Use of Ambient vibration testing digital systems in the analysis of the Emergency Limit Conditions of the Strategic Public Buildings

Deliverable number 4.2.1

Project Acronym	Firespill
Project ID Number	10255377
Project Title	Fostering Improved Reaction of crossborder Emergency Services and Prevention Increasing safety LeveL
Priority Axis	Safety and resilience
Specific objective	2.2 - Increase the safety of the Programme area from natural and man-made disaster
Work Package Number	4.2
Work Package Title	JOINT EVALUATION OF THE PILOTS WITH DEFINING TRANSFERABILITY OPTIONS & FOLLOW-UP INTERVENTIONS
Activity Number	4.2.1
Activity Title	Report on Use of ambient vibration testing digital systems in the analysis of the Emergency Limit Conditions of the SPBs
Partner in Charge	Consorzio Punto Europa (PP2)
Partners involved	Consorzio Punto Europa (PP2)
Status	Final
Distribution	Public
Authors	L'Aquila University Laboratorio di Dinamica delle Strutture "Francesco Benedettini": Prof. Daniele Zulli Prof. Rocco Alaggio Ing. Andrea De Flaviis
Date of release:	26/06/2023

Sommario

1. Motivations and Organization

The primary objective of this work is to illustrate the current state of the art in commercially available sensor technology, which is useful for structural monitoring in the field of civil engineering. It provides an overview of the technical characteristics of various devices, their areas of application, and the advantages and disadvantages of their use, with the aim of giving the reader greater awareness in choosing the most suitable type of sensor for their specific needs. The report does not claim to be exhaustive nor to provide detailed information on the functioning of each sensor, as these technical formalities should be further investigated on a case-by-case basis.

After a brief introduction, which lists the various types of sensors and highlights the most commonly used ones, the report reviews the various devices according to a standard format. This format includes a brief history and a general explanation of how each sensor works, providing basic information useful for understanding their characteristics.

The fields of application are then listed, both within civil engineering and, occasionally, in other fields. Some specifications are also provided, which can be used to understand the technical datasheets and the actual range of use. General price indications are given, along with a final comment on the possible advantages and disadvantages of each device.

After listing and describing the various types of sensors, the conclusions are drawn, providing insights into which types of sensors are actually usable in various civil engineering applications, with a particular focus on seismic monitoring of structures.

Finally, there is a brief section on data acquisition, transmission, and processing systems, which are also considered fundamental within a monitoring system.

At the end of the work, a bibliography is provided, divided into scientific articles, websites, and technical datasheets consulted for the preparation of this report. This allows the reader to delve deeper into certain aspects of interest.

2. Introduction

The main components of a monitoring system are: sensors, data acquisition systems, data transmission, data processing and management, to which diagnostic and alarm systems are added [1][2]. An example is shown in Fig. 1.

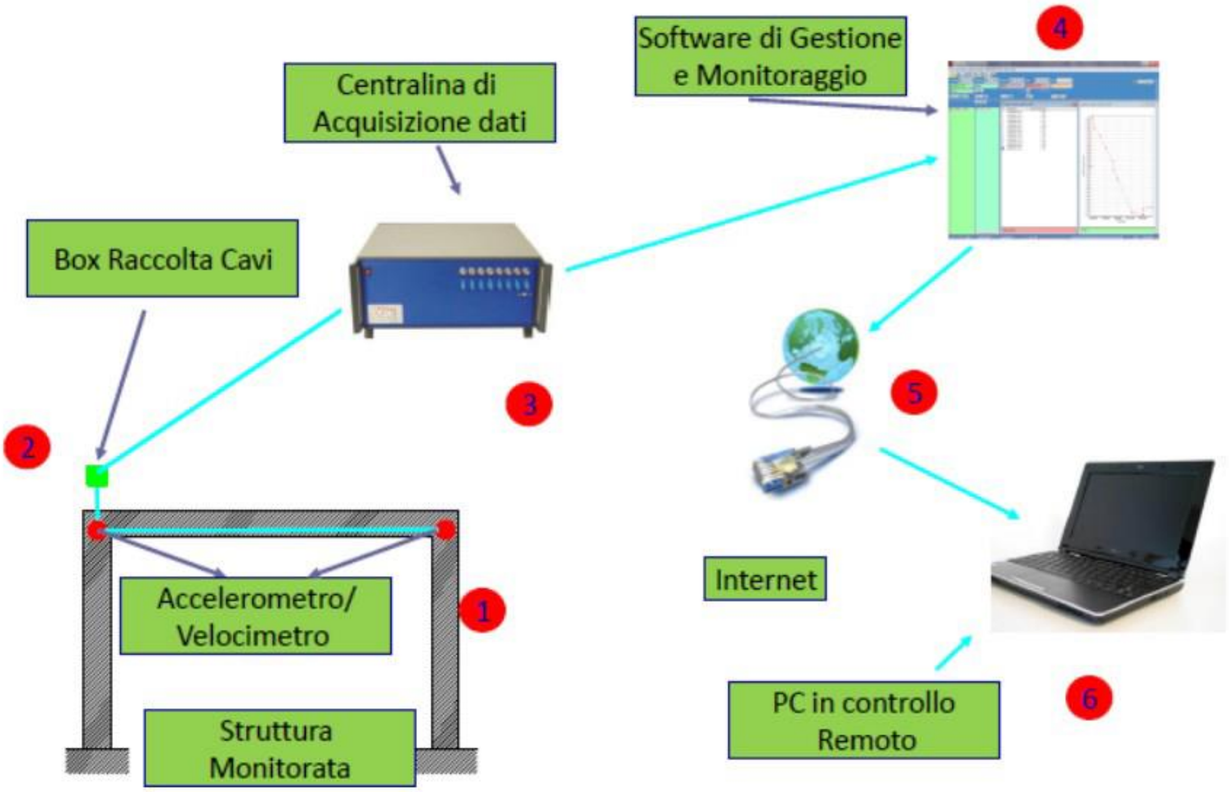


Fig. 1 – Esempio di schema di monitoraggio strutturale (credit: webthesis.biblio.polito.it)

Regarding the sensors/devices currently in use, which are necessary for detecting the quantities of interest, the most commonly used traditional sensors in structural monitoring are strain gauges, accelerometers, velocimeters, geophones, inclinometers, and displacement transducers. Among the more recent ones, the so-called smart sensors include fiber optic sensors, sensors based on MEMS technology, and GNSS systems (including GPS).

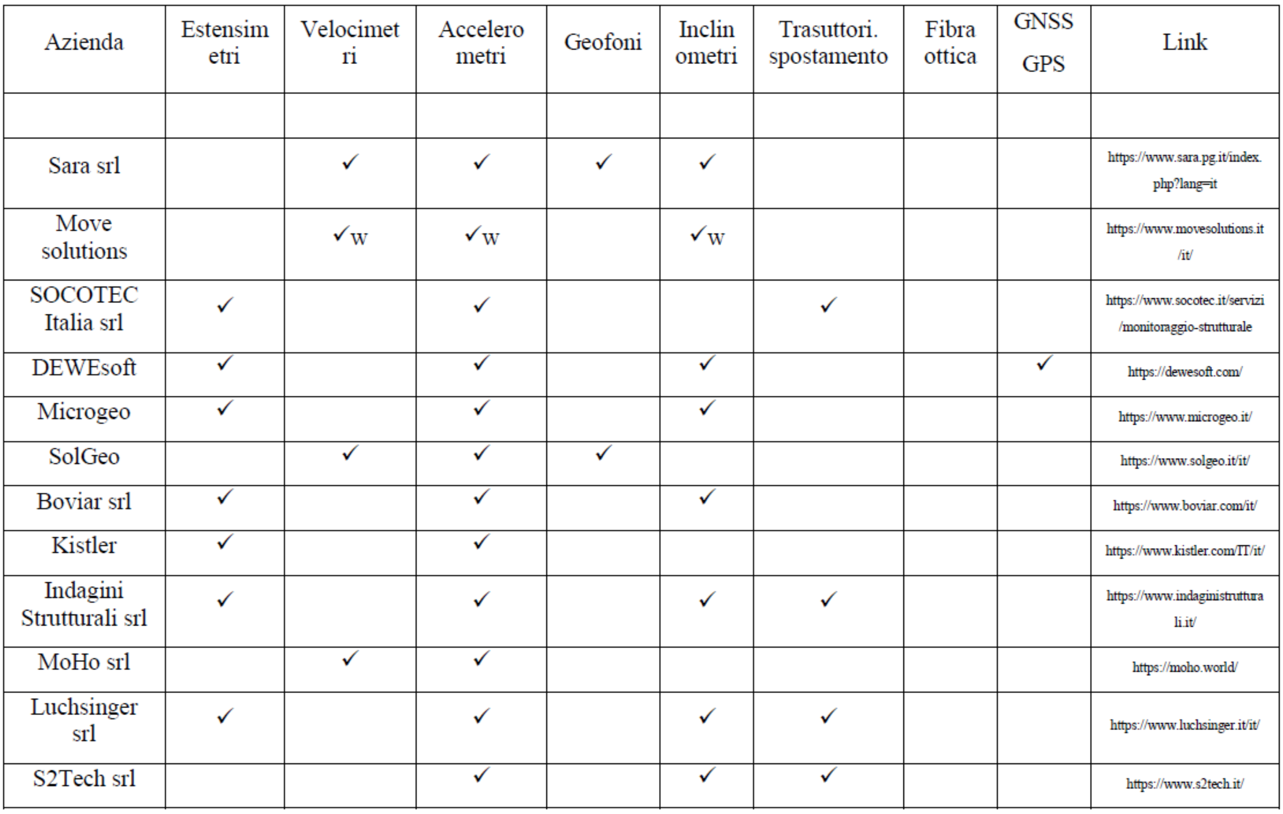
Table 1 below, created by consulting the online sites of several companies, provides an initial, albeit not exhaustive, idea of the most widely sold and thus currently employed structural monitoring devices in Italy (w = wireless).

In particular, from the companies consulted, the most prevalent devices are accelerometers (mostly wired), followed by strain gauges and inclinometers. Additionally, many companies offer geophones (and velocimeters in general) and displacement transducers. The more recent systems based on fiber optics and GPS devices are rarer, but as previously mentioned, this data pertains exclusively to the companies considered. Given the rather limited number, they cannot provide a comprehensive picture of the situation, as there are companies specializing solely in these technologies that were not taken into account.

Notes for the subsequent chapters:

The information reported in the "CHARACTERISTICS" section has been taken from the technical datasheets of multiple manufacturers, so it should be considered representative of the type of device that reflects all the technical characteristics listed in that section.

Regarding the prices of the devices, they refer to the period when this document was produced and are indicative. They are intended solely to provide a range and should not be taken as fixed prices. Additionally, the cost of acquisition, transmission, and processing systems must be added, as indicated in the dedicated chapter.



Azienda	Estensimetri	Velocimetri	Accelerometri	Geofoni	Inclinometri	Trasuttori. spostamento	Fibra ottica	GNSS GPS	Link
Sara srl		✓	✓	✓	✓				https://www.sara.pg.it/index.php?lang=it
Move solutions		✓w	✓w		✓w				https://www.movesolutions.it/it/
SOCOTEC Italia srl	✓		✓			✓			https://www.socotec.it/servizi/monitoraggio-strutturale
DEWEsoft	✓		✓		✓			✓	https://dewesoft.com/
Microgeo	✓		✓		✓				https://www.microgeo.it/
SolGeo		✓	✓	✓					https://www.solgeo.it/it/
Boviar srl	✓		✓		✓				https://www.boviar.com/it/
Kistler	✓		✓						https://www.kistler.com/IT/it/
Indagini Strutturali srl	✓		✓		✓	✓			https://www.indaginistrutturali.it/
MoHo srl		✓	✓						https://moho.world/
Luchsinger srl	✓		✓		✓	✓			https://www.luchsinger.it/it/
S2Tech srl			✓		✓	✓			https://www.s2tech.it/

Table 1 – Devices Sold by Some Consulted Companies

3. Strain Gauges

Sources: [3][4][30]

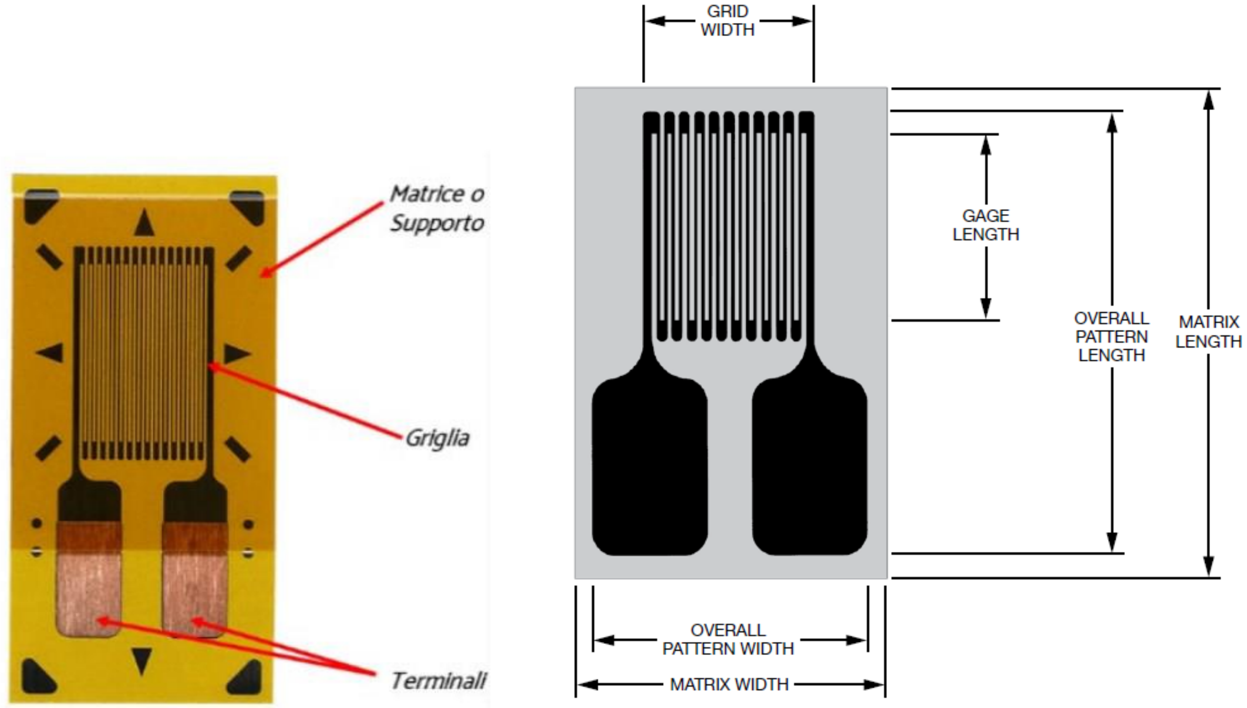


Fig. 2 – Strain Gauge (credit: LUCHSINGER)

HISTORY: From the second half of the 17th century—but more extensively from the late 19th century—strain gauges were developed with amplification mechanisms using micrometer screws, levers, and lever systems (mechanical or optical), gears, and other systems. Subsequently, from the late 1930s, electrical resistance strain gauges became prominent.

FUNCTIONING: Traditional strain gauges (electrical resistance) provide local deformation measurements via electrical signals. They are glued to the surface of a structure, measuring deformation when the structure is subjected to forces. The strain gauge can be considered a resistor whose value changes due to deformation. They are also known as strain gauges. To measure the change in resistance, which provides the deformation value since the resistance is proportional to elongation, a Wheatstone bridge circuit, consisting of multiple resistors, is used. By replacing one or more of these resistors with strain gauges, specific measurement circuits are obtained.

There are also strain gauges with more than one sensor, capable of measuring deformation in multiple directions simultaneously. These are generally referred to as strain gauge rosettes and are available in various geometries for different applications.

Not all strain gauges are like the aforementioned (electrical resistance); there are more recent devices such as laser, wireless, and fiber optic strain gauges, for which extensive documentation exists.

APPLICATION: Their use is vast and spans various sectors, including industrial applications (weighing systems, testing rotating parts, wind turbine tests), aerospace (monitoring deformation and stress of components), automotive (during crash tests, airbag deployment), railways (track condition monitoring), civil engineering (measuring deformation, crack opening), medical (multiple applications), and domestic (scales, appliances).

CHARACTERISTICS: Nominal resistance: 120/350/1000 Ohms; gauge length: 0.6-200 mm; strain range: ±3%/±5%; sensitivity (Gauge Factor): 2.0-4.0; temperature range: -269°C to 300°C.

PRICE: On average, from a few euros to a few tens of euros per piece. Some cost between 100 and 150 euros per piece.

PROS: High measurement accuracy, wide measurement range, small size, low cost, well-known and established technology, stable performance over time.

CONS: They can accurately detect damage only within their range of influence; they are affected by environmental conditions, such as temperature variations and electromagnetic interference.

4. Accelerometers

Sources: [3][5][12][23]

Fig. 3 – MEMS Triaxial Accelerometer (credit: Boviar)

HISTORY: Here are some historical highlights from 1920 onwards, derived from [5]. The first accelerometer used in civil and industrial fields dates back to 1923. It was made with an E-frame and carbon rings in a half Wheatstone bridge configuration. The first biaxial accelerometer appeared in 1936. The large-scale development of accelerometers began in the late 1930s with the invention of strain gauges. The first accelerometers were indeed strain gauge-based, mostly used in aeronautics, and from there, their development continued steadily.

From the 1950s, piezoelectric accelerometers were introduced to address transient response issues present in earlier models, also featuring higher resonance frequencies (ranging from about 200 to 10,000 Hz). Since the 1990s, digital electronic systems have become widespread, laying the groundwork for the development of MEMS (Micro Electro-Mechanical System) technology.

NOTES: Accelerometers are essential for gathering information on the dynamic behavior of structures. They can measure acceleration in 1, 2, or 3 orthogonal directions.

Currently, in addition to the long-used devices, wireless devices have been introduced to overcome some limitations of electrical sensors, albeit with the disadvantage of being susceptible to electromagnetic interference. Consequently, further accelerometers based on GPS, GNSS systems, and other MEMS types have been developed.

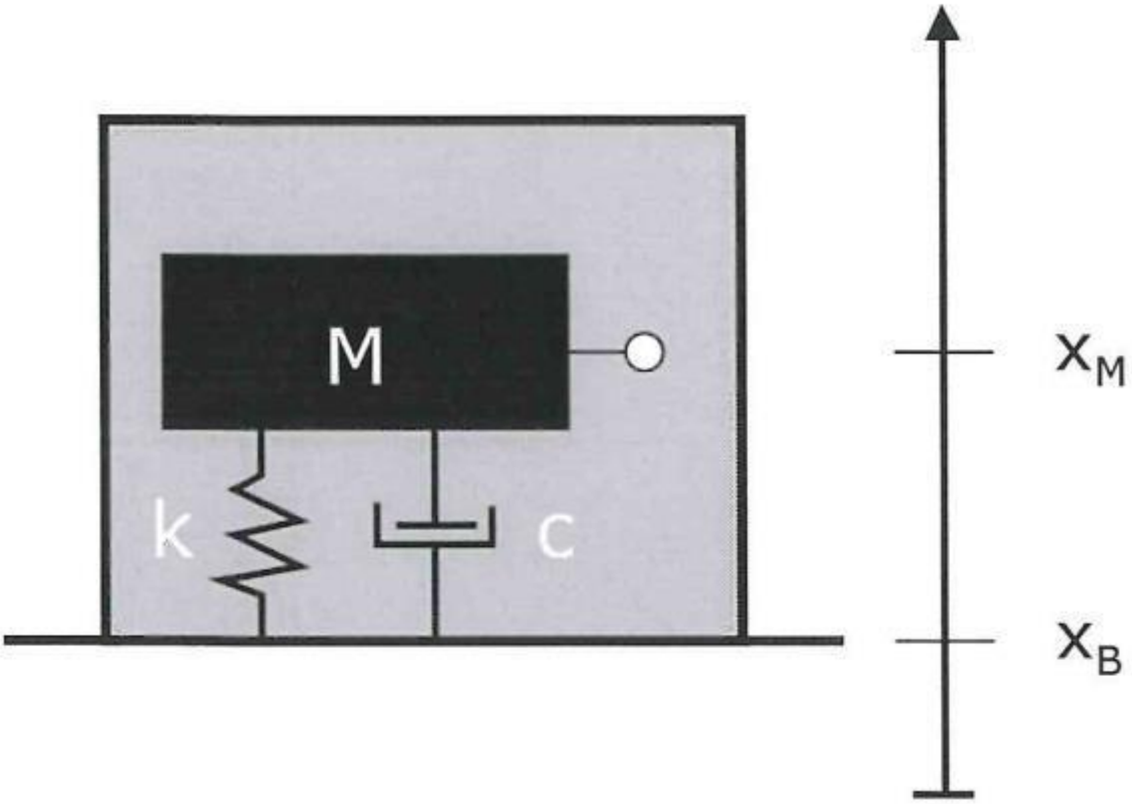


Fig. 4 – Schematic of an Accelerometer (credit: M. De Cecco Lucidi from the Mechanical and Thermal Measurements I course)

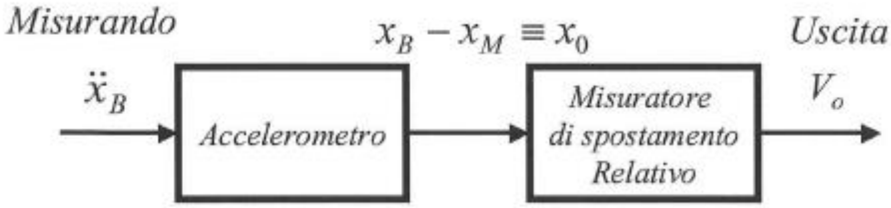


Fig. 5 – Input-output of an Accelerometer (credit: M. De Cecco Lucidi from the Mechanical and Thermal Measurements I course)

The operation of the device is based on detecting the inertia of a mass when subjected to acceleration: what is measured is the displacement of the mass, and what is returned as output is an electrical signal. As illustrated in Fig. 4, the mass is connected to an elastic spring, a damping element, and a sensor that detects its relative displacement with respect to the fixed structure of the device. When the mass experiences acceleration, it moves from its rest position proportionally to the detected acceleration. The sensor's task is to transform the measured displacement of the mass into an electrical signal that is acquired. For this reason, it is correct to say that the accelerometer is a transducer, as it converts a mechanical quantity into an electrical one.

Among the characteristics that identify these devices and can guide their selection, the following are highlighted:

- Frequency measurement bandwidth (measured in Hz)
- Damping factor (whose value for maximum bandwidth is 0.67, emphasizing the importance of the damper)
- Inertial mass weight (which should be small compared to the structure being measured)
- Nominal sensitivity (measured in mV/g for analog sensors, indicating the output voltage generated by a certain force, and in LSB/g for digital sensors, where g is the acceleration due to gravity and LSB stands for Least Significant Bit)
- Cross-axis sensitivity (indicating sensitivity to transverse vibrations, which should be small compared to the sensitivity of the main axis)
- Non-linearity (measured as a percentage of the full-scale output, indicating how much the sensor's sensitivity varies with changes in excitation amplitude)
- Full scale (measured in g, the maximum value of measurable acceleration)
- Output (measured in volts for analog sensors)
- Dynamic range (measured in dB, indicating the logarithmic scale ratio between maximum value (full scale) and minimum value (background noise))
- Degree of protection (IP index for dust and liquid)

- Tolerated humidity and temperature levels
- Resolution (measured in µg for analog sensors and in mg/LSB or mg/digit for digital ones, indicating the accuracy of the output, particularly the smallest measurable acceleration variation)
- Spectral noise density (measured in µg/√Hz, representing the power of the system noise (Analog to Digital Converter + analog conditioning) distributed in the band and indicating the influence of noise at various frequencies, which decreases as frequency increases: integrating it into the band of interest yields noise in terms of RMS – Root Mean Square)
- Alternatively, spectral noise (measured in µVrms).

Among classic technology accelerometers, they are classified based on how the mass displacement is detected: strain gauge, capacitive, piezoelectric, Force Balance, and LVDT accelerometers. Among MEMS technology accelerometers, there are capacitive and piezoresistive ones. Laser-type accelerometers also exist, but documentation for these is available separately.

Another general classification is based on output: analog accelerometers and digital ones. Analog ones output a continuous voltage proportional to acceleration (e.g., 2.5 V for 0 g, 2.6 V for 0.5 g, 2.7 V for 1 g). A problem with these devices is noise on the outputs, even at rest; mathematical functions such as the Kalman filter are used to reduce it. Digital ones use pulse width modulation (PWM), meaning the output is represented by a square wave of a certain frequency, and the time during which the voltage is high is proportional to the amount of acceleration.

Lastly, it should be noted that the accelerometer, like other sensors, can have an AC (alternating current) or DC (direct current) response. The former is not particularly suitable for measuring static acceleration like gravity, constant acceleration, or centrifugal acceleration but only dynamic events. The latter can successfully measure both static and dynamic acceleration. Below are the main characteristics of the various types of accelerometers, primarily distinguished based on the sensor's operation.

4.1. Strain gauge accelerometers

OPERATION: The operation is similar to that already seen for the electrical resistance strain gauge. The mass is suspended on thin sheets, to which strain gauges connected to a Wheatstone bridge are fixed. In the presence of acceleration, the mass moves, bending the sheets, and consequently, the strain gauges undergo elongation. Through a voltmeter, it is possible to read an unbalance voltage of the Wheatstone bridge proportional to the acceleration.

APPLICATION: It is widely used in the automotive field to ensure optimal vehicle performance, for example, in the anti-lock braking system, airbags, and traction control system. On the other hand, low-frequency strain gauge accelerometers are used in industrial applications and laboratories.

FEATURES: DC type, Number of axes from 1 to 3, measuring bandwidth up to 500 Hz, damping 0.70, nominal sensitivity nr mV/g, transverse sensitivity between 3% and 5%, non-linearity 1%, full scale up to ±50 g, output up to ±5 V, IP67 protection degree, temperature range from -50°C to 150°C, resolution nr, spectral noise density nr.

PROS: High accuracy and reliability (ideal for precision applications), wide frequency range (useful for various applications), compact size, low power consumption.

CONS: Higher cost compared to other technologies.

4.2. Capacitive accelerometers (and MEMS capacitive)

OPERATION: The capacitive accelerometer exploits the variation of the electrical capacity of a capacitor as the distance between its plates changes. The seismic mass (made of conductive material) constitutes one plate, while the other is made on the fixed structure of the device, near the mass. The mass is suspended on a relatively rigid elastic element (typically a membrane). The current generated by the two plates (device + conductive mass) varies the voltage (electrical capacity), and hence the distance. From the detection of electrical capacity, the device deduces the mass displacement and generates a proportional electrical signal.

In recent years, capacitive accelerometers have been made in MEMS technology, born with the aim of reducing size and costs. Typically, when MEMS accelerometers are referred to, capacitive ones are implicitly meant, not piezoresistive ones. In this case, the individual plates are comb-shaped to increase the capacity value, allowing the realization of a differential capacitor that allows, in the first approximation, to linearize the relationship between the plates' displacement. The mass position is directly proportional to the acceleration.

APPLICATION: Widely used, both in common applications such as airbags and mobile devices (for example, smartphones), and for civil structure monitoring.

FEATURES: DC type, Number of axes mainly 3, measuring bandwidth typically up to 500 Hz but also higher, damping 0.70, nominal sensitivity up to 4000 mV/g, transverse sensitivity between 1% and

3%, non-linearity between 0.1% and 0.5% of FS, full scale usually up to ±200 g, output up to ±8 V, IP67 protection degree, temperature range from -55°C to 125°C, resolution up to about 1 μg, spectral noise density generally < 25 μg/√Hz (not specified at which frequency level).

PROS: Reduced size and cost (for MEMS), good for measuring low-frequency vibrations and constant accelerations (being DC type), easy to integrate into other systems, good linearity, high stability of the output signal.

CONS: Low signal-to-noise ratio, bandwidth limited to a few hundred Hz (sufficient range in civil engineering), maximum acceleration levels generally less than 200 g.

4.3. Piezoelectric Accelerometers

OPERATION: Piezoelectric accelerometers utilize the electrical signal generated by pressure applied to a piezoelectric crystal (typically lead zirconate titanate PZT) as the principle for detecting mass displacement. In these accelerometers, the mass is suspended on the piezoelectric crystal, which serves as both the sensor and the elastic element. When subjected to acceleration, the mass compresses the crystal, generating an electrical signal proportional to the compression (or other stresses depending on the operation).

In practice, when the crystal is stressed, a charge migration occurs, which, through the circuit in which the crystal is inserted, translates into a voltage that is measured. A distinction is made between:

- high-impedance measurement chain (a property indicating how "impeded" the passage to alternating current is in a circuit, measured in the ratio of voltage to current; in a direct current circuit, it coincides with resistance), when the accelerometer has a charge output and the circuit is external to the accelerometer, inside a charge amplifier connected in series with it;
- low-impedance measurement chain, when the accelerometer has a voltage output and the electronic circuit is integrated into the transducer, without an external preamplifier. Examples of low-impedance chains are ICP (Integrated Circuit Piezoelectric) and IEPE (Integrated Electronics Piezo-Electric) accelerometers, among the most common.

Due to the presence of the crystal, these accelerometers have particular characteristics, such as low sensitivity (indicated by Sq and expressed as the amount of charge generated per unit of acceleration, or indicated by Sv and expressed as the voltage generated per unit of acceleration), the ability to detect exceptional accelerations without damage due to the high stiffness of the crystal, the inability to detect constant accelerations over time (as if the compression on the crystal persists, the generated signal tends to dissipate after a short period, a phenomenon known as leakage), and the high value of the material's elastic constant.

APPLICATION: The predominant use of these accelerometers concerns the measurement of short-duration impulses, for example, in laboratories or to measure dynamics following impacts, detonations, or combustions (also in aerospace).

FEATURES (IEPE): AC type, Number of axes mostly 3, measuring bandwidth also beyond 20,000 Hz, damping nr, nominal sensitivity 10-100 mV/g, transverse sensitivity between 25% and 5%, non-linearity ±1 of FS, full scale also up to ±2000 g, output ±5 V, IP68 protection degree, temperature range from -50°C to 120°C, resolution in the order of hundreds of µg, spectral noise density around hundreds of µg/√Hz at 1 Hz frequency.

PRICE: Average cost from around €500/600 for triaxial piezoelectric accelerometers and upwards.

PROS: Ability to investigate wide frequency ranges (from 1 Hz to tens of thousands of Hz), wide dynamic range, good linearity, possibility of use in various hostile environmental conditions, no need for power supply, compact size, robustness and resistance to high stresses, low noise level in the signal, wide range of sensors given their high popularity, wide temperature range (between -200°C and +400°C for accelerometers with charge output).

CONS: Inability to measure static accelerations, low sensitivity, susceptibility to electromagnetic noise, maximum operating temperature limited for accelerometers with voltage output to about 125°C.

4.4. Piezoresistive MEMS Accelerometers

OPERATION: This type of accelerometer is a variant of the strain gauge accelerometer, in which piezoresistive sensors are used to detect resistance changes. These sensors behave similarly to strain gauges but with greater elongation and sensitivity, despite some stability issues with temperature variation. Often, the mass is suspended on a plastic membrane, to which the piezoresistive elements are attached.

APPLICATION: Typical applications are similar to those of piezoelectric accelerometers, given their similar characteristics.

FEATURES: DC type, Number of axes from 1 to 3, measuring bandwidth up to 40,000 Hz, almost negligible damping except in cases where gas or fluid damping is introduced, nominal sensitivity proportional to excitation voltage, transverse sensitivity less than 3%, non-linearity between ±1% and ±3% of full scale, full scale up to ±6000 g, output nr V, IP67 protection degree, temperature range from -55°C to 125°C, resolution nr, spectral noise typically < 10 µVrms (not specified at which frequency).

PRICE: Not specified.

PROS: High bandwidth, compact size, very high natural frequencies (no resonance issue), low power consumption.

CONS: Without any intentional damping, the material is solely responsible for energy dissipation, with very low damping values (0.01), although gas or fluid damping can be used, low sensitivity, sensitive to temperature variations, higher cost compared to capacitive MEMS.

4.5. Force Balance Accelerometers (Servoaccelerometers)

OPERATION: These force balance accelerometers utilize the principle of feedback and function like a galvanometer, the instrument that measures the intensity of electric currents in a circuit. More precisely, they operate like a Deprez-D’Arsonval galvanometer, with a movable coil suspended by a torsion wire around a fixed magnet. When the magnet, carrying an electric current, generates an electromagnetic field, the coil polarizes by induction and is subjected to two balancing forces: one that rotates it and another elastic force due to the torsion of the wire that keeps it still. In practice, it's as if the spring of a conventional accelerometer were replaced by an "electrical" spring. The equilibrium point of these two forces (which do not cancel each other out) is the angle of rotation, proportional to the current being measured. The signal is then electronically processed and transmitted at low frequency. The device operates as a closed loop.

Given their functioning, it's evident that they have been developed for applications requiring greater accuracy compared to instruments using mechanical spring transducers for force and displacement.

APPLICATION: Due to their characteristics, they can be used in aerospace, industrial, automotive, or vibration monitoring applications. They are particularly useful in civil structural monitoring due to their accuracy at low frequencies.

FEATURES: DC type, Number of axes from 1 to 3, measuring bandwidth up to 200 Hz, damping 0.70, nominal sensitivity up to 5000 mV/g, transverse sensitivity less than ±1%, non-linearity less than ±0.5% of full scale, full scale typically up to ±5 g, output typically up to several tens of volts, IP68 protection degree, maximum temperature range from -40°C to 80°C, resolution up to approximately 1 µg, spectral noise between tens and thousands of µVrms.

PRICE: Approximately: single-axis 900 €, dual-axis 1500 €, triaxial 1700 €.

PROS: High linearity, wide dynamic range, absence of hysteresis behavior in the spring, good sensitivity, low noise, no damping-related issues, robustness, and durability.

CONS: Sensitivity to high levels of noise and vibration (due to the presence of various mechanical components), sensitivity to temperature variations, larger dimensions, higher cost compared to other devices, not suitable for high-frequency measurements.

4.6. LVDT Accelerometers

OPERATION: This type of accelerometer utilizes an LVDT (Linear Variable Differential Transformer) sensor integrated into the structure of the accelerometer itself to detect the displacement of the mass. The mass itself serves as the ferromagnetic core of the LVDT sensor and moves (suspended on springs or other elastic elements) within a channel around which coils are wound to detect the position of the mass. A dedicated circuit detects the position of the core relative to the coils and generates an electrical signal proportional to the displacement from the rest position. The device operates as an open loop.

APPLICATION: While this type of accelerometer, once used, has now been largely replaced by Force Balance accelerometers, LVDTs can still be an alternative when accelerations are of the order of hundreds or thousands of g and the servoaccelerometer is not usable.

CHARACTERISTICS: Given the limited current use of the instrument, no information regarding its characteristics was found.

PRICE: Given the limited current use of the instrument, no pricing information was found.

PROS: Very high maximum accelerations, low power consumption, no need for electronics.

CONS: Requires additional setup, rather rare to find commercially, larger dimensions, sensitivity to temperature.

5. Velocimeters/Geophones

Sources: [6][7][12][17][18][36]

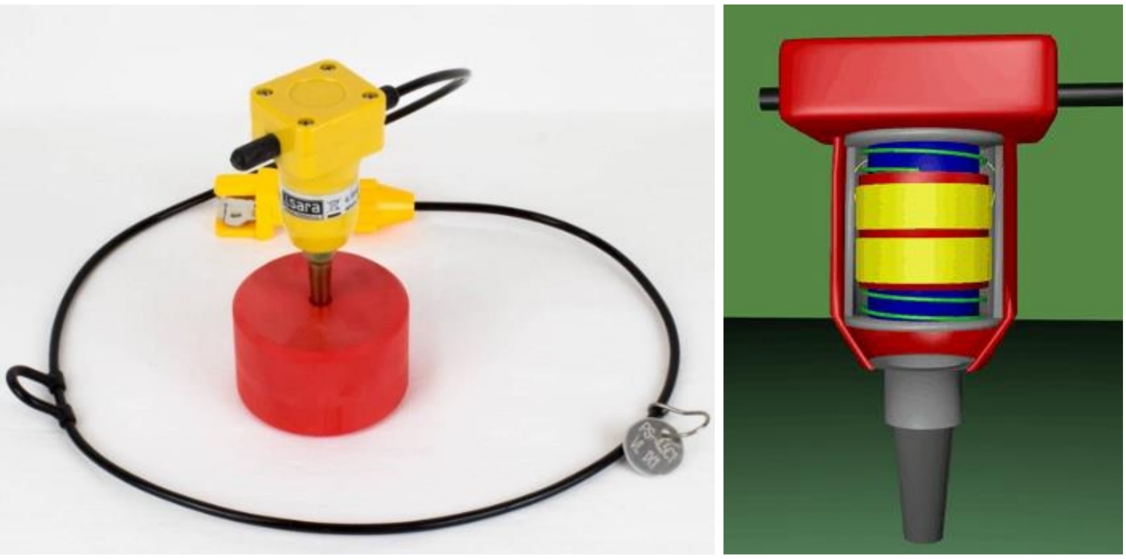


Fig. 6 - Geophone (credit: SARA Electronic Instrument and Studio Geologico Bellucci)

HISTORY: An ancestor of the geophone (made with bronze vessels that resonated due to air vibration) seems to have been invented by Trifon, a Greek architect who lived in the Hellenistic period, to detect the paths of enemy tunnels by perceiving the vibrations caused by pickaxe blows, as these devices were able to detect waves propagating in the ground. The same use was made during the First World War to detect the noise of enemy excavations and calculate their direction and speed of advance.

FUNCTIONING: Velocimeters differ from accelerometers in the type of measurement they provide, namely velocity instead of acceleration. The geophone is a velocimeter as it converts velocity into voltage and can be defined, in its classic sense, as a passive analog device that converts ground movements into electrical impulses. The classic geophone includes an inertial mass wrapped by a coil of conducting wire and suspended on springs free to move up and down around the field of a fixed permanent magnet attached to the container and thus anchored to the ground via a metal spike. Alternatively, bases are available for use on asphalt and other rigid substrates. In case of vertical stresses, the mass suspended on the springs does not move along with the rest of the geophone but remains still, while the magnet, integral with the housing and with the ground, oscillates up and down inside the coil fixed to the mass, thus generating an electric voltage proportional to the ground velocity. Inside, there is also a damper that prevents the coil from continuing to oscillate. A characteristic of these devices is that they can only monitor frequencies higher than their natural frequency (generally between 4 and 12 Hz), up to a certain frequency (even 500 Hz). Therefore, they may not be used in all applications, although through appropriate deconvolution of the signal, it is possible to study what happens at low frequencies below the natural one. Regarding the macro-category of velocimeters, there are several types, depending on how the displacement of the mass is detected, although piezoelectric and MEMS devices are predominantly found in the market.

USE: Speaking generally of velocimeters, they are used in seismic stations, often in combination with accelerometers, with the substantial difference that the velocimeter detects seismicity up to the smallest vibrations without being degraded by the instrument's intrinsic electronic noise, while the accelerometer is used to detect strong ground shaking without reaching signal saturation. Specifically, geophones are primarily used in active and passive geotechnical investigations, but are also used in seismic networks and structural monitoring, both in the context of operational modal analysis (OMA) and in monitoring induced movements. They can also be used to monitor movements and deformations of train tracks.

CHARACTERISTICS: Number of axes from 1 to 3, measurement band from 1 Hz (with appropriate operations) up to about 500 Hz (even up to a few thousand Hz for piezoelectric velocimeters), damping factor 0.70, nominal sensitivity about 25 mV/mm/s, transverse sensitivity between 2% and 5%, non-linearity between ±1% and ±5%, full scale up to 300 mm/s (up to 1200 mm/s for piezoelectric velocimeters), IP67 protection rating, temperature range from -40°C to 70°C, resolution up to about 0.01 mm/s, spectral noise density between hundreds and thousands of µmm/s/√Hz at 10 Hz.

PRICE: It depends on the type of velocimeter/geophone; however, for the same technology (piezoelectric, MEMS, etc.), the cost is lower than accelerometers.

PROS: Direct measurement of velocity in mm/s without conversions, excellent signal-to-noise ratio, good sensitivity, reduced cost, no need for power supply.

CONS: Limited frequency range, limited excursion of the coil due to the limited length of the system, i.e., mechanical saturation problem.

6. Inclinometers

Sources: [12][19][20][21][37]

Fig. 7 – Capacitive and wireless inclinometer (credit: LUCHSINGER)

HISTORY: This instrument has ancient origins: there are testimonies dating back to a Persian mathematician who lived in the 10th to 11th century; furthermore, Leonardo da Vinci himself invented a pendulum inclinometer (around 1500) to determine the inclination during flight relative to the horizontal. There are also testimonies related to Galileo Galilei (around 1600), while more recently, the invention of Abney's level dates back to the end of the 19th century.

OPERATION: Inclination sensors measure the inclination of a surface by monitoring its rotation. These sensors can be fixed or removable, monoaxial or biaxial (for roll and pitch), capacitive, servo inclinometers, electrolytic, MEMS, laser, with or without wires capable of measuring inclinations ranging from ±1° to ±360° in the case of some monoaxial inclinometers.

In capacitive inclinometers, there is a fluid that acts as the dielectric of a capacitor and the inclination of the sensor causes a variation proportional to the detected capacitance, which is then converted into an analog or digital signal. MEMS inclinometers are also capacitive, consisting of a small mass suspended by springs, and when the device tilts, the mass moves slightly, causing a capacitance variation between two electrodes, from which the inclination angle is calculated.

Servo inclinometers have a pendulum, whose movement depends on the force generated by the magnetic field, with intensity proportional to the inclination. There is another type, mechanical, consisting of mass, spring, and damper, whose operation is similar to a pendulum that moves from the equilibrium position due to the gravitational field.

In electrolytic inclinometers, there are electrodes and an electrolytic fluid (based on electrolysis, a process that uses electrical energy to induce chemical transformations). When the sensor tilts, the fluid remains horizontal, thanks to gravity. It is conductive, and the conductivity is proportional to the length of the immersed electrode. In short, the output voltage is proportional to the sensor's inclination.

Furthermore, it should be specified that inclinometers can be static or dynamic. The former might not be suitable in case of vibrations or sudden movements due to the presence of only structural damping, which generates disturbances only partially mitigated. Therefore, for applications requiring certain characteristics, dynamic inclinometers come into play, with a fast response and undisturbed output. These combine an accelerometer and a triaxial gyroscope internally to provide the inclination measurement quickly, compensating for the effects of acceleration.

Finally, there are systems based on laser inclinometers for distance measurements that include a distance laser sensor measuring the distance between itself and the target surface, an inclinometer (e.g., MEMS), and a control system (generally wireless).

APPLICATION: The applications are varied, ranging from leveling systems for campers, construction vehicles (e.g., cranes), antenna positioning, obviously in geotechnical monitoring (e.g., for inclinometric probes), and civil engineering (buildings, retaining walls, dams, towers), and in many other fields.

FEATURES: Number of axes 1 or 2, measurement range from ±1° to ±360° (monoaxial), from ±1° to ±90° (biaxial), non-linearity up to 0.1% FS, output from 0 V to 5V, degree of protection up to IP69, temperature range from -40°C to 85°C, resolution up to ±0.0001°.

PRICE: Depends on the type of inclinometer, as reported in the "PRO" and "CON" sections; approximately for biaxial MEMS around €500/600 per device.

PROS: Low cost (mechanical), low size and cost (MEMS), excellent accuracy (servo inclinometers), good accuracy and low cost (capacitive), high accuracy and low size and cost (electrolytic).

CONS: Low accuracy and larger size (mechanical), suboptimal accuracy and durability (MEMS), higher size and cost (servo inclinometers), larger size (capacitive).

7. Displacement Transducers

Sources: [22][23][24][38]

Fig. 8 – Linear Displacement Transducer (credit: MAE advanced geophysics instruments)

HISTORY: Regarding LVDTs (see below), they were first patented by G.B. Hoadly in 1936, with a functionality almost identical to current ones. Subsequently, in 1946, an article by H. Schaevitz directly referenced the term LVDT. Their initial use was in the military field until cost reduction led to their development in other sectors.

OPERATION: As mentioned, the transducer is a device that converts an input physical quantity, in this case, displacement, into an output quantity of a different nature, such as an electrostatic or electromagnetic signal, to monitor the linear displacement of an object in a single direction.

There are various types of displacement transducers, depending on their operation, such as resistive displacement transducers, including potentiometers, which are based on voltage dividers; capacitive displacement transducers, which exploit capacitor capacitance as seen before; inductive displacement transducers, with electromagnetic operation using two coils; variable differential transformer displacement transducers (Linear Variable Differential Transformer, also called Linear Variable Displacement Transducer), which have the same basic structure as the former but with an additional coil and are based on the principle of the completely different differential transformer from the previous one.

Among the most common are certainly LVDTs, so in the following sections, reference will be made to this type of displacement transducer.

USE: Applications include machine tools, aerospace field tests, automotive and train testing, turbines, robotics, and of course, the geotechnical and civil engineering field (e.g., measuring vertical deformations of foundation piles during load tests, measuring movements of bridge joints or seismic joints) with measurable displacements on the order of mm.

FEATURES: AC/DC type, Number of axes 1, measurement range from 2 to 150 mm, damping 0, non-linearity up to 0.2% FS, output up to 5 V, IP67 protection rating, temperature range from -40°C to 160°C, repeatability up to about 0.10 µm.

PRICE: Average cost starting from about €300/400 upwards.

PROS: High resistance and reliability (almost total absence of friction ensures durability), ease of use, high resolution (capable of detecting even the smallest displacements), high temperature range, excellent linearity, low power consumption.

CONS: Limited measurement range, sensitivity to magnetic fields (shielding required), DC models perform less well than AC models.

8. Temperature/Humidity Sensors

Sources: [14][22][39]

Fig. 9 – Thermocouple and Infrared Thermal Camera (credit: RS Components)

HISTORY: Around 1592, it seems that Galileo built a device that showed temperature variations by the height of a column of water in a container, while the invention of what we know as the thermometer is attributed to the Italian Santori in 1612, later improved by Fahrenheit with the use of mercury. In 1821, Seebeck discovered that when the ends of different metals are joined and exposed to different temperatures, a voltage is generated, and later Peltier discovered that this thermocouple effect is reversible and can be used for cooling, while Davey demonstrated that the electrical resistivity of a metal is related to temperature. The thermocouple was then invented by Nobili in 1829.

As for infrared devices, the American Langley invented the bolometer in 1878, which used two platinum foils, one of which was blackened, to build a Wheatstone bridge: heating by infrared radiation caused a measurable change in resistance. After 1959, with the discovery of the cadmium telluride and mercury alloy, detectors were developed for specific wavelengths, leading to the current instruments.

OPERATION: Temperature sensors are instruments used to quantitatively detect the temperature of an object and its variations. They are mainly distinguished by the type of measurement, which can be made with or without contact. In this case, they are referred to as transducers because they convert temperature into an electrical signal.

Among the contact temperature sensors, thermocouples are very common, based on the relationship between temperature and resistance of metals: generally, as temperature increases, resistance also increases, meaning the opposition to the passage of electric current increases, while in some metals, resistance decreases and electrical conductivity increases with temperature. Consequently, these sensors are constructed with conductive or semiconductive metals to detect temperature variations. The thermocouple consists of two metallic conductors joined at the point of measurement and connected at the other ends by an electric terminal, linked to the measuring instrument.

Among those without contact, infrared sensors, such as thermometers or thermal cameras, are very useful, measuring temperature through the infrared radiation emitted by any object. As for infrared thermal cameras, they detect the thermal distribution of an area by processing a matrix of points through digital image processing, generating a thermal image representing the heat distribution of the reference object. They are generally powered by lithium batteries.

On the other hand, for the purposes of this work, it is certainly interesting to consider sensors for continuous monitoring of temperature and humidity in certain environments, for example, to highlight the influence of temperature (daily and seasonal) and humidity variations on the structural parameters to be monitored, to understand whether they are negligible or not.

For example, data loggers with thermocouples can be used, data recorders that allow real-time measurements, transferable via USB, Ethernet, or wireless. In practice, the data logger is connected to one or more thermocouples or to wireless or Bluetooth sensors, depending on the adopted technology, reading and storing the data. Therefore, it may not be necessary for the instrument to be in the same environment where the temperature is measured. These sensors are not expensive and work in a fairly wide temperature range, with up to 20 channels (and more), with a battery life of over 1 year.

Similarly, data loggers can be used for continuous monitoring of relative humidity in environments from 0 to 99%.

The list of sensors for temperature and humidity measurement is much broader; one could think of thermo-hygrometers, which perform a function similar to data loggers capable of detecting temperature and humidity. Anemometers should also be mentioned, which have the function of monitoring wind speed, an important factor in certain applications, such as monitoring suspension bridges, where different wind speeds can affect cable properties such as stiffness and damping. For further information, reference is made to the extensive existing documentation.

USE: In general, temperature and humidity sensors (both those mentioned here and others) find applications in any field. The usefulness in the civil field has already been mentioned in the previous section; one application could be, for example, on bridge decks subjected to load tests to detect whether the state of stress generated due to the temperature difference between the intrados and extrados leads to substantial variations or not.

FEATURES: Measurable temperature range up to 1750°C for thermocouples and from -20°C to 1500°C for thermal cameras. Further information is not provided due to the vastness of existing sensors, which would deserve separate treatment.

PRICE: Thermocouples do not exceed €100/piece. Thermal cameras range from a few hundred euros to over €20000 for more advanced models that measure very high temperatures.

PROS: Low cost, ability to measure very high temperatures, no external power supply required (thermocouples). Greater accuracy, ability to measure very high temperatures (thermal cameras).

CONS: Lower accuracy than other sensors, greater wear, inadequate for fast processes (thermocouples). Higher cost (thermal cameras).

9. Fiber Optic Sensors (FOS)

Sources: [3][8][9][12][25][40]

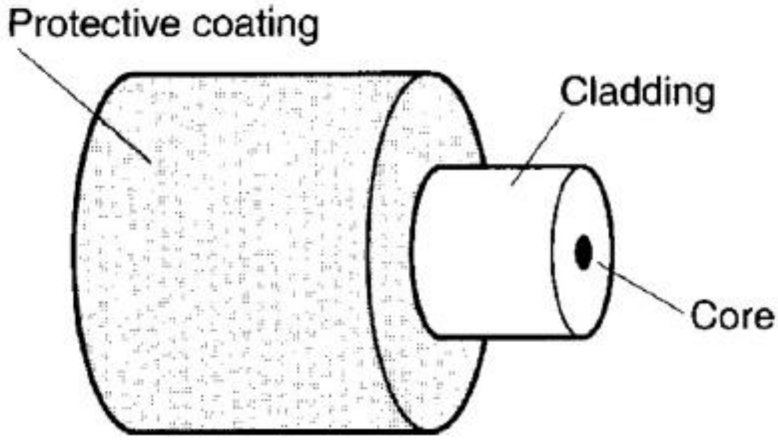


Figure 10 - Fiber Optic Diagram (Credit: [3])

HISTORY: The principle of fiber optics was first demonstrated by Colladon and Babinet in Paris around 1840, but the first optical fiber was physically produced over 100 years later, in 1956, by Curtiss and others in the development of the gastroscope (an endoscope used for examining the esophagus, stomach, and duodenum). From then on, this technology was increasingly developed, especially when it was understood that it would be an excellent means for communication systems.

OPERATION: Fiber Optic Sensors (FOS) are sensors in which optical fibers are used as a means to transmit the signal and/or as transducers, providing the measurement of the quantity of interest through optical signals; they have several advantages, both in general and compared to other technologies, as detailed in the following sections. They are very versatile, with the same sensor capable of providing, among other measurements, deformation, vibration, acceleration, temperature, humidity, and reinforcement corrosion development.

They consist of a core, a thin strand of glass or polymer fibers, a cladding that acts as confinement of light within the core, and a protective coating that ensures mechanical resistance, offering high durability of the fibers. The base material of the fibers is silica, capable of withstanding extreme temperatures both positively and negatively. This technology is declined into 3 main types: point sensors (Fiber Bragg Grating sensors - FBG), quasi-distributed sensors (long gauge sensors or quasi-distributed sensor or multiplexed Fiber Bragg Grating sensors), and distributed sensors (Brillouin Optical Time Domain).

In the following, some hints will be given on sensors based on this technology, specifically the most widespread - FBG - trying to give an idea of their operation and utility. In particular, reference will be made to extensometers and accelerometers based on this technology. For further details, please refer to the existing documentation.

In extensometers where the fiber acts as a sensor, it should be considered that the FBG grid creates "windows" in the material, and when light hits the element, some wavelengths are reflected while others pass through. These windows are positioned at intervals, and when the fiber deforms, the intervals vary, with the consequence that the reflected light takes more or less time to return, and the wavelength varies, due to the refractive index of the FBG indicating the percentage of refracted light, providing the deformation measurement. Many FBGs can be present inside the sensor.

In fiber optic accelerometers, acceleration must be coupled with a mechanical load on the FBG, so as to calibrate the acceleration level on the wavelength variation. Depending on how this is achieved and the properties of the optical fiber (length, section, mass, etc.), the accelerometer has certain characteristics, in terms of frequency range, maximum acceleration, sensitivity, and other parameters, also taking into account problems related to the maximum load on the optical fiber and any instability phenomena. The ability of FBG to measure the wavelength variation is comparable to that of traditional accelerometers measuring the potential difference.

APPLICATION: Fiber optics has countless applications in many sectors, just think of the world of telecommunications. In civil engineering, sensors based on it can be used in new structures, for example, embedded in the casting of pre-stressed beams made in the factory, as well as in existing structures like any other sensor.

FEATURES: They depend on the use intended for the sensor (extensometer, accelerometer, etc.). In this case, a general treatment has been conducted, so please refer to the individual data sheets provided in the bibliography for details.

PRICE: It depends on the type of device considered.

PROS: Insensitivity to radio and electromagnetic interference, high flexibility, high reliability even in difficult environments, small size, easy to interrogate over long distances, high spatial coverage with excellent resolution.

CONS: Need for adequate protection due to intrinsic fragility, high cost, still underutilized, so users need to become familiar with this technology, complex installation.

10. GPS/GNSS Technologies

Sources: [1][10][11][12][26][41]

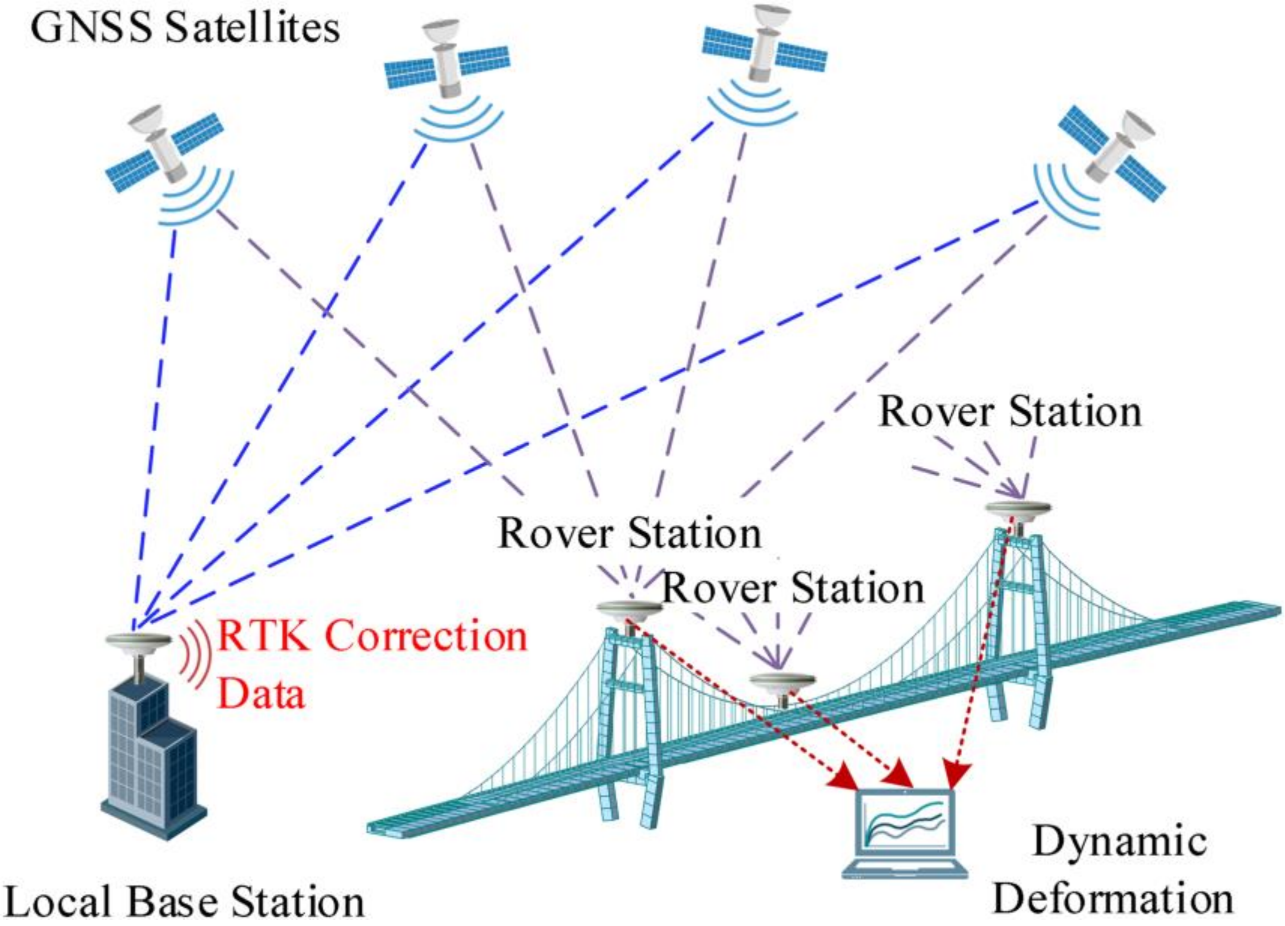


Fig. 11 - GNSS Operation in RTK Mode (credit: [10])

HISTORY: The first satellite navigation system was the American Transit, dating back to the 1960s, based on the Doppler effect between the satellites, which moved on known orbits transmitting signals with a specific frequency, and the receiver, which received a different frequency due to the satellite's movement, with the position being determined by the frequency change. GPS dates back to 1973, also developed for military purposes, and became fully operational by 1995. However, GNSS technology has seen significant development over the years.

OPERATION: When referring to GPS (or GNSS) systems, one can refer to both monitoring performed with devices based on these technologies, explained in this chapter, and the use of GPS sensors integrated into some of the devices discussed in previous chapters to enhance their performance (for example, using GPS on accelerometers of any type allows them, among other things, to be interconnected and data to be acquired synchronously).

The Global Navigation Satellite System (GNSS) is a system of geo-radiolocation and navigation based on artificial satellites in orbit and pseudolites (pseudo-satellites positioned on the ground), which includes, among others, the American Global Positioning System (GPS), the Russian GLONASS, the European GALILEO, and the Chinese BeiDou.

Among the satellite positioning techniques based on GNSS, the main one is Real-Time Kinematic (RTK), which requires at least one base station (reference) at a known point, with rover stations located at the measurement points. Measurements are made in real-time with the aid of at least 4 satellites, and data correction is performed by the base station. Another technique is Network-based RTK (NRTK), which, unlike the former, receives data correction from continuously operating reference stations (CORS) instead of the base station. Another technique is Post-Processing Kinematic (PPK), where the solution is computed not in real-time.

GNSS technology can be used alone to provide the required information or in combination with traditional technologies, such as accelerometers, to increase measurement redundancy and operate over a wider frequency range (GNSS more suitable for low frequencies). There are many works in the literature on this subject, some of which are indicated in [10].

Regarding the antennas, which constitute the link between the satellites and the receivers, as they are capable of calculating the position from the signal transmitted by the satellite - rover stations are just one of many - there are several types, classifiable according to the shape of the sensitive element, such as patch, turnstile, helical, spiral, choke-ring, and so on, or according to the application in geodetic, rover, and portable, each with peculiar characteristics.

The characteristics of these devices depend on the element considered, such as base stations or antennas, of which, as mentioned, there are many types, so for specific information, refer to the data sheets, and in the features section, some of the main parameters are reported.

APPLICATION: GNSS technology has numerous applications in any sector. Also in civil engineering, applications are numerous, such as monitoring displacements and deformations of bridges, buildings, chimneys, both in the presence of static actions and in the presence of wind, temperature variations, seismic actions.

Furthermore, an interesting aspect is that GNSS can be used to evaluate the dynamic response of structures in terms of natural frequencies (the first ones) and damping factors, starting from the coordinates of the monitored points, applying appropriate filters and algorithms.

CHARACTERISTICS: Measurement accuracy of the order of mm and even lower, maximum number of channels also over 500, initialization time of a few seconds, IP68 protection degree, temperature range from -40°C to 80°C.

PRICE: n/a

PROS: Sensors based on satellite technology have remarkable accuracy and precision (of the order of mm), providing both static (displacements) and dynamic (displacements in the presence of dynamic forcing, modal properties) measurements.

CONS: Limitations related to typical errors of satellite positioning of various types: on ephemerides (orbits), ionospheric refraction (due to the presence of free electrons), tropospheric refraction (related to atmospheric parameters), multipath (multiple reflections), errors in the receiver, and others.

11. Wireless Technologies

Sources: [1][3][12][42]

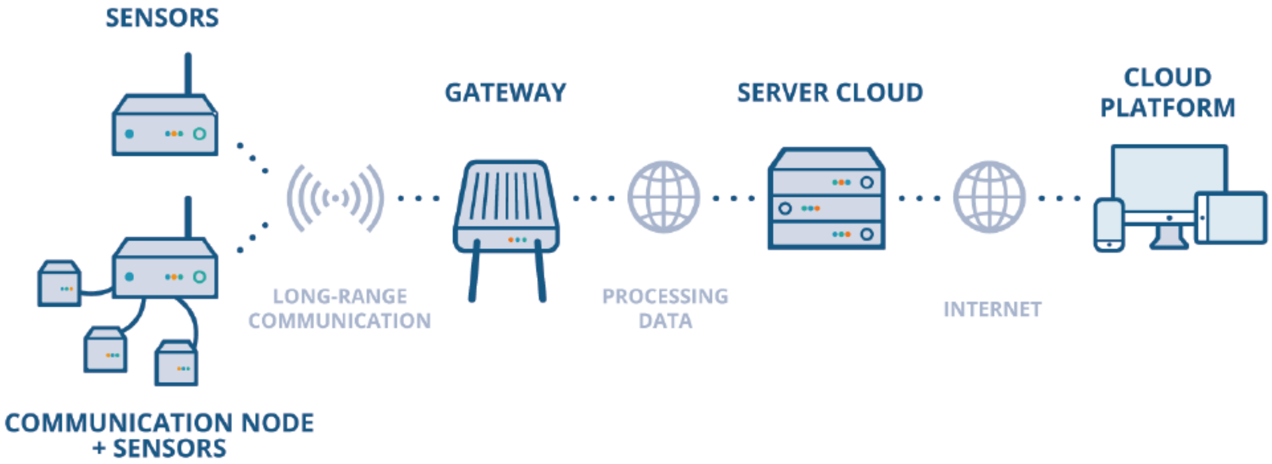


Fig. 12 – Wireless Monitoring System Operation (credit: move solutions)

HISTORY: Wireless communication has been discussed since 1890, with reference to Guglielmo Marconi's invention of the radio, which enabled the transmission of communications over considerable distances without wires. Around 1920, the term "radio" began to be used to identify this type of communication. Subsequently, from the 1980s/1990s, the term "wireless" returned to use to distinguish digital devices capable of wireless communication (such as cell phones, computers, etc.) from wired ones, according to the meaning we still understand today.

OPERATION: When referring to wireless technology, it involves the same sensors seen in previous chapters (and systems illustrated in Chapter 14), operating without cables. Generally, such systems consist of a sensor, a converter between analog and digital signals, memory, a processor, and wireless communication. Among the wireless sensors are extensometers, accelerometers, velocimeters, inclinometers, displacement sensors, anemometers, temperature sensors, all used together with transmitters to provide data to the wireless base station. In summary, the operation of these devices is no different from what has already been explained (for example, for MEMS accelerometers), while what changes is how the acquired data is transmitted from the sensor to the acquisition system and from there to the control system.

APPLICATION: In this case as well, the applications are multiple, as this technology can be applied to almost all types of sensors already mentioned.

CHARACTERISTICS: They depend on the intended use of the sensor (extensometer, accelerometer, etc.). In this case, a general treatment has been conducted, so details are referred to the individual technical sheets listed in the bibliography.

PRICE: It depends on the type of device considered.

PROS: Possibility to monitor parts of structures that are difficult to access and therefore difficult to install wired systems, cost-effectiveness and effectiveness of the system, possibility of self-powering with photovoltaic panels or "resonant vibration harvesters," or alternatively, power supply from batteries with multi-year duration and therefore extended monitoring duration.

CONS: Possibility of data loss in case of malfunction, problems in the case of power supply exclusively with photovoltaic panels during non-sunny days or at night or inside buildings, sensitivity to electromagnetic interference.

12. 5G Technologies

Sources: [12][27][28][29]

This chapter has a less schematic structure than the previous ones because 5G technology is very recent—globally deployed since 2019—and applications are still under development. The full potential is not yet entirely known, and its dissemination is not yet complete nationwide. Here, we describe its characteristics and usage modalities for structural monitoring, particularly seismic.

5G technology (the 5th Generation of the global telecommunications network) was born in the mobile telephony domain as the fifth generation, with significant advancements over 4G technology, aiming for greater efficiency and versatility in network applications. Compared to 3G and 4G networks, 5G represents a rather sharp discontinuity in three fundamental aspects: higher network access speeds (up to 10 Gb/s), lower latency (down to 1-2 ms), and a greater number of connections to low-power devices (up to 1 million devices per km2).

5G allows for the combination of aspects previously in conflict, such as reliability and low latency, interconnection of many sensors and limited physical spaces, high speed, and user density. Moreover, it's possible to create multiple separate virtual networks from the same physical network (slicing), establish new 5G networks without new installations but through simple configurations, and integrate services with various clouds.

Regarding signal transmission, as the frequency increases, the usage distance decreases but the available bandwidth increases. Thus, there is a low band (<1 GHz) that provides coverage in rural areas, a medium band (<6 GHz) that reconciles coverage and capacity, and a high band (<30 GHz) for applications with high capacity, highly localized due to signal attenuation over distance. Therefore, to ensure adequate services in certain applications (high band), a high number of transmitters need to be installed.

Among the various fields of application, in addition to mobile telephony, are the energy sector (monitoring consumption, enhancing device connectivity, better connectivity), automotive (improving in-vehicle services, greater safety, autonomous driving), infrastructure sector (autonomous delivery vehicles, platooning - piloting a fleet of vehicles - infrastructure monitoring), manufacturing (collaborative robots, remote piloting of industrial vehicles, predictive maintenance), agriculture (field monitoring and management, remote piloting of agricultural machinery), healthcare (monitoring vital signs, robotic tele-surgery), and many others.

The characteristics that make this technology very interesting in the field of civil structure monitoring, particularly seismic aspects, are reliability, measurement redundancy, low latency (of the order of tens of milliseconds in seismic fields), crucial for recording the event and issuing alerts, high pervasiveness, i.e., high network diffusion, which implies a greater chance of recording the event, data transmission speed, and lower energy consumption.

On the other hand, like other technologies and devices mentioned in this discussion, 5G also faces the problem of electromagnetic interference. Furthermore, another disadvantage is its dissemination, as mentioned, requiring the installation of new antennas, a more complex operation in less accessible areas. Another aspect to consider is related to cybersecurity and privacy, given the enormous amount of data that will be transferred via 5G in the future.

In the field of civil engineering, being a very recent technology, there are not many already realized applications. However, a project carried out by the University of L'Aquila, in collaboration with Open Fiber, Wind-Tre, and the Chinese telecommunications company ZTE, stands out. The city of L'Aquila, together with Milan, Prato, Bari, and Matera, was among the Italian cities where the first phase of 5G experimentation started in 2017. In particular, this project aims to monitor structures to assess and locate maintenance interventions and immediately raise the alarm in the event of an earthquake, starting from the initial seismic waves that generally precede the main event by a few seconds, thanks to the low latency.

13. Choosing the Most Suitable Sensor Type

In this section, after summarizing all the various types of sensors, including their history, functionality, usage, price, pros, and cons, conclusions are drawn to assist the reader in selecting the most suitable sensors for each need, with reference to the monitoring of civil structures, such as new buildings, historical buildings, bridges, viaducts, with particular attention to seismic aspects.

It's been observed that there are many types of sensors. Not all of them have been detailed in this report; some have simply been mentioned, directing the reader to existing documentation. Each sensor type is more suitable for a specific purpose, based on its characteristics and field of application. For instance, after discussing the most common accelerometers, it's evident that there isn't one type of accelerometer capable of performing all tasks optimally, as applications vary widely, requiring features tailored to the specific case.

Following the order of the previous chapters, strain gauges are a very useful tool in civil engineering, as evidenced by their widespread popularity, with limitations already explained. If monitoring a newly constructed building, one could consider embedding fiber optic strain gauges directly into the beams and pillars to measure deformations. Otherwise, the classic and well-established resistance strain gauge could be used. The latter can be a useful tool for existing buildings and bridges to monitor the opening of potential cracks, by positioning them where cracks are likely to occur due to seismic events or ground settlement, or where they are already present to monitor their evolution. Given the low cost, it is a particularly convenient tool to use. Advanced technologies like laser sensors (using triangulation) have also been mentioned, with their higher complexity and cost justified in contexts where highly accurate measurements are necessary, such as monitoring structures with high exposure, such as schools, hospitals, or cultural heritage sites like churches and monuments.

Regarding the extensive chapter on accelerometers, central to this work, and remaining within the scope of civil engineering, it is difficult to imagine a seismic monitoring system without this type of device. Particularly, considering the typical frequencies of civil structures and the accelerations they undergo, as well as the modal analyses based on ambient noise and the induced acceleration on the structure from a seismic event, as discussed in previous chapters and reported in the technical data sheets of various products, currently, the most credible options mainly involve MEMS accelerometers (capacitive) and Force Balance accelerometers. MEMS accelerometers are potentially suitable for monitoring seismic events, while FB accelerometers, very accurate even at lower frequencies and acceleration levels, are particularly suitable for continuous monitoring of the modal characteristics of the structure. However, they can obviously also be used to record seismic events. The choice between these two types—without forgetting the others—depends on many factors, both technical (frequency range, maximum acceleration, resolution, axes, dimensions) and economic, specific to each monitoring campaign.

Continuing with velocimeters and the sub-category of geophones, still within the scope of structural monitoring, these devices can be a valid alternative to accelerometers, especially for environmental monitoring, i.e., at low excitation levels, with reduced costs, thanks to their ability to perform well at low vibration levels. However, they are not the most suitable devices for directly detecting seismic events but can be useful for detecting seismicity related to minor aftershocks of the main seismic sequence, which is why they are used in seismic stations.

Moving on, for seismic monitoring purposes, inclinometers can be considered if there is a need to measure, for example, the inclination of a wall of a historical building or a retaining wall concerning the vertical axis. If there is a suspicion that an earthquake event could cause rotation and thus a risk of overturning the wall out of plane, these sensors can be useful. In the event that the sensor detects an inclination, the user can act promptly to reduce the likelihood of major damage, for example, by inserting chains or bracing walls with orthogonal walls and the roof, or in other ways deemed more appropriate.

The use of displacement transducers in the civil field has already been discussed in the relevant section. In particular, from a seismic monitoring perspective, it can certainly be interesting to install this type of sensor across seismic joints to study their evolution in the presence of an earthquake and evaluate whether the joint is sufficient or needs to be increased. They can also be used to monitor the status of cracks.

As for temperature and humidity sensors, they do not directly provide measurements that can be correlated with a seismic event. However, as already mentioned, they can be useful for continuous monitoring of particularly important works, such as bridges, historical buildings, and/or protected structures, to understand the influence of these two parameters on the static and dynamic properties of the structure, thus obtaining a more detailed knowledge of the work. On the other hand, they are fundamental in other applications, always in the civil field, concerning energy aspects.

Finally, regarding the most cutting-edge technologies, such as fiber optics, GNSS, wireless, these can be applied to various sensors (as is the case with FOS and wireless) or used in combination with them (as with GNSS/GPS), for which what has already been written remains valid. It is clear that the use of each of these technologies brings advantages such as wirelessness, the ability to measure more quickly, immediate availability of some data, and a greater quantity of data; however, the applications of the various sensors in the seismic field remain almost unchanged.

A separate consideration should be made for 5G, still in the experimental phase but which, once fully operational, could significantly influence the concept of structural monitoring, creating that connection between structure, sensors, software, and operators that represents the fulfillment of the objectives of SHM (Structual Health Monitoring).

14. Data Acquisition, Transmission, and Processing Systems

In the last chapter, we focus on data acquisition, transmission, and processing systems, for which a distinction can be made between traditional and more recent systems.

Traditional systems rely on wired connections that link various components of the monitoring system and transfer data from acquisition units to processing units. While they prove to be inefficient for large structures with high costs and long implementation times, they suffice for most common applications.

In recent years, systems based on Wireless Sensing Networks (WSN) have been developed. These systems consist of hardware components (sensors, acquisition modules, and transmitters) and software components (data analysis system and alert system). This setup allows for the acquisition and transmission of data to systems responsible for their analysis in a more agile and efficient manner, saving time, costs, and energy.

14.1. Data Acquisition

Fig. 13 – Data Acquisition System (Credit: DEWESoft)

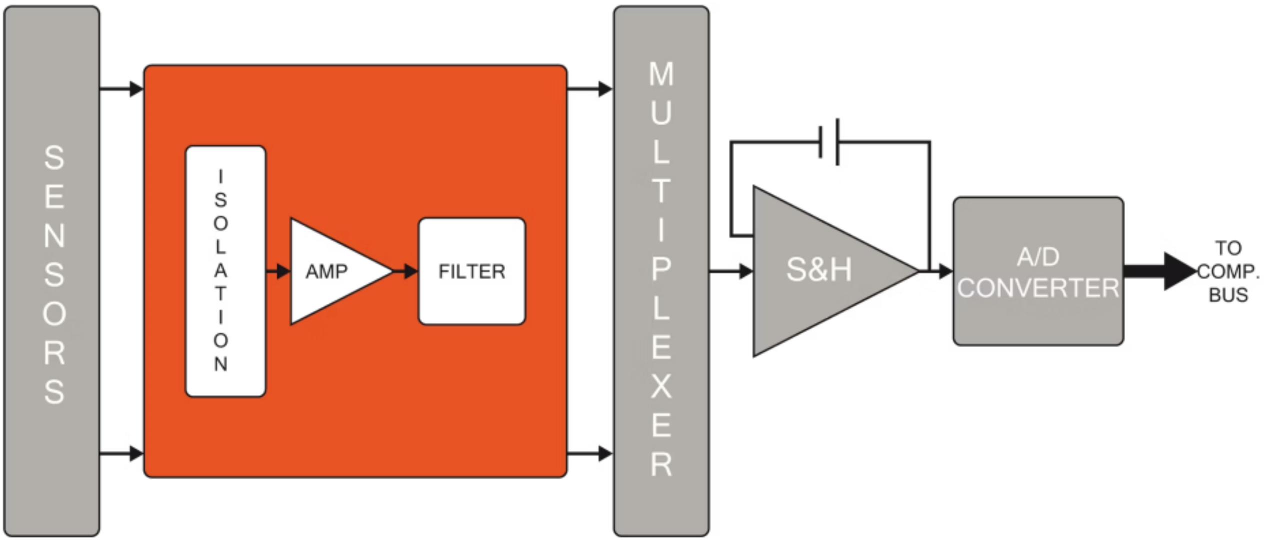


Fig. 14 – Diagram of a data acquisition system (Credit: DEWESoft)

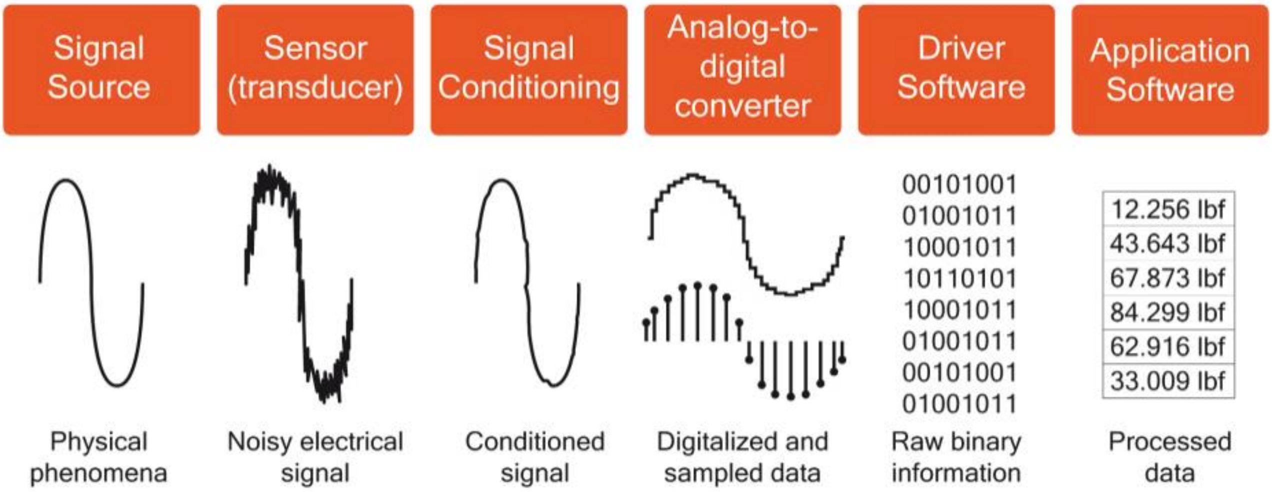


Fig. 15 – Signal acquisition process (Credit: DEWESoft)

The first data acquisition systems were analog, with data recorded on electromechanical plotters, magnetic tapes, or paper (as seen in seismographs, for example). Nowadays, signals are converted from analog to digital domain and then recorded in this form, as also happens with data loggers (small, affordable, and portable), which, compared to DAQ systems (explained later), have lower sampling frequencies, intended for slowly changing data over time (such as temperature variations).

The main components of a DAQ (Data Acquisition) or DAS (Data Acquisition System) include the sensors discussed in previous chapters, the signal conditioning circuit, consisting of conditioners that amplify, filter (for electromagnetic interference and noise), linearize, isolate (electrically), and generally standardize the signal provided by the sensor, preparing it for digital sampling. There's also the Sample and Hold (S&H) system for signal preparation before conversion at an appropriate sampling rate, an Analog-to-Digital Converter (ADC) to convert the signal to digital format (typically ADC 24-bit for dynamic signals, but not less than 16-bit), and finally, the computer with software for signal recording and analysis. In Fig. 13, the central unit serving as conditioning and ADC converter is depicted, while Fig. 14 illustrates the acquisition scheme, and Fig. 15 demonstrates the signal evolution.

The main goal of a data acquisition system is data collection and storage, which, in certain cases, can also be directly visualized and analyzed and potentially used for real-time control.

Some key aspects to consider in choosing DAQ systems include compatibility with the type of sensor intended for use, bit resolution, dynamic range in dB, resolution in terms of the smallest measurable quantity, maximum sampling frequency, measurement accuracy, need for electrical (or galvanic) isolation, required filter type (low-pass, high-pass, band-pass, band-stop, anti-aliasing), maximum number of channels, expansion capability, mobility requirements, standalone operation necessity, resistance to shocks, vibrations, temperature variations, dust, liquids, and other factors.

Regarding prices, DAQ systems range from around €200/channel for low-end systems to over €2000/channel for high-end ones.

14.2. Data Transmission

Regarding data transmission between sensors and the acquisition instrument, there are two alternatives: wired or wireless transmission. The development of wireless monitoring systems in recent years doesn't necessarily mean they're always the best choice, as both systems have advantages and disadvantages, some of which are detailed in Chapter 11.

Specifically, among the advantages of a wired connection are higher transmission speed and generally greater reliability at present. Also, the presence of cables allows signal transmission over longer distances, forming sensor chains, with issues related to voltage drops that can be addressed, for instance, by inserting capacitors along the cable. Moreover, there are no problems in cases of obstacles like thick walls, where wireless signals may significantly degrade.

Among the advantages of a wireless system, the main one is easier installation and absence of cables, allowing for more sensors to be distributed in an environment with less impact and easier network expansion, without problems of cable damage, which may occur in the other case. Additionally, the cost may be lower. However, a drawback of this system is the somewhat challenging temporal synchronization of different sensors in a network, a problem largely absent in wired networks.

Regarding data transmission to the processing system, data can either be physically retrieved from internal, possibly removable memories within acquisition instruments, or more conveniently transferred to the cloud or dedicated servers directly from acquisition units or a connected PC (with or without cables), making them accessible remotely for subsequent processing.

14.3. Data Processing

Data processing is carried out using specific software. No further considerations are made here because every application requires suitable programs.

References

[1] He Z., Li W., Salehi H., Zhang H., Zhou H., Jiao P., 2022. Integrated structural health monitoring in bridge engineering. Automation in Construction, 136 104–168, https://doi.org/10.1016/j.autcon.2022.104168.

[2] Li H., Ou J., 2011. Structural Health Monitoring: From Sensing Technology Stepping to Health Diagnosis. Procedia Engineering, 14 753–760, https://doi.org/10.1016/j.proeng.2011.07.095.

[3] Das S., Saha P., 2018. A review of some advanced sensors used for health diagnosis of civil engineering structures. Measurement, 129 68–90, https://doi.org/10.1016/j.measurement.2018.07.008.

[4] Del Grosso A., 2018. The role of structural monitoring in building located in seismic areas. Atti della VI Edizione HILTI Seismic Academy, Roma.

[5] Walter P. L., 2007. The History of the Accelerometer 1920s-1996 – Prologue and Epilogue, 2006. Sound and Vibration, 41 84–90.

[6] Iskander M., 2018. Chapter 3 - Geotechnical Underground Sensing and Monitoring. Underground Sensing, 141–202, https://doi.org/10.1016/B978-0-12-803139-1.00003-5.

[7] Borlenghi P., Piniotis G., Perakis H., Gikas V., Gentile C., 2020. Measuring the dynamic displacements of bridges using geophone data: application and validation on a lively footbridge. XI International Conference on Structural Dynamics, EURODYN.

[8] Guemes A., 2014. Fiber Optics Strain Sensors. https://api.semanticscholar.org/CorpusID:147701943.

[9] Baldwin C., Niemczuk J., Kiddy J., Salter T., 2004. Review of Fiber Optic Accelerometers. https://api.semanticscholar.org/CorpusID:180260894.

[10] Yu J., Meng X., Yan B., Xu B., Fan Q., Xie Y., 2019. Global Navigation Satellite System-based positioning technology for structural health monitoring: a review. Structural Control Health Monitoring, 27. https://doi.org/10.1002/stc.2467.

[11] Meo M., Zumpano G., Meng X., Cosser E., Roberts G., Dodson A., 2006. Measurements of dynamic properties of a medium span suspension bridge by using the wavelet transforms. Mechanical Systems and Signal Processing, 20 1112–1133. https://doi.org/10.1016/j.ymssp.2004.09.008.

Websites

[12] https://it.wikipedia.org/wiki/

[13] https://blog.endaq.com/

[14] https://www.internet4things.it/

[15] https://www.mechanicaleducation.com/

[16] https://www.electricity-magnetism.org/

[17] https://www.studiogeologicobellucci.it/

[18] http://sismiko.ingv.it/

[19] https://www.frederickscompany.com/it/

[20] https://www.fierceelectronics.com/

[21] https://www.posital.com/en/

[22] https://sea.omega.com/tw/

[23] https://dewesoft.com/it

[24] https://www.elprocus.com/

[25] https://www.hbm.com/tw/

[26] https://gssc.esa.int/navipedia/index.php?title=Main_Page

[27] https://bim.acca.it/

[28] https://blog.osservatori.net/it_it

[29] https://www.cnit.it/

Technical data sheets

[30] HBM, Luchsinger, DEWESoft.

[31] Bestech Australia.

[32] Boviar, DEWESoft, Dytran Kistler Group, Microgeo, S2Tech, Solgeo.

[33] Dytran, DSPM, Kistler Group, Metra Mess- und Frequenztechnik in Radebeul e.K.

[34] Endevco, PCB Piezotronics, PM Instrumentation.

[35] Earth System, IMV Corporation, Jewell, PM Instrumentation, Sherborne Sensors, Solgeo.

[36] Althen Sensors, Boviar, Cemb, Meggitt, Norsonic, Resensys, Sigicom, Solgeo, Zetlab.

[37] ASM Sensor, elap, Fredericks Company, Geo Instruments, Geokon, Gestecno, Luchsinger, Microgeo SIM Strumenti, U-Control.

[38] Micro-Epsilon, Microgeo, Omega Engineering, Tecnosens.

[39] Flir, Luchsinger, Omega Engineering, Pico Tech, RS Components, Sauermann Group, Tecnosoft.

[40] HBK FiberSensing, Luna Inc, Smartec

[41] Leica

[42] Erbessd instruments, Luchsinger, Mouser Electronics, move solutions