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EUROPEAN NETWORK FOR 3D PRINTING OF BIOMIMETIC MECHATRONIC SYSTEMS

MODULE 5

Sensors and Electronics

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1 Introduction

1.1 Measurement systems

A **measurement system** is a set of devices, apparatus, equipments etc, used for extracting information from a process and to pass that information further (figure 1).

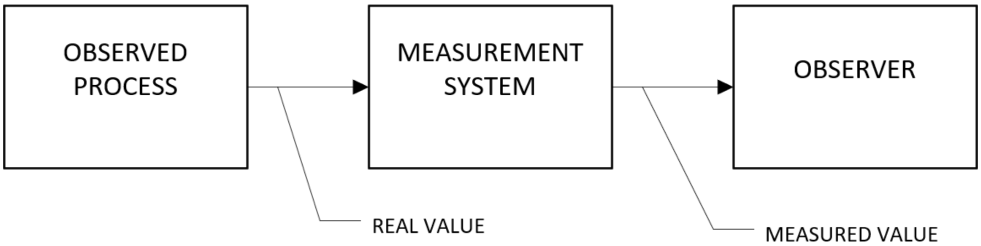

Figure 1. Measurement system's place, between the observed process and the observer.

In most cases, information reffers to the values of one or more physical quantities: mechanical, thermical, electrical, chemical, optical etc. As information can not be transmitted without a transfer of matter and without an energy transfer, some material connection has to be established between the observed process and the measurement system. This material connection does not necessarily has to be thought as a mechanical one. Matter means also electrons or photons, so this connection could also be in the form of an electro-magnetical wave, either radio, infrared or visible light.

For a connection to exist, some part of the measurement system has to be in contact with the observed process. In figure 2, this component is described as the **sensor**.

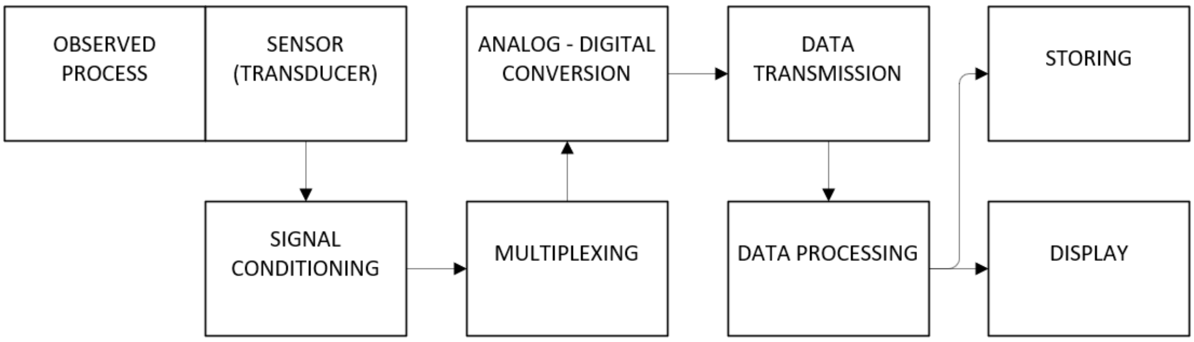

Figure 2. General structure of a measurement system.

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One or more sensor's parameters are changing their values according to the value of the measured physical quantity. For example: a piece of wire, which is changing its length when a pulling force is applied to the wire, the mercury in a thermometer, changing its volume when the temperature is changing, or a specific substance, changing its chemical properties when in contact with a certain gas. This leads to the conclusion that, when designing the measurement system, the sensor has to be chosen according to the physical quantity to be measured. Also, a separate sensor is needed for each physical quantity to be measured in in the process.

For the sensor to be influenced, a certain amount of energy has to be extracted from the observed process. Because the measurement has to influence the observed process as less as possible, the sensor is designed so that the amount of energy passed to it is usually very small, so the changes in sensor's parameters, which may be not directly observable, are also very small. These changes represents the signal which the sensor is generating.

This is one of the roles of the **signal conditioning** module in figure 2. Being powered from an external source, the module amplifies the sensor's signal, making it compatible and able to be processed in the next components of the measurement system. If the sensor's signal it's not an electrical one, the signal conditioning consists also in transforming the energy generated by the sensor in electrical energy, a voltage signal being generated.

When the component containing the sensor contains also a signal conditioning module, that component is called a **transducer**. A measurement system can contain more signal conditioning components, some of which may be in the transducers.

When a measurement system contains more than one sensor, a **multiplexer** is needed to receive the various signals from the sensors, on separate transmission paths, and send them to the next components using a single transmission path. A good example of using a multiplexer is the way in which cable TV works: the cable company is receiving the signals from different TV channels, each on its own transmission path, the signals are multiplexed and all arrive in one user's TV using a single cable. There is a demultiplexer in the TV, the channel selector, which is extracting the desired signal from the multiplexed one and is sending it to the displaying components.

Till the multiplexer, the electric signals are transmitted in analogue ones, the information contained in them is represented by the voltage or electric current levels. If this information is to be processed by a computer system, the signals have to be transformed into the digital format, where the voltage level can reperesent one of the two binary digits, 0 or 1. The

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conversion from one signal format to the other is performed by the **analog to digital converter**.

Modern transducers contain not only a signal conditioning component but also their own analog to digital converter, and even a microprocessor which allows sending the digital signal following a specific data transmission protocol. In these cases, if a multiplexer is needed, this is a digital one, in fact a microprocessor subsystem, and is placed after the digital transducers.

The next components of the measurement system are those specific to a microprocessor based system, or a computer: digital data can be send at a certain distance, using for example the Internet, serial communication or radio transmission, data is processed according to a algorithm, results are displayed in various formats and data is also stored.

1.2 Types of sensors and transducers

There are many criteria to clasify the sensors and the transducers, but one of them is taking into account where the energy containing the information is generated.

When interacting with the observed process, some sensors are changing some of their parameters without generating any amount of energy. These are called **parametric (passive) sensors**.

Another category of sensors are those which are generating a certain amount of energy when interacting with the observed process. These are called **generative (active) sensors**.

1.2.1 Parametric sensors

Discussing only about electrical parameters based sensors, parametric sensors can be further classified, according to the variable parameter, in **resistive**, **capacitive** and **inductive** sensors.

One of the most used category of **resistive** sensors are the **strain gages** (figure 3).

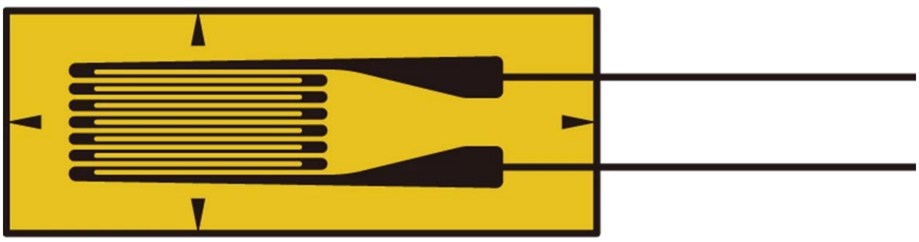

Figure 3. Strain gage example.

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These consist in a metallic pattern on an insulating flexible support. To allow the metallic pattern to be connected in an electrical circuit, wires are attached to the gage's solder pads.

The strain gage is attached to the object whose strain is to be measured using an adhesive, so is deforming in the same way the object does. Deforming the strain gage causes the length of its metallic pattern to change, thus causing a change in its electrical resistance according to equation (1).

$$RR = \rho\rho\frac{LL}{S}\ [\Omega] \qquad (1)$$

where ρ is the rezistivity of the material, in $\Omega \cdot m$, L is the length of the wire and S is the area of a transversal section in the wire.

If the strain gage is part of an electrical circuit, powered with a certain voltage, changing its resistance will cause the voltage across that portion of the circuit to change, so an electrical signal is obtained, which is proportional with the object's strain.

Apart from measuring the strain of the object to which the strain gage is attached, if a relation is known between the strain and the force applied to the object, then force can be measured, this being one of the main applications where strain gages are used.

An other type of rezistive sensors is represented by the **Resistance Temperature Detectors** (RTD). These are built from materials which are changing their electrical resistance when temperature changes. Made from platinum, nickel or sometimes copper, RTDs are capable of measuring temperatures up to 300 – 600 C, with a tolerance of up to ±0.15 C [1]. A thin film miniature RTD, 3 mm long, is presented in figure 4.

Figure 4. Miniature thin film RTD

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A **capacitor** is an electronic component which can store energy in the form of an electrical charge, producing a potential difference across its plates. It consists of two or more parallel conductive plates which are not connected or touching each other, but are electrically separated either by air or by some form of an insulating material (figure 5).

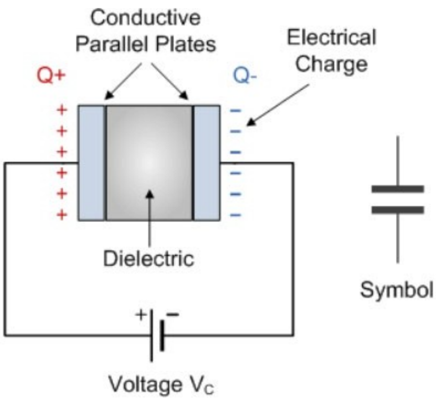

Figure 5. Capacitor's structure.

Its capacitance, measured in microfarad, the ratio of the amount of stored electric charge to the difference in electric potential, can be computed as in equation (2),

$$C = \varepsilon\varepsilon_0 \cdot \varepsilon\varepsilon_r \cdot \frac{S}{d} \; [\mu F] \tag{2}$$

where C is the capacitance, ε_0 is an electric constant, in F/m, ε_r is the relative permitivity of the insulating material, S is the overlaping area of the two conductive plates and d is the distance between the two plates.

If one of the variables ε_r, S or d from equation (2) is changing, due to the relative motion between the plates and insulating material (ε_r is changing) or between the two plates (S or d are changing), then the capacitance will change its value and the displacement can be measured.

A special type of capacitive sensor is that called proximity sensor, which can measure the distance to an object, either metallic or non-metallic. In this case, the insulating material is composed both from the air in front of the sensor's measuring face and from the object to be measured. When the object moves, the value of the relative permitivity is changing, so the displacement can be measured (figure 6).

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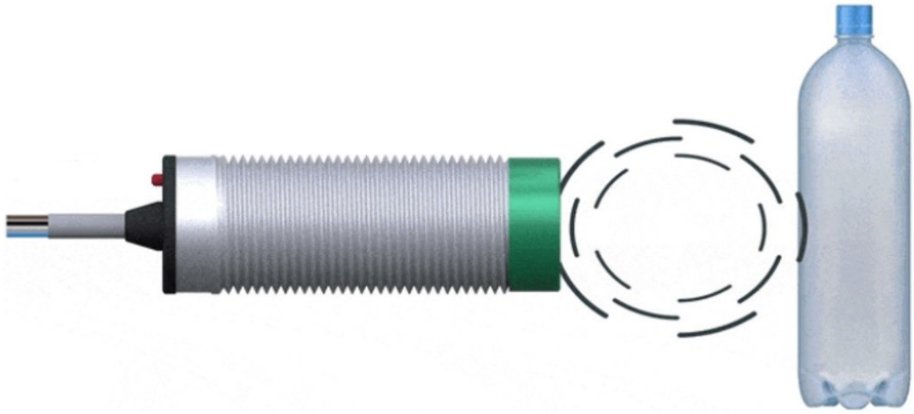

Figure 6. Proximity capacitive sensor.

Another type of capacitive sensors are measuring the capacity of an seismic mass under acceleration (figure 7). They are called **MEMS** (Micro-Electro-Mechanical System) **accelerometers** and one of their main advantage is that they have extremely small dimensions and their manufacturing is very cheap.

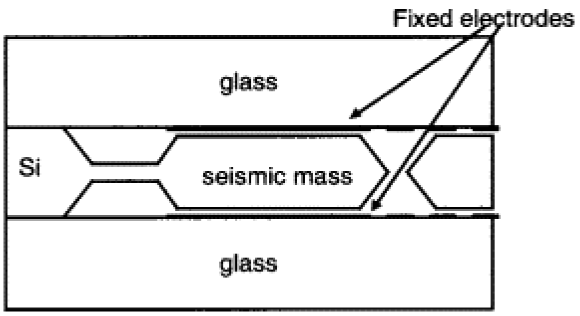

Figure 7. The structure of a MEMS accelerometer

MEMS sensors have an extremely large number of applications, one of them being inside the mobile phones, allowing for example to determine the phone's rotation angle and thus to rotate the screen image accordingly.

An **inductive sensor** uses the principle of electromagnetic induction, discovered by Michael Faraday: an electromotive force is produced across an electrical conductor in a changing magnetic field. The value of the electromotive force can be described by equation (3), where ε is the electromotive force, Φ_B is the magnetic flux, in weber (Wb) or volts-seconds, and t is the time.

$$\varepsilon\varepsilon = -\frac{d\Phi_{BB}}{dt}[NN] \quad (3)$$

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A metallic object moving in the sensor's magnetic field will create an electrical current which will flow in the sensor's circuits (figure 8), so the principle can be used in the inductive proximity sensors to detect metallic objects or to measure the distance between the object and the sensor's face.

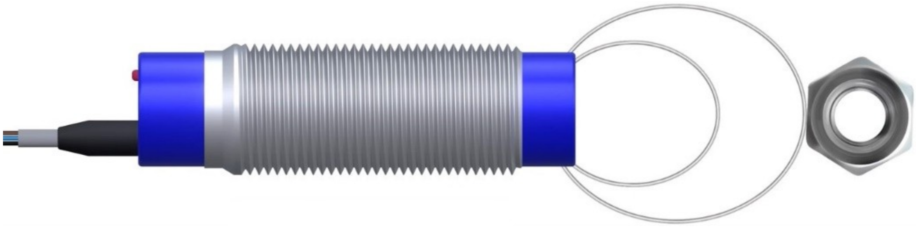

Figure 8. Inductive proximity sensor detecting a metallic object.

A different type of inductive sensors, called **Linear Variable Differential Transformers** (LVDT), are used for measuring displacement by having a shaft attached to the moving object. Inside the sensor, the shaft is attached to a magnetically conductive core which moves inside the sensor's coil (figure 9).

Figure 9. LVDT Inductive displacement sensor.

1.2.2 Generative sensors

Generative (active) sensors are usually classified according to the physical quantity they are measuring. One of the most used types are those for measuring temperature, called thermocouples. A **thermocouple** is made from two electrical conductors, from different materials, connected at one end called hot junction (figure 10). The other end, where the measurement device is placed, is called the cold junction.

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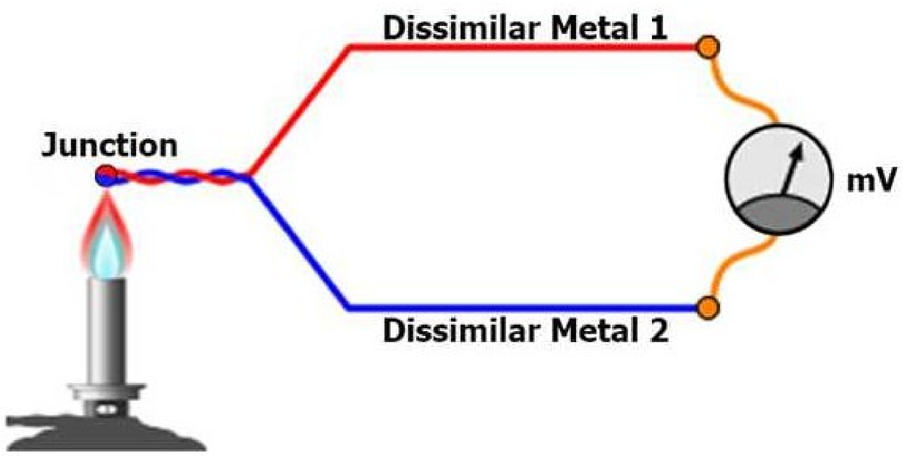

Figure 10. A thermocouple's structure.

According to Seebeck (thermoelectric) effect, when the two ends of a thermocpuple are placed at different temperatures, electricity is flowing from the hot junction to the cold junction, so a difference in potential (a voltage), can be measured at the cold junction.

There are several materials couples from which thermocouples can be made: nickel-alloy (type E: chromel–constantan, type J: iron–constantan, type K: chromel–alumel, type N: Nicrosil–Nisil, type T: copper–constantan), platinum / rhodium-alloy (types B, R and S), tungsten / rhenium-alloy (types C, D and G), Chromel–gold / iron-alloy, platinum / molybdenum-alloy and iridium / rhodium alloy being the most well known.

Using thermocoules, temperatures up to 1700 C can be measured, but their accuracy can go down to several degrees and their response time can be as long as several seconds. Miniature thermocouples can have their diameters as small as 0.25 mm.

A distinct and important category of generative sensors are build based on the **direct piezoelectric effect**, which is the property of some materials to generate electric charges when a mechanical stress is applied. **Converse (reverse) piezoelectric effect** also exists, which consists in generating a stress when an electrical field is applied, this effect being used for building actuators and piezoelectric motors. Examples of piezoelectric materials are: the quartz, lead zirconate titanate (PZT), barium titanate and lithium niobate.

The **piezorezistive pressure sensors**, one of the most used type of pressure sensors, are using strain gages attached to a thin membrane which is bending when pressure is applied. The strain gages are made from semiconducting materials, usually dopped silicon [2]. A change

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in the strain gage's resistance appears due to the piezorezistive effect. A change in length also appears, accompanied by a change in resistance, but this is much smaller than the change due to the piezorezistive effect, this being the reason for each these sensors are considered as belonging to the generative category and not to the parametric one.

Pressure sensors may be clasified according to the type of pressure they are measuring: absolute pressure, when the pressure is compared with the one of a vacuum volume inside the sensor, relative pressure, when the pressure is compared with the atmospheric air pressure, and relative pressure, when the sensor has two inputs and is measuring the pressure difference between them.

Piezoelectric sensors can be used for measuring not only pressure, but also acceleration, temperature, strain and force.

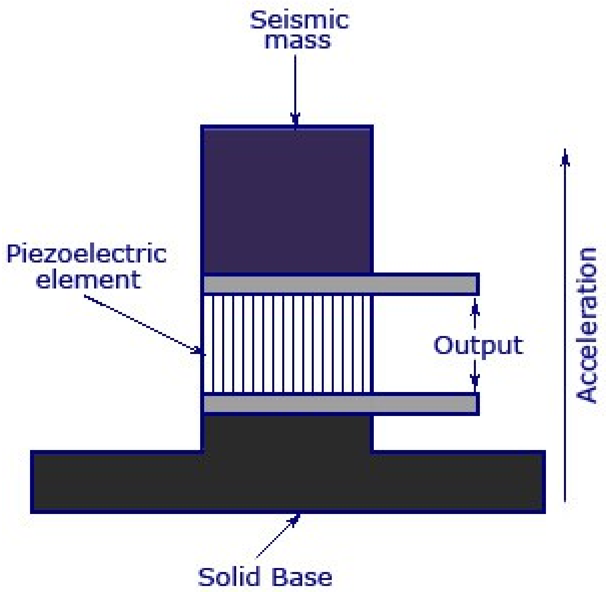

Figure 11. An accelereometer's structure.

A piezoelectric acceleration sensor, called an **accelerometer** (like also the capacitive ones), is using a piezoelectric element, made from natural quartz or from lead zirconate titanate (PZT), which is in contact with a so called seismic mass, a body with a weight much higher than that of the piezoelectric element (figure 11).

When acceleration is applied, the seismic mass is creating a stress in the piezoelectric element, so electrical charges appear on its faces. Piezoelectric accelerometers are mainly used in measuring high frequency vibrations, but they work also well at lower frequencies.

Piezoelectric temperature sensors consist in a multilayer cantilever containing, between thers, a layer of dopped silicon and an aluminium layer (figure 12). Due to the different thermal expansion coefficients of the multilayer materials, a thermal stress is generated in the silicon layer, thus being generated an electrical signal which is proportional to the temperature.

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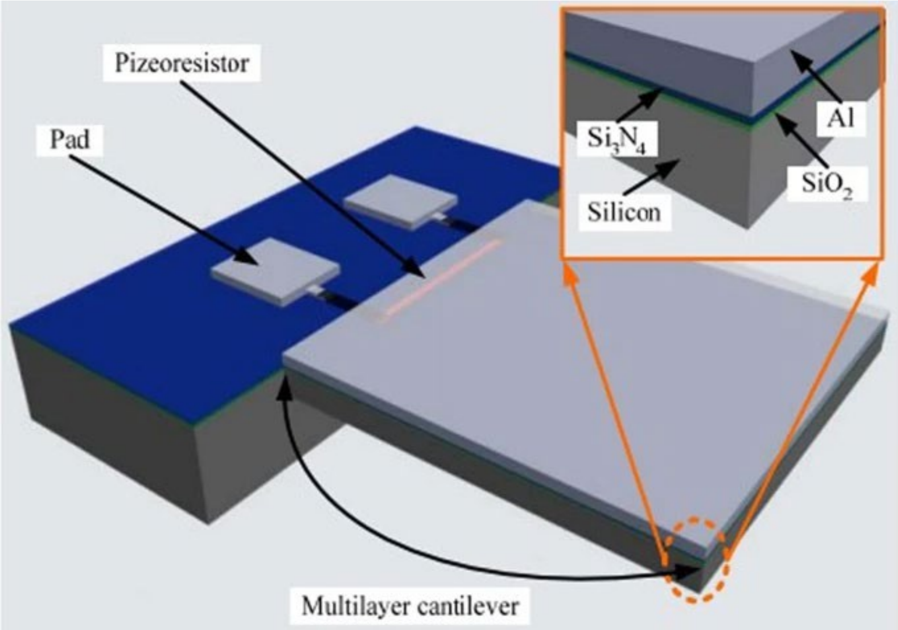

Figure 12. The structure of a piezorezistive temperature sensor.

Piezoelectric components can be also attached to different types of membranes, cantilevers or other elastic components, so a force applied to the elastic component will induce a stress in the piezoelectric material, allowing to measure the applied force or the strain of the elastic component.

Photoelectric generative sensors are based on the **photoelectric effect**, when electrons are emitted by a material which is hit by light. The best materials for obtaining an usable photoelectric effect are semiconductors like silicon, cadmium telluride, gallium arsenide and copper indium diselenide [3]. One main category of photoelectric generative sensors are the **photodiodes**. One immediate use of this type of sensors is the measurement of illuminance, the amount of light falling on a certain area.

If it’s not the amplitude of the signal which is measured, but the signal’s presence or absence, then a whole family of sensors can be built for detecting the presence of an object or for measuring one object’s displacement.

For the first category, **photodetectors**, one possible configuration is that in which the object to be detected is situated between the light emittor (transmitter) and the photoelectric sensor (figure 13), the so called thrubeam model. Other configurations are possible, with the

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emittor and the sensor on the same side of the object: when the emitted light is reflected by the detected object (reflective model) or when the light from a reflector (on the other side of the object) is interrupted by the object (retroreflective model). The last case is often used in automatic parking or garage barriers, to avoid closing the barrier when the presence of a car or person is detected (figure 14).

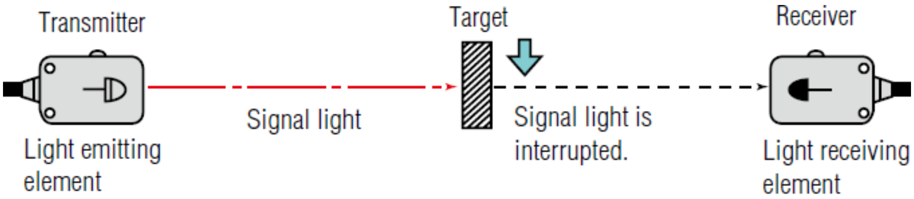

Figure 13. Thrubeam photodetector model.

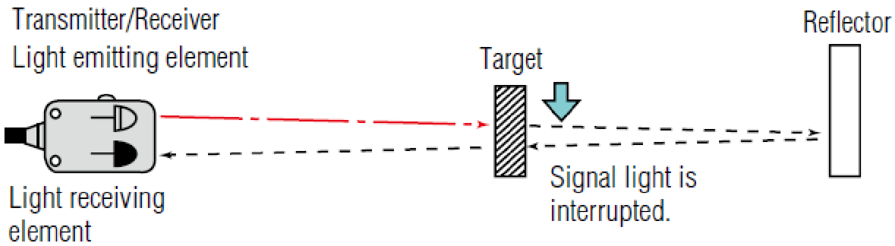

Figure 14. Retroreflective photodetector model.

When the light from the emitter is reaching the receiver, a pulse type signal appears in the measurement system's circuits. If each pulse is corresponding to the displacement of an object over a certain distance and is the measurement system is able to count the signals, then a displacement sensor can be built using the photoelectric effect.

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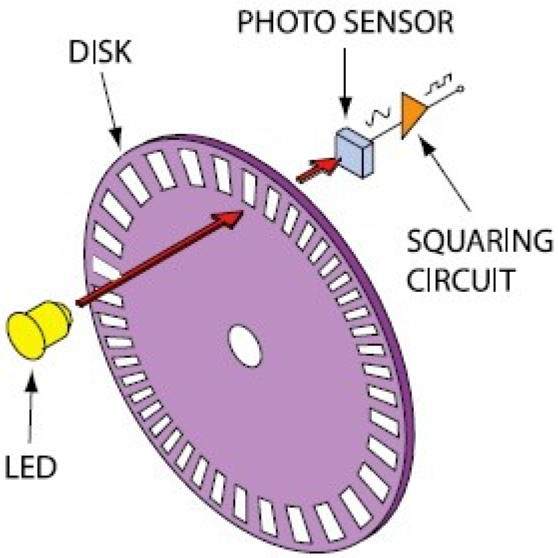

Figure 15. A rotary encoder.

A **rotary encoder** is a sensor in which a disk, having alternating opaque and transparent sections, is rotating between a light source and a photodetector (figure 15). Each time the light passes through a transparent section, a pulse is registered, so it is known that the disc rotated with a certain angle.

The same principle can be applied for building linear encoders, where the disk is replaced by a linear scale.

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2 Signal conditioning

Signal conditioning represents the transformation of an analog signal in such a way that this becomes compatible with the next components of the measurement system. Extracting only the useful part of one signal also represents a category of signal conditioning. There are many types of signal conditioning operations, depending on the sensor's type, signal's type or on the requirements of the measurement system.

2.1 Input coupling

Input coupling is used for conditioning signals which contain both AC and DC components and where only the AC component is of interest. The DC component, which is an offset of the signal, usually equal with the signal's mean amplitude, is removed by using the so called capacitive coupling, placing a capacitor between the signal and the rest of the measurement system (figure 16).

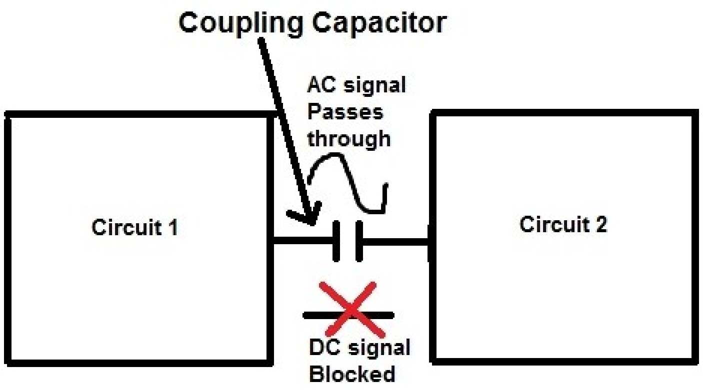

Figure 16. Input coupling circuit.

In simple circuits, the capacitor can be replaced by a **gimmick loop**, a capacitor made by two twisted insulated wires, having a capacitance on the order of 0.5 to 1 pF/cm. The capacitance of a gimmick loop may be changed by tightening or loosening the windening or by changing the wires length.

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2.2 Filtering

Filtering is a type of signal conditioning which removes the signal's components having certain frequencies. One criteria to classify the electronic filters is according to the frequencies they are allowing to pass further in the measurement system: **high-pass filters** allow only the signal component having a frequency above a certain value (cutoff frquency), **low-pass filters** allow only the frequencies below the cutoff frequency, **band-pass filters** allow only the frequencies belonging to a certain interval and **band-stop filters** remove the frequencies belonging to a certain interval. Figure 17 shows an example of composition between a 10 Hz signal and a 2 Hz one, both sinusoidal.

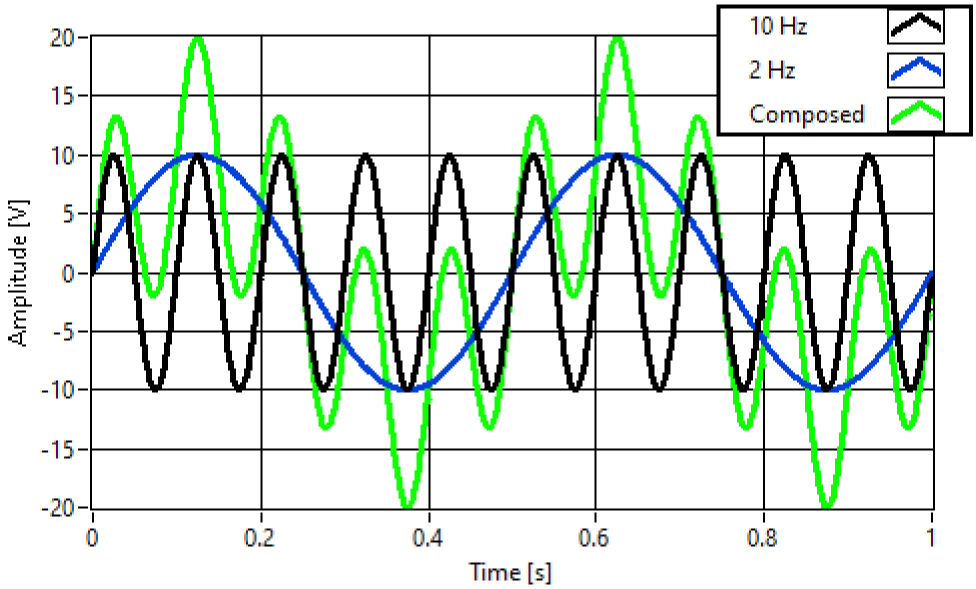

Figure 17. Signals composition.

In figure 18 there are pictured the results of applying two filters on the composite signal. When applying a high-pass filter with the cutoff frequency of 3 Hz, the 10 Hz sinusoidal signal is extracted from the composite signal, while when applying a low-pass filter at 4 Hz the 2 Hz is extracted. It can be observed that, doe to the specific design of the applied filters, the extracted signals can suffer various distortions, like an amplitide reduction in the first case or a form distortion in the second one.

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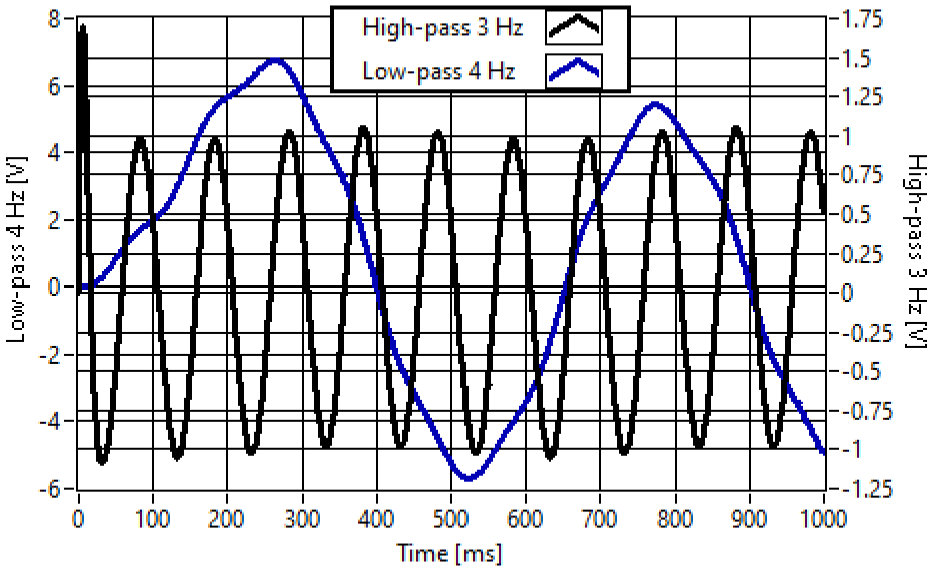

Figure 18. Signal filtering results.

2.3 Amplification

Amplifying a signal means increasing its amplitude (voltage or current), which is useful, for example, for reducing the influence of the electrical noise on the signal quality, the so called **signal-to-noise ratio** increasing. Increasing the signal's amplitude is performed by increasing its power, so the amplifier needs an own power source to deliver the additional energy in the electrical circuit. One very often used application is encountered in temperature measurements using thermocouples, where the milivolts range signal generated by the thermocouple has to amplified in the volts range to better fit with the measurmeent range of the analog-to-digital converter.

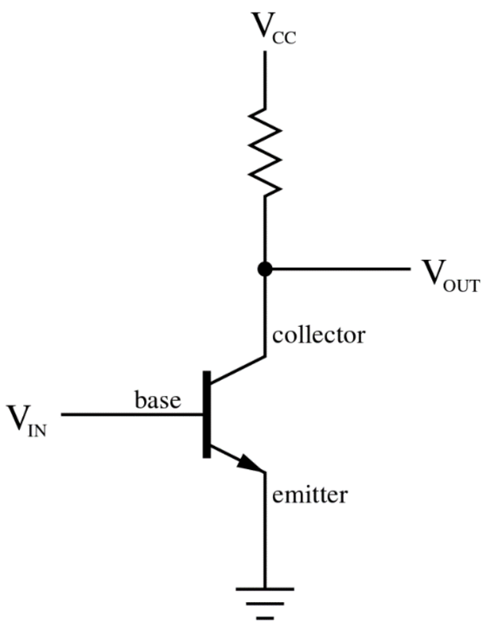

Figure 19. A transistor's circuit.

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An **amplifier** can take the form of a separate equipment, like audio amplifiers, a part of an electronic circuit or an integrated circuit. In all these forms, **transistors** are used as the main amplifier components, based on their functioning principle: controlling the high amplitude of the current flowing between their **collector** and **emitter** terminals, based on the small amplitude current received at the **base** terminal and flowing also to the emitter (figure 19).

2.4 Attenuation

Attenuation represents the decreasing of a signal's amplitude (the opposite of amplification) and is often used when the amplitude is greater than the maximum accepted by the analog-to-digital converter. The most used design of an **attenuator** is that of a so called voltage divider (figure 20), where the ratio between the output and the inpus voltages is determeined by the values of the two resistors.

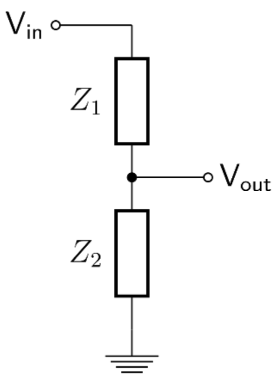

Figure 20. Voltage divider circuit.

$$V_{out} = \frac{Z_2}{Z_1 + Z_2} \cdot V_{in} \quad (4)$$

2.5 Excitation

Excitation consists in providing external energy, from a voltage or from a current source) to a parametric sensor. A very well known case when excitation is used is when measuring with strain gages. A special circuit is used, called the **Wheatstone bridge**, consisting of four resistors from which either one, two or all four can be strain gages (figure 21).

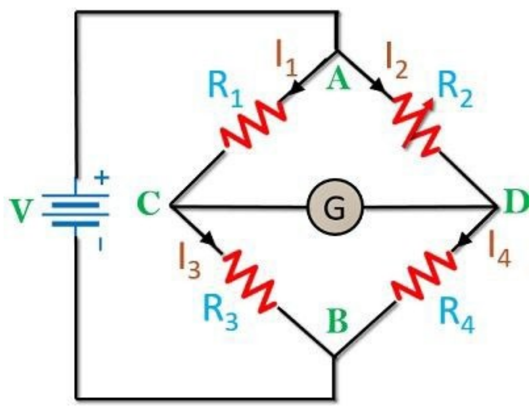

Figure 21. The Wheatstone bridge.

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If a voltage is applied between points A and B, the voltage measured between points C and D depends on the values of the four resistors.

$$V_{CD} = V_{AB} \cdot \left(\frac{R_3}{R_1 + R_3} - \frac{R_2}{R_2 + R_4}\right) \tag{5}$$

Equation (5) shows that, when all the four electrical resistances are equal (balanced bridge), the output voltage is zero. If some or all of the four resistors are replaced with strain gages, when their electrical resistances are changing, the value of the output voltage can be written as in equation (6), so is dependent on the resistances' variations.

$$V_{CD} = k \cdot V_{AB} \cdot \left(\frac{\delta\delta R_1}{R_1} - \frac{\delta\delta R_2}{R_2} + \frac{\delta\delta R_3}{R_3} - \frac{\delta\delta R_4}{R_4}\right) \tag{6}$$

It can be seen in equation (6) that the ratios corresponding to **adiacent sides** of the Wheatstone bridge (1 and 2, 2 and 3, 3 and 4, 4 and 1) have **opposite signs**, while the ratios corresponding to **opposite sides** (1 and 3, 2 and 4) have the **same sign**.

This means that, if same sense variations of the electrical resistance appear on adiacent sides, their effects on the V_{CD} measured voltage will compensate each other, so the total effect will be null. If same sense variations appear on opposite sides, their effects will be added, so the total effect will be doubled.

The first conclusion is useful, for example, when force has to be measured and the effect of the temperature variation has to be eliminated (figure 22). The R_1 strain gage, placed on an object which is deforming when an F force is applied to it, is sensing not only the strain due to the applied force, but also the strain due to the dilating or contracting of the object due to temperature variation.

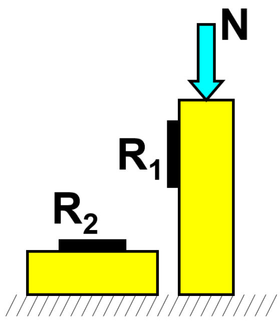

Figure 22. Compensating temperature variation effects.

If a strain gage R_2 (placed on an adiacent side to R_1) is placed on a second object, made from the same material (to have the same dilatation coefficient) and placed close to the first object (to suffer the same temperature variations), then the effects on R_1 and R_2 due to

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temperature variations (having the same sign) will compensate each other and the total effect at the Wheatstone bridge output will depend only on the strain sensed by R_1.

Another design is used when force signal amplification is needed (figure 23). If the R_1 and R_2 resistors (on adiacent sides of the Wheatstone bridge) are placed on the opposite faces of a body on which the force to be measured is acting, due to object's bending to the left, the length of R_1 will decrease and the length of R_2 will increase, so the variations of their electrical resistances will have opposite signs, but the effects on the Wheatstone bridge output will have the same sign, so the output will e double, so more precise.

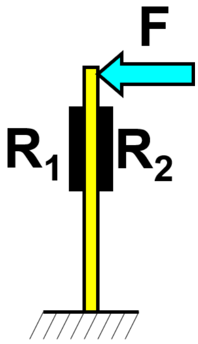

Figure 23. Sensitivity doubling.

2.6 *Linearization*

Linearization is a type of signal conditionig used when the sensor's output signal is not linearly proportional with the value of the measured physical quantity. Figure 24 shows the variation of the Seebeck coefficient (output voltage vs Temperature) for different types of thermocouples, while figure 25 shows a thermistor's characteristic curve.

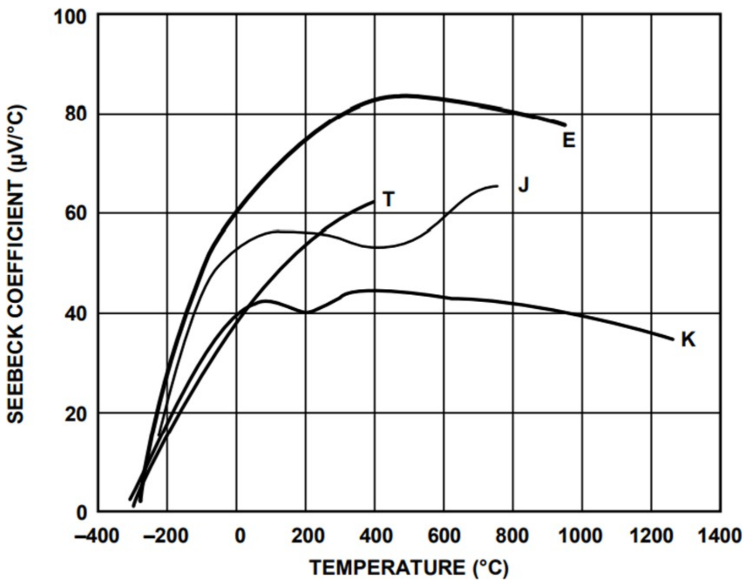

Figure 24. Seebeck coefficient.

Both cases indicate a non-linearity between the temperature value and the output voltage.

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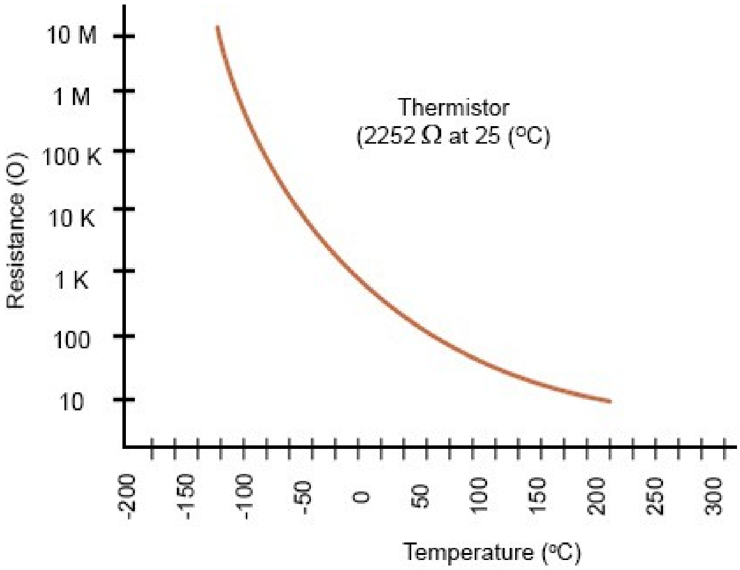

Figure 25. A thermistor's characteristic curve

Different solutions can be used for compensating the non-linearity and providing a linear ratio between the output voltage and the measured temperature.

For example, thermistor signal linearization can be performed by using a cheap analog signal conditioning circuit which consists of a single resistor in parallel with the thermistor [4]. The resistor's value has to be about equal to the thermistor value at the centre of the range of interest. To be noted that only an approximation of a linear relation will be obtained, but this may prove to be enough in certain cases.

More precise linearization solutions are represented by integrated circuits containing instrumentation amplifiers and thermocouple cold junction compensators. Such a circuit, built by Analog Devices Corp, is AD8495, shown in figure 26 on a breakout provided by Adafruit.

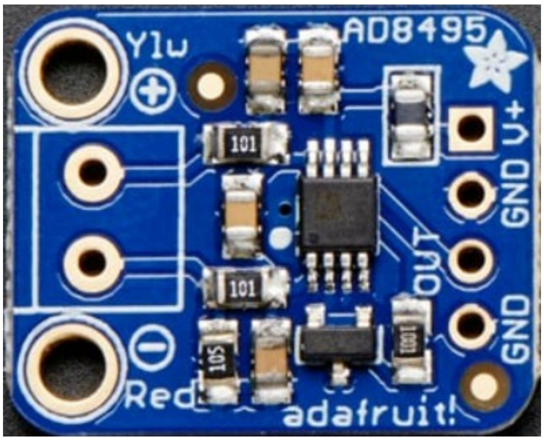

Figure 26. Adafruit breakout with AD8495 IC.

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2.7 Isolation

Signal conditioning by **isolation** is used when the signal has to be passed further in the measuement system without a physical connection, either for avoiding the electrical noise which may appear in the connection lines, or for protecting the next components from potential damaging perturbations.

Most used solutions consist either of a magnetic isolation, which converts the signal into a magnetic field which is further transmitted in the measurement system, or of an optical isolation, which is modulating an electronic signal using the sensor's signal to be transmitted. In both cases, magnetic or optical signals have to be decoded and transformed back into electrical signals, before being passed to the analog-to-digital converter.

Magnetic isolators for analog signals, called **transformers**, consists of two coils which are magnetically coupled using an iron core (figure 27). Transformers are very well avoiding energy spikes, but low-frequency energy increases are harder to be filtered, because transformers are working in the AC domain, so DC analog voltages cannot be isolated. The same principle of transmitting the energy through a magnetic field is also used in current transducers, when the amplitude of the measured signal (current intensity) is very high. The **current transducers** (figure 28)are containing only the secondary circuit, the primary circuit being represented by the wire in which the current has to be measured.

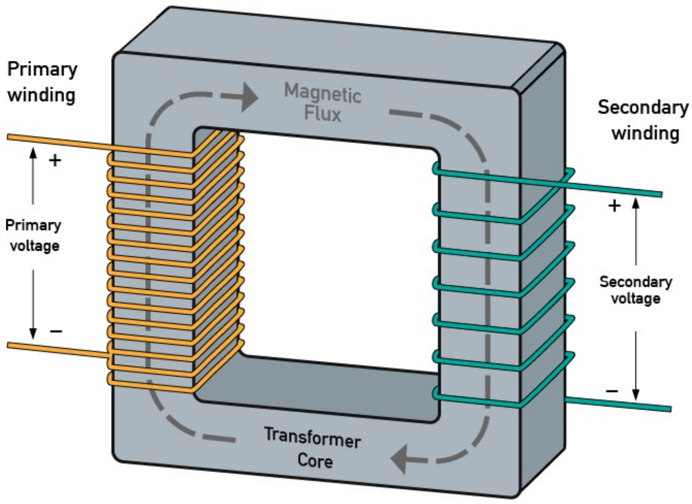

Figure 27. Current transformer.

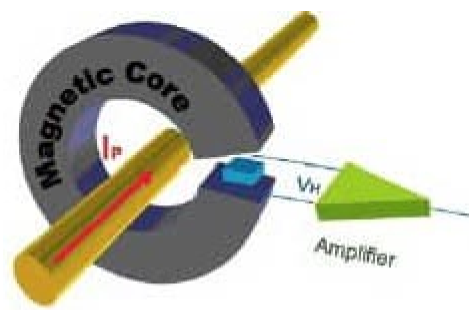

Figure 28. Current sensor.

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For isolating digital signals, **optical isolators** are mainly used, consisting in a LED and an optical sensor (a photoresistor, a photodiode, a phototransistor, a silicon-controlled rectifier (SCR) or a triac.), both working in the infrared domain (figure 29).

The LED converts the electrical signal input into light, while the photosensor detects the light and converts it back into an electrical singal.

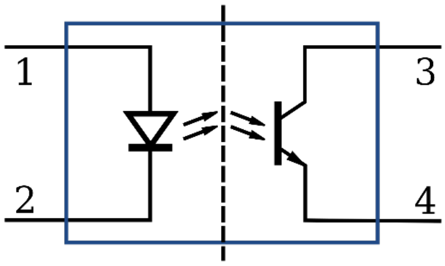

Figure 29. An optoisolator diagram

The same principle is used in the solid-state relays, where the photosensor is replaced by a pair of MOSFETs (metal–oxide–semiconductor field-effect transistor) which are opening or closing an electric circuit.

A method for **isolating DC analog signals** consists in first converting the analog signal to a digital pulse width modulation (PWM) signal, whereby the duty cycle of the PWM represents the analog value. This PWM signal, being digital, is then isolated using an optoisolator and the output of the optoisolator is then converted back into an analog signal using an RC circuit [5].

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3 Analog-to-digital converters

An **analog-to-digital converter (ADC)**, as its name suggests, is converting an analog signal into a digital one. It is an integrated circuit whose very simplified block diagram is looking like in figure 30.

The analog signal input has to be contained in a certain interval, named ADC's **measurement range**.

The number of bits on which the ADC is outputting the voltage value is called **resolution**.

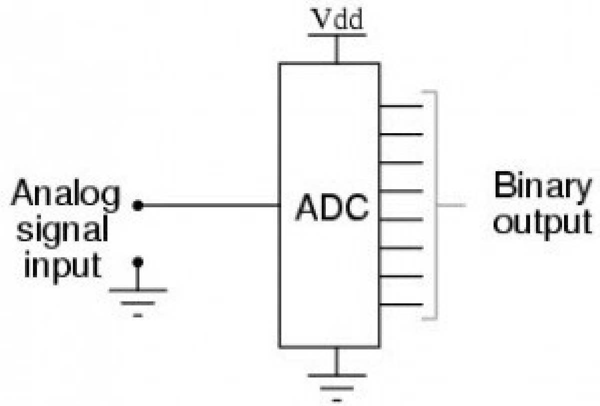

Figure 30. An ADC's diagram

A value belonging to the measurement interval can be expressed in digital format using only the number of bits represented by the resolution (let's call it **N**), which means that the ADC is dividing the measurement interval into 2^N subintervals. As an example, in figure 31 it is represented the conversion of a sinusoidal signal in the [0, 10] Volts interval, using a three bits ADC. The ADC is dividing the [0, 10] Volts interval into eight subintervals, each 1.25 Volts high. The amplitude of one subinterval represents the ADC accuracy, the precision with which the ADC can transform the analog input into a digital value.

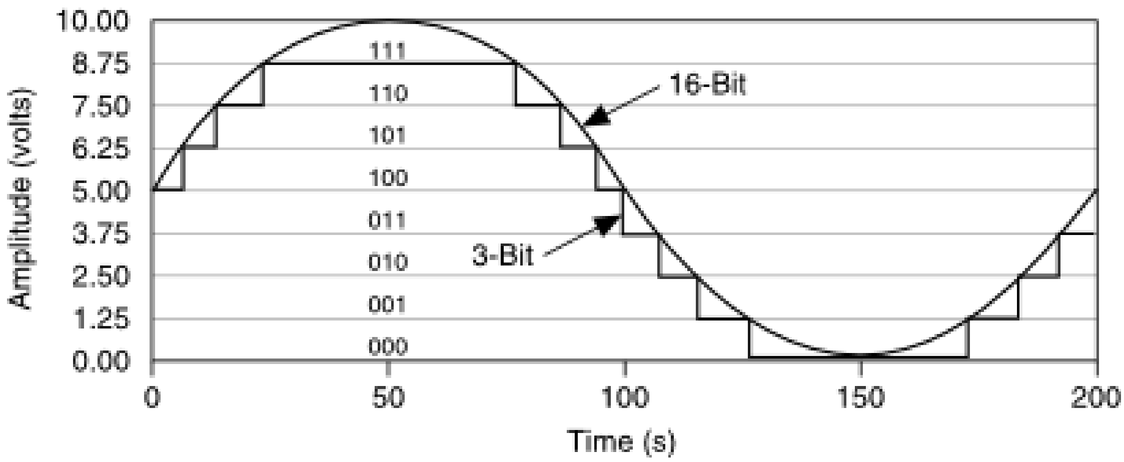

Figure 31. Dividing the measurement interval.

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An input voltage between 0 and 1.25 V will be represented as 0, between 1.25 and 2.5 V as 1, between 2.5 amd 3.75 V as 2 and so on. It is clear that the measurement interval and the resolution are directly determining the accuracy of the ADC: when the measurement interval is larger, for the same resolution, the accuracy is lower and when the resolution is increasing, for the same amplitude of the measurement interval, the accuracy is higher.

The measurement interval of an usual ADC is tipically between -10 and 10 V or sometimes between -5 and 5 V. Advanced ADCs has configurable measurement intervals, going down to [-0.1 … 0.1] V.

A low performance ADC has a resolution of 10 bits. Measuring with this resolution in a [0 … 5] V interval will allow a maximum accuracy of $5 / 2^{10} =$ 4.88 mV. Measuring with a high performance ADC, with a resolution of 16 bits, in the [-0.1 … 0.1] V interval, will provide a maximum accuracy of 3.05 μV, which is 1,600 times more precise.

For performing the conversion, an ADC is repeatedly increasing an internal voltage and is comparing this with the voltage to be converted, till these two voltages are falling in the same subinterval (figure 32). While increasing and comparing, the ADC is counting the number of increasing steps, each step having an amplitude equal to the ADC's accuracy.

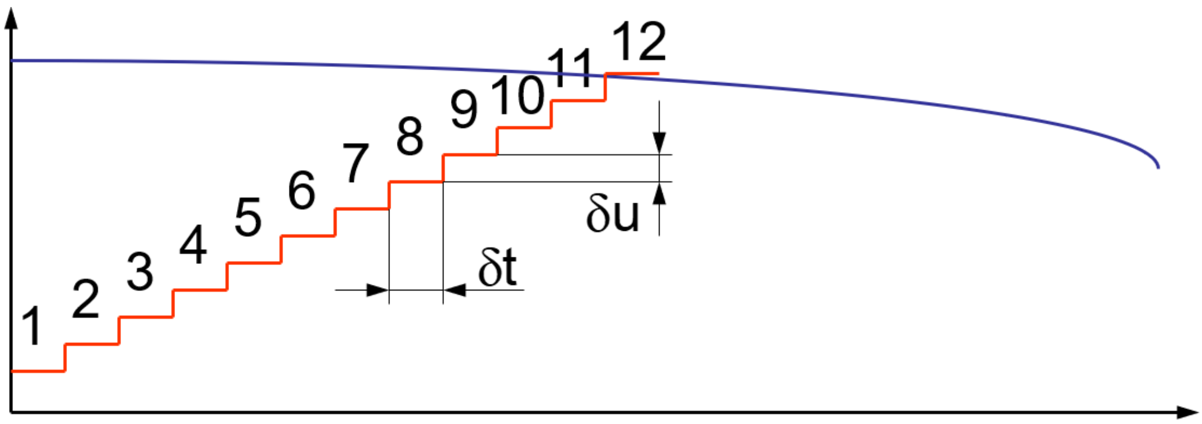

Figure 32. Performing the comparison for conversion.

It is clear that the ADC needs a certain time for performing one conversion, and the number of conversion which can be performed in one second is called the **scan rate**. Usual ADC scan rates are from 10 kHz, for cheaper solutions, up to several MS/s (mega samples per second).

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4 Summary

A **measurement system** is a set of devices, apparatus, equipments etc, used for extracting information from a process and to pass that information further. In most cases, information reffers to the values of one or more physical quantities: mechanical, thermical, electrical, chemical, optical etc. As information can not be transmitted without a transfer of matter and without an energy transfer, some material connection has to be established between the observed process and the measurement system. This material connection does not necessarily has to be thought as a mechanical one. Matter means also electrons or photons, so this connection could also be in the form of an electro-magnetical wave, either radio, infrared or visible light. For a connection to exist, some part of the measurement system has to be in contact with the observed process. In figure 2, this component is described as the **sensor**.

When interacting with the observed process, some sensors are changing some of their parameters without generating any amount of energy. These are called **parametric (passive) sensors**. Another category of sensors are those which are generating a certain amount of energy when interacting with the observed process. These are called **generative (active) sensors**.

Discussing only about electrical parameters based sensors, parametric sensors can be further classified, according to the variable parameter, in **resistive** (strain gages, Resistance Temperature Detectors etc) **capacitive** (e.g. proximity sensors, MEMS accelerometers etc) and **inductive** sensors (proximity sensors, LVDT sensors etc). Generative (active) sensors are usually classified according to the physical quantity they are measuring: thermocouples, piezorezistive pressure sensors, accelerometers, piezoelectric temperature sensors, photodiodes, photodetectors, rotary encoders etc).

Signal conditioning represents the transformation of an analog signal in such a way that this becomes compatible with the next components of the measurement system. Extracting only the useful part of one signal also represents a category of signal conditioning. There are many types of signal conditioning operations, depending on the sensor's type, signal's type or on the requirements of the measurement system.

An **analog-to-digital converter (ADC)**, as its name suggests, is converting an analog signal into a digital one.

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