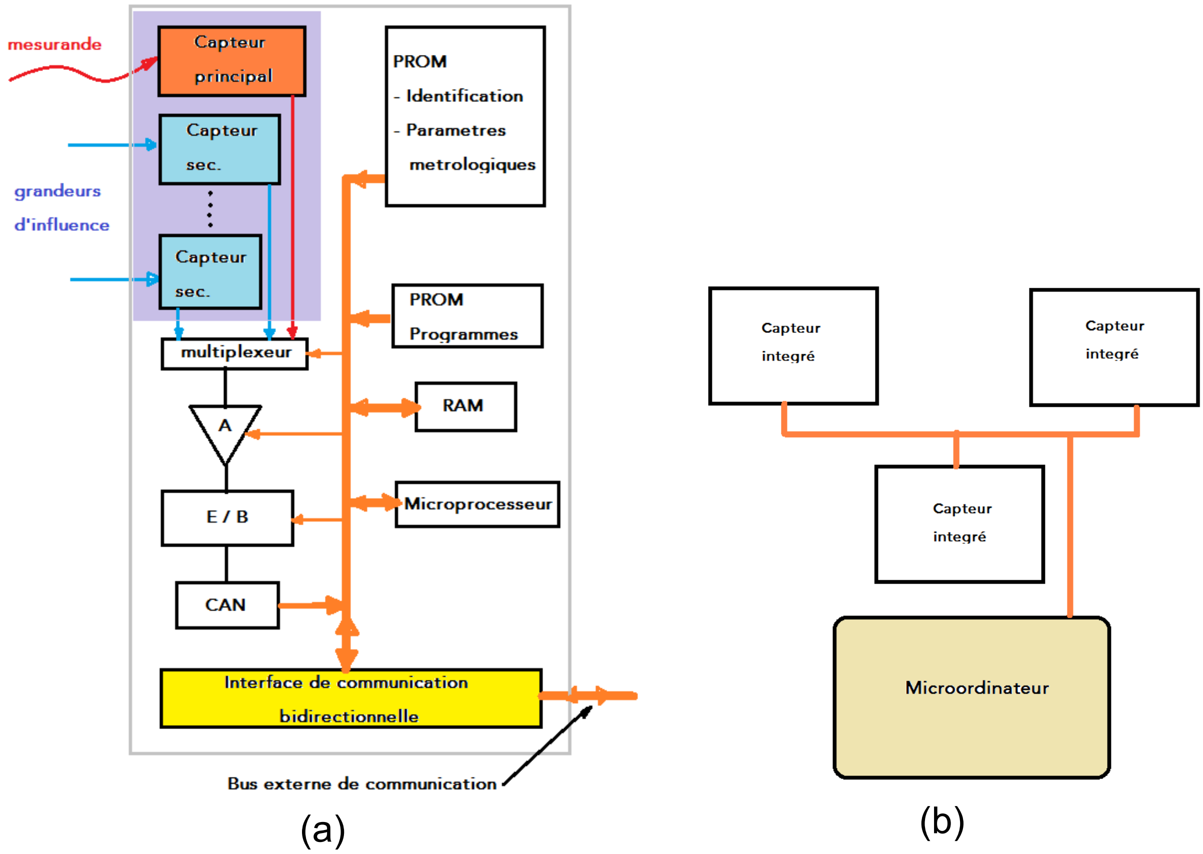


Fig.4 Intelligent sensor: a) General structure, b) Link by bus of a set of intelligent sensors to a microcomputer.

The measurement chain includes:

• The main sensor specific to the measurand studied, and identifiable by a code stored in PROM.

• The secondary sensors specific to the influence quantities likely to affect the response of the main sensor.

• Conventional devices for obtaining in digital form the output quantity of each sensor:

- Conditioner ;

- Multiplexer;

- Blocker sampler;

- Digital analog converter.

• A microprocessor assigned to the following tasks:

- Acquisition management;

- Correction of the effect of the influence quantities by means of the parameters stored in PROM and the data provided by the secondary sensors;

- Linearization;

- Sensor diagnostics.

The bidirectional interface ensures the connection of the sensor to a microcomputer (central computer) via a bus shared between several intelligent sensors.

The smart sensor offers specific advantages:

• Remote configurability;

• Increased credibility of measurements and maintenance assistance thanks to the status information provided;

• Distribution of tasks, relieving the central computer.