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Advancing Post-Mining Waste Dump Safety and Sustainability

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Work Package 3 - A new dumps monitoring system for continuous measurements

Deliverable 3.1

Reports on monitoring equipment possibilities

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1. INTRODUCTION

In the framework of enhancing safety and sustainability in post-mining landscapes, particularly for waste dumps in opencast lignite and coal mines, Work Package 3 focuses on the development, evaluation, and application of advanced monitoring systems to detect deformations, displacements, and related risks such as slope instability and vegetation changes.

This task centers on the design and specification of a new measuring equipment system tailored for waste dump monitoring. Key considerations include measuring accuracy and reading error, planned installation methods, equipment security, data collection and transmission protocols, and optimal measuring intervals.

UP, in collaboration with UAB and CEO, has conducted a comprehensive market review and documentation of commercially available measurement equipment. Additionally, POLT and VUHU present the potential of UAV-based stereo photogrammetry for monitoring dumping sites in opencast lignite mines, while POLT outlines suitable equipment options for dump surface control. SUB investigates the integration of multispectral and visual sensors on UAV platforms. Defined flight plans over selected waste dumps enable image interpretation to correlate geological and geomorphological properties of the waste materials.

The outcomes of this task are consolidated in Deliverable 3.1, a documentary report that details both classical and modern methods, techniques, and technologies for monitoring slope behavior, deformations, and displacements in waste dumps.

Following consultations during progress meetings in Prague (Czech Republic) and Chania (Greece) in 2025 with all grant partners, the structure and content of D3.1 have been finalized. This deliverable serves an informational role, providing a thorough overview of monitoring approaches for waste dump deformations and displacements, including equipment options, installation methods, measurement accuracy, and data handling processes.

UP, together with UAB and CEO, has completed extensive documentation, with the material scheduled for partner review before final upload to the EU platform.

The report covers:

Classical methods, techniques, and technologies for monitoring slope behavior:

- Topo-geodetic methods for horizontal displacements: trigonometric method (microtriangulation), alignment method, microtrilateration method.

- Geodetic methods for vertical displacements: high-precision geometric leveling, precision trigonometric leveling, hydrostatic leveling methods.

Modern methods, techniques, and technologies for monitoring slope behavior:

- GNSS-based monitoring systems.
- Remote sensing and photogrammetry (including UAV applications).
- Terrestrial LiDAR and laser scanning.
- Strain sensors, accelerometers, inclinometers, extensometers, piezometers, and accelerometers.
- Radar interferometry.
- Geotechnical modeling and numerical simulation.
- Automated monitoring and control systems.

Presentation and use of the new monitoring system, building on T3.1, this task involves the practical demonstration and deployment of the proposed monitoring system for dump stability, with a strong emphasis on UAV measurements. UAV campaigns are planned to align with ongoing soil material dumping activities as coordinated in WP2.

POLT, in close collaboration with UAB and VUHU, conducts UAV photogrammetry campaigns across selected Romanian, Polish, and Czech mines. Acquired data are uploaded to a central server, enabling all project partners to update 3D models iteratively (linked to WP4). SUB performs UAV flights on designated coal mine waste dumps to assess changes in vegetation vitality, plant species composition, and related risks, leading to the development of a criteria catalogue for vegetation change monitoring and risk assessment. Results from this task are documented in Deliverables 3.2 and 3.3.

Due to strong interdependencies with WP2 (particularly T2.3 and D2.2) and WP4 (T4.1 and D4.1), Task 3.2 (and associated D3.2) has been addressed in tight collaboration with TUC.

This work package integrates traditional geodetic approaches with cutting-edge UAV-based remote sensing, multispectral analysis, and automated systems to provide robust, real-time insights into waste dump stability — ultimately supporting safer mining operations, environmental rehabilitation, and risk mitigation in lignite and coal mining regions.

2. CLASSICAL METHODS, TECHNIQUES AND TECHNOLOGIES USED TO MONITOR SLOPE BEHAVIOR

2.1. Topo-geodetic methods used to track horizontal displacements

Topographic and geodetic methods for tracking horizontal displacements. Monitoring the deformations or horizontal displacements of slopes is an essential activity, especially in the case of massive surface mining, such as coal, copper, etc.

Tracking the behavior of slopes over time, in the horizontal plane, will always be done by referring to a network of support points located outside the area of influence of the target.

Considering the monitoring possibilities and the proposed objectives, the methods used can be (Ortelecan et al, 2005):

- microtriangulation method;
- alignment method.
- microtrilateration method;

The main advantage and reason why topo-geodetic methods are among the most used in monitoring the behavior of land and buildings over time is their ability to provide an overview of displacements and deformations, both relative and absolute.

2.1.1. Trigonometric method – microtriangulation

The trigonometric method based on microtriangulation is one of the most frequently applied techniques for monitoring land movements and stability in surface mining operations, as well as their slopes. The method involves the use of local geodetic networks, consisting of well-determined fixed points, to measure with high precision the displacements and deformations caused by various factors.

At the same time, monitoring the effects of subsidence or displacements on slopes is also carried out by the microtriangulation method.

A specific aspect of microtriangulation consists in maintaining the accuracy of measuring angles characteristic of higher-order triangulations, but this is done in triangles with short sides, of approximately 100-300 m.

To determine the displacement vector of the monitored objects, it is necessary to perform repeated measurements in cycles, with the same precision as that used in the first determination of the microtriangulation network. All compensations must be carried out rigorously, using the least squares method, while evaluating both the precision of the compensation and that of the determination of the displacement vector.

The main elements of the support network, created for monitoring behavior over time, are:

- Sighting marks – these are made up of points signaled on the object subject to monitoring, with the role of rendering the magnitudes and directions of displacement or deformation.
- Observation stations (A, B, C, D, …), from which observations are made towards the tracking marks (P1, P2, P3, …), according to Figure 2.1.

To materialize the observation stations, depending on the characteristics of the terrain and the geological approvals, cylindrical, frustoconical or prismatic patches will be built from reinforced concrete. They will have a deep foundation and will usually be equipped with special centering devices, such as Wild type, located on the top. To protect these devices during the measurements, metal covers will be installed above them.

Regarding the location of the observation stations, the distance from the monitored object will not exceed 300 m.

In the design stage of the tracking network, the accuracy required to determine the displacements will be taken into account, as well as ensuring the stability of the network throughout the observations.

Tracking networks also include the following components:

- Control or reference points (K1, K2, K3) from which the observation stations (A, B, C) will be monitored. These points are located outside the area of influence, at distances of more than 200 – 300 m from the target to be tracked.
- Orientation points (O1, O2, O3) which are also located outside the area of influence, being located in such a way as to ensure the accuracy of determining the tracking marks. (Ortelecan et al., 2011, 2012)

Within the tracking networks, the angles, orientations and coordinates of the points obtained in the first measurement stage become, after compensation, reference elements for subsequent measurement cycles.

The monitoring of the position of the tracking marks is carried out by determining them by intersection from at least three views.

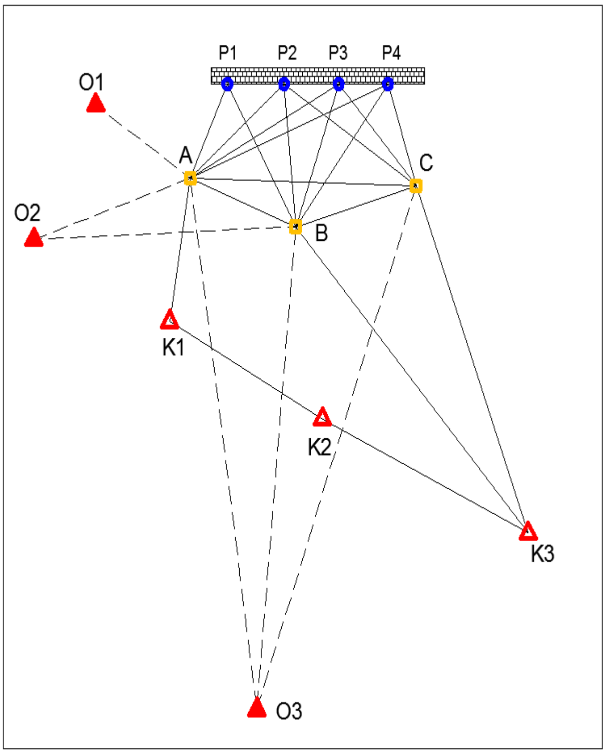


Figure 2.1. *Microtriangulation networks for measuring horizontal displacements*
Source: (Ortelecan et al, 2011, 2012).

At the design stage of the network, it will be optimized so as to ensure the necessary precision in determining the position of the tracking marks, by bringing the observation stations closer to them, without affecting their stability.

Measurements in the microtriangulation networks will be carried out with the precision corresponding to the networks of the I, II and III orders, using the iteration or Schreiber method.

In addition, an attempt will be made to eliminate systematic errors, as far as possible. Each observation cycle will begin with checking the stability of the observation points in correlation with the control points, and if their displacement is found, the necessary corrections will be applied.

- Monitoring the stability of reference points in the semi-stable/stable area of the microtriangulation network

Microtriangulation has its main applications in open-pit mining, as follows:

- Monitoring slope stability and landslide hazards:

Microtriangulation allows the detection of fine movements of slopes or ground surfaces that could lead to landslides or collapses, playing an essential role in preventing accidents.

- Monitoring mining infrastructures:

This method helps to monitor the stability of access roads, tailings dumps and other structures near the mining area. The movements of these structures can be monitored to prevent damage.

- Assessing the risks of mine collapse:

Microtriangulation can detect subtle ground movements that could indicate instability in mining pits, allowing rapid corrective measures before a major accident occurs.

- Checking the impact of excavations on the environment:

This method can be used to track how mining activities affect the environment, such as changes in ground level or deformations caused by excavation.

➢ The principle of applicability of microtriangulation to slope stability monitoring

In microtriangulation networks, repeated angular measurements are made at different times. Theoretically, these measurements should be identical from one period to another, but usually there are variations, which is why it is necessary to analyze the admissibility of the stability of the reference points. In general, the reference points are determined in a local coordinate system. In figure 2.2. a section of the microtriangulation network is shown. (Ortelecan et al, 2011, 2012)

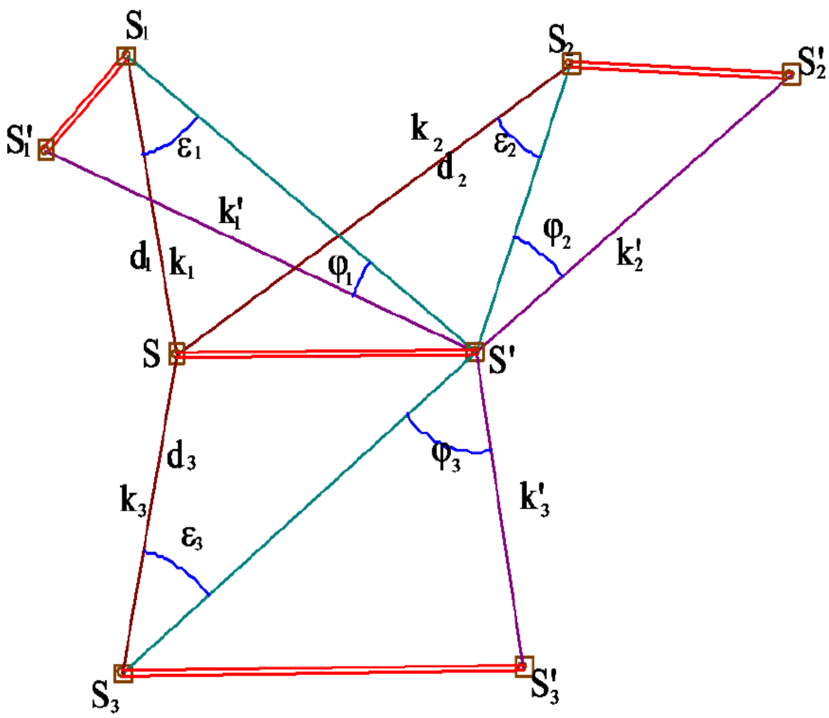


Figure 2.2. *Microtriangulation network*
Source***:*** (Ortelecan M., et al, 2012), (Ortelecan M., et al, 2011)

In figure 2.2, the reference point S targets the points S_1, S_2, S_3, and the directions k_1, k_2 and k_3 are measured. At another measurement epoch, the reference point may undergo displacements and reach a new position S'. Thus, in this measurement interval, the points S_1', S_2', S_3' will be targeted, and the directions k_1', k_2' and k_3' will be measured.

The displacement of the reference point led to a variation in the measured directions, denoted by ε_1, ε_2, ε_3, and the displacements of the targeted points caused a variation in the measured directions, denoted φ_1, φ_2 and φ_3.

The differences between the angles, which appeared in the two measurement intervals, depend on both the magnitude of the displacements and the measurement errors. The most probable components of the displacements of the reference points will be determined based on these differences.

All these procedures require a large amount of work and, implicitly, substantial expenses.

The study of the invariability of the angles formed in the network of reference points is one of the simplest and most economical methods, but it will not provide satisfactory results when the distances between the reference points are large. This is due to the fact that a small linear displacement of a point will generate a small angular variation, which could fall within the limits of measurement errors.

2.1.2. Alignment method

The alignment method is a geodetic technique frequently used to monitor the stability of slopes, especially in areas such as mining or infrastructure works. It involves the periodic measurement of the positions of strategically placed points on the slope surface, in order to detect any displacements caused by natural or anthropogenic factors.

- The method of observing an alignment along its entire length

This method consists of observing and monitoring an alignment defined by several points arranged along its entire length, being frequently used to track the movements and stability of slopes, dams, levees or other structures exposed to the risk of deformation. It is used when the distance between the end points of the alignment is relatively small (between 300-500 m), thus ensuring good sighting conditions between the end points, but also between them and the control points that are materialized on the monitored object. (Cacoń S., 2001)

Principle of the method

An alignment is made up of a series of well-defined points, arranged along a straight or curved line. Successive observations of the positions of these points allow the identification of any displacements.

Measurements include:

- Horizontal angles and/or distances between successive points.
- Lateral deviations from the initial alignment (drawn in the reference stage).
- Point elevations, if it is necessary to monitor vertical movements.

Method steps:

- Establishing the initial alignment, a line is chosen that intersects the area to be monitored.
- The points on the alignment are materialized with terminals, observation marks or other stable landmarks.
- Initial measurements, initial observations are made to establish the coordinates of the points on the alignment. These initial values will be used as a reference for subsequent comparisons.
- Periodic measurements, the positions of the points along the alignment are periodically measured.
- The instruments used include theodolites or total stations, for measuring angles and distances, level meters, for determining elevations.
- Deviation analysis, the positions of the points observed over time are compared with the initial positions.
- The deviations of the points in the perpendicular and parallel direction to the alignment are calculated.
- Interpretation of the results, the calculated deviations indicate displacements and deformations.
- The causes of the displacements are analyzed and, if necessary, stabilization measures are taken.

➢ Parallactic angle observation method

The parallactic angle observation method involves establishing an alignment as close as possible to the line joining the points of the monitored target

The method is based on measuring the angular (parallactic) differences between the directions to the monitored points, relative to two fixed observation points, in two or more measurement epochs. These angular differences are used to determine the displacements of the monitored points.

The alignment support points, S_1 and S_2 (Figure 2.3), are used as station points. At the collinear points of the alignment, metal bushings are mounted, in which stable sighting marks will be installed during the measurements, which will then be aimed for measuring horizontal angles. (Brunner et al, 2009)

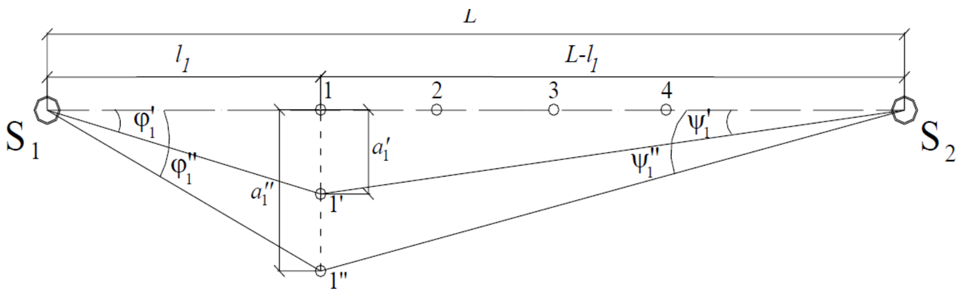


Figure 2.3. *Alignment method – measurement of parallactic angles*
Source (Brunner F.K. et al 2009)

The method of observing parallactic angles is a practical technique, successfully used in geodesy and land stability monitoring, especially in situations where fast and efficient solutions are needed to detect displacements.

- The method of observing supplementary parallel alignments

The method of observing supplementary parallel alignments is used to monitor displacements and deformations of surfaces, structures or slopes. It involves drawing and monitoring of supplementary parallel alignments relative to a main alignment, in order to detect relative movements between points located on these lines.

Principle of the method

Supplementary parallel alignments are straight lines, drawn on the ground, located parallel to a main alignment that serves as a reference.

The points on the supplementary alignments are monitored over time, and repeated measurements indicate their relative or absolute displacements.

By analyzing the variations between the alignments, the movements of the monitored area are determined, either in the horizontal or vertical plane.

This method involves establishing a new alignment, A'B', parallel to the original alignment AB. The distances AA' and BB', which separate the old and new base points, must be equal to the average value of the deviations of control points 1, 2 and 3. In order to accurately measure these distances, it is necessary to determine the deviations L_A and $L_{A'}$ simultaneously from both alignments (Figure 2.4.) (Brunner et al, 2009)

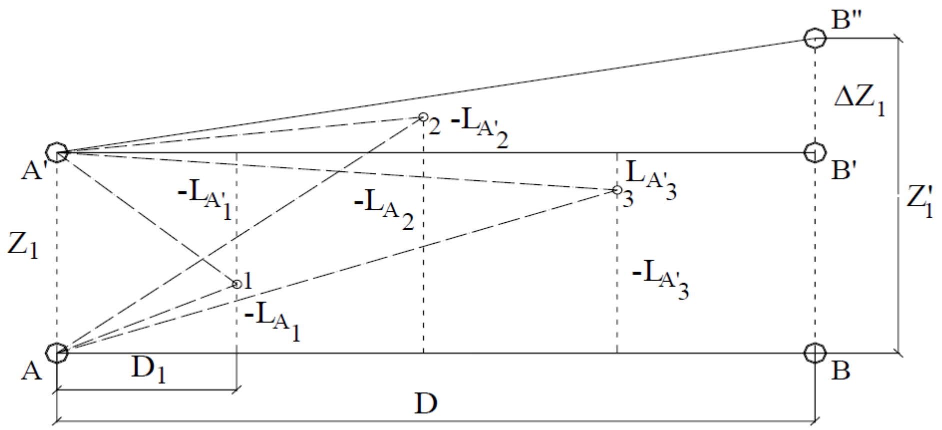


Figure 2.4. *Method of observing additional parallel alignments*
Source (Brunner F.K., et al, 2009)

2.1.3. Microtrilateration method

Microtrilateration is a geodetic technique used to monitor deformations and displacements of the terrain or structures, based on the precise measurement of distances between the network points. This method is frequently used in civil engineering projects and in open-pit mining, due to its ability to provide very accurate results over small distances.

The basic principle of the method is based on measuring the distances between points of a local geodetic network, called a microtrilateration network. By using a set of geometric equations, the positions of the monitored points are calculated based on the measured distances. This allows the detection of position changes caused by displacements or deformations of the terrain.

Microtrilateration networks are formed by points that have been determined strictly by distance measurements, these usually representing the sides of triangles.

Linear networks can be realized either as constrained networks, in which the axis system used to calculate the position of new points is defined in advance by a set of elements larger than the minimum required (the X,YX, YX,Y coordinates of a point and the orientation of a side), or as free networks, where the axis system is chosen in a convenient way.

In the case of constrained networks, the axis system is usually given abundantly, by means of at least two pairs of old points of known coordinates A(XA,YA), B(XB, YB), these forming the so-called base of linear intersections and C(XC,YC), D(XD,YD), which form the so-called control base, or the constraint element of the network.

Starting from these bases, of known orientations in the plane, the coordinates of the new points are calculated gradually, by ordinary intersections or the radiation method.

In the case of the free linear network, the coordinates of the new points are recalculated in a conveniently chosen local system. The determination of the plane coordinates (X,YX, YX,Y) of a PPP point, or of a group of PiP_iPi points, based on the measured distances, can be achieved by: simple linear intersection, multiple linear intersection, point group compensation.

Particularities regarding the determination of horizontal displacements

By using constrained linear networks, it will be possible to determine more easily and with greater precision the displacements ΔX and ΔY of the points subject to monitoring.

The horizontal displacements of the points can be calculated only if they are referred to a system of points located outside the area affected by the displacements, which requires the use of a reference network with points considered fixed. This involves the application of a calculation algorithm based on the group of points. In the tracking network, consisting of the reference points A, B, C, D and the new points to be monitored, measurements will be performed in cycle I and cycle II. Using the simple linear intersection method, in cycle I the provisional coordinates of the new points (1, 2, 3) will be determined, without compensating them. Repeated measurements in cycle II will be able to determine any new distances between the points, thus providing the free terms l_{ij}. (Brunner F.K., et al 2009)

2.2. Geodetic methods used to track vertical displacements

Monitoring of vertical displacements and slope failures is an essential aspect in the fields of geodesy, civil engineering and environmental protection. Landslides and vertical movements can endanger the stability of structures and the safety of the population, which is why it is necessary to use precise geodetic methods to monitor these phenomena. Various geodetic techniques are used to measure and monitor vertical land displacements, especially in areas susceptible to landslides and slope failures.

Among the most important methods used for this monitoring are:

- High-precision geometric leveling method
- Precision trigonometric leveling method
- Hydrostatic leveling method

These methods are used to assess vertical movements of the soil or structures, providing vital information for preventing slope failures and managing the risks associated with them. Continuous monitoring using these techniques allows for the early detection of displacements and landslides, facilitating rapid and effective interventions to protect lives and property.

2.2.1. High-precision geometric leveling method

High-precision geometric leveling is one of the most accurate and widely used geodetic techniques for measuring height differences between points located at large or small distances. This method is particularly important in monitoring vertical displacements and slope slides, having the ability to detect subtle ground movements that can affect the stability of structures and infrastructures. (Stéphane C. et al, 2016)

Geometric leveling

Its principle consists in the fact that the aiming axis is horizontal. Measurements are performed with a level and a plumb line.

Depending on the position of the instrument with respect to the measured points, geometric leveling is classified into mid-geometric leveling and end-geometric leveling.

2.2.2. Precision trigonometric leveling method

The method is characterized by the fact that level differences will be determined by measuring the distance between points and the vertical angle. The instrument used is the theodolite with which vertical angles and distances will be measured. Distances can also be determined by calculation from coordinates if these have been previously determined. The principle of trigonometric leveling consists in determining the level difference as a function of the horizontal distance and the vertical angle. Within this method, two cases are distinguished:

- ►ascending sight;
- ►descending sight;

2.2.3. Hydrostatic leveling method

Hydrostatic leveling is a measurement method used to monitor slope displacements and stability, based on the principle of communicating vessels and the use of a liquid (usually water) to detect differences in level. This method is effective for determining variations in the vertical position of points located on slopes or other monitored surfaces.

The method is based on the fact that in a system of communicating vessels, the level of the liquid remains constant regardless of the shape of the vessels, if the liquid is not subjected to other external forces. Any variation in the vertical position of a point produces a difference in level in the liquid, which can be measured accurately. (Jiří P. et al, 2018)

If the hydrostatic system includes both tubes mounted in fixed references and tubes attached to control points, the determination of the vertical displacements of the control points is carried out similarly to geometric leveling, with support at the ends on reference marks with known elevations (Jiří P. et al, 2018)

To automate the process of measuring the vertical displacements of slopes, it is necessary to fix two contacts in each measuring tube. The upper contact is fixed higher than the initial level of the liquid, at the assumed size of the displacement, and the lower one is inserted into the liquid. By reaching the limit displacement of one of the tubes, the contact is closed, because the liquid touches the upper contact. In such a system, an electrical signal can be connected, or all circuits can be connected to a control panel.

The accuracy of hydrostatic leveling depends on the construction of the system itself, the properties of the liquid, the measurement methodology and the influence of environmental factors. The main sources of errors that influence measurements are the change in the initial level of the liquid in the system as a result of settling of the measuring tubes and the temperature changes and readings on the tubes.

Two types of hydrostatic systems are used to measure vertical displacements of slopes, the open hydrostatic system in which the upper level of the liquid comes into direct contact with the air and the closed hydrostatic system in which the liquid is isolated from the atmosphere.

A disadvantage of open hydrostatic systems is related to the evaporation of the liquid, which makes them incompatible with the use of easily volatile liquids, such as antifreeze, required in low temperature conditions. To ensure long-term operation and high accuracy, the components of the hydrostatic system must meet certain requirements, established as a result of continuous improvements.

The hoses that connect the components of the hydrostatic system can be made of various materials, such as metal, rubber or plastic and they have lengths ranging from 10 to 30 m. At long lengths, most of the liquid volume is in these pipes, and the variation in the volume of polyethylene hoses can reach up to approximately 5% for a temperature change from +5°C to +30°C. In such situations, if the volume of water in the system tank is less than 5% of the total volume of liquid in the system, the water may drain completely from the tank due to the temperature change, making it impossible to take measurements. To prevent this problem, a compensation system is introduced. In closed hydraulic systems, the liquid is protected from atmospheric influence, eliminating the need for filters and preventing dust or oil from entering the hydraulic system. This allows the use of slightly volatile liquids. However, due to the hermetic sealing, temperature variations can cause changes in pressure in the hydraulic system. If the connecting hoses are made of materials such as thin polyethylene or rubber, their stretching can lead to an increase in the volume of the liquid, loss of liquid, a decrease in the level in the graduated tubes and, implicitly, to the appearance of significant errors in the measurements.

To prevent these problems, the connecting hoses must be made of resistant materials, such as metal, or have a reduced section. Also, volume changes can be compensated by introducing hermetic siphons that include a volume of air, which helps to balance the pressure due to temperature variations.

The hydrostatic leveling method allows the determination of vertical displacements with high accuracy, between ±0.01 m and ±0.005 m. (Jiří P. et al, 2018).

3. MODERN METHODS, TECHNIQUES AND TECHNOLOGIES USED FOR MONITORING SLOPE BEHAVIOR

Modern methods for monitoring slope deformations in mining works have become essential for risk management and the optimization of mining operations. Several modern solutions and advanced technologies are used to monitor deformations in mining works, enabling precise and real-time assessment of ground stability and mining infrastructure. The main modern methods employed in investigations include: monitoring using GNSS systems, remote sensing monitoring, terrestrial LiDAR and laser scanning, deformation sensors and accelerometers, radar interferometry, geotechnical modeling and numerical simulation, as well as automated monitoring and control systems. These methods provide a detailed understanding of the behavior of mining structures, which is essential for risk management and the optimization of mining operations. The integration of these technologies ensures precise and efficient monitoring of deformations, contributing to the safety and durability of mining works.

In conclusion, the use of these modern investigation and monitoring methods ensures more efficient risk management and better protection of mining works, thereby enhancing safety and durability in the mining industry.

Modern solutions for monitoring deformations in mining works

As is well known, in recent decades we have witnessed an exponential acceleration of technological progress, which has also led to significant developments in solutions for monitoring deformations in mining works. This development is highly welcome in the context of a continuously growing industry and an ever-expanding market.

The methods that have experienced an exponential acceleration in technological progress are described below:

3.1. Monitoring using GNSS systems

GNSS (Global Navigation Satellite System) positioning technology is essential for precise position determination in various applications, ranging from everyday navigation to geodetic monitoring and ground deformation monitoring. GNSS includes satellite constellations such as GPS (Global Positioning System) of the United States, GLONASS of Russia, Galileo of the European Union, and BeiDou of China.

Here is a detailed description of how GNSS works and how position determination is performed:

GNSS uses a network of satellites that transmit radio signals to receivers on Earth. These signals contain information about the satellite's position and the transmission time. The GNSS receiver calculates the distance to each satellite by measuring the time required for the signal to travel from the satellite to the receiver. By using distances from at least four different satellites, the receiver can determine its exact position in three dimensions (latitude, longitude, and altitude). (Toby M. et al, 2022)

GNSS Position Determination Methods:

a) Absolute Positioning (Single Point Positioning – SPP)

The principle of absolute positioning uses signals from multiple satellites to determine the receiver's position based on the signal propagation time and the satellites' almanac (orbital information).

This is applicable in standard navigation, such as automotive or maritime navigation, with accuracy in the order of meters.

b) Differential Positioning (DGPS – Differential GPS)

The principle uses a network of ground-based reference stations, whose positions are known, to calculate corrections for GPS signal errors and transmit them to mobile receivers.

This is applicable for improving accuracy in maritime navigation, aviation, and precision agriculture, with accuracy in the order of sub-meters.

c) Real-Time Kinematic (RTK – Real-Time Kinematic)

The principle uses signals from satellites and corrections from a base station (whose location is well known) to provide real-time positioning with very high accuracy.

It is used in surveying, construction, and other applications requiring high precision, with accuracy on the order of centimeters.

d) Static Positioning

The GNSS receiver is left in a fixed location for an extended period, collecting data from satellites to calculate a highly precise average position.

Used in geodesy, cadastral surveying, and ground deformation monitoring, it achieves accuracy on the order of millimeters.

Factors Affecting GNSS Accuracy:

a) Satellite Geometry (DOP – Dilution of Precision)

The distribution of satellites in the sky affects positioning accuracy. Good geometry (satellites widely distributed across the sky) leads to higher accuracy.

Indicators such as GDOP (Geometric DOP), PDOP (Position DOP), HDOP (Horizontal DOP), and VDOP (Vertical DOP) reflect the quality of satellite geometry.

b) Ionospheric and Tropospheric Errors

GNSS signals are affected by delays caused by the ionosphere and troposphere. Modeled corrections can improve accuracy.

Use of ionospheric and tropospheric models or differential measurements to correct errors.

c) Multipath Errors

Reflections of GNSS signals from buildings, terrain, or other objects can cause errors.

Placement of receivers in open areas, use of advanced technologies to mitigate multipath effects.

d) Synchronization and Clock Errors

Differences between satellite and receiver clocks can introduce errors.

Use of synchronization corrections and signals from additional satellites to minimize errors.

Main GNSS Equipment and Technologies:

GNSS Receivers

Consumer receivers (e.g., in mobile phones), professional receivers (e.g., in surveying equipment).

Variety of features including the ability to receive signals from multiple GNSS constellations, post-processing capability, and integration with other sensors (IMU – Inertial Measurement Unit).

GNSS Reference Stations

Fixed stations with high-precision receivers that collect GNSS data to provide differential corrections.

CORS networks (Continuously Operating Reference Stations) provide corrections for differential and RTK positioning.

Post-Processing Software

Software allows analysis and correction of GNSS data to improve accuracy.

Used for geodetic applications, cadastral surveying, and deformation monitoring.

GNSS technology is fundamental for a variety of applications requiring precise positioning. Ongoing developments in this technology contribute to increased accuracy and reliability of positioning, opening new opportunities in various fields. (Toby et al, 2022)

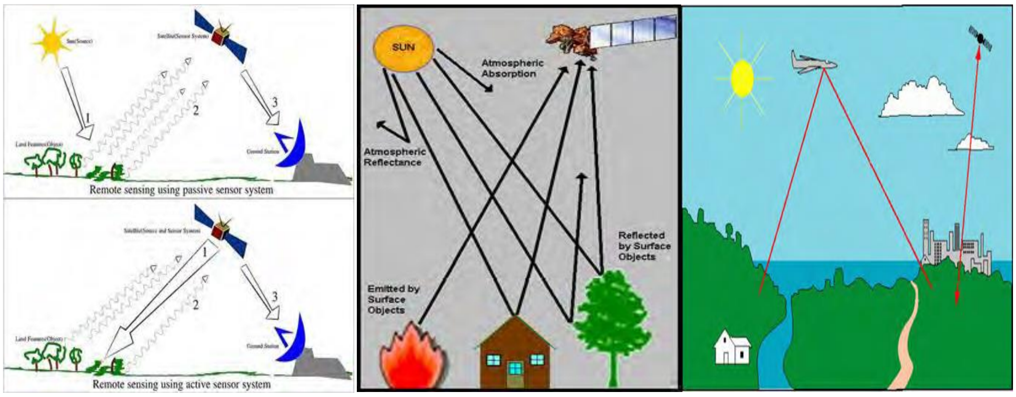
3.2. Monitoring through remote sensing and photogrammetry

Remote sensing monitoring involves the use of satellite imagery and remote sensing techniques (Figure 3.1), which can provide detailed information about topographic changes and ground deformations in mining areas. The obtained images can be processed using image analysis algorithms to identify and monitor deformations.

Remote sensing is the technical field that deals with the detection, measurement, recording, and visualization in the form of images of electromagnetic radiation emitted by objects and phenomena on Earth or in the Universe, from a distance, without direct contact with them. The final part of the definition is intended to best specify the meaning of this technical field.

Remote sensing is not a science, but a set of applications of physics and engineering aimed at obtaining images. The ultimate goal of this technical field is the remote sensing image, obtained through various means.

Remote sensing, regardless of the nature of the applications—passive or active—uses electromagnetic radiation to obtain images of bodies from altitude, from aircraft, satellites, balloons, or helicopters, because in this way, the image can be used to produce maps and plans, and the interpretation of objects is optimal. (Bonn et al, 1992; Bogdan-Andrei, 2008)



a b c

Figures 3.1. a, b, c, *Illustration of the Remote Sensing Principle*

Figure 3.1 a. Source (https://en.wikipedia.org/wiki/Remote_sensing)

Figure 3.2. b. Source (http://employees.oneonta.edu/baumanpr/geosat2/RS-Introduction/RS-Introduction.html)

Figure 3.3. c. Source (https://saralubkin.com/2015/12/06/harmful-algal-blooms-part-4-what-is-a-spectral)

Among the fundamental principles of remote sensing are:

- Electromagnetic interaction: Remote sensing sensors measure electromagnetic radiation (EM) emitted, reflected, or absorbed by the Earth's surface. This radiation can range from visible to infrared and microwave radiation.
- Spectral specificity: Materials and objects have unique spectral signatures, meaning they absorb or reflect different wavelengths of light. These spectral signatures allow the identification and characterization of different objects and surface properties.
- Spatial and temporal resolution: Spatial resolution refers to the sensor's ability to distinguish between different objects and features on the Earth's surface, while temporal resolution refers to the frequency with which data are collected over time.
- Remote sensing sensors are devices used to collect data about the Earth's surface and atmosphere using different wavelengths of electromagnetic radiation. These can be mounted on satellites, aircraft, or installed on the ground. Here are some examples of remote sensing sensors used on different platforms:

The main satellite sensors are:

- Landsat Thematic Mapper (TM) and Operational Land Imager (OLI): These sensors are mounted on Landsat satellites and are used to collect high-resolution multispectral images covering the entire Earth's surface. These images are used for a wide range of applications, including monitoring land changes and vegetation.
- Sentinel-2 Multi-Spectral Instrument (MSI): This sensor is mounted on the European Space Agency's Sentinel-2 satellites and provides multispectral data with a spatial resolution of up to 10 meters. It is used for environmental monitoring, agriculture, forestry, and other applications.
- MODIS (Moderate Resolution Imaging Spectroradiometer): This sensor is mounted on NASA's Terra and Aqua satellites and provides medium-resolution images for monitoring climate, land changes, vegetation fires, and other global phenomena.

Aerial Sensors:

- Photographic Cameras: These are cameras mounted on aircraft and can be equipped with various filters to capture images in different light spectra, such as visible, infrared, and ultraviolet (Figure 3.2.).
- LIDAR (Light Detection and Ranging): LIDAR sensors mounted on aircraft use lasers to measure distances and create precise three-dimensional models of surfaces and objects.

Ground-Based Sensors:

- Photographic Cameras: Ground-mounted sensors can be fixed or mobile cameras that capture images of the surrounding environment from different perspectives.
- Meteorological Sensors: These collect data on meteorological parameters, such as temperature, humidity, and wind speed.
- Air Quality Sensors: These measure concentrations of pollutants and other substances in the atmosphere.

PHOTOGRAMMETRY, a term frequently used in geography as well (emerging in the 19th century, in 1864, in Germany), is a technical field or method that uses remote sensing images for the purpose of producing topographic or thematic maps and plans, based on precise measurements of objects appearing in the images and their accurate scaled representation, on paper (analog format) or in digital format. It is the primary method currently used to prepare topographic plans, cadastral maps, etc., and transitioned at the end of the 1980s from a complex mathematical apparatus and analytical procedures (analytical photogrammetry) to applications in a digital environment (digital photogrammetry, see Figure 3.2.). (Bonn et al, 1992), (Bogdan-Andrei, 2008)

Figure 3.2. *Preparation of a topographic plan of a quarry using digital technologies*

Currently, photogrammetry represents an advanced technology widely used in various fields, from topography and civil engineering to environmental monitoring and cultural heritage conservation.

It employs a wide range of devices and instruments to capture and analyze data from photographic images, providing precise and efficient solutions for measurements and 3D modeling. Here are some of these essential pieces of equipment: camera, aerial camera, ground-based camera, drone (UAV – Unmanned Aerial Vehicle), GNSS sensors (Global Navigation Satellite System), inertial sensors, processing software.

The camera is the basic element in photogrammetry. Digital cameras are the most widely used today, as they offer high image quality and allow rapid data capture.

Currently, photogrammetry relies on the use of high-performance digital cameras, which provide high resolution, portability, and advanced functionalities.

High-resolution digital cameras (DSLR and Mirrorless) have as main characteristics large sensors that offer superior image quality and high accuracy in details, as well as the ability to change lenses to achieve varied fields of view, etc.

The aerial camera is used for aerial photogrammetry; it is mounted on special aircraft to obtain images from height. These types of aerial cameras are specially designed to capture high-quality images during flight, being integrated into drones, airplanes, or helicopters. They feature advanced technical characteristics that enable them to meet the precision and detail requirements needed for complex projects.

The main characteristics of aerial cameras are: high resolution, stabilization, calibrated sensors, multispectral and hyperspectral technology, low weight, automated capture systems, etc.

High resolution refers to sensors with numerous megapixels for capturing fine details of the terrain or objects, and the ability to generate large images for precise mapping.

Stabilization involves equipping them with stabilization systems to reduce the effects of aircraft movements and vibrations, ensuring clarity even in turbulent flight conditions.

Calibrated sensors and lenses to minimize geometric errors and optical distortions, as well as compatibility with processing software for orthorectification and 3D model generation.

Multispectral and hyperspectral technology means that some aerial cameras allow image capture in the visible spectrum and infrared for agricultural, environmental, or industrial applications.

Low weight refers to a compact design to enable integration on drones or light aircraft.

Automated capture systems involve equipping them with automatic functionalities that synchronize image capture with the aircraft's trajectory, as well as the ability to achieve correct overlaps between images for stereoscopic photogrammetry.

The ground-based camera used for terrestrial photogrammetry can be mounted on a tripod or held manually to capture images at ground level.

Currently, these are equipped with high-resolution sensors (20 MP – 100 MP or more), capable of capturing fine details of the analyzed surfaces. They are also provided with interchangeable lenses featuring a varied range of lenses (wide-angle, telephoto, macro) for optimal capture of different types of subjects, as well as lenses with reduced distortions, calibrated for photogrammetric use.

Sometimes, ground-based cameras are equipped with laser levels or other measurement devices to ensure positioning accuracy.

UAV platforms (Unmanned Aerial Vehicles), also known as drones, are aerial vehicles without a human pilot on board, controlled remotely or autonomously. They are increasingly popular for being equipped with photographic cameras or specialized sensors for photogrammetry. They can be programmed to fly along predefined routes to capture images from different angles and perspectives, being used in a variety of fields, from photogrammetry and environmental monitoring to security and entertainment .

Below are shown some key aspects of UAV platforms:

- Frame – represents the basic structure of the UAV that supports all other components and equipment.
- Motors and propellers – play a role in UAV propulsion, ensuring movement and stability in the air.
- Battery – is the power source for supplying the motors and electronic systems of the UAV.
- Control system – consists of electronic devices and software that enable UAV control, either remotely or autonomously.
- Sensors – are devices that collect data and information about the surrounding environment. These can include photographic cameras, thermal cameras, LIDAR sensors, GPS sensors, etc.
- Communication system – enables communication between the UAV and the operator or control system.

At the same time, over time, several types of UAV platforms have been developed, such as:

- Multirotors – are UAVs with multiple motors and propellers, offering excellent maneuverability and suitable for aerial photography, monitoring, and other applications.
- Fixed-wing – are UAVs with fixed wings, similar to traditional aircraft. They are efficient for long-duration flights and large distances and are often used for mapping and extensive terrain monitoring.
- Hybrids – some UAVs are designed to combine the characteristics of multirotors with the advantages of fixed wings, thus providing versatility in different flight scenarios.
- GNSS sensors (Global Navigation Satellite System) – are used to determine the exact position and altitude of the camera during image capture. These data are essential for ensuring the geospatial accuracy of photogrammetric data.

- Inertial sensors – measure the movements and accelerations of the camera during image capture. This information is useful for correcting distortions and ensuring data recording accuracy.

Processing software is necessary to transform captured images into geospatial data and three-dimensional models; various specialized photogrammetry software programs are used. These programs perform processes such as orthorectification, stereorestitution, and the creation of digital terrain models. Examples of such software include Pix4D, Agisoft Metashape, and ERDAS IMAGINE.

The difference between the earliest photograms and those created by drones is enormous, due to technological advancements and new image capture methods. Here are some major differences between the two:

- **Image capture method**

The earliest photograms were obtained using film cameras mounted on balloons or aircraft. These cameras had technical limitations, and producing photographs was a costly and laborious process. In contrast, drones are equipped with digital cameras or specialized sensors that allow rapid and precise image capture.

- **Image quality**

Early photograms were usually black-and-white and had limited resolution and clarity. Additionally, distortions and errors recorded during the capture and development process could affect their quality. In comparison, drones can capture high-resolution color images, providing extremely precise and clear details of the terrain and objects.

- **Accessibility and cost**

In the past, aerial photography was a costly and restricted activity that required special equipment and trained personnel. In contrast, drones are more accessible and easier to use, allowing anyone to capture aerial images without significant investment in equipment or special training.

- **Flexibility and maneuverability**

Past aerial photography involved risks and restrictions related to the maneuverability and control of aircraft. Drones offer significantly greater flexibility and maneuverability, being able to access and photograph areas that are difficult or dangerous for traditional aircraft.

- **Data processing and analysis**

Photograms from the past required a laborious manual process for development and interpretation. In contrast, images captured by drones can be processed and analyzed quickly and automatically using specialized photogrammetry and image processing software. (Bonn, F. et al 1992), (Bogdan-Andrei M., 2008), (Gheorghe M.T., 2020).

Overall, drone-created photograms represent a significant evolution compared to traditional photograms of the past, offering greater accessibility, quality, and flexibility in collecting and analyzing spatial data. These advances have enabled a wider range of applications and uses for photogrammetry, including in fields such as mapping, topography, architecture, urban planning, and mining operations.

Currently, following the implementation of modern capture technologies, rapid image processing methods have also been implemented.

Image pre-processing is the first procedure preceding image capture; these can be initially processed to eliminate minor errors and prepare them for further processing. This pre-processing may include distortion correction, exposure adjustment, or noise removal from the image.

Following this procedure, obtaining orthophotograms and digital orthophoto plans requires going through the following stages:

Geometric correction, through which the captured images undergo a geometric correction process to bring them into an orthogonal or planar projection. This involves eliminating distortions caused by the tilt and altitude of the camera at the time of image capture.

Georectification is performed after geometric correction; the images are georectified to associate them with a specific geographic coordinate system or cartographic projection. This ensures that each pixel in the image is assigned a precise geospatial coordinate.

Compilation and mosaicking occur if the area of interest is covered by multiple images; these are compiled and mosaicked to create a continuous and homogeneous image of the entire area. This process may also involve correcting overlaps between images to ensure a smooth transition.

Adding geographic information involves, at the end, implementing additional information, such as altitude data or thematic information, which can be added to the orthophotogram to provide richer and more useful context for end users.

Nowadays, orthophotograms and digital orthophoto plans are widely used, thus creating minimum precision requirements for their creation as follows. (Bonnet al 1992), (Bogdan-Andrei, 2008), (Gheorghe, 2020)

In the table below, the technical specifications for producing digital orthophoto plans at a scale of 1:5000 by ANCPI are presented, as well as the minimum requirements regarding their accuracy. (https://surveytransfer.net/what-is-a-dtm/).

Table 3.1. *Geometric precision criteria – minimum requirements*

Orthophoto map scale	Pixel size on orthophoto map	Accuracy MDT	Orthophoto plane accuracy
1:5000	±0.50	±1.00	±1.50

DTM – Digital Terrain Model

Planimetric accuracy is less than 1.5 pixels. (https://surveytransfer.net/what-is-a-dtm/). Therefore, remote sensing monitoring is an efficient and non-invasive method for collecting information about the Earth's surface using sensors mounted on satellites, aircraft, balloons, helicopters, or drones. In the context of mining operations, remote sensing can be used to monitor changes in the terrain and mining infrastructure.

The main ways in which remote sensing can be used in monitoring surface mining operations are satellite imagery, change detection, assessment of impact on vegetation, water quality monitoring, land planning and management.

- Satellite Imagery

These are used to obtain information about the land surface, including details on topography, vegetation, and changes in mining infrastructure. These images can be used to monitor the progress of mining works, as well as to identify areas of interest for additional monitoring.

- Change Detection

Remote sensing enables the detection of changes in the terrain, including landslides, mass movements, and relief changes. These changes can be monitored in real time using satellite imagery and can be used to assess the risk of land collapses and other natural or anthropogenic events.

- Assessment of Impact on Vegetation

Remote sensing can be used to evaluate the impact of mining operations on surrounding vegetation. Satellite images can be used to monitor changes in vegetation and to identify areas affected by deforestation and degradation.

- Water Quality Monitoring

Remote sensing can be utilized to monitor water quality in areas affected by mining operations. Satellite images can be used to detect and map water pollution, including leaks of toxic chemicals and other contaminations.

- Land Planning and Management

Satellite images and remote sensing data can be used for planning and managing land in mining operations (Figure 3.3.). This information can be used to identify and evaluate natural resources, to monitor changes in land use, and to develop sustainable land management strategies.

Overall, remote sensing is a valuable tool in monitoring mining operations, providing detailed and up-to-date information about the terrain and mining infrastructure, which can be used to assess environmental impact and to develop risk management strategies. (Bonn et al 1992), (Bogdan-Andrei, 2008), (Gheorghe, 2020).

a b c d

Figures 3.3., a, b, c, d *The four categories of platforms used for remote sensing*

Figure 3.3. a Ground-Based Platforms

Source: (https://theconstructor.org/others/remote-sensing-applications/398/),

Figure 3.3. b Unmanned Aerial Platforms (Drone)

Figure 3.3.c Manned Aerial Platforms (helicopters, low-altitude aircraft, high-altitude aircraft)

Source: (https://theconstructor.org/others/remote-sensing-applications/398/)

Figure 3.3.d Space-Based Platforms (space shuttles, polar-orbit satellites, and geostationary satellites)

Source: (Hua-Dong G et al, 2015)

3.3. Terrestrial LiDAR and Laser Scanning

Modern techniques of terrestrial LiDAR and laser scanning provide the ability to obtain high-precision data regarding the configuration, shape, and structure of the terrain surface in mining areas. These advanced technologies are capable of rapidly and detailed capturing information about the natural relief and associated infrastructure, ensuring an accurate representation of the studied area. The use of these methods enables the generation of detailed three-dimensional terrain models, which are essential for topographic analysis and planning mining operations. Additionally, these techniques are extremely useful in identifying and monitoring subtle changes in the relief, such as settlements or landslides, and in detecting potential deformations of mining

infrastructure, such as dams, slopes, or other critical structures. Thus, terrestrial LiDAR and laser scanning contribute to optimizing the management of mining activities and preventing risks, ensuring a detailed and precise assessment of the exploitation environment.
Terrestrial LiDAR and laser scanning are advanced technologies widely used to obtain extremely precise data about the terrain surface configuration, the condition of mining infrastructure, and slope stability. These state-of-the-art systems use laser beams to perform detailed and high-resolution scans, capturing information about the physical characteristics of the terrain and objects in the surrounding environment. By emitting laser pulses and measuring their reflection time, the technologies generate a dense point cloud that accurately describes the scanned surface.
This method allows the creation of complex three-dimensional maps and digital models of the terrain (DTM - Digital Terrain Model) or surfaces (DSM - Digital Surface Model), providing essential information for monitoring and analyzing conditions in mining operations. In the case of slopes, these technologies are particularly useful for assessing stability and identifying potential risks, such as landslides or erosions.
Furthermore, terrestrial LiDAR and laser scanning contribute to better management of mining infrastructure, such as access roads, dams, and ramps, accurately detecting deformations or degradations. The ability of these technologies to collect data rapidly and with millimeter precision makes them indispensable tools for planning, monitoring, and securing mining works, significantly contributing to accident prevention and optimization of operations. (Gheorghe M.T., 2020).

3.3.1. Terrestrial LiDAR (Terrestrial LiDAR)

Terrestrial LiDAR is an advanced technology that uses laser beams emitted from the ground to measure precise distances between the measurement sensor and the surfaces of objects in its field of view. Through the reflection of these beams from various surfaces, the sensor collects information that enables precise measurements of distances and coordinates, thus generating a point cloud that represents details from the terrain or infrastructure. This point cloud can be processed to create complex three-dimensional models of the studied surface, with extremely high resolution, achieving sub-centimeter precision, ideal for applications requiring very fine details.
Terrestrial LiDAR is widely used in various fields, including monitoring relief changes and ground deformation processes, such as ground movements, landslides, or settlements. In the mining context, this technology becomes an indispensable tool for assessing the stability of mining infrastructure. It enables detailed monitoring of slopes, dams, and other critical structures, detecting

potential deformations or erosions at an early stage, which helps prevent accidents and implement rapid corrective measures.
Additionally, terrestrial LiDAR is crucial in creating extremely precise terrain maps, essential for planning and managing mining works. Due to its ability to provide accurate images of the exploitation environment, the technology contributes to optimizing mining operations, reducing risks, and enhancing safety in mining activities. (Gheorghe, 2020).
In Figure 3.4, two LiDAR scans performed in a surface mining exploration area are illustrated, highlighting the capability of this technology to provide data with a remarkable level of precision. Analyzing the two scans, the details of the terrain geometries can be clearly observed, with high accuracy, faithfully reflecting the physical characteristics of the mineral surface. This precision allows for a much more detailed assessment of terrain conditions and more efficient monitoring of their evolution, thus facilitating correct decision-making in mining operations.

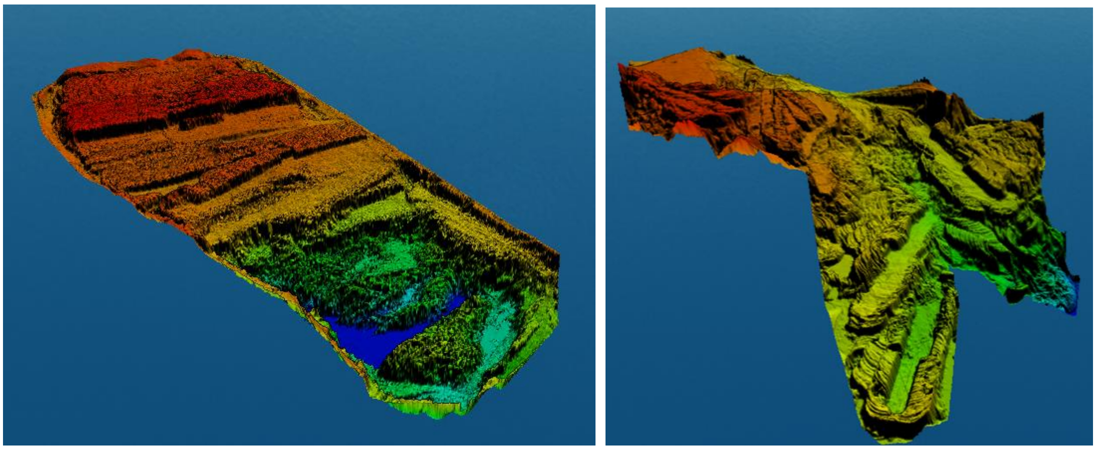


Figure 3.4. *LiDAR scanning in surface mining exploration*
Pesteana Nord and Valea Negomir waste dumps (S-W view) – elevation factor 1/5

The principle of terrestrial LiDAR is based on the use of laser beams to measure distances between the sensor and objects in its detection field.

The operation of terrestrial LiDAR can be described as follows:

- Laser pulse emission:

The LiDAR sensor emits high-speed laser pulses (millions of pulses per second) toward the terrain surface or objects within its range.

- Reflection of laser pulses:

When these pulses hit a surface, they reflect back to the sensor. The time required for each pulse to travel from the sensor to the object and back is measured with high precision.

- Distance calculation:

Using the reflection time of each pulse and the speed of light, the exact distance between the sensor and the object surface can be calculated. The formula used for distance calculation is:

$$D = \frac{c \cdot t}{2} \quad (3.1)$$

where:
1. D is the distance from the sensor to the object,
2. c is the speed of light (approximately 299,792,458 m/s),
3. t is the round-trip time of the pulse.

- Point cloud creation:

By repeating this process for each emitted laser pulse and measuring multiple points on the scanned surface, the sensor collects data that are subsequently processed to form a point cloud. Each point in this cloud has precise coordinates in space (X, Y, Z).

- Generation of 3D models:

The collected data are then used to create detailed three-dimensional models of the surface, which can be utilized for various applications, including terrain analysis, mapping, monitoring relief changes, assessing infrastructure stability, and many others.

Through this principle, terrestrial LiDAR enables the acquisition of highly precise images of the terrain or structures, essential in various fields such as geodesy, topography, mining, environmental conservation, or natural risk analysis. (Gheorghe, 2020).

3.3.2. Laser scanning

Laser scanning, also known as scanning with a laser, represents an advanced technology which uses laser beams to record precise data about the terrain areas and objects from the surrounding environment. This method works by emitting a laser beam which, when meeting an object or the terrain, it reflects back to the scanning sensor. Measuring the necessary time for the laser beams to travel to the object and back, the technology can calculate precise distances between the sensor and the scanned objects. Thereby, the obtained data are transformed into a cloud of 3D points, which represents structural and topographic details of the environment.

Laser scanning can create extremely detailed tridimensional models of the surface, which are used in numerous analysis and monitoring applications. In the mining explorations domain, this technology has an essential role in the exact evaluation of the volume of the excavated material, by creating precise 3D models of the terrain and extracted objects. These models allow a more efficient management of the resources and a better control of the mining operations.

Also, laser scanning is used to monitor the mining infrastructure in real time. This allows detection in existent structures, such as slopes, barrages or access ways, in this way facilitating the identification of stability problems or risk before these become critical. In addition, the technology is capable of providing precise data which help project preventive maintenance solutions, reducing such accident or deterioration risks of the mining exploitation infrastructure.

Thus, laser scanning becomes an essential element in continuous monitoring and risk evaluation, contributing to improve the safety and efficiency in the mining sector, providing precise information in a non-invasive and quick way. (Gheorghe et al, 2020), (Traian et al 2017)

Figure 3.5. **Polaris Terrestrial Laser Scanner (TLS) Series**
Source: https://www.e-mj.com/features/slope-monitoring-tech-trends-spread-safety/

Laser scanning is based on the principle of distance measurement using a laser beam. The technology works by emitting a laser beam from a sensor to an object or an area, and the beam reflects back to the sensor of origin. Measuring the return time of the reflected beam, the sensor can calculate the exact distance up to the scanned object. This technique is also known under the name of time-of-flight (ToF) or the measurement of the flight time, because it measures how much it took for the laser light to travel to an object and return to its original point.

Using multiple laser beams which are emitted from different angles and positions, the laser scanners can record a vast quantity of data, generation a cloud of 3D points (point cloud). Each point from this cloud represents a point measured on the scanned terrain and has precise information about the tridimensional position of that point in space.

These points can then be processed to create detailed digital models of objects, surfaces, or even entire terrains, in an extremely fast and accurate manner. Due to this ability to capture a large number of points in a short time, laser scanning is extremely useful for obtaining high-precision data in a wide range of applications, from 3D mapping and modeling, to infrastructure monitoring and safety assessment in various industries, including mining.

In conclusion, by using a laser beam and the time-of-flight measurement technique, laser scanning allows obtaining precise 3D models of objects and surfaces, with applications in multiple fields, including monitoring ground stability and mining infrastructure.

Electromagnetic radiation, including light, has both wave and particle characteristics.

This is described by parameters such as wavelength, frequency, and intensity.

In this context, equation (3.2) describes light as being made up of photons, particles without mass, but with an energy E, which is inversely proportional to the wavelength λ.

$$E = \frac{h \cdot c}{\lambda} \quad (3.2)$$

where h=Planck's constant (6.6262 10-34Js) and c=speed of light (299,792,458 m/s).

Figure 3.6. describes the classification of electromagnetic radiation according to wavelength. (George et al, 2009)

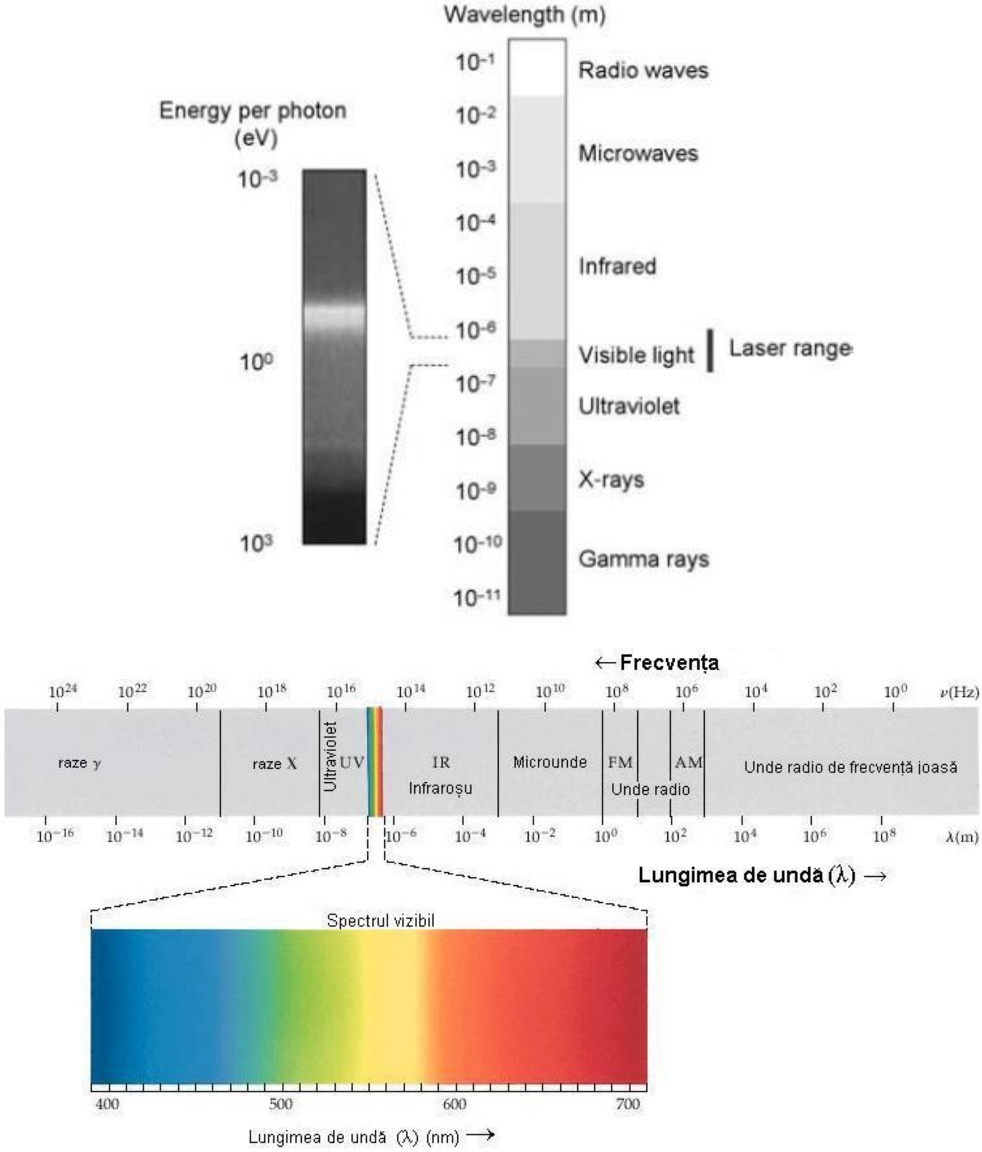


Figure 3.6. *Electromagnetic spectrum and the wavelength for a laser*
Source (George et al, 2009)

The visible spectrum is between 400 nm and 700 nm wavelengths, while the laser range covers a range between the infrared and ultraviolet regions of the electromagnetic spectrum. The emitted light follows distinct paths, and when it hits an object, some of the electromagnetic radiation is reflected by its surface.

Reflectance is defined as the ratio of the radiation reflected to that received by the surface. A surface can reflect (Rλ), transmit (Tλ), and/or absorb (Aλ) the energy (E) of the incident radiation (Iλ) received, according to Equation 3.3.

$E_{I_\lambda} = E_{T_\lambda} + E_{A_\lambda} + E_{R_\lambda}$ (3.3)

where λ=wavelength of electromagnetic radiation.

For most surfaces, as the angle of incidence increases, so does the amount of reflected light. This effect is more apparent on reflective or glossy surfaces (for example, at sunrise or sunset, when sunlight strikes the water surface). According to Equation 2, the degree of reflection is influenced by wavelength. (George L. et al, 2009)

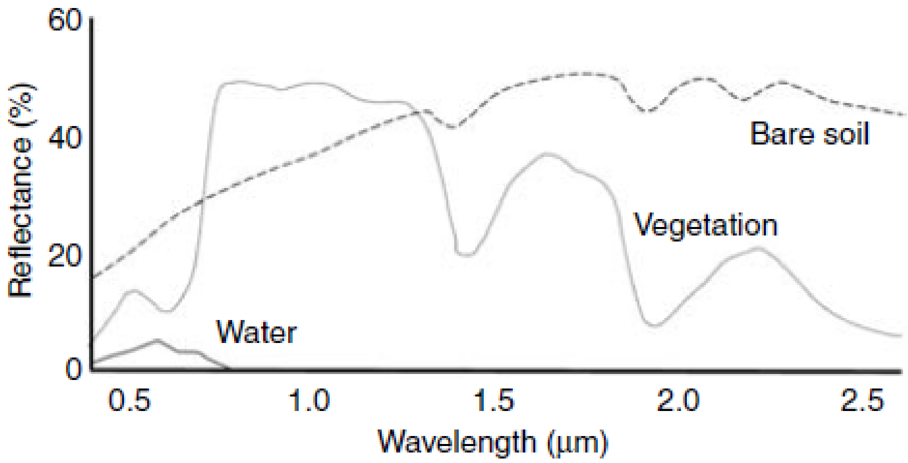


Figure 3.7. *Reflectance of soil, water and mixed vegetation*
Source (George et al, 2009)

Surfaces absorb certain components of the electromagnetic spectrum and reflect at the same time at specific wavelengths (Figure 3.7.). The results of absorption and reflection determine the colors we perceive in the visible spectrum. LiDAR (Light Detection And Ranging) is a remote sensing technique that uses the properties of scattered light to analyze various characteristics of objects at a distance. Synge (1930) was the first to argue that the density of a light beam can be determined by detecting its dispersion in the atmosphere.

LiDAR scanning systems can be classified into three types, each with specific functions:

Differential Absorption LiDAR (DIAL) - measures the concentration of chemicals in the atmosphere, using two different wavelengths of laser light;

Doppler LiDAR - measures the speed of an object based on changes in the wavelength and frequency of the signal returned by the moving object. (George L. et al, 2009)

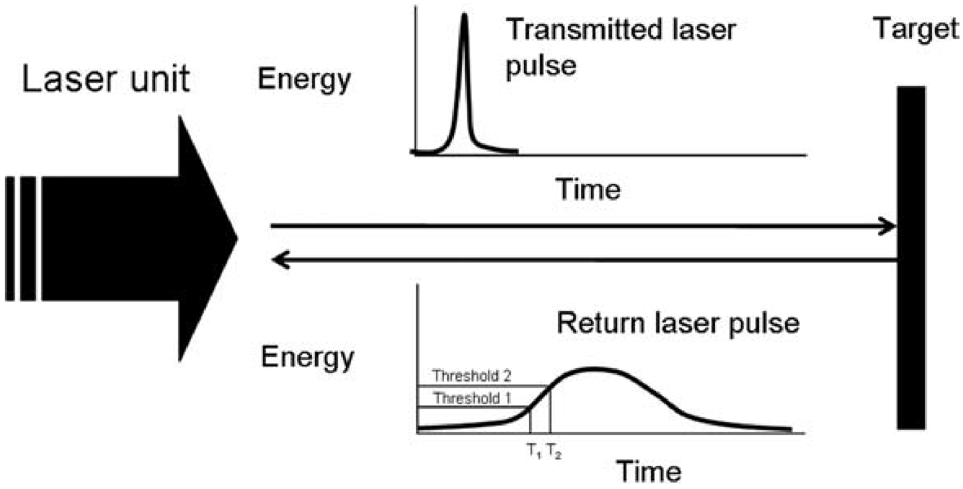


Figure 3.8. *The influence of laser pulse on time of flight for pulsed LiDAR systems*
Source: (George et al, 2009)

Backscatter LiDAR - refers to the reflection of particles or waves in the direction of the beam's origin. Part of the laser pulse returns to the instrument, and the round-trip time of the signal, correlated with relation (3.4) and the ortho geometric information of the device, allows the determination of the 3D position of the target object in space (Brebu F.M. et al, 2010)

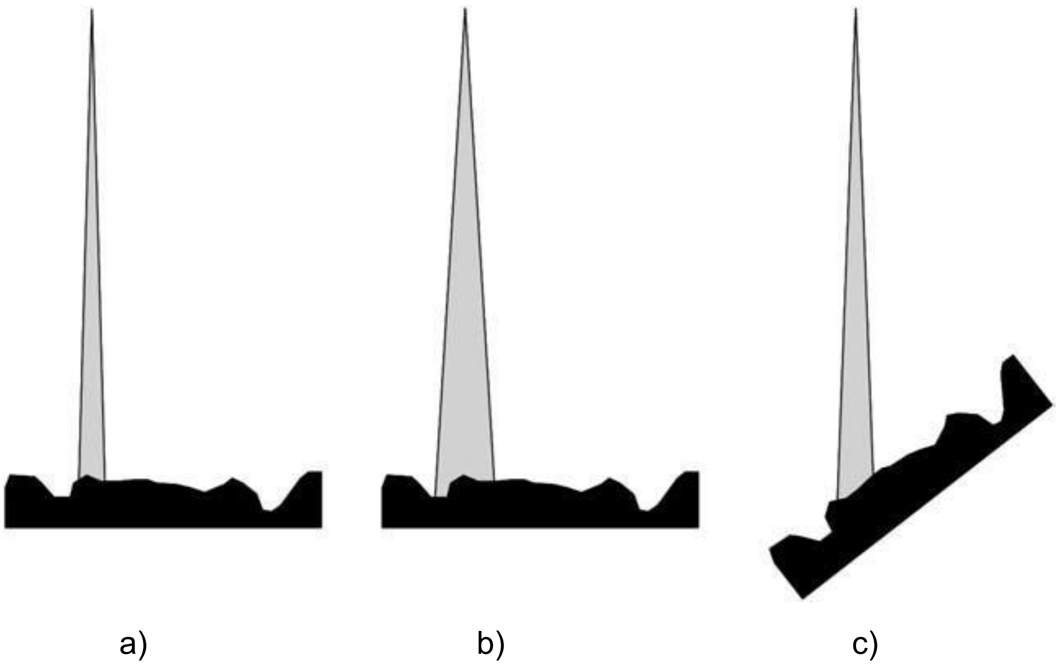


Figure 3.9. *Influence of beam divergence on a) small aperture beam on level terrain b) larger aperture on level terrain and c) small aperture on sloping terrain - for pulsed LiDAR systems*

$D = \frac{c \cdot t}{2}$ (3.4)

where c=constant, the speed of light and t=round-trip time of the emitted pulse. (George L.H. et al, 2009)

3.4. Strain sensors and accelerometers

Mounting strain sensors and accelerometers on mining infrastructure allows for continuous monitoring of stress and strain changes in mining structures. These sensors can provide real-time data and can detect even the smallest changes in stability conditions.

Strain sensors and accelerometers are devices used in monitoring mining infrastructure and the surrounding terrain to detect and measure their deformations and movements. These devices provide essential data for assessing the stability and safety of mining operations, allowing rapid interventions in case of detection of critical conditions. (Delia et al, 2010)

Real-time geotechnical sensors are represented by networks of integrated sensors, such as:

- Inclinometers: Measure lateral movements of slopes.
- Extensometers: Detect the opening of cracks.
- Piezometers: Monitor groundwater pressure.
- Accelerometers: Detect vibrations and rapid movements. (Ebrahim et al., 2024)

3.4.1. Inclinometers

Compared to extensometers, inclinometers have the advantage of measuring deep displacement with a vertical spatial resolution of 0.5 – 1 m.

Measurements are made periodically by installing a single inclinometer in a grooved vertical pipe, located in deep boreholes, to analyze its deformations. Later research introduced the use of multiple analog inclinometers or a set of digital inclinometers, positioned at different depths inside the pipes, to allow continuous measurements. However, inclinometers have certain limitations: they are difficult to install, require laborious efforts to operate, have low sensitivity, and are vulnerable to environmental conditions and hazards.

The use of an inclinometer to determine the precise location of slip surfaces is limited by the vertical spatial resolution, especially when the shear band thickness is small.

This approach is impractical for measuring significant lateral deviations for two reasons: the limited range of travel and the high cost of the guide housing.

Electrical inclinometers are the most widely used devices for monitoring subsurface displacements. However, in practice, this method has certain disadvantages, such as limited stability and durability, low sensitivity to electromagnetic interference, high dependence on gravitational force, and considerable signal loss in long-distance transmissions.

Thus, inclinometers are suitable for very slow to slow-moving landslides with a thick shear bandwidth (Figure 3.10.), for which a long monitoring interval and low spatial resolution would be sufficient. Smart landslide monitoring has been widely studied. Recently, numerous research studies have been conducted to overcome the disadvantages of inclinometers by improving spatiotemporal resolution, decreasing costs, providing real-time data, and enabling wireless data transmission.

- Time-domain reflectometry (TDR) is a relatively new method that, similar to radar, uses a coaxial cable and a cable tester (Figure 3.10). A TDR device consists of a TDR step pulse generator, an oscilloscope (or receiver), and a transmission line coupled to a multiplexer for multipoint and multifunction use through various types of sensing waveguides. An electrical pulse is sent down a coaxial cable that has been grouted into a hole by the cable tester. The pulse is reflected when it encounters a crack or distortion in the cable. The reflection is represented by a “crow” in the cable signature. The relative magnitude and rate of displacement, as well as the position of the deformation zone, can be measured instantaneously and accurately. (Lin et al., 2009) examined TDR behavior using laboratory and numerical simulations in an attempt to quantify TDR displacement. (Ebrahim et al., 2024)

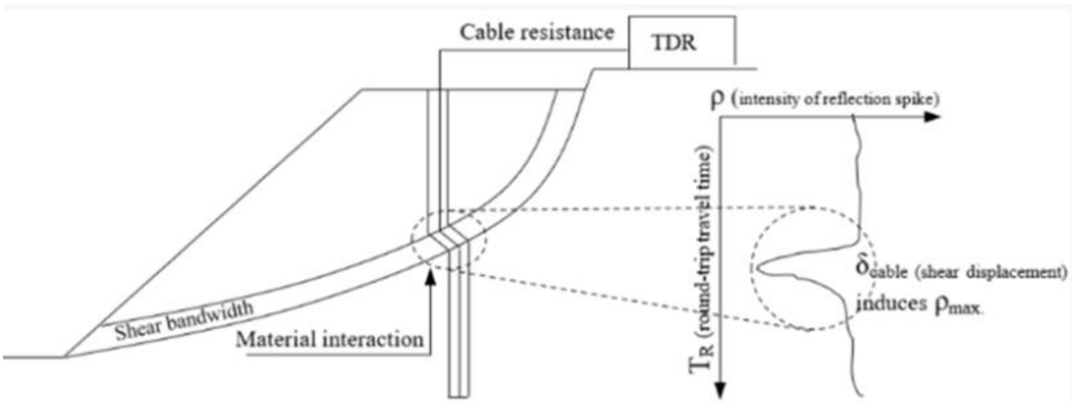


Figure 3.10. *TDR deformation mechanism and influencing factors*
Source (Ebrahim, K.M.P., et al 2024)

- This approach, however, faces challenges when quantifying the amount of displacement. This is because numerous factors influence displacement, including cable strength, soil-grout-cable contact, and shear interaction and bandwidth. As a result, each cable has unique calibration measurement characteristics. TDR is not suitable for fault zones with multiple landslides. TDR is not recommended for fast-flowing landslides or steep slopes that are difficult to access. This method works best on rocky slopes and is less effective on soft soils. Reflection interference from closely spaced landslide surfaces requires further investigation. (Ebrahim et al., 2024)

3.4.2. Extensometer

A conventional wire extensometer enables the continuous monitoring of surface movements that may precede a landslide event. In emergency situations, data may be collected at intervals of 1–3 hours, whereas under routine monitoring conditions, measurement intervals are typically approximately 6 hours. However, to ensure the accuracy of the readings, the wire must be maintained under constant tension.

The magnitude and rate of movement are measured and calculated manually within a centimeter-scale range. Nevertheless, critical events may be overlooked if measurements are not obtained in a timely manner. To overcome the aforementioned limitations, potentiometric extensometers detect displacement through a variable resistance mechanism, in which a movable arm establishes electrical contact along a fixed resistive track. One advantage of this type of instrument is that the cables may be buried.

A cable-extension transducer consisting of a stainless-steel cable connected to a potentiometer housed within a protective casing, where the output voltage is subsequently converted into absolute linear displacement. Fiberglass extensometers were initially installed (horizontally drilled into boreholes) within the S landslide to provide more precise data. This type of extensometer is suitable for rockslide applications, as it is capable of detecting movement within the millimeter range.

- Ebrahim et al., (2024) developed an optical wire extensometer equipped with a rotary optical encoder to count optical pulse signals and convert them into units of length. This approach provides a high resolution of 0.011 ± 0.0083 mm and a velocity limit of approximately 36 mm/s.

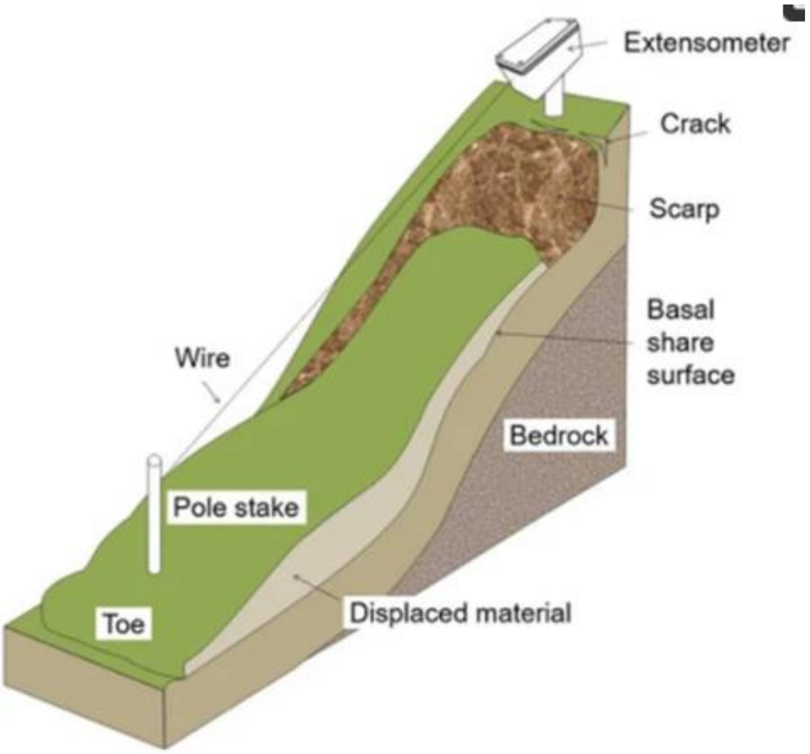


Figure 3.11. *Schematic representation of the extensometer system*
Source: (Ebrahim et al., 2024)

The wire extensometer presents the major disadvantage of collecting data exclusively at the surface of the landslide, thereby limiting the analysis of displacement distribution at depth. Furthermore, this method is considerably costly, with an approximate expense of 1000 EUR for a single monitoring site. As a point-based measurement technique, it does not allow for distributed monitoring.

- Nevertheless, with technological advancements, wire extensometers are capable of providing real-time measurements with high resolution. These devices can be integrated with data logging units and combined with other sensors to enable dynamic landslide analysis. Although the technique is more effective for monitoring translational landslides, it may also be applied to roto-translational landslides and has demonstrated good performance in field experiments involving ground displacements ranging from 12 mm to 150 mm. (Ebrahim et al., 2024)

3.4.3. Piezometers

These devices, although often overlooked or underestimated, play a fundamental role in environmental protection and in supporting the implementation of advanced engineering technologies. They are essential not only for monitoring and preventing environmental risks, but also for optimizing industrial processes and ensuring their long-term sustainability. Through the integration of these innovative technologies, potential ecological issues can be rapidly identified and mitigated, thereby significantly reducing negative impacts on ecosystems and contributing to the development of a more responsible and resource-efficient industry. (Chaulya S.K. et al, 2016)

Figure 3.12. *Piezometer*

Source: (Chaulya S.K. et al, 2016)

These devices are capable of measuring groundwater pressure, providing essential data regarding its depth and level fluctuations. Through the solutions they offer in the fields of environmental conservation and engineering projects, piezometers play a crucial—though often unseen—role in the protection and management of natural resources. Although they may not always receive explicit recognition, they make a significant contribution to ecological balance, exerting a subtle yet essential impact on the preservation of environmental health (Chaulya S.K. et al, 2016).

Figure 3.13. *Piezometers for Groundwater Monitoring*
Source: (Chaulya S.K. et al, 2016)

Piezometers operate based on the principle of hydrostatic pressure, which explains the pressure exerted by a fluid at equilibrium at a specific point. The water column inside the piezometer is influenced by variations in the groundwater level, and this pressure is measured to obtain valuable information regarding the depth and behavior of groundwater.

The data collected by piezometers are highly versatile and have numerous applications. For instance, they play an essential role in ensuring the stability of foundations for high-rise buildings by providing real-time information regarding groundwater levels. In the field of environmental conservation, piezometers monitor both quantitative and qualitative changes in groundwater, enabling rapid intervention to protect ecosystems. Consequently, piezometers have become indispensable instruments in engineering, geology, and ecology (Chaulya S.K. et al, 2016).

3.4.4. Accelerometers

Accelerometers are sophisticated devices that measure the linear and/or angular acceleration of an object relative to a fixed reference system. They operate based on several technological principles, including piezoelectricity, microelectromechanical systems (MEMS), and capacitive sensing technologies for motion detection (Chaulya S.K. et al, 2016).

Essentially, accelerometers detect inertial forces acting on an internal mass when the device is subjected to motion. These measurements are converted into electrical signals that can be interpreted to determine acceleration, velocity, direction, and amplitude of movement.

In the mining industry, accelerometers are primarily used for:

- **Ground movement monitoring:** Detection of vibrations and ground movements caused by blasting, landslides, or other mining activities.
- **Infrastructure stability:** Surveillance of mining structures such as tunnels, shafts, and retaining walls in order to identify early signs of instability.
- **Equipment safety:** Monitoring vibrations in machinery and heavy equipment, such as excavators and haul trucks, to prevent wear or mechanical failure.
- **Dynamic assessment:** Analysis of the impact of controlled blasting on ground and structural stability to optimize operations and reduce associated risks.

Advantages of using accelerometers:

- **High accuracy:** Modern accelerometers can measure very small accelerations, making them suitable for detailed monitoring.
- **Real-time data acquisition:** These devices can provide real-time data, which is essential for rapid hazard response.
- **Versatility:** They can be integrated into complex monitoring networks to provide a comprehensive overview of movements and vibrations.

Disadvantages and challenges:

- **Sensitivity to noise:** Accelerometers may record ambient noise, which can affect measurement accuracy.
- **High costs:** High-precision accelerometers may be expensive, particularly when deployed within large monitoring networks.
- **Installation dependency:** Proper installation and calibration are essential to ensure accurate results.

Accelerometers are essential in mining operations for accident prevention, operational optimization, and continuous monitoring of infrastructure and ground safety. They represent a critical component in risk management and in the development of safer and more efficient mining technologies (Delia T. et al, 2010)

3.5. Radar Interferometry

Radar interferometry (InSAR) is a technique that uses radar data to measure ground movements with high precision. It can detect and monitor terrain movements, ranging from landslides to subtle ground deformations, thereby providing a comprehensive representation of ground dynamics in mining areas.

Interferometric Synthetic Aperture Radar (InSAR) is an advanced remote sensing method that employs microwave radar systems mounted on satellites or aircraft to measure and monitor changes in the Earth's surface with very high accuracy. This technique is based on the principle of interference, whereby two or more radar images of the same area are compared in order to detect changes in elevation or ground displacement.

The following are key characteristics and applications of radar interferometry in the context of mining operations:

- **Detection and monitoring of ground deformation:** InSAR can be used to detect and monitor ground deformation in areas affected by mining activities. This includes landslides, slope failures, and other geomorphological changes that may compromise the stability of mining works.
- **Assessment of mining infrastructure stability:** InSAR provides detailed information regarding movements affecting mining infrastructure, such as retaining walls, waste dumps, and other structures associated with mining operations. This facilitates the evaluation of structural stability and the identification of potential risks.
- **Subsidence monitoring:** Mining activities may induce subsidence, defined as the sinking or collapse of the ground above underground excavations. InSAR can be employed to detect and monitor subsidence in near real time, enabling the implementation of preventive or corrective measures when hazardous conditions arise.
- **Risk and damage management:** InSAR supports risk and damage management in mining operations through continuous monitoring of terrain and infrastructure changes, as well as the early identification of emerging hazards. (Delia T. et al, 2010), (https://www.radartutorial.eu/02.basics/rp29.en.html)

3.6. Geotechnical Modeling and Numerical Simulation

The use of geotechnical models and numerical simulations enables the analysis of ground behavior and mining infrastructure performance under various loading and environmental conditions. These models can be employed to assess the risk of ground collapse and other adverse events, as well as to develop appropriate risk management strategies.

Geotechnical modeling and numerical simulation constitute two essential tools for evaluating and managing the stability of mining works in hard rock quarries. These techniques allow engineers and geo-ecologists to analyze the behavior of both the ground and mining infrastructure under different loading and environmental conditions, to identify potential hazards, and to develop effective mitigation strategies.

Key aspects of geotechnical modeling and numerical simulation in mining operations include:

- **Development of three-dimensional models of terrain and mining infrastructure:**
Through the use of specialized software, engineers can create detailed three-dimensional models of the terrain and mining infrastructure, including extraction zones, retaining walls, underground galleries, and other relevant elements. These models provide a comprehensive understanding of site geometry and geotechnical characteristics.
- **Analysis of ground behavior under various loading conditions:** Geotechnical modeling and numerical simulation allow the assessment of ground response to different loading scenarios, such as stresses induced by rock masses, waste dumps, vibrations, and mechanical disturbances. These analyses help identify zones of weakness or degradation and evaluate the risk of collapse or landslides.
- **Evaluation of mining infrastructure stability:** These techniques facilitate the assessment of the stability of mining infrastructure, including retaining walls, pillars, and other support structures. Structural capacity can be determined, and potential stress concentration zones or weak points can be identified.
- **Design and optimization of mining works:** Geotechnical modeling and numerical simulation support the design and optimization of mining operations, including gallery layout and material extraction strategies. These approaches contribute to risk minimization and operational efficiency.
- **Risk and damage management:** These techniques enable the evaluation of risks associated with mining activities and the development of mitigation strategies. Failure scenarios may be simulated to assess their potential impact on the environment and mining infrastructure, thereby supporting preventive and corrective decision-making. (Agnieszka T. et al, 2020)

3.7. Automated monitoring and control systems

The implementation of automated monitoring and control systems within mining infrastructure enables the rapid detection and management of unforeseen changes in operating conditions. Such systems may include alarms and notification mechanisms that alert personnel in the event of hazardous conditions or significant changes in infrastructure behavior.

Automated monitoring and control systems represent essential components of modern mining operations, facilitating continuous monitoring of operational conditions and real-time decision-making for efficient management and worker safety. These systems integrate various technologies and sensors to collect data and regulate different aspects of mining activities.

Key aspects of automated monitoring and control systems in mining include:

- **Environmental condition monitoring:** Automated monitoring systems collect and analyze data on environmental parameters such as air quality, noise levels, radiation levels, and other factors relevant to worker health and safety. These data are used to assess compliance with environmental standards and to identify potential health risks.
- **Operational condition monitoring:** Automated systems monitor and control various operational parameters, including temperature, pressure, flow rate, fluid levels, and equipment performance indicators. These data contribute to performance optimization and the prevention of failures or malfunctions.
- **Failure detection and incident management:** Automated monitoring systems are equipped with sensors capable of detecting incidents such as fires, toxic substance leaks, or equipment malfunctions. They can issue automatic alerts and activate response mechanisms to minimize damage and protect both personnel and the environment.
- **Optimization of operational efficiency:** Automated control systems enhance operational efficiency by continuously monitoring equipment and process performance, identifying areas for improvement, and implementing automated adjustments to maximize productivity.
- **Fleet management:** Automated monitoring and control systems enable centralized management of mining equipment fleets, including tracking location, operational status, and efficiency. These systems support optimal equipment utilization and preventive maintenance planning.

4. INTEGRATED UAV AND TAILORED WIRELESS SENSOR NETWORK DESIGN FOR LAND STABILITY MONITORING

4.1. Possibilities to use UAV equipment

Unmanned Aerial Vehicles (UAVs), commonly known as drones, have transitioned from niche military tools to versatile equipment utilized across nearly every major industry. Their core value lies in their ability to serve as high-altitude data-gathering platforms, performing tasks that are often too dangerous, expensive, or impractical for human personnel

UAVs (drones) have revolutionized land stability assessment by providing a safe, rapid, and high-resolution alternative to traditional ground-based surveying. They are primarily used to capture complex topography and detect early signs of failure, such as tension cracks or subtle displacements, in hazardous or inaccessible terrains. (Paul S. et al, 2022)

Photogrammetry is a valuable tool for slope stability monitoring, offering precise, detailed, and often near real-time surface geometry measurements. It excels at detecting surface changes such as deformations, cracks, subsidence, and bulging - key indicators of instability. Photogrammetry allows surveying of large or hazardous areas without physical access, enhancing safety while capturing critical data. Repeated surveys can be integrated into Geographic Information Systems (GIS) for advanced geotechnical analysis and risk mapping (Hannah et al., 2014), (Dreghici et al., 2025).

By combining multiple aerial or ground-based photographs, photogrammetry generates detailed 3D models of slopes. Comparing models over time highlights changes like surface cracks, erosion, or slumping, especially in carbonate deposits (Dimen et al., 2024), (Hannah et al., 2014), (Dreghici et al., 2025).

Photogrammetry integrates precise visual data with geospatial analysis, making it suitable for both broad and localized monitoring projects (Dimen et al., 2024), (Hannah et al., 2014). Unmanned Aerial Vehicles (UAVs or drones) enhance this method by providing efficient, flexible platforms for capturing aerial imagery. Equipped with GNSS, cameras, sensors, and specialized software, UAVs collect data from hard-to-reach locations (Hannah et al., 2014), (Dreghici et al., 2025).

Images captured by UAVs are processed with photogrammetry software to produce 3D models, orthomosaics, and contour maps. Algorithms triangulate points from overlapping images, generating accurate spatial data correlated with field measurements (Hannah et al., 2014)

Challenges include the need for good lighting and unobstructed views (vegetation can interfere), and reliance on ground control points and camera/software quality. Photogrammetry primarily tracks surface movements and should be combined with geotechnical data to assess subsurface conditions (Dreghici et al., 2025).

4.2. Commercial vs Tailored Smart Sensor Networks for land stability monitoring

Smart sensor networks are increasingly used for land stability and landslide monitoring to provide early warning, support risk mitigation, and improve understanding of slope behavior. Two main implementation approaches are commonly adopted: (i) commercial, vendor-provided monitoring systems and (ii) custom-built wireless sensor networks. This document presents a structured, scientific-style comparison of these approaches, including system architecture, performance, cost, scalability, and operational considerations. A shortlist of representative commercial products is also provided. (Leica Geosystems AG. Monitoring Landslides and Slopes with GeoMoS. Leica Geosystems technical documentation)

Land stability monitoring requires long-term, reliable measurement of geotechnical and environmental parameters such as displacement, pore water pressure, tilt, and rainfall. Advances in low-power electronics, wireless communications, and cloud computing have enabled distributed smart sensor networks capable of near-real-time data acquisition and analysis. Selecting between commercial monitoring systems and custom IoT builds is a critical design decision that affects reliability, cost, and lifecycle performance.

4.2.1. Commercial Monitoring Systems

General Characteristics

Commercial monitoring systems are turnkey solutions provided by specialized vendors. They typically integrate: - Certified geotechnical and geodetic sensors (e.g. piezometers, inclinometers, GNSS) - Ruggedized data loggers and wireless gateways - Proprietary or semi-proprietary software platforms for data management, visualization, and alarms - Vendor-supported installation, calibration, and maintenance services. (Sixense Group. Geotechnical and Deformation Monitoring Solutions. Sixense technical brochures and case studies)

These systems are usually designed to meet industrial or infrastructure standards and are field-proven in large-scale projects.

Advantages

- High reliability and environmental robustness

- Faster deployment and commissioning
- Integrated data quality control and alarm management
- Vendor support, warranties, and long-term service agreements

Limitations

- High capital and operational costs
- Limited flexibility beyond the vendor ecosystem
- Potential data and platform lock-in

Representative Commercial Products

Leica Geosystems – GeoMoS Monitoring System

Automated deformation monitoring platform integrating GNSS, robotic total stations, geotechnical sensors, and environmental sensors with advanced alarm logic.

The very interesting information is: it stores all monitoring information. that is including:

- Long-term deformation history
- Pore pressure vs. displacement relationships
- Rainfall and reservoir level correlation

It is supporting trend analysis, forensic investigations, and regulatory reporting.

Sixense Group – Cyclops™ and GNSS Monitoring Systems

High-precision, automated deformation monitoring solutions for slopes and large infrastructure, including ground-based radar and GNSS-based systems.

The monitoring systems gather measurements and the data is typically processed and visualized via a central platform such as Sixense's Geoscope / Beyond Monitoring to allow engineers to inspect movements and set alarms or reports. 4DBloc are GNSS receivers that monitor ground, structural or surface displacement in real time by computing position changes relative to reference points.

Worldsensing – Loadsensing & Connectivity Platforms

Wireless IoT connectivity and gateway systems designed to network geotechnical instruments over large and remote sites. (Worldsensing. Wireless IoT Connectivity for Geotechnical Monitoring. Worldsensing white papers.)

The core information is: it measures forces, deformation, stress, or displacement, and it produces raw sensor signals

Used in mining, infrastructure, construction, and geotechnical monitoring.

Sisgeo / Geokon / Geosense

Manufacturers of high-quality geotechnical sensors (piezometers, inclinometers, extensometers) often integrated into larger commercial monitoring platforms.

The measurement platform is composed by:

- Vibrating wire sensors (widely used in soil and concrete monitoring)
- Inclinometers and tiltmeters
- Load cells, stress meters, and strain gauges
- Piezometers and data loggers

It is focused on geotechnical monitoring and civil engineering instrumentation, at surface level to ensure safety and stability.

Campbell Scientific

Industrial-grade data loggers and environmental monitoring systems widely used in slope and landslide monitoring projects.

They provide sensors and data loggers that can measure:

- Soil moisture and pore water pressure – to track water infiltration that can destabilize slopes.
- Ground movement – using inclinometers, tiltmeters, or extensometers to detect shifts in slopes, embankments, or landslide-prone areas.
- Seismic activity or vibrations – to detect triggers for slope failures.
- Cracks and deformations – through crack meters and other strain sensors.

The monitoring software platform is closed operable with Campbell's implementation

Common aspects of the commercial implementations

The general architecture of commercial systems

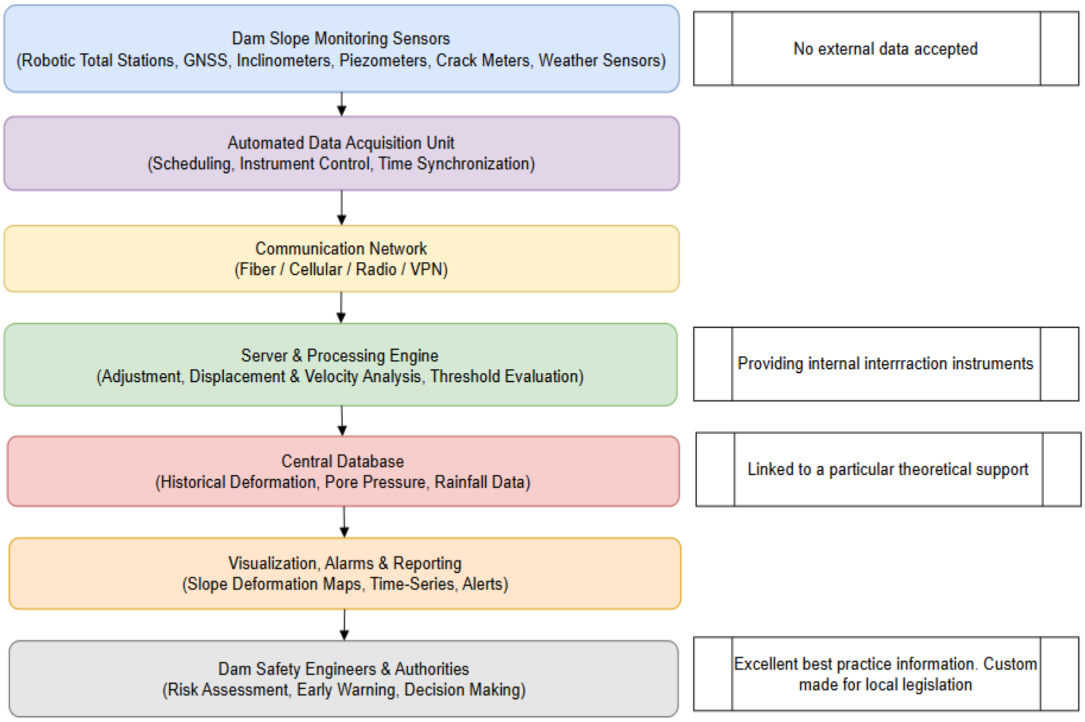


Figure 4.1. *Synthetic representation of "7-layers" monitoring systems (from data entry to regulation process****)***

On the right side of the picture there are emphasized restrictions.

4.2.2. Tailored Network Sensors Architecture Design

General Characteristics

Tailored (custom IoT) builds are designed and implemented by project teams using off-the-shelf components. Typical elements include: - Low-power microcontrollers (e.g. Arduino, ESP32) - MEMS-based sensors (tilt, acceleration, soil moisture) - Wireless communications (LoRaWAN, NB-IoT, LTE-M) - Open-source or custom-developed back-end software (e.g. MQTT, Grafana, custom databases), or, Zigbee- based system on-chips. We could comprise them in a simple name: wireless sensor network (WSN). (Sisgeo S.r.l. Geotechnical Instrumentation Catalogue. Sisgeo technical manuals)

Advantages

- High flexibility and full control over hardware and software
- Lower unit cost, enabling dense spatial sensor deployment
- Easier integration of experimental analytics or machine learning models

Limitations

- Lower robustness compared to industrial-grade systems if not carefully engineered
- Significant in-house expertise required (hardware, firmware, data management)
- Greater responsibility for calibration, maintenance, and long-term reliability

Observation:

That limitation can be reframed as a strength by highlighting the benefits that come from having more control and accountability. We can think to this limitation in the frame of "Enhanced control over performance and quality through proactive calibration and maintenance, ensuring superior long-term reliability and consistent results." (Bennett, G. L., et al 2020)

Typical Use Cases

- Academic and research-oriented monitoring
- Pilot or demonstration projects
- Low-budget or community-based early warning systems

Table 4.1. *Comparative Analysis Reduced only to Common Applications*

Criterion	Commercial Systems	Tailored WSN Builds
Deployment speed	High	Moderate to low
Reliability	High, field-proven	Variable, design-dependent
Cost	High	Low to moderate
Customization	Limited	Very high
Scalability	Moderate	High (node count)
Support & maintenance	Vendor-supported	Self-managed

Hybrid Approaches

In many real-world applications, a hybrid strategy is adopted. High-precision or safety-critical measurements (e.g. pore pressure, deep displacement, GNSS benchmarks) are obtained using commercial sensors and platforms, while custom IoT nodes are deployed to increase spatial density or monitor secondary parameters (e.g. rainfall, shallow soil moisture). This approach balances reliability with cost efficiency. (Intrieri, E., et al 2019)

Conclusions

Commercial monitoring systems and tailored wireless sensor networks each offer distinct advantages for land stability monitoring. Commercial systems are best suited to high-risk, long-term infrastructure applications where reliability and support are paramount. Custom IoT builds are advantageous for research, pilot projects, and cost-sensitive deployments requiring high flexibility. System selection should be guided by project risk level, budget, available expertise, and expected lifecycle duration.

4.3. Designing a Tailored WSN Sensor Architecture: A Layered Approach

A Tailored Internet of Things (IoT) Sensor Architecture is an application-specific framework engineered to meet the unique requirements of domains such as environmental monitoring, industrial automation, and healthcare. It integrates sensing, communication, computation, and data analytics within a hierarchical and modular structure, allowing flexibility and optimization according to the target application.

4.3.1. Layered Architecture - Perception Layer (Sensing Layer)

Objective: Establish a physical interface with the environment to acquire raw data.

Components:

- Sensors: Devices measuring temperature, humidity, motion, gas, pressure, and biomedical parameters, selected based on application-specific needs.
- Actuators: Mechanisms that respond to sensor inputs, e.g., valves, motors, or alarms.

- Edge Microcontrollers: Low-power embedded devices (e.g., Arduino, ESP32, STM32) responsible for initial data acquisition and preprocessing.
- Tailoring Considerations: Sensor selection, placement, and sampling frequency are optimized according to environmental constraints and application objectives.

4.3.2. Network Layer (Communication Layer)

Objective: Facilitate reliable and efficient transmission of sensor data to processing units.

Components and Protocols:

- Short-Range Communication: Zigbee, BLE, LoRaWAN for low-power local networks.
- Long-Range Communication: Wi-Fi, LTE/5G, NB-IoT for cloud connectivity.
- Gateways: Aggregate, preprocess, and translate data from multiple sensors across heterogeneous networks.
- Tailoring Considerations: Network topology (star, mesh, or hybrid) is selected based on coverage, latency, and reliability requirements.

4.3.3. Edge Computing Layer

Objective: Perform local computation to minimize latency and reduce network bandwidth consumption.

Components:

- Edge servers or microprocessors capable of performing local analytics, including real-time anomaly detection.
- Local storage for buffering and temporary data retention.
- Security modules for encryption and authentication.
- Tailoring Considerations: Computational algorithms are selected according to real-time processing needs, with support for AI inference at the edge when required.

4.3.4. Data Management and Cloud Layer

Objective: Enable centralized data storage, advanced analytics, and scalable computation.

Components:

- Cloud platforms or data centers (e.g., AWS, Azure, GCP).
- Database systems (SQL or NoSQL) configured according to sensor data type and volume.
- Big Data analytics pipelines and machine learning models for predictive and prescriptive insights.
- Tailoring Considerations: Cloud-based analytics can be customized for predictive maintenance, environmental forecasting, or healthcare monitoring, depending on the application context.

4.3.5. Application Layer

Objective: Provide end-users with interfaces to visualize, control, and derive actionable insights from IoT data.

Components:

- Web and mobile dashboards for real-time monitoring.
- Alert and notification systems (e.g., SMS, email, push notifications).
- APIs for integration with external platforms, such as smart city infrastructures or industrial SCADA systems.
- Tailoring Considerations: User interface design and analytics outputs are application-specific, focusing on actionable intelligence and operational efficiency.

4.3.6. Security and Management Layer (Cross-Cutting)

Objective: Ensure the integrity, confidentiality, and reliability of the IoT system across all layers.

Components:

- Authentication and authorization mechanisms (e.g., OAuth, digital certificates).
- Data encryption protocols (TLS, AES).
- Firmware update management and device lifecycle monitoring.

- Tailoring Considerations: Security policies are adapted based on risk assessment, differing between industrial, commercial, and domestic IoT deployments.

The simplified architecture of the system is shown in figure 4.2.:

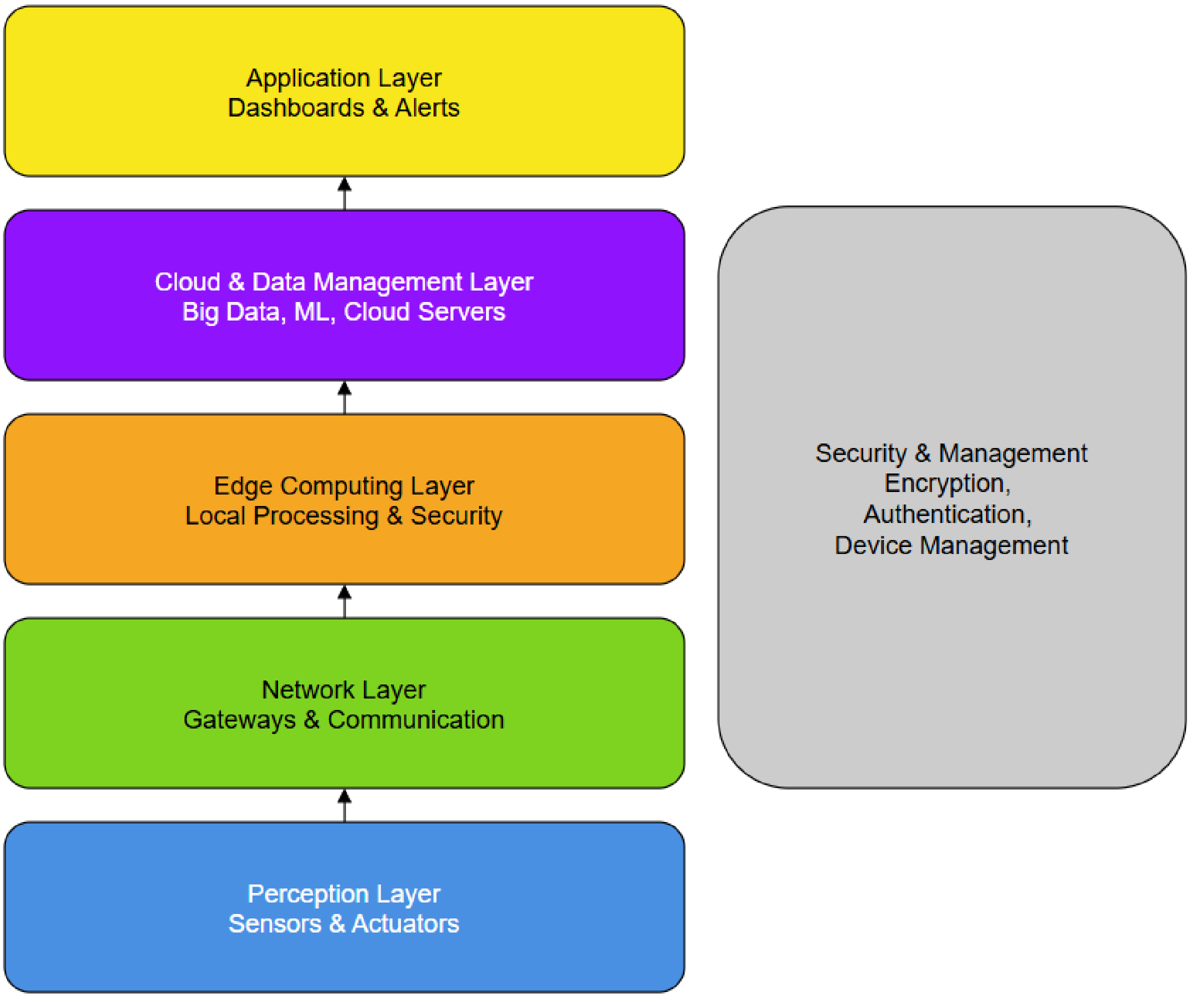


Figure 4.2. *Layered representation of the end-to-end layered architecture: from perception to application*

After adding some perception components, it looks like in figure 4.3:

Figure 4.3. *Examples of the used components in each layer: the representation allows understanding communication flow and typical perceptions*

4.3.7. Data Flow Overview

The typical data flow is shown next:

1. Sensors acquire raw environmental or operational data.
2. Edge devices perform local preprocessing and filtering.
3. Gateways transmit processed data over the network.
4. Edge servers or cloud platforms execute analytics and data processing.
5. Application layer presents actionable insights to users.
6. Actuators respond according to system logic or user commands.

4.4. Design of wireless sensor network

4.4.1. Layout- based design of wireless sensor network

According to preliminary information gathered from the field, the proposed architecture is shown in figure 4.4.:

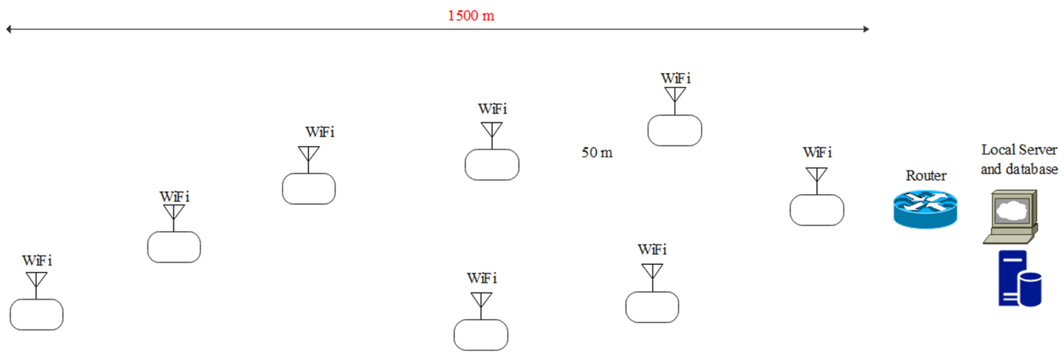


Figure 4.4. *Schematic representation of the network of sensors, and associated components by functions*

The nodes under consideration are equipped with wireless communication capabilities and are distributed along a 1500 m length, with a maximum distance of 50 m between two nodes. It is posited that one of the nodes will assume the role of master, with the remainder functioning as slaves (or, more simply, nodes). In terms of flexibility and production, the architecture of a single node incorporates one or more sensor systems, as illustrated in Figure 4.5.

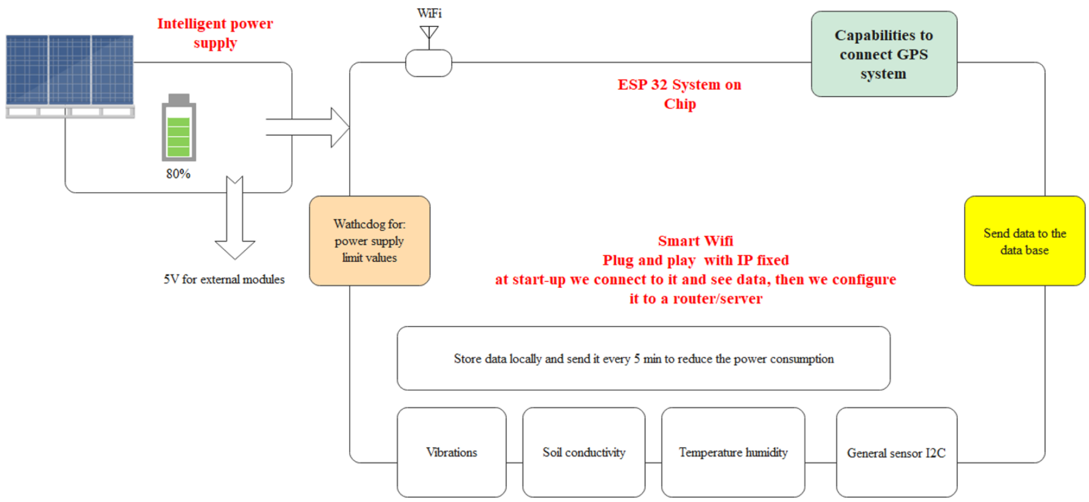


Figure 4.5. *Typical architecture of the designed measurement sensors-conceptual representation*

The core component is a high-level processing microcontroller integrated in one System-on-Chip, with communication facilities (Wi-Fi). The intelligent power supply allows independence of the system in terms of working.

4.4.2. Data exchanging architecture

The general proposed architecture for data exchanging between institutions is shown in figure 4.6.

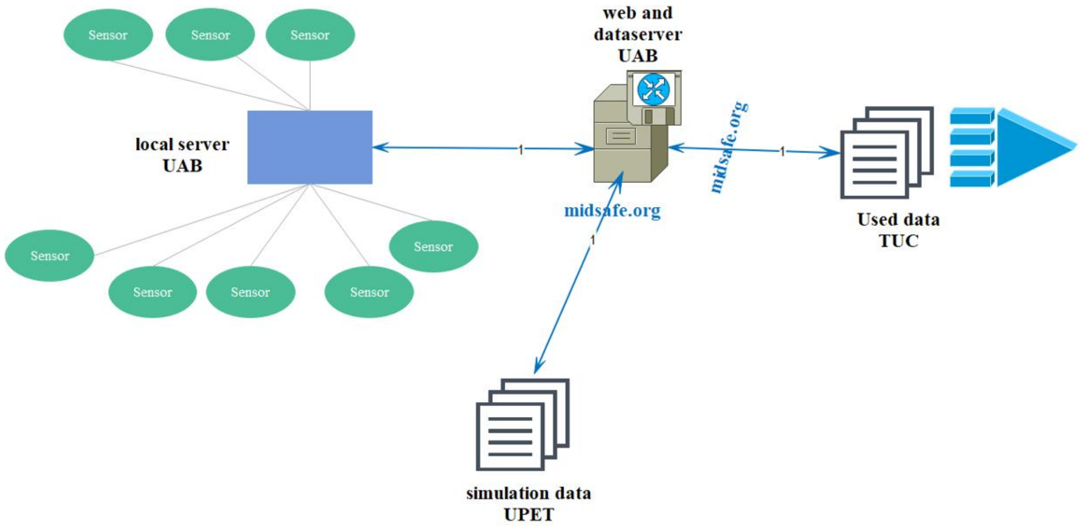


Figure 4.6. *Representation of the collaborative integration of the network of sensors into the partners' roles.*

Three institutions are involved, each with a specific role in the project:

- UAB pushes data to web server
- UPET provides simulation data
- TUC uses data to design rules

The front-end of applications that facilitates data exchanging is in figure 4.7:

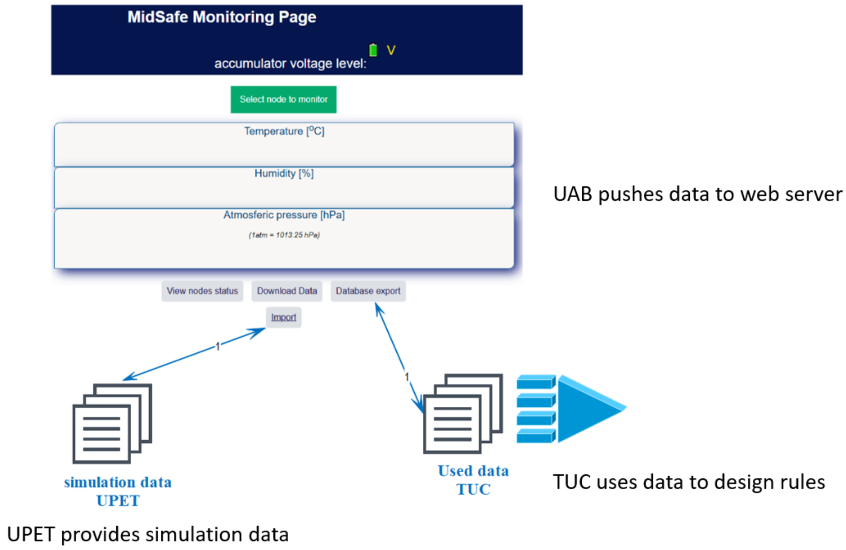


Figure 4.7. *Representation of the collaborative integration for data exchanging with partners' demands.*

From the data flow and usage point-of-view, the structure is able to exchange data in one of the formats, shown in figure 4.8:

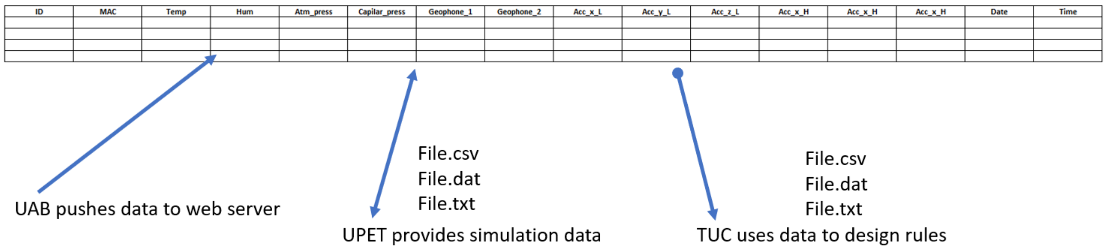
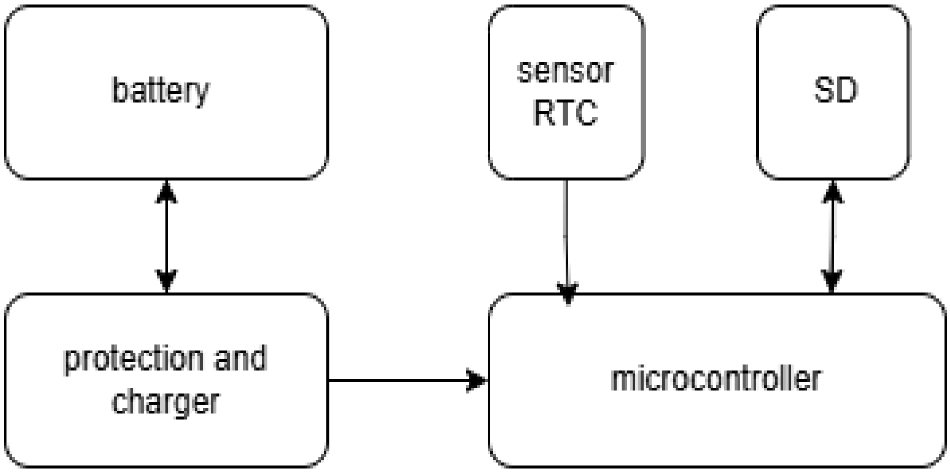


Figure 4.8. *Proposal of the data fusion standardization*

4.4.3. Master module design

The block diagram is shown in figure 4.9.:

Figure 4.9. *Functions- based architecture of a network gateway*



The system presented is a main node in a wireless sensory network, based on the ESP32 microcontroller, powered by a package of 6 Li-Ion 18650 batteries, rechargeable and managed by a charge controller. The stored energy is regulated by a stabilizer and protected against deep discharge. The ESP32 master module communicates with peripheral (slave) modules over Wi-Fi and coordinates data collection from integrated sensors, storing them on an SD card.

Electrical Diagram for Master Node

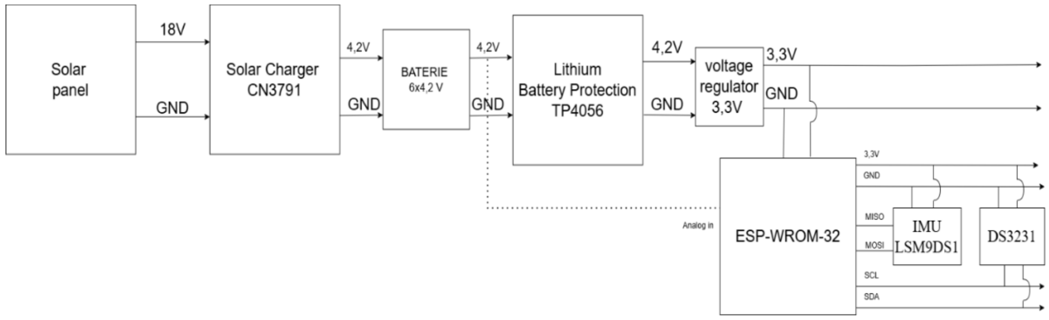


Figure 4.10. *Proposal for secured design of a smart sensor from the power quality point of view- focused of the load generated by the accelerometers-high rate of sampling*

The power supply for the master module is based on an 18.2V solar panel, connected to a CN3791 solar charger, optimized for Li-Ion cells. The stored energy is supplied by six parallel-mounted 2600mAh Li-Ion 18650 batteries, which provide a total capacity of approximately 15.6Ah at 4.2V. In the master module scheme (Figure 4.10.), the battery level is monitored using a resistive divider connected to an ADC channel of ESP32. This divider reduces the maximum voltage of ~4.2V of the battery to a safe value for analog input of the microcontroller.

After the charging stage, the signal passes through a TP4056 protection module that prevents deep cell discharge and ensures system safety. The voltage is then regulated by a 3.3V LDO stabilizer, which is required to supply the ESP-WROOM-32 module directly and the connected sensors: IMU LSM9DS1and DS3231 RTC.

This source is designed to support around 300mA of permanent consumption due to active Wi-Fi communications and continuous operation of attached components.

Essential components:

- Solar panel: 18V
- Charging controller: CN3791
- Battery: 6x Li-ion 18650, 2600mAh, in parallel
- Battery protection: TP4056
- Voltage regulator: 3.3V LDO

The 3D assembly of the master module is made on a PCB with approximate dimensions of 50 mm x 60 mm, where both the ESP32 microcontroller and the associated sensors are mounted (such as RTC DS3231 and IMU LSM9DS1). The plate can be encapsulated in a sealed housing with IP65 protection, suitable for use in outdoor environments, protecting the assembly from dust, moisture and thermal variations. The component layout on the board has been optimized for short, clear routes, ensuring signal integrity and energy efficiency. 18650 Batteries are mounted in parallel, and internal connections are made both by fixed soldering and clamps, depending on positioning or maintenance needs.

3D Design master

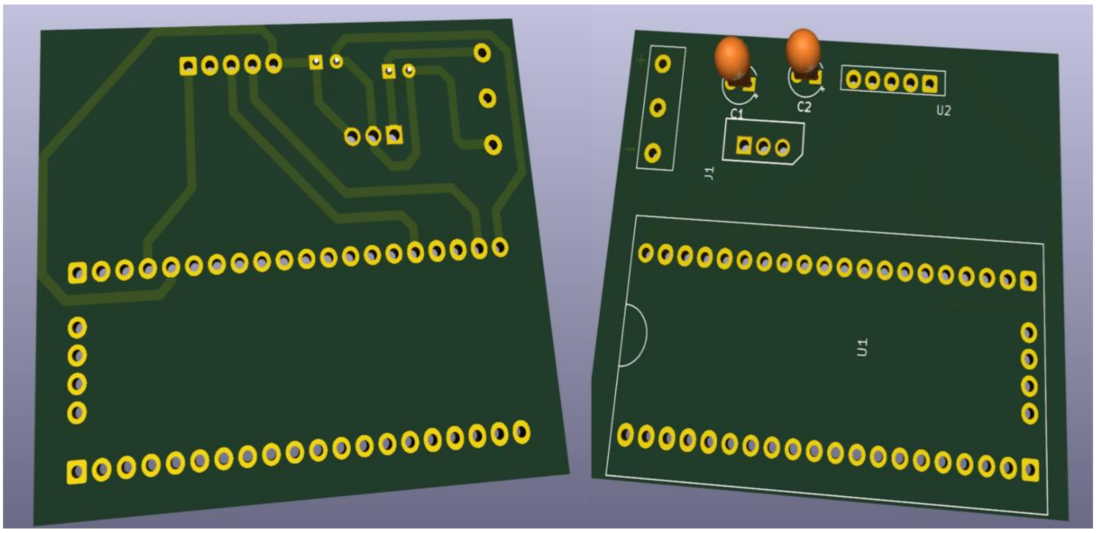


Figure 4.11. *Samples of designed PCB's for the gateway's prototypes*

4.4.4. Power supply autonomy considerations

The master module, based on the ESP32 microcontroller, is powered by an autonomous system consisting of six Li-Ion 18650 batteries of 2600 mAh connected in parallel, providing a total capacity of about 15.6 Ah, recharged through a mono-crystalline solar panel of 18.2V, controlled by a CN3791 circuit optimized for Li-Ion cells. Charging is efficiently managed, and deep discharge protection is provided by the TP4056 module, while voltage stabilization at 3.3V is done with an LDO regulator, necessary for powering ESP32 and integrated sensors such as RTC and IMU. This power system is designed to support a constant consumption of about 300 mA, ensuring a range of over 24 hours, including in conditions where the solar panel is not active, making it ideal for autonomous applications in external environments.

Degree of voltage fluctuation on master (~30 hours)

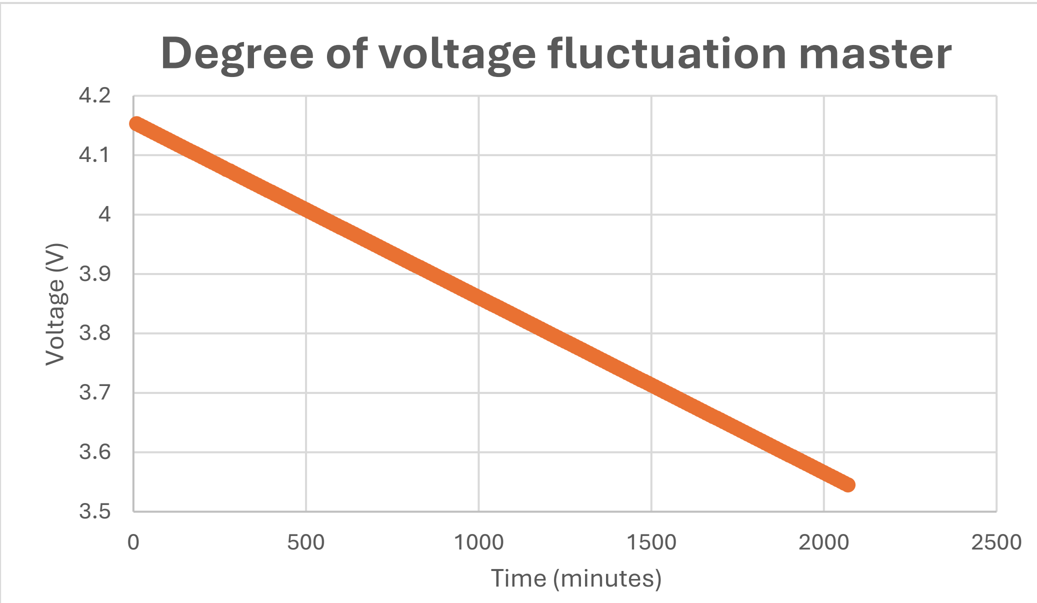


Figure 4.12. *Voltage variation during the power consistency tests*

Estimation of autonomy is about 27–30 hours made in the form of a graphic in the previous figure.

4.4.5. Designing the node measuring hydrostatic pressure, humidity and temperature

The block diagram is shown in figure 4.13:

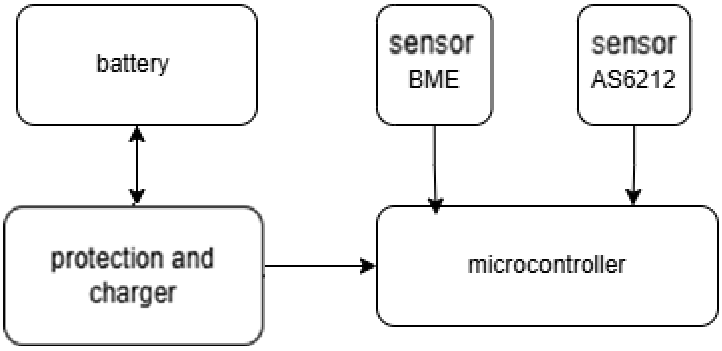


Figure 4.13. *Functions- based architecture of a smart sensor*

The slave module illustrated in the block diagram is intended for monitoring environmental parameters, being equipped with two main sensors: BME680, which measures temperature, humidity, atmospheric pressure and air quality, and AS6212, a high-precision pressure sensor. Power is provided by a rechargeable Li-Ion 18650 battery. The heart of the system is an ESP8266 (ESP-01S) microcontroller that processes sensor data and transmits it to the master node over Wi-Fi. The module is optimised for low energy consumption, ideal for hydrostatic and ambient monitoring applications in external environments.

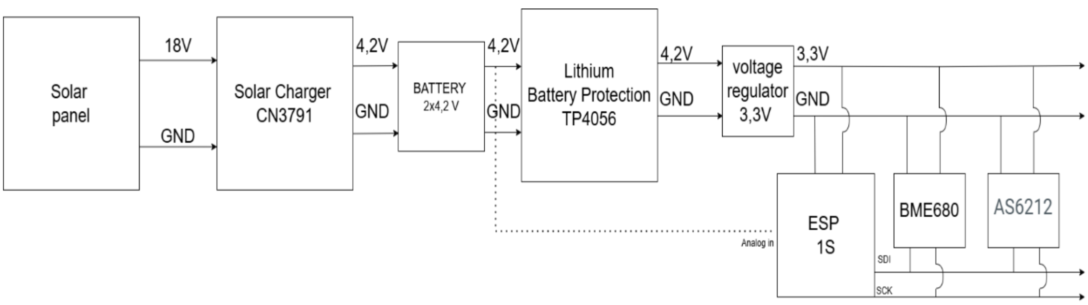


Figure 4.14. *Proposal for secured design of a smart sensor from the power quality point of view- focused on general load- low rate sampling*

Electrical Diagram slave node with bme680

The BME680 sensor-powered slave module is designed as an autonomous unit for the acquisition and transmission of environmental data, integrating an ESP8266 (ESP-01S) microcontroller, powered by two parallel-connected Li-Ion 18650 batteries, into a compact structure. The energy is managed by a solar system consisting of a photovoltaic panel of 18.2V, a charge controller CN3791 and a protection module TP4056, which provides both efficient battery recharge and protection against deep discharge. The voltage is stabilized at 3.3V via an LDO regulator to power both the microcontroller and the connected sensors. The BME680 sensor provides data on temperature, pressure, humidity and air quality, and the AS6212 sensor provides additional pressure measurements with high precision. The microcontroller manages data acquisition and wireless communication with the ESP32 master node, ensuring synchronization through an RTC module. Thanks to its low consumption (approx. 50–70 mA) and distributed power architecture, the module achieves a range of over 36 hours without recharging, being suitable for ambient and hydrostatic monitoring applications in external environments. The electrical scheme reflects this efficient component integration, supported by a 3D design optimised for energy stability and durability. The 3D assembly is shown in Figure 4.15.

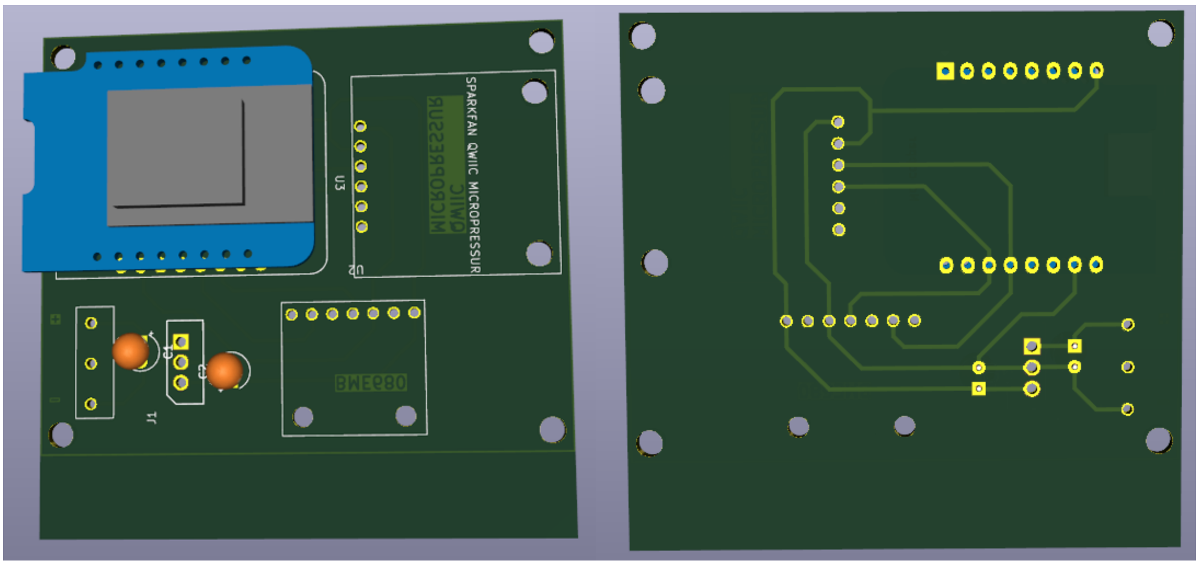


Figure 4.15. *Samples of the PCB's for the sensors' prototypes*

Figure 4.15 shows the three-dimensional model of the first slave module, part of a distributed wireless sensor network built around the ESP-01S microcontroller and equipped with the BME680 ambient sensor. This module is powered autonomously by a Li-Ion 18650 battery-based solar-charged power source, according to the electric scheme.

The PCB design is optimized for compactness and functional simplicity, with approximate dimensions of 50 mm x 60 mm. On top of the board (left in picture) the connector for the ESP-01S module is mounted, which provides Wi-Fi connectivity and control of the attached sensors. Next to it, the footprint for the BME680 sensor is observed, which measures temperature, humidity, pressure and air quality, with I2C communication.

The passive component visible in the model (two SMD capacitors) is part of the module power supply filter circuit, contributing to the stability of the 3.3V voltage provided by the LDO regulator. The connection of the power supply is made by edge pins or plugs with glued terminals.

On the lower side of the PCB (right in the picture), copper paths and ground areas are observed, arranged symmetrically to minimize electromagnetic interference and ensure good signal integrity. The structure is clearly segmented between power (power supply) and data paths, ensuring logical separation and reduction of coupling noise.

The module is part of a network with distributed architecture, in which the ESP32 master node communicates permanently with two such slavic nodes. The module described is dedicated to the acquisition of environmental data, especially for outdoor applications, which can be encapsulated in an IP65 housing according to the requirements of resistance to humidity and extreme temperatures (operation between -35°C and +85°C, according to the datasheet of the components).

4.4.6. Power autonomy considerations

The module operates autonomously, powered exclusively from its own sources, sized to ensure a continuous operating autonomy of at least 24 hours, even in the absence of sunlight.

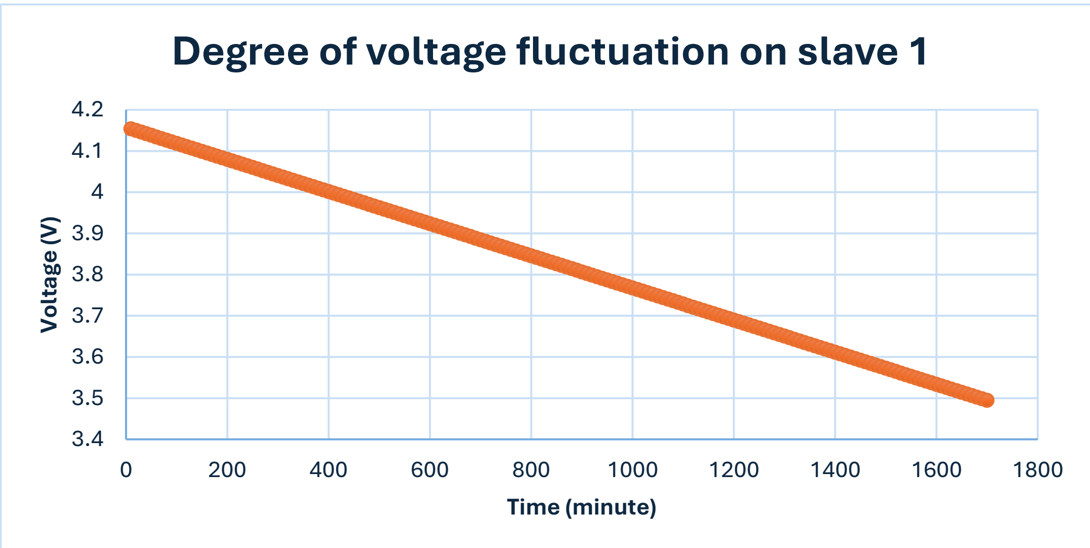


Figure 4.16. *The voltage variation of the sensor with high rate of sampling (x-axis minutes)*

In real operating conditions, where the solar panel is idle (no light), the battery autonomy was measured between 27 and 32 hours, significantly exceeding the minimum projected threshold of 24 hours.

Under direct solar lighting, the current supplied by the panel is sufficient to fully recharge the batteries within a day. Charging system efficiency managed by CN3791 was estimated at over 90% under optimal conditions, according to the report.

However, Li-Ion batteries are most sensitive to extreme temperatures:

- at temperatures below 0°C, the effective capacity drops drastically (below 50% at -20°C).
- 60°C above, it is necessary to limit the charging current and supervise the temperature to avoid electrochemical degradation.

4.4.7. Designing nodes for general data acquisition

The block diagram is shown in figure 4.17:

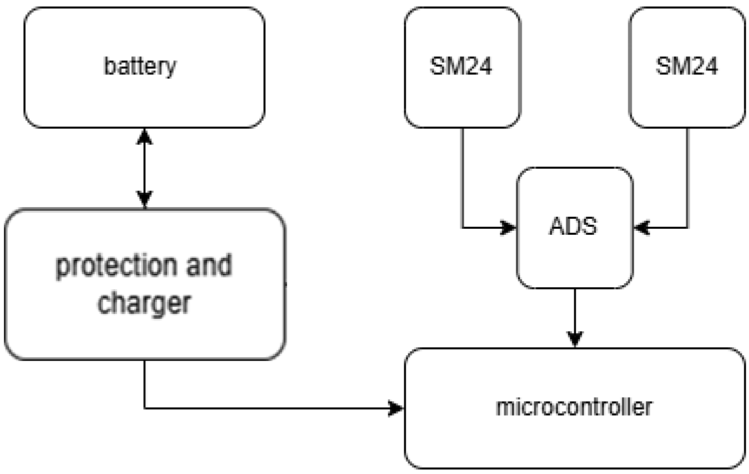


Figure 4.17. *Functions-based architecture of the protection sensor*

The second slave model represented in the block scheme (Figure 4.18) is intended for the acquisition of analog signals from SM24 vibration transducers, integrated by an analog-digital converter, coupled to a microcontroller. The module is powered from a Li-Ion battery, charged using a photovoltaic projection and charging system. The working voltage is adjusted to 3.3V, ensuring optimal operation of the microcontroller and related circuits. Data taken from SM24 sensors is converted by ADS1115 and transmitted over Wi-Fi to the ESP32 master node.

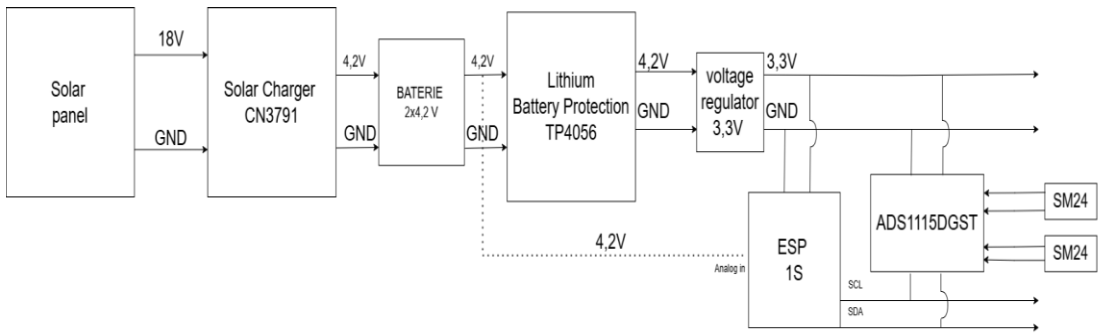


Figure 4.18. *Proposal for secured design of a smart sensor from the power quality point of view- focused on geophone load- highrate sampling*

The slave module shown in the electrical scheme is designed for the acquisition of high-resolution analog data and is built around the ESP-01S microcontroller. Power is provided by an 18.2V solar panel, connected to a CN3791 charging controller, which charges two parallel-mounted Li-Ion 18650 batteries. They are protected against deep discharge through the TP4056 module, and the voltage is stabilized at 3.3V with the help of an LDO regulator, necessary for the correct operation of the microcontroller and the associated circuits.

The module is optimized for vibration monitoring applications and the ADS1115 converter enables precise acquisition of analogue signals from sensors such as SM24, used for vibration detection. Communication with the ESP32 master node is done wirelessly, via Wi-Fi, and the average energy consumption of about 50–70 mA. The 3D assembly is shown in figure 4.19.

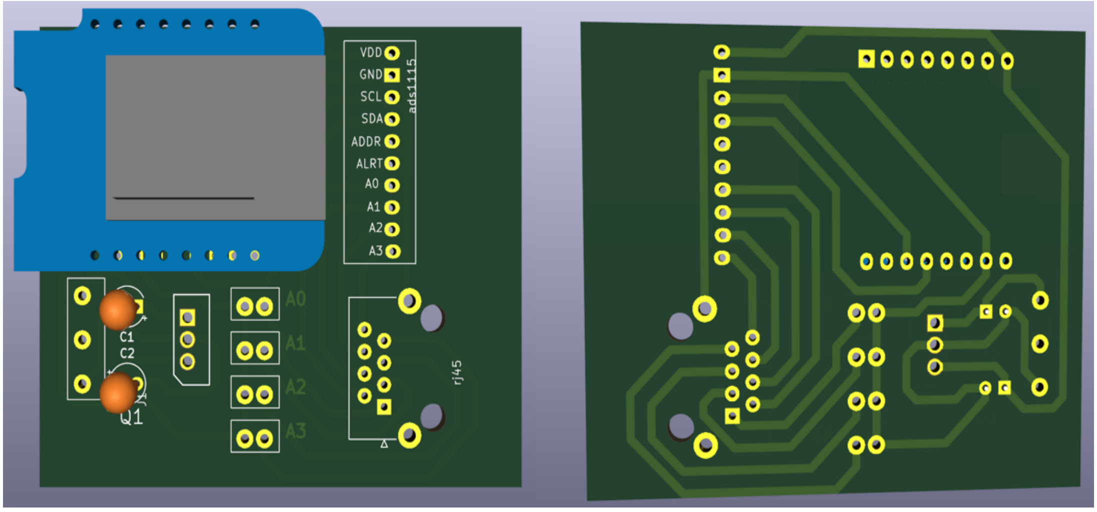


Figure 4.19. *PCB's for the geophone's prototypes*

The Figure 4.19, presented above, shows the three-dimensional model of the slave 2 module, designed for the acquisition of analog data from geophones. This module is built around the ESP-01S microcontroller, which provides Wi-Fi connectivity and data transmission to the central node (master ESP32).

On the top face of the board (left in picture) is the ESP-01S module, and in the immediate vicinity is the footprint for the ADS1115DGST analogue-to-digital converter. This is a high-resolution (16 bit) converter capable of picking up differential signals from the SM-24 geophone or other sensitive analogue sources.

On the board are provided four analogue inputs A0–A3, corresponding to ADS1115 channels, which allow direct connection of two geophones in a differential mode, the ads1115 is obsessed with the rj45 footprint to which they come connected via the SM24 sensors wires. Visible on the left are passive decoupling and stabilization components (capacitors C1 and C2), as well as the integrated voltage regulator circuit, essential for signal conditioning.

The lower part of the board (right in the picture) illustrates the copper paths, carefully routed to separate the analogue signal lines from the digital or power lines, minimizing interference and preserving signal integrity. The I2C lines (SCL, SDA) that link the ESP-01S to the ADS1115 are also observed.

This module is essential in the sensory network infrastructure, ensuring accurate pick-up of geophone signals for applications such as vibration monitoring, seismic waves or structural testing.

4.4.8. Power considerations for autonomy ensuring

The slave 2 module, equipped with ESP-01S microcontroller and high resolution ADS1115 analog-digital converter, is powered from an autonomous source designed to ensure continuous operation in isolated mode for a minimum of 24 hours without external power input. The energy architecture of this module is built on the basis of efficient and reliable components, optimized for low consumption and operation in outdoor environments.

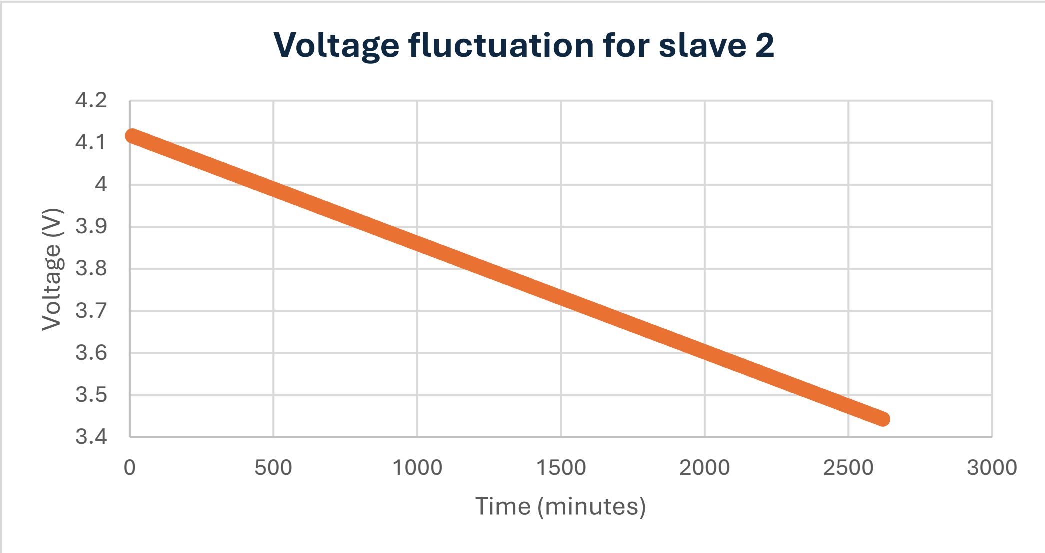


Figure 4.20. *Voltage variation of the power for the geophone sensor (x- axis minutes)*

The experienced autonomy, in the absence of solar lighting (full discharge without recharging), ranged from 36 to 42 hours (Figure 4.20), demonstrating a significant energy reserve above the minimum 24-hour threshold imposed by design requirements.

Under moderate to good sunlight conditions, the solar panel generated current is enough to fully recharge the batteries in the course of a day, and the CN3791 controller maintains the conversion efficiency above 90% in optimal conditions.

The whole system is designed to operate in the thermal range -35°C to +85°C. Electronic components, including ESP8266 and ADS1115, are industrially qualified, and solar panels and connections are mechanically and electrically adapted for this regime.

However, Li-Ion batteries are most sensitive to extreme temperatures:

• at temperatures below 0°C, the effective capacity drops drastically (below 50% at -20°C).

• 60°C above, it is necessary to limit the charging current and supervise the temperature to avoid electrochemical degradation.

4.4.9. Particular design for analogue vibration and seismic sensors

Software- based approach in designing is shown in Figure 4.21. The image is a simplified block diagram of a 4-geophone data acquisition system, structured around an ESP32 microcontroller, two ADS1115 analog-digital converters, and a PC running a data reading and processing application.

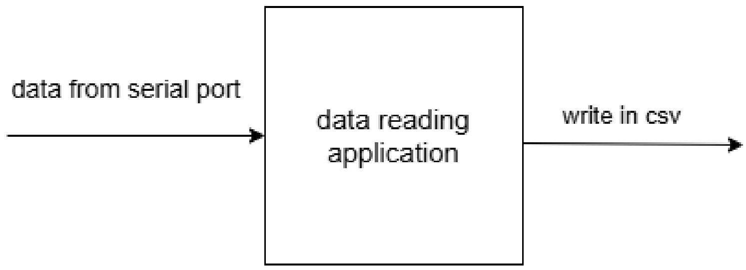


Figure 4.21. *Blackbox representation the hardware- software synthesis*

The proposed acquisition system is based on the use of four geophones each capable of capturing vibration variations or seismic waves. The signal from each geophone is converted to digital format using an analog-to-digital converter (ADC) and integrated into a microcontroller (ESP32), either separately, with an ADS1115 module in differential mode. The data thus obtained is transmitted through serial port to a computer, where it is retrieved by a software application made in Processing.

The software interface (Figure 4.22) made in the Processing environment plays a key role in the operation of the system. This allows to configure the system, receive and display data, as well as save them to a CSV file, ready for further analysis. The graphical interface is created using the ControlP5 library, which provides visual components such as drop-down menus, buttons and text fields.

The main software functions are:

• Series of serial port: from an automatic list of detected ports, the user selects the correct device.

• Definition of the number of variables: the application allows the setting of a number from 1 to 10, corresponding to the active purchasing channels. By default, the system starts with *WinOS* default channel.

- Variable denomination: user enters custom names for each channel (e.g. G1, G2, G3, G4), which will be used as a header in the resulting CSV file.
- Save to folder: with the help of a *fileChooser*, the user can choose the exact location where the CSV file will be written.
- Toggle button and logout stop: a toggle button allows switching between active and inactive purchase status. At the time of activation, the CSV file is initialized and the data is saved in real time.
- Serial data processing: the *serialEvent* function triggers automatically at each new line of data received, where content is parsed (with delimiters such as tab, space or comma), checking the format consistency and saving valid lines.
- Write to CSV file: the system creates the custom header file and then writes each row of data, comma separated, in a format compatible with Excel, MATLAB or Python (pandas).
- System status: at the bottom of the interface is displayed in real time if logging is active or inactive, providing clear feedback to the user.

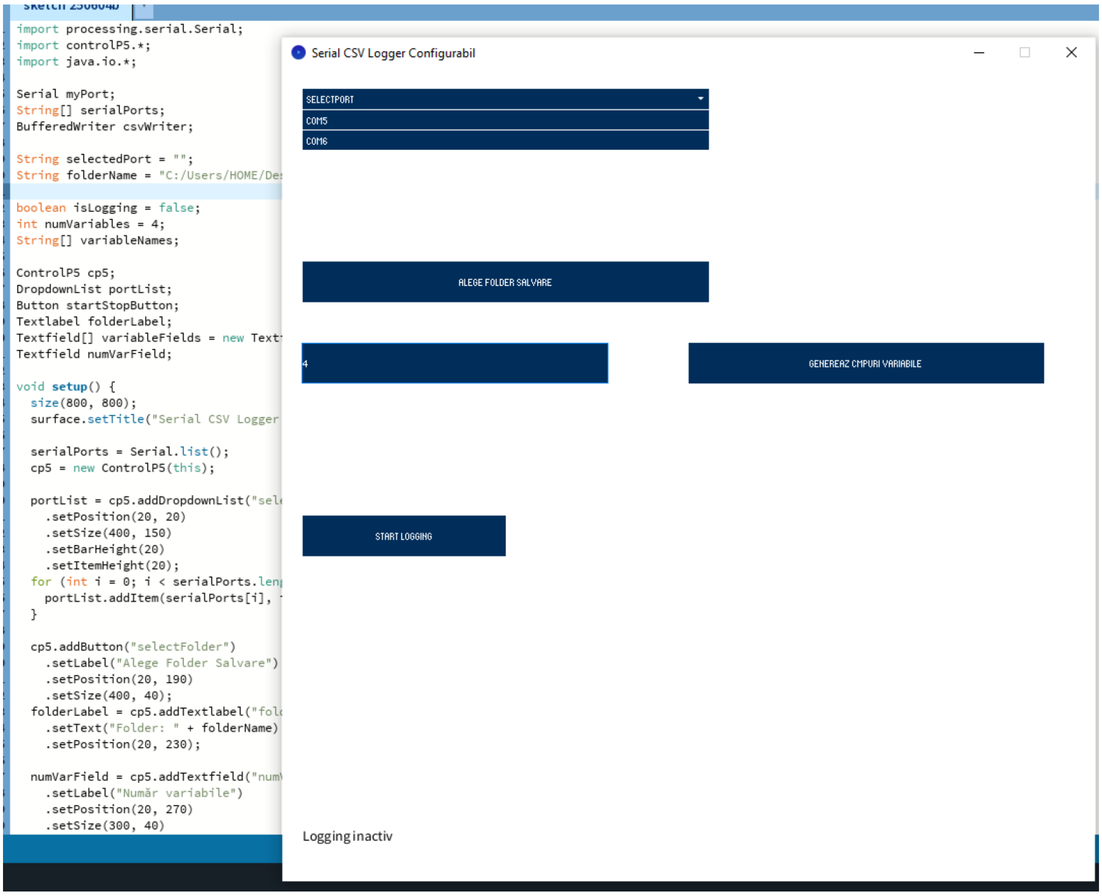


Figure 4.22. *Sample application used by UAB for data integrity testing- for Serial data incoming to the plain text in CSV each sensor is tested*

This modular software structure allows for great flexibility since the number of geophones can be quickly changed from the interface, as can channel names or save location. Thus, the application can be used not only for seismic monitoring, but also for other types of analog purchases in the acoustic, structural or experimental field.

Due to the fact that the data is saved in text format (CSV), they can be further analyzed with a variety of scientific and statistical tools. The interface is designed to require minimal user interaction after configuration, and can also be run in the background during long-term tests.

4.5. System communication architecture design

The system communication is used for sending data from reading nodes to a centralization node and is based on Esspressif ESP-NOW protocol designed by Espressif developers. The protocol functionality is briefly described below.

4.5.1. Communication protocol description

ESP-NOW is a "*protocol developed by Espressif, which enables multiple devices to communicate with one another without using Wi-Fi. The protocol is similar to the low-power 2.4GHz wireless connectivity (…) The pairing between devices is needed prior to their communication. After the pairing is done, the connection is safe and peer-to-peer, with no handshake being required*."

This means that after pairing a device with each other, the connection is persistent. In other words, if suddenly one of your boards loses power or resets, when it restarts, it will automatically connect to its peer to continue the communication.

ESP-NOW supports the following features:

- Encrypted and unencrypted unicast communication;
- Mixed encrypted and unencrypted peer devices;
- **Up to 250-byte** payload can be carried;
- Sending callback function that can be set to inform the application layer of transmission success or failure.

ESP-NOW technology also has the following limitations:

- Limited encrypted peers. 10 encrypted peers at the most are supported in Station mode; 6 at the most in SoftAP or SoftAP + Station mode;
- Multiple unencrypted peers are supported; however, their total number should be less than 20, including encrypted peers;
- **Payload is limited to 250 bytes**.

In simple words, ESP-NOW is a fast communication protocol that can be used to exchange small messages (up to 250 bytes) between ESP32 boards.

ESP-NOW is very versatile and allow one-way or two-way communication in different setups.

Communication diagram

ESP-NOW is very versatile and you can have one-way or two-way communication in different setups. For our particular setup we are using the following topology shown in Figure 4.23.

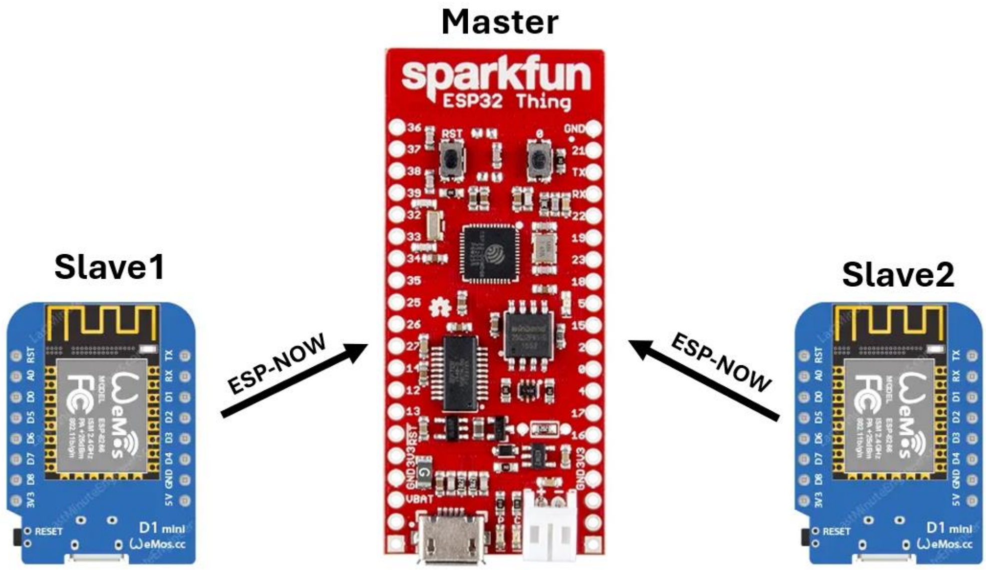


Figure 4.23. *Simplified architecture of the two different System-on-Chip working with the same management protocol (ESP-NOW)*

This configuration is ideal to collect data from several sensors nodes into one ESP32 board. Master device can be configured as a web server to display data from all the other boards.

4.5.2. Master – software design

The used SparkFun ESP32 Thing, is equipped with the ESP32 and everything necessary to program, run and develop directly on the chip. In addition to the WiFi SoC, the Thing includes an FTDI FT231x, which converts USB to serial, and allows your computer to program and communicate with the microcontroller.

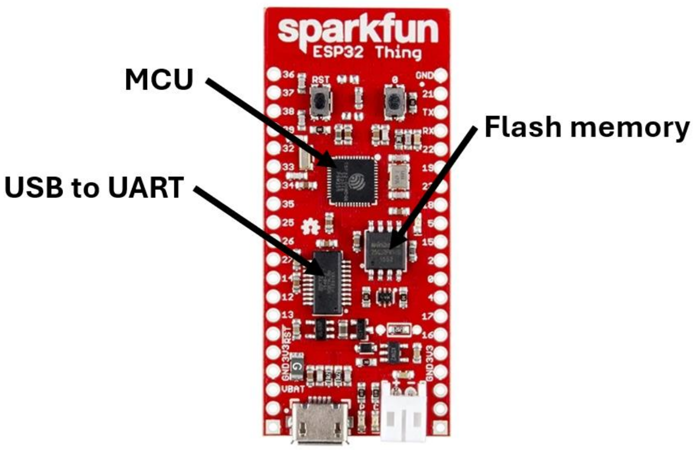


Figure 4.24. *Simplified identification of the main used components from the System-on-Chip used as data concentrator*

Features & Specs

- Dual-core Tensilica LX6 microprocessor
- Up to 240MHz clock frequency
- 520kB internal SRAM
- Integrated 802.11 BGN WiFi transceiver
- 3.0 to 3.6V operating range
- 2.5 μA sleep current under hibernation
- 28 GPIO
- 10-electrode capacitive touch support
- Hardware accelerated encryption (AES, SHA2, ECC, RSA-4096)
- 4MB Flash memory
- Integrated LiPo Battery Charger

The integration of SoC in the node is shown in Figure 4.25.

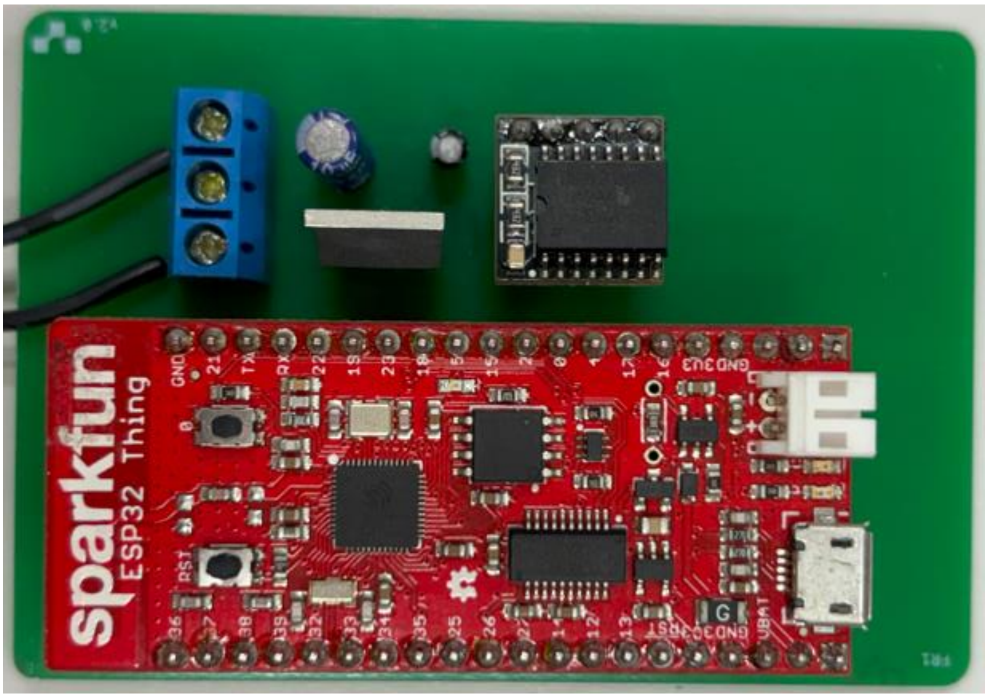


Figure 4.25. *The master prototype is designed with own Real-time clock for ensuring the restoration of the data integrity by labeling with data-time components*

File system diagram

LittleFS is a lightweight filesystem created for microcontrollers that lets you access the flash memory like you would do in a standard file system on your computer, but it's simpler and more limited. You can read, write, close, and delete files and folders. Using a filesystem with the ESP32 boards is especially useful to:

- Create configuration files with settings;
- Save data permanently;
- Create files to save small amounts of data instead of using a microSD card;
- Save HTML, CSS, and JavaScript files to build a web server;
- Save images, figures, and icons;

As you can see in the diagram below, an external SD card is used to store data received from reading nodes and the onboard flash memory stores the web server files used for displaying data in a webpage and managing the system.

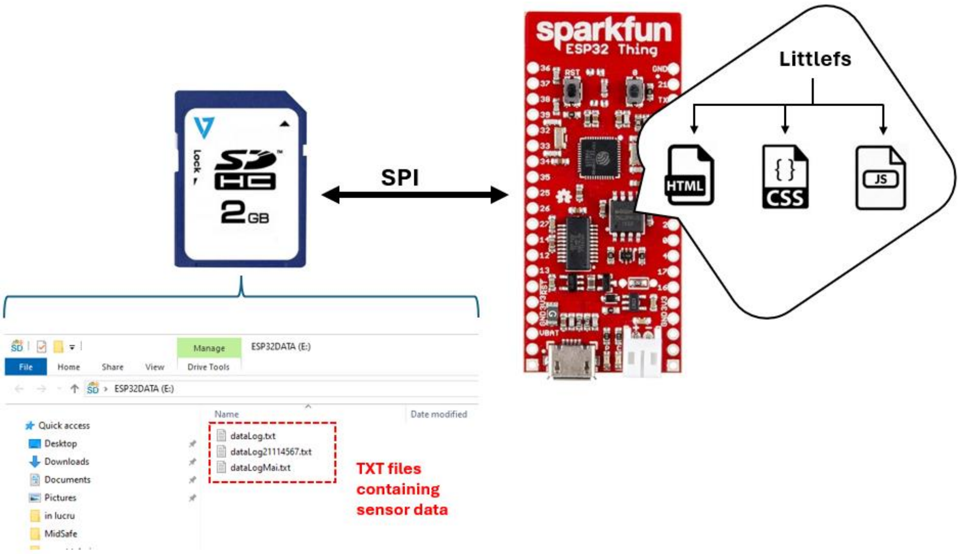


Figure 4.26. *The re-engineered software design for master's optimization from the thermal stress point of view*

4.5.3. Software block diagram design

Software main functions are:

- Receives sensor data from nodes

- Saves sensor data in text file with timestamp
- Creates an Access Point so that other devices can connect to it
- Hosts a web server
- Displays real-time data in web page
- Provides functionality for downloading sensor data over WiFi

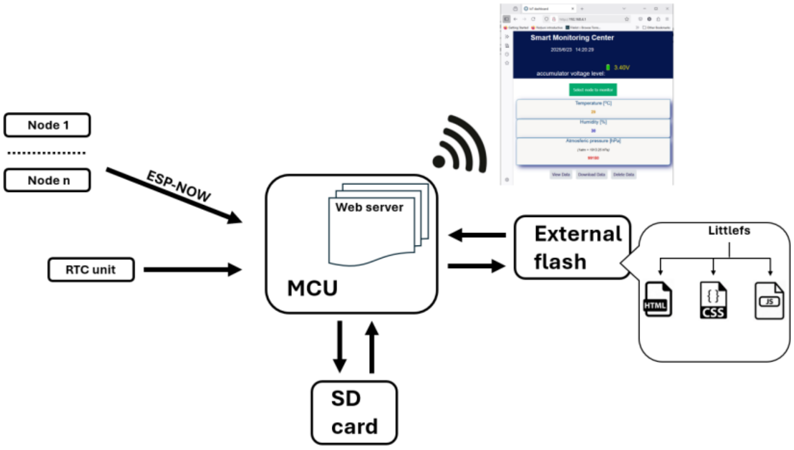


Figure 4.27. *The general software architecture from sensors (nodes) to the local storage support for avoiding data losses*

4.5.4. Node software architecture (pressure, humidity, temperature)

It is built around Lolin D1 mini, a mini Wi-Fi board with 4MB flash based on ESP-8266EX.

Features:

- 11 digital IO, interrupt/pwm/I2C/one-wire supported (except D0)
- 1 analog input (3.2V max input)
- Type-C USB Port
- LOLIN I2C Port
- Compatible with MicroPython, Arduino, nodemcu

The device is shown in figure 4.28.

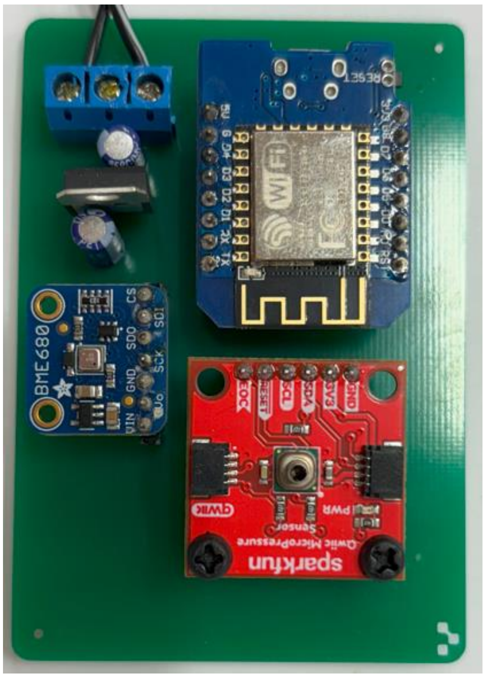


Figure 4.28. *The prototype of the sensor that is measuring the capillarity pressure (requires thermal compensation for avoiding errors)*

4.5.5. Software block diagram

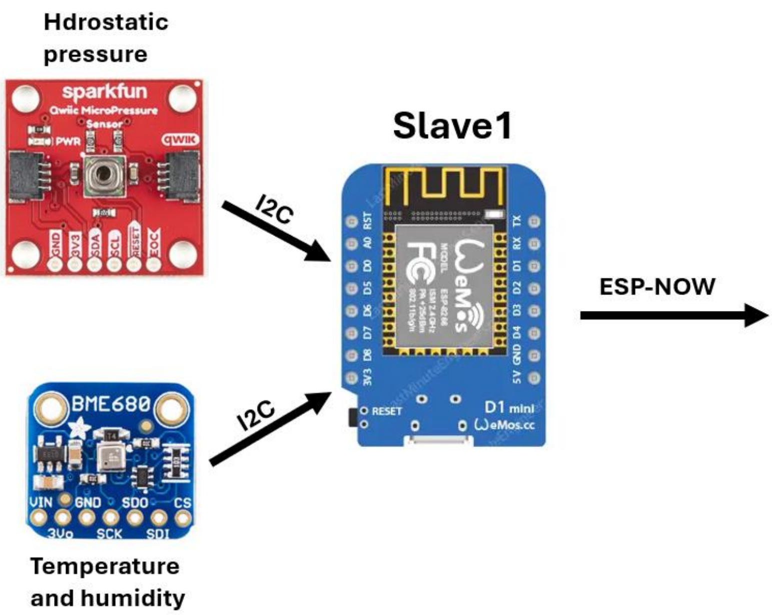


Figure 4.29. *The associated System-on-Chip, uses the same management protocol (ESP-NOW) for gathering data from sensors and forwarding it to the master*

<u>Software main functions</u>

- Read sensor data (pressure, temperature and humidity)
- Send data to master device

4.5.6. Software architecture design of the general data acquisition module

It is built around Lolin D1 mini, a mini WIFI board with 4MB flash based on ESP-8266EX.

Features

- 11 digital IO, interrupt/pwm/I2C/one-wire supported (except D0)
- 1 analog input (3.2V max input)
- Type-C USB Port
- LOLIN I2C Port
- Compatible with MicroPython, Arduino, nodemcu

ADS analogue to digital converter

For microcontrollers without an analogue-to-digital converter or when you want a higher-precision ADC, the ADS1115 provides 16-bit precision at 860 samples/second over I2C. The chip can be configured as 4 single-ended input channels, or two differential channels. As a nice bonus, it even includes a programmable gain amplifier, up to x16, to help boost up smaller single/differential signals to the full range. We like this ADC because it can run from 2V to 5V power/logic, can measure a large range of signals and its super easy to use. It is a great general purpose 16-bit converter.

Specifications:

- WIDE SUPPLY RANGE: 2.0V to 5.5V
- LOW CURRENT CONSUMPTION: Continuous Mode: Only 150μA Single-Shot Mode: Auto Shut-Down
- PROGRAMMABLE DATA RATE: 8SPS to 860SPS
- INTERNAL LOW-DRIFT VOLTAGE REFERENCE
- INTERNAL OSCILLATOR
- INTERNAL PGA
- I2C INTERFACE: Pin-Selectable Addresses
- FOUR SINGLE-ENDED OR TWO DIFFERENTIAL INPUTS
- PROGRAMMABLE COMPARATOR

• This board/chip uses I2C 7-bit addresses between 0x48-0x4B, selectable with jumpers

The real device is shown in figure 4.30.

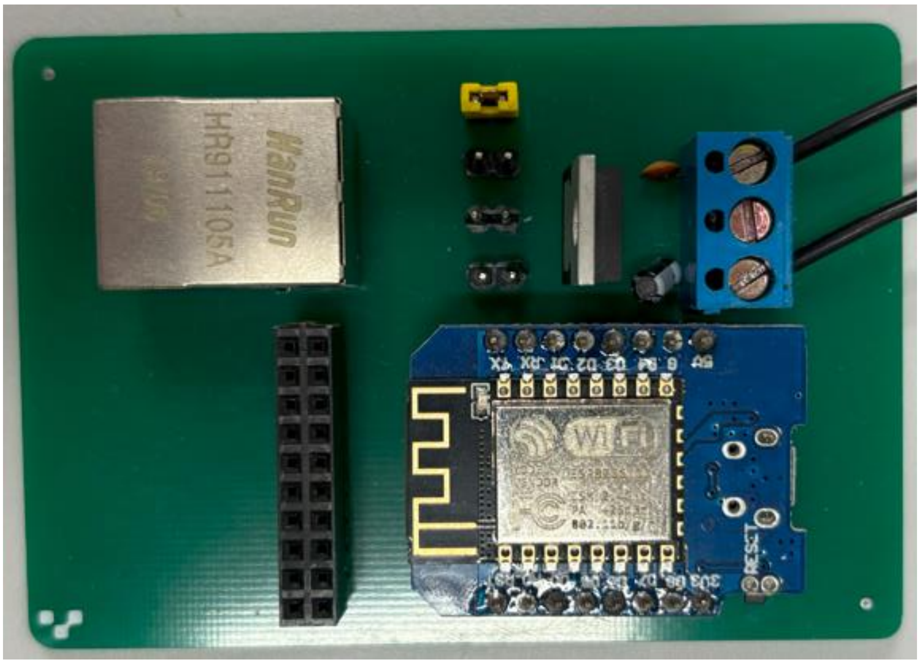


Figure 4.30. *The prototype of the sensor equipped with geophone module uses UTP cable for interconnection (up to 25 m between geophone and prototype), and frequency and thermal compensation data acquisition system (DAQ)*

4.5.7. Software block diagram

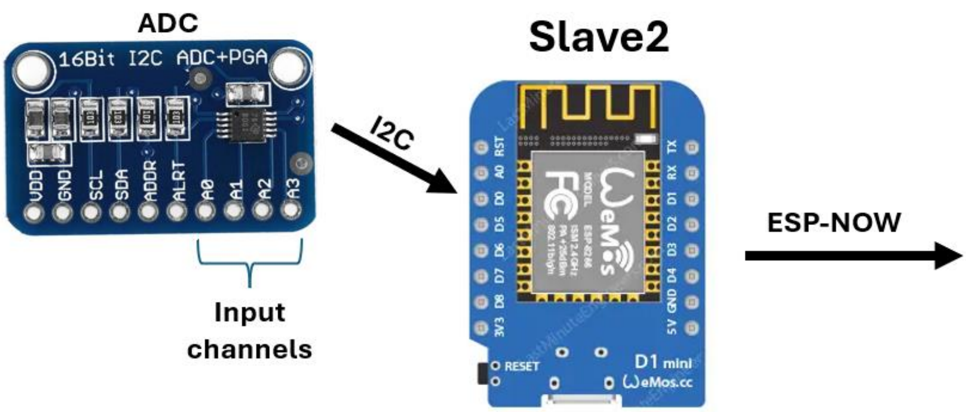


Figure 4.31. *The System-on- Chip takes data from DAQ and send it to master using the same management protocol (ESP-NOW).*

Software main functions:

- Read sensor data (differential analog channels)
- Send data to master device

4.5.8. Example of application using geophone systems

In the figure 4.32., two data acquisition systems are used with the possibility to connect 4 geophones with the distance between them of 15 m.

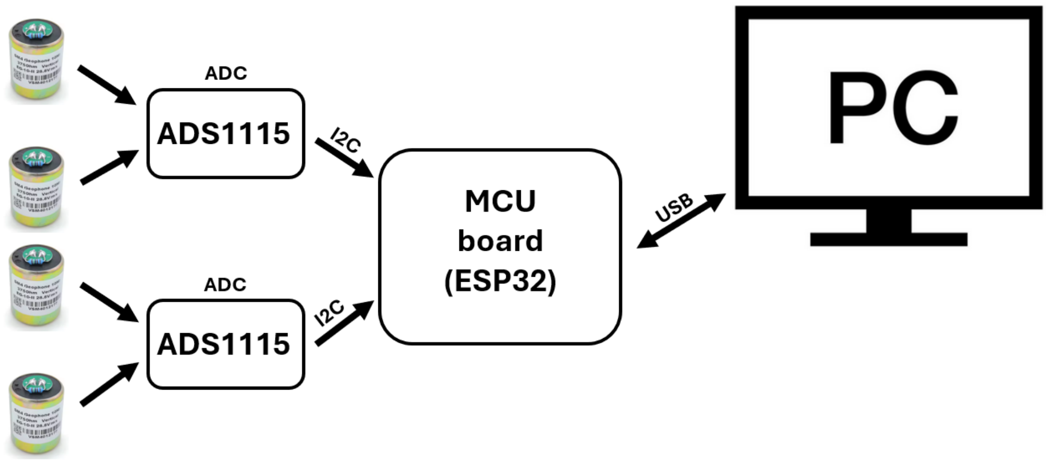


Figure 4.32. *The function- based architecture of the test stand for the geophone (qualitative testing: immunity and repeatability)*

The Figure 4.33 shows the real connection between two components, a geophone and a data acquisition board.

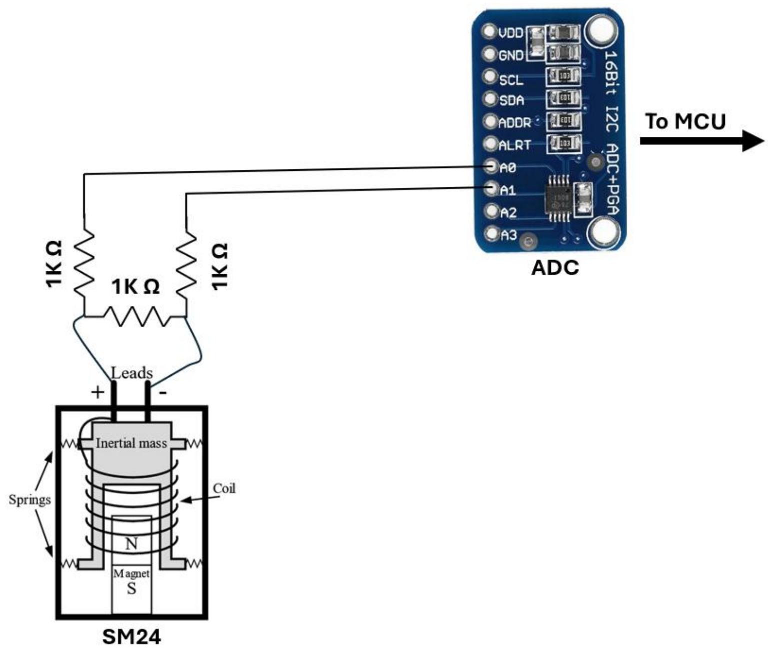


__Figure 4.33.__ The interconnection between geophone and DAQ requires cable consistency tests for ensuring the high level of required immunity

4.6. Design test procedures for data validation from wireless sensors

4.6.1. Accelerometers vs geophone processing design

The choice of transducer would seem to depend on what you want to measure – an ACCELEROMETER for measuring acceleration (VDV, MTVV, etc) and a GEOPHONE for measuring velocity (PPV).

We can get velocity by integrating the accelerometer output, so this would appear to be the ideal solution. Well, it works well, but integrating can cause some side-effects. If you consider that the integration process emphasizes low frequencies (think of the -6dB/octave slope in the spectrum), any noise present at low frequencies in the amplifier chain, or extraneous environmental effects can cause spurious results. Some accelerometers, due to their physical design, can be sensitive to temperature transients. This shows up as a very low-frequency signal, which, when integrated, generates a large velocity output.

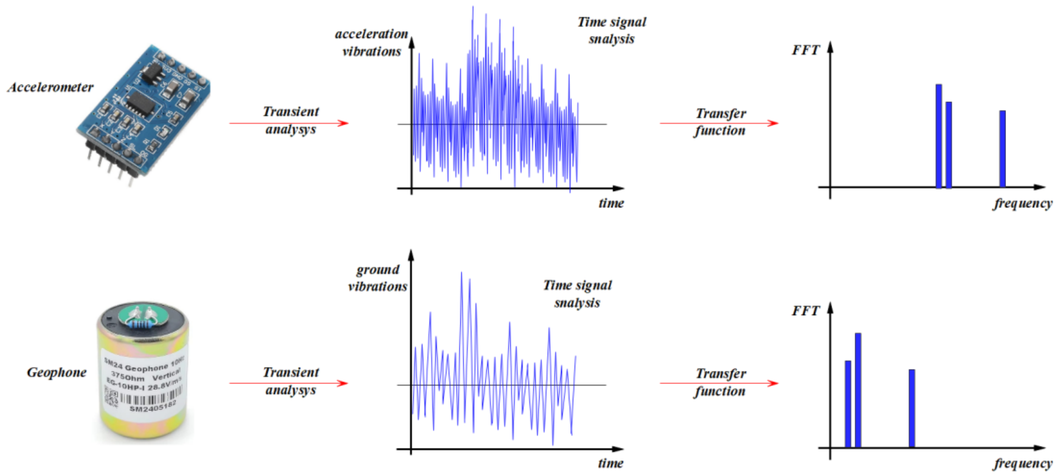


__Figure 4.34.__ MATLAB- based processing steps for ensuring repeatability (identical FFT patterns) of the measurements using geophone

Careful design of high pass filters can mitigate these effects, but these can introduce phase errors, which might be important when trying to measure the peak amplitude of the velocity signal (PPV). It's interesting but beyond the scope of this report to compare the raw output of an integrated accelerometer and a geophone for the same signal and measure its peak. Of course, integrating the acceleration signal in the frequency domain is a lot easier, but generally will not yield a PPV value, almost all spectra being RMS values. (Lalanne, 2009)

A geophone is excellent for its design purpose since we could calculate acceleration by differentiating the signal, but often they have a limited dynamic range, compared to accelerometers so this can result in noise being amplified. Also, as their resonance is often bang in the middle of the frequency range of interest, the phase performance becomes very significant, and needs careful design.

4.6.2. Accelerometers analysis

The majority of accelerometers for our applications are piezoelectric devices. A small piezoceramic crystal is sandwiched between the base and a seismic mass, so when the base is accelerated, the crystal is stressed, causing a proportional charge output. Because it is a simple mass/spring system, it will have a fundamental resonance – the crystal is very stiff, so this will be high, some kilohertz for most devices. Below that resonance, the response is virtually flat and linear, making an excellent transducer. To manufacture a sensitive accelerometer, it is necessary to increase both the mass and/or the crystal size. However, this results in a reduction in resonance, thereby necessitating a trade-off. It is fortunate that the majority of requirements for sensitive accelerometers occur at low frequencies.

The output of the crystal is a charge, which requires a specialized charge amplifier, with extremely high input impedance, in order to drive our measuring system. These used to be separate boxes, with specialised low noise cabling, but nowadays, the charge amplifier is built into the accelerometer itself, and this uses a 'phantom' powering system known as IEPE (integrated electronic piezo-electric), also known by a variety of proprietary names such as ICP®, CCP etc. This means that long cables can be driven, and as long as your instrument can provide the powering, you should be in business. But always check that you have an IEPE accelerometer rather than a charge accelerometer first (Piersol, 2010)

When the accelerometer experiences acceleration, the seismic mass exerts a force on the crystal, causing it to deform. This deformation produces an output voltage calculated by the formula:

$$E = gt \times ma/A \text{ or } E = gt \times F/A \rightarrow gtP$$

Where:

E = Output voltage

g = Voltage sensitivity (Vm/N)

t = Crystal thickness

m = Mass

a = Acceleration

A = Crystal surface area

F = Applied force

P = Pressure

Piezoelectric accelerometers have a high resonant frequency and fast response time that makes them sensitive to high-frequency vibrations, which reach a certain limit called the upper-frequency limit. This limit ranges from 5 to 80 kHz.

The lower cut-off frequency of piezoelectric amplifiers determines the lower frequency limit of the sensor, which typically ranges from 0.2 to 0.8 Hz. At this frequency, the sensors' response to DC will not be unique, and the noise level may increase, making it difficult to regulate signals. (Edward, 2009)

However, engineers have made some improvements to this limitation by modifying the accelerometers' design with multiple mode damping to maintain measurement accuracy and a wider range of lower frequency responses.

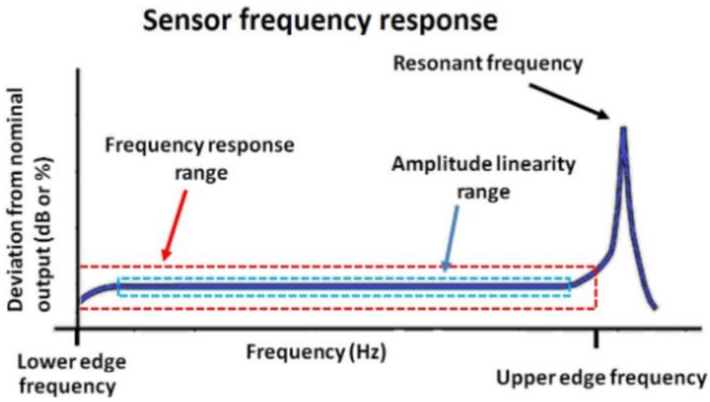


Figure 4.35. *MATLAB- based processing steps for ensuring repeatability (identic bandwidth of the response) of the measurements using geophone*

Due to being a capacitor, such accelerometers do not have a DC response and will roll-off at low frequencies. Make sure you select one suitable for your task if you want to measure down to 0.5Hz for example. Accelerometers are rugged and will measure in any axis, but being a mass stuck to a piece of glass, the crystal can crack, not always obviously. This is particularly true for the sensitive ones with big seismic masses, so don’t drop them on a concrete floor.

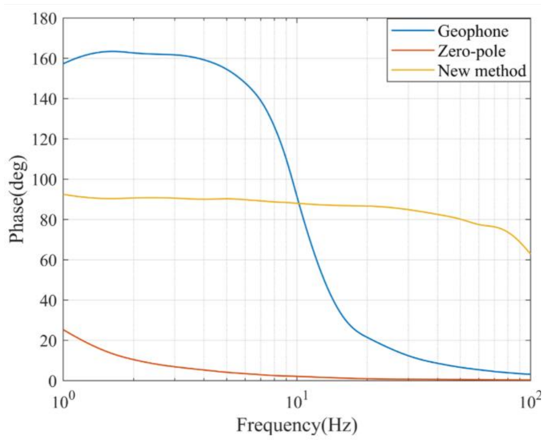
4.6.3. Geophones analysis

A typical geophone is a moving coil device. Think of a loudspeaker backwards. A magnet is suspended in a coil (sometimes vice-versa), attached to the base of the transducer. As the base is moved, a current is induced in the coil, which can then be used as an output proportional to velocity.

Like an accelerometer, the geophone is a resonant device, but this time, the resonance is low frequency due to the mass (magnet) being suspended. Typically, **this is around 3-4Hz**, and the usable linear range is above this.

Within 1~100 Hz, the sensitivity is approximately 194 mV/(m/s2), and the sensitivity attenuation is approximately −3 dB at 0.5 Hz and 200 Hz. Theoretical and actual tests of this method prove that, after the correction network, the response in the effective frequency range is flatter, the low-frequency extension can be effectively realized, and the improvement effect is good. (Yan et al., 2020)

The phase difference curve with the reference sensor is shown in Figure 4.36. below. The graph includes the original geophone and the curve after improvement by both methods. The curves were smoothed by using an interpolation function shown in figure 4.36.



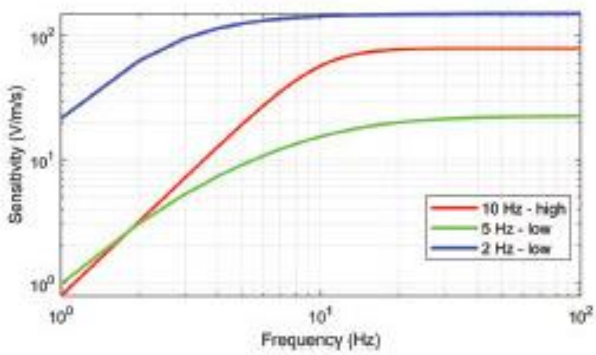


Figure 4.36. *Laboratory tests for ensuring the reference bandwidth of geophone's response for latter adjustment of bandwidth deviation*

This potentially gives an issue with measuring low-frequency vibration – we are often interested in measuring vibration at just the frequencies that a geophone has a resonance. However, the design of geophones is a mature technology, and careful damping and linearization will provide excellent performance.

Geophones are normally designed to operate in one axis, either vertical or horizontal, so they must be oriented to their design axis. If we have a triaxial unit, it will have one vertical, and two horizontal coils. It is imperative to note that if the device is affixed to a wall rather than a floor, there is a high probability of signal loss. To mitigate this issue, it is recommended that the device is consistently mounted in the same orientation, such as on a bracket. (https://blog.endaq.com/shock-analysis-response-spectrum-srs-pseudo-velocity-severity.)

Conditioning an active geophone is very specific, but recent devices also support the IEPE system, already dominant in accelerometers. A significant benefit of geophones is their lower price, and they are very rugged, hence their popularity in the mining engineer's toolkit.

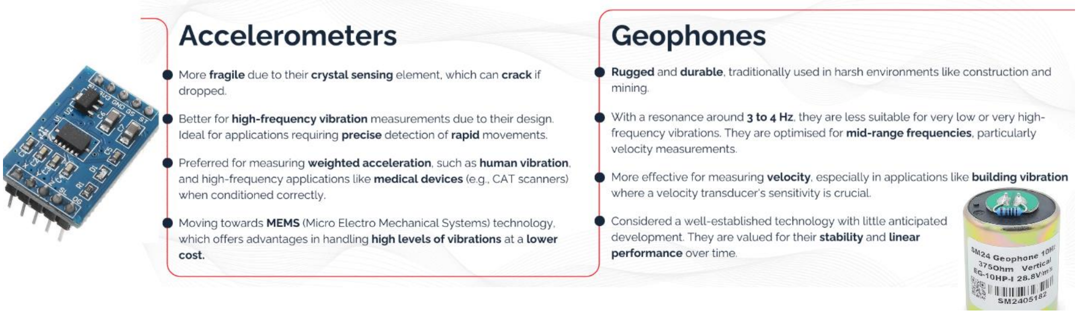


Figure 4.37. *Re-engineering analysis of the accelerometer vs geophone for optimizing data processing (thresholds vs slope rate)*

A mechanical vibration is often characterized by its amplitude σa, mean σm, maximum σ_{max}, minimum σ_{min}, and range Δ_{σ}. These parameters are shown in the figure 4.38.

- A *half cycle* is a pair of two consecutive extrema in the stress signal, going from a minimum to a maximum or from a maximum to a minimum. For a variable-amplitude stress history, the definition of one cycle is not clear and hence a *reversal* is often considered. Two consecutive half cycles or reversals constitute a *full cycle*.

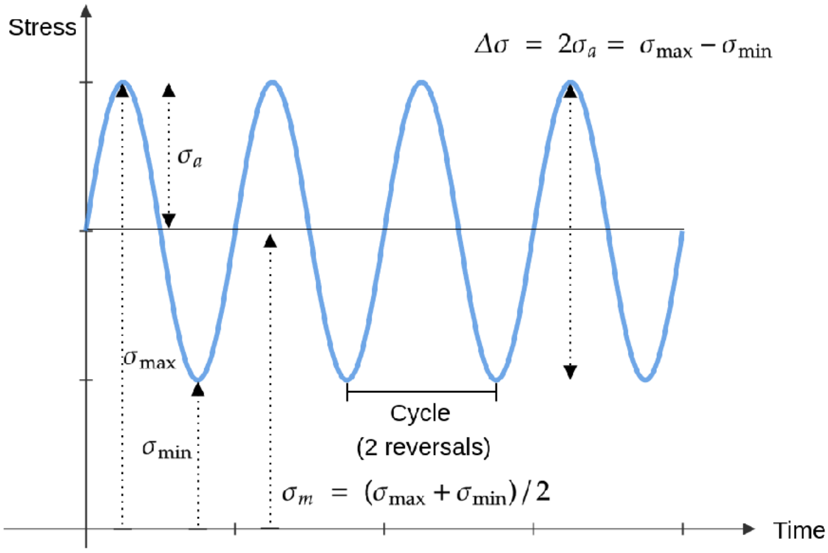


Figure 4.38. *The response of the analysis approach (cycle & standard deviation) for defining threshold alerts of the accelerometers*

Geophone Waveform time and spectrum analysis

- The shock response spectrum (SRS) is a graphical representation of how various single-degree-of-freedom systems react to a transient acceleration input. SRS is commonly used to determine the ***frequency response of shock environments and to estimate the maximum dynamic response of structures***. Additionally, SRS is utilized as a tool for designing specifications to characterize impulsive loads such as earthquakes, underwater explosions, stage separation forces, and pyrotechnic events.

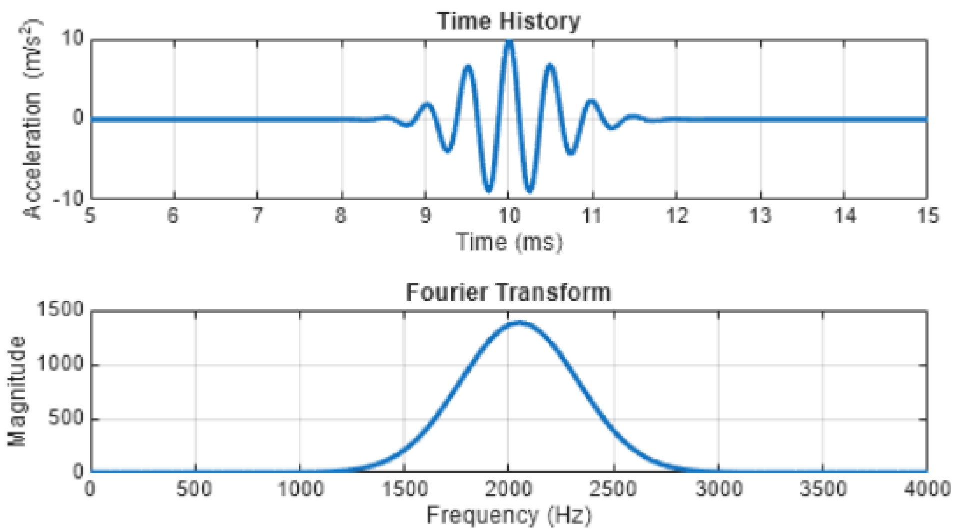


Figure 4.39. *The response of the analysis approach (frequency response) for defining threshold alerts of the geophones*

- An input to a system is considered *transient* if the input parameters change faster that the system time scale. Suppose that the output of an oscillator is fed to a second-order filter resonant at 100 Hz. Let the amplitude change linearly by some factor *A* in a time interval *T*. If *T* is 10 minutes, the output at any time during this period can be accurately predicted. The output is a sine wave of the same frequency as the input, and its magnitude varies linearly with time by the same factor *A*. If, on the other hand, the change in level occurs in 1 millisecond, transient analysis techniques must be used to predict the output during the change and shortly thereafter. Thus, the classification of a particular time history as transient depends on how the system of interest responds to this time history. Mechanical shocks are usually of great interest in the design and operation of physical systems because the instantaneous input levels are larger than the steady-state inputs by an order of magnitude or more.

A qualitative graphical representation of the construction of a shock response spectrum is shown below. It depicts a transient acceleration-time history input applied to a base on which a series of linear oscillators of different natural frequencies are mounted. The base is assumed to be massive enough that the motion of the oscillators does not affect its motion and there is no coupling between masses and the base. (European Cooperation for Space Standardization, 2015.)

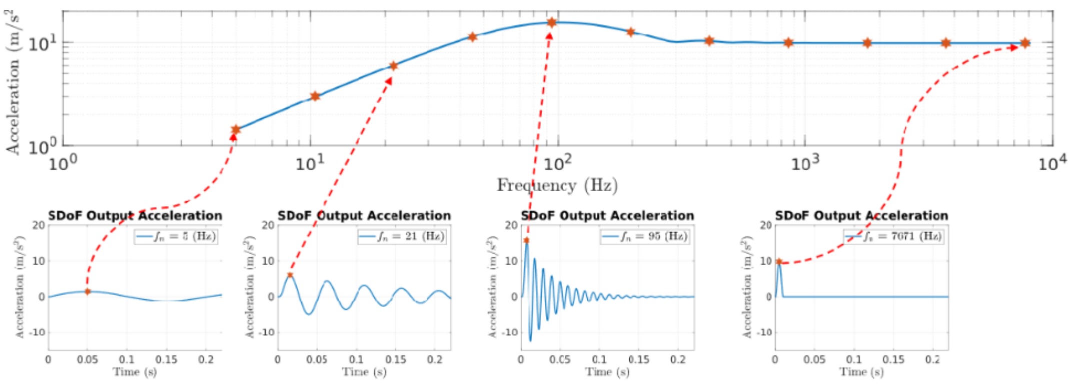


Figure 4.40. *The response of the analysis approach (vibrations & shock discrimination) for defining threshold alerts of the accelerometers*

The transient acceleration response of each oscillator is shown graphically above each oscillator. In this case, oscillator 1 has the lowest frequency and lower maximum acceleration amplitude and oscillator ℓ has the highest maximum response relative to the others. As the frequency increases to the right, the maximum acceleration response decreases. The SRS graph at the top of the Figure 4.40 is used to characterize the frequency content of the transient shock input signal. The maximum response drops off for systems of higher and lower frequencies, representing stiffer and softer systems, respectively.

- The ultimate goal of transient analysis is the determination of the damage potential of a shock upon a physical system. The objective is to design the system to survive the shock environment or to attenuate the shock input to the system using packaging or attenuation devices. *Survival* of a shock excitation can mean one of two things:
- The system exhibits no permanent damage after the shock
- The system exhibits no degradation of performance either during or after the shock
- As an example of the first definition, consider a microwave oven that has been accidentally dropped on the floor. Whether the microwave functions properly during the drop is of no concern. Even if calibration has to be performed after the drop, it is of no concern as long as the microwave is not permanently damaged by the fall and continues to function. As an example of the second definition, consider the launching of a satellite. If the shock that occurs in the satellite's body structure due to the separation of the satellite from the rocket in space causes even a brief malfunction of the onboard systems, the satellite will fail to propel itself to orbit and complete its mission. In this case, the system is not damaged permanently yet fails the second definition of survival. (Justin et al., 2012)
- The design of a system that withstands its shock environment requires the definition of this environment with reasonable accuracy because survival is not the only design factor. For example, weight and size are also frequently important and, yet, usually inversely related to the shock resistance of a system. The strength of a system is usually weight-dependent, while the packaging of the system to reduce shock input is usually size-dependent. However, in many applications, size and weight must be minimized, for example, in space applications where small weight increases require large increases in booster performance. Thus, the system must be able to withstand the shock environment but cannot have a large safety factor because of the weight restriction.

4.6.4. Designed steps in analysis process

a. Importing data into Matlab
b. Signal Processing Toolbox used for analyzing vibrations and dynamic data measured by the geophone acquisition module
c. The processing module will allow temporal analysis of signals measured in situ
d. The processing module will perform spectral analysis (FFT) to convert signals from the time domain to the frequency domain

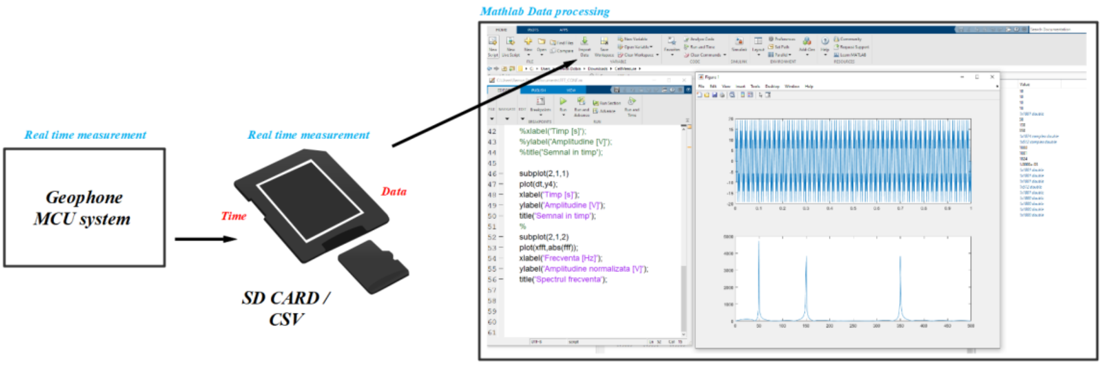


Figure 4.41. *Sample application used by UAB for data integrity testing- for Serial data incoming to the plain text in CSV – study case: geophone*

Designing specific objectives:

- Determining the number of FFT points (N)
- Determining the Nyquist frequency (fs/2)
- Affecting spectral analysis in MATLAB

5. MULTISPECTRAL AND VISUAL SENSORS ON UAV

Sensor data capacities

Here two unmanned aerial vehicles (UAVs) acquired by Systra Subterra are presented the DJI Mavic 2 Enterprise Advanced and the DJI Mavic 3 Multispectral. Both platforms offer distinct yet complementary capabilities: the Mavic 2 Enterprise Advanced provides high-resolution **thermal** and visual imaging for structural assessment and anomaly detection, while the Mavic 3 Multispectral delivers **multispectral** analysis for vegetation health monitoring and environmental compliance. This analysis examines each drone's technical specifications, sensor capabilities, flight performance, and capacities for waste dump monitoring operations.

5.1. DJI Mavic 2 Enterprise Advanced: Technical Profile

The Mavic 2 Enterprise Advanced features a dual-sensor gimbal system that integrates thermal and visual imaging for comprehensive site assessment (Table 5.1).

Table 5.1. *Mavic 2 Enterprise Advance specifications taken from DJI manual, 2021*

Mavic 2 Enterprise Advanced	Characteristic	
Device	Maximum take-off weight	1100 g
	Maxi flight time	31 min (at 25 km/h in windless conditions)
	Max. wind resistance	10 m/s
RGB sensor	Camera resolution	48-megapixels
	Digital zoom	32X
	Photo formats	JPEG
	Video format	MP4
	Maximum image size	8,000 x 6,000-pixel resolution
Thermal sensor	Spatial Resolution	640 x 512-pixel resolution
	Temperature accuracy	±2°C
	Spectral sensor	8-14 μm
	Temperature range	-40 to 150 °C (high gain) -40 to 550 °C (low gain)
Positioning and Navigation	RTK mode	± 1 cm accuracy
	GNSS	GPS + GLONASS
	Internal storage	24 GB

The platform supports Real-Time Kinematic (RTK) module integration, achieving centimeter-level positioning accuracy through correction of camera location data in real time (DJI manual, 2021). This precision is vital for creating repeatable flight paths for longitudinal monitoring and accurate georeferencing of detected anomalies. The aircraft can program up to 240 waypoints, enabling automated systematic surveys of complex dump geometries (Figure 5.1).

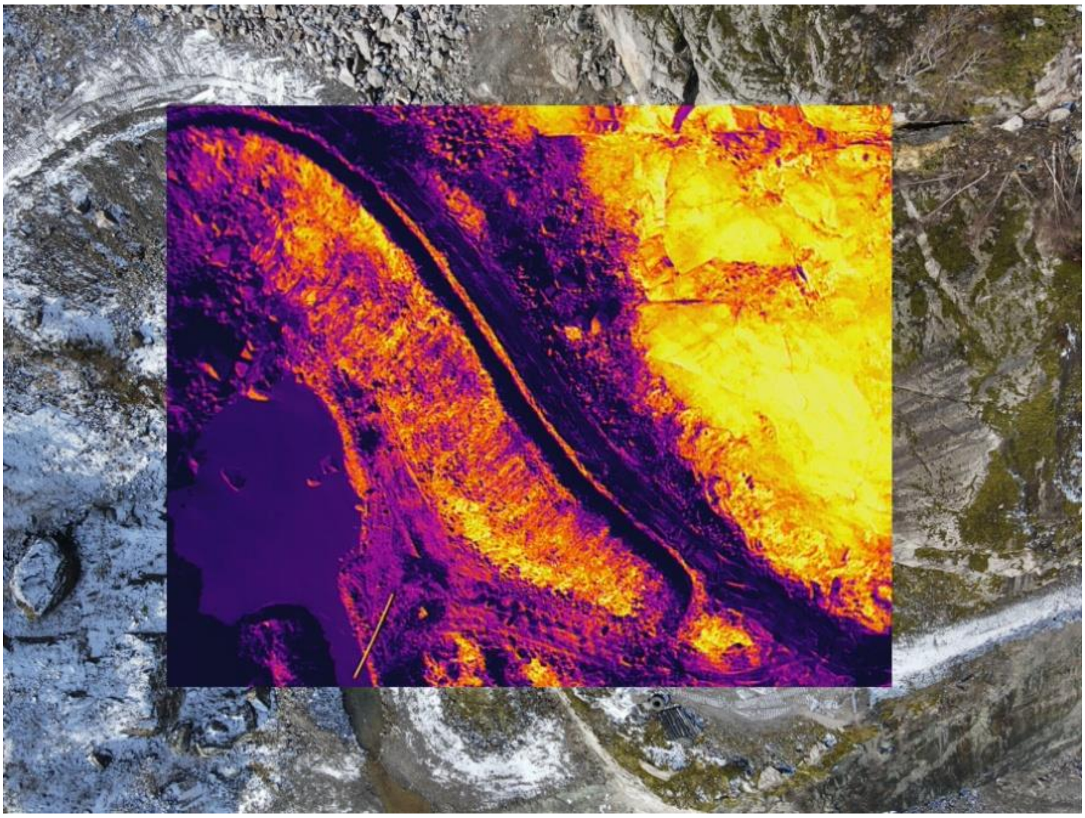


Figure 5.1. *Image size comparison between RGB and Thermal sensors. Image taken from Mavic 2 Enterprise Advance*

The thermal imaging capability is particularly valuable for detecting subsurface combustion and exothermic reactions within waste piles. The 640x512 thermal resolution enable early identification of fire risks before surface combustion. The 48MP visual camera facilitates high-resolution orthomosaic generation for volumetric change detection and erosion monitoring, while the 32X zoom allows detailed inspection of gas collection infrastructure and leachate collection systems without exposing personnel to hazardous areas.

Mavic 2 accuracy and limitations

For thermal data measurement the temperature accuracy is ±2°C through its radiometric thermal sensor, with reading errors increasing at extreme temperatures or under reflective conditions. Its visual camera enables 48MP image collection at 4K resolution, storing up to 24 GB of data onboard; however, critical limitation involves the RTK module that does not synchronize with the camera shutter, resulting in horizontal and vertical positioning errors, requiring extensive ground control points for survey-grade accuracy. Data transmission occurs via DJI OcuSync 2.0, providing a 10 km range with 720p live streaming, though bandwidth constraints may limit real-time thermal analysis during flight.

5.2. DJI Mavic 3 Multispectral: Technical Profile

The Mavic 3M integrates a dedicated multispectral array with a high-resolution RGB camera for environmental monitoring:

Table 5.2. *Mavic 3 Multispectral specifications taken from DJI Agriculture web page*

Mavic 3 Multispectral	**Characteristic**	
Device	Maximum take-off weight	1050 g
	Maxi flight time	43 minutes (at 25 km/h in windless conditions)
	Max. wind resistance	12 m/s
RGB	Camera resolution	20-megapixels
	Definition	FHD / 4K
	Digital zoom	32X
	Photo formats	JPEG / JPEG + RAW
	Video format	MP4 (MPEG-4 AVC/H.264)
	Maximum image size	5280 x 3956
Multispectral	Camera resolution	4 X 5-megapixels
	Maximum image size	2,592 x 1,944-pixel resolution
	NIR sensor	860 ± 26 nm
	Red-Edge sensor	730 ± 16 nm
	Red sensor	650 ± 16 nm
	Green sensor	560 ± 16 nm
	Max. image size	2592 x 1944
Positioning and Navigation	RTK mode	Horizontal: 1 cm + 1 ppm Vertical: 1.5 cm + 1 ppm
	GNSS	GPS + Galileo + BeiDou + GLONASS
	Internal storage	64 GB
Detection system	Type	Multidirectional Obstacle Detection

The multispectral capability is ideal for monitoring vegetation health on coal waste dumps, detecting stress indicators (including chlorophyll degradation, moisture anomalies, and biomass reduction) that may signal underlying geotechnical failures such as liner breaches, subsidence features, gas migration pathways, or leachate seepage zones. The Red Edge and Near-

Infrared bands enable early detection of vegetation stress, which may correlate with slope instability or landslide precursor conditions, enabling proactive geotechnical intervention before failure.

Mavic 3 Multispectral accuracy and limitations

This device achieves centimeter-level measuring accuracy through built-in RTK with microsecond-level time synchronization, delivering horizontal precision of ±1 cm and vertical of ±1.5 cm, with mapping accuracy consistently within 1-2 times the ground sample distance (e.g., 2.6-5.2 cm error at 100m altitude). Reading errors are minimized via an integrated sunlight sensor that calibrates each multispectral capture for ambient irradiance, ensuring radiometric consistency across surveys. Data collection encompasses 20MP RGB imagery plus four 5MP spectral bands (Green, Red, Red Edge, NIR) captured through a mechanical shutter eliminating motion blur, enabling radiometrically calibrated datasets for vegetation index calculation. Transmission leverages DJI O3 Enterprise architecture with 15 km range and enhanced interference resistance, facilitating reliable streaming of multispectral previews and rapid post-flight data offload for processing in platforms like PIX4Dfields (DJI, 2022; DJI Agriculture).

6. CONCLUSIONS, RECOMMENDATIONS AND FUTURE DIRECTIONS

The biggest challenge in this work package is to find a way to integrate the different types of data (geological and geotechnical, classical and modern topographic measurements, related to vegetation changes, numerical models, etc.) provided by the in-situ monitoring system into a unified, working and viable model.

Work Package 3 integrates classical geodetic techniques with state-of-the-art UAV-based photogrammetry, multispectral remote sensing, and automated monitoring systems to deliver comprehensive, accurate, and real-time assessment of deformations, displacements, and stability risks in post-mining waste dumps. Through collaborative market analysis, equipment specification, field campaigns across multiple countries, and the production of key deliverables (D3.1–D3.3), the work package establishes a robust framework for enhanced safety, environmental rehabilitation, and sustainable management of opencast lignite and coal mine landscapes, effectively bridging traditional methods with innovative technologies to support long-term risk mitigation and responsible mine closure.

Implement classical topo-geodetic monitoring effectively we need:

- Establish stable geodetic networks outside the deformation influence zone, including control/reference points (K1, K2, K3), orientation points (O1, O2, O3), and durable reinforced-concrete observation stations (A, B, C, …) equipped with precise centering devices (e.g., Wild type) and protective covers.
- Materialize sighting/tracking marks on the slope or dump surface to clearly capture displacement magnitudes and directions.
- Perform repeated measurement cycles in order for precision using the iteration or Schreiber method for microtriangulation, rigorously compensating angles via least squares and checking reference-point stability between epochs.
- Apply the alignment method (full-length, parallactic angle observation from fixed stations, or supplementary parallel alignments) for linear slope sections, measuring horizontal angles, lateral deviations, and elevations periodically with theodolites or total stations.
- Implement microtrilateration using distance-only networks (constrained or free), calculating coordinates via simple/multiple linear intersections or group compensation, and determining horizontal displacement vectors relative to fixed external reference points.

- Carry out high-precision geometric leveling (mid- or end-point) with levels and invar rods to achieve sub-millimeter vertical accuracy for broad slope coverage.
- Conduct precision trigonometric leveling by measuring slope distances and vertical angles (ascending/descending sights) with theodolites or total stations to compute elevation differences.
- Install hydrostatic leveling systems (open or closed, with communicating vessels, temperature/volume compensation mechanisms, and optionally automated electrical contacts) for continuous vertical monitoring, selecting resistant hose materials and appropriate liquids to minimize errors from evaporation, temperature, or pressure changes.
- Regularly analyze displacement vectors, check admissibility of reference-point stability, correct for detected movements, and eliminate systematic errors to ensure reliable absolute and relative results.
- Document all network designs, initial/reference measurements, periodic cycles, compensations, and displacement interpretations to support risk assessment, early landslide/subsidence detection, infrastructure protection, environmental impact evaluation, and validation of modern monitoring techniques.

These steps must be executed with high metrological discipline to guarantee accurate, defensible monitoring of slope behavior and waste dump stability in opencast lignite and coal mining environments.

The analysis of modern methods, techniques, and technologies used for monitoring slope behavior in mining operations highlights the significant advancements achieved in this field, particularly in the context of accelerated technological development over recent decades. These innovations have fundamentally transformed the approach to monitoring, shifting from traditional, discontinuous methods to integrated systems capable of delivering precise, continuous, and real-time data.

The results emphasize the essential role of modern monitoring technologies in ensuring the stability and safety of mining works. Their implementation enables a comprehensive understanding of the behavior of slopes and mining infrastructure, thereby contributing to improved risk management and the prevention of potentially hazardous events, such as landslides, subsidence, or structural failures.

A fundamental conclusion of this study is that the efficiency of monitoring activities is directly dependent on the combined use of multiple complementary methods. Individual techniques, when applied in isolation, provide limited information; however, their integration allows for a more complete and reliable assessment of ground behavior.

GNSS-based monitoring systems represent a fundamental component of modern geodetic monitoring, offering high positioning accuracy that can reach millimeter-level precision under appropriate conditions. These systems are particularly suitable for detecting slow and progressive deformations over extended periods.

Remote sensing and photogrammetry constitute essential tools for large-scale monitoring, enabling the acquisition of spatial data without direct contact with the investigated area. Through the use of satellite imagery, aerial platforms, and unmanned aerial vehicles, these methods facilitate the detection of terrain changes, the assessment of environmental impact, and the generation of orthophotoplans and digital terrain models necessary for analysis and planning.

Terrestrial LiDAR and laser scanning technologies provide highly detailed three-dimensional representations of the terrain and mining infrastructure. Their capacity to capture high-density spatial data with very high precision allows for the identification of subtle deformations and morphological changes, thus playing a crucial role in the early detection of instability phenomena.

At the same time, geotechnical instrumentation—such as inclinometers, extensometers, piezometers, and accelerometers—ensures continuous monitoring of both surface and subsurface conditions. These devices supply essential information regarding displacements, stress distribution, groundwater pressure, and dynamic effects, thereby complementing remote and geodetic monitoring techniques.

Radar interferometry (InSAR) further enhances monitoring capabilities by enabling the detection of ground deformations over large areas with high precision. This method is particularly effective in identifying subsidence and slow-moving landslides, contributing to a broader understanding of regional-scale processes.

In addition, geotechnical modeling and numerical simulation play a significant role in the analysis and prediction of ground behavior under various loading and environmental conditions. These approaches allow for the simulation of potential failure scenarios, the identification of critical zones, and the development of appropriate mitigation strategies.

An increasingly important aspect of modern monitoring systems is the implementation of automated monitoring and control solutions. These systems integrate data from multiple sources, enabling continuous observation, rapid detection of anomalies, and timely intervention in the event of critical conditions. As a result, they contribute to both operational efficiency and the enhancement of safety standards.

In conclusion, the adoption and integration of modern monitoring technologies represent a fundamental requirement for contemporary mining operations. Their use leads to improved accuracy in deformation detection, more effective risk management, and increased protection of mining infrastructure and the environment. Ultimately, these technologies contribute to ensuring the long-term stability, safety, and sustainability of mining activities.

The analysis presented highlights the essential role of monitoring systems in ensuring the stability and safety of slopes within mining environments. The increasing complexity of geological conditions, combined with the operational demands of modern mining activities, necessitates the use of advanced monitoring approaches capable of providing accurate and timely information regarding ground behavior.

The results underline the importance of implementing monitoring systems that allow for the early detection of deformations and potential instability phenomena. Early identification of such processes is critical in preventing the occurrence of major failures, reducing associated risks, and minimizing economic and environmental impacts.

A significant conclusion is that the effectiveness of slope monitoring depends not only on the accuracy of the instruments used, but also on the frequency of measurements, data processing methods, and the interpretation of results. Continuous or high-frequency monitoring provides a more reliable representation of ground behavior compared to discontinuous observations, allowing for the identification of both gradual and sudden changes.

The study also emphasizes the necessity of correlating monitoring data with geological, geotechnical, and hydrogeological conditions. Slope instability is a complex process influenced by multiple factors, including lithology, structural discontinuities, groundwater conditions, and external loads. Therefore, a comprehensive approach that integrates monitoring data with field investigations and laboratory analyses is essential for obtaining accurate assessments.

Another important aspect highlighted is the role of data analysis and interpretation in the decision-making process. The mere collection of data is insufficient; it must be properly processed, analyzed, and transformed into actionable information. This process enables the identification of critical thresholds, the establishment of warning systems, and the implementation of appropriate preventive or corrective measures.

Furthermore, the implementation of automated monitoring systems represents a major step forward in improving the efficiency and reliability of slope monitoring. These systems facilitate real-time data acquisition, rapid detection of anomalies, and immediate response to critical situations, thereby enhancing the overall safety of mining operations.

The results also indicate that monitoring should be considered an integral component of the risk management strategy in mining activities. By providing continuous feedback on slope behavior, monitoring systems support proactive interventions, reducing the likelihood of catastrophic events and optimizing operational planning.

The DJI Mavic 2 Enterprise Advanced and Mavic 3 Multispectral provide with a robust, dual platform monitoring capability tailored to waste dump management challenges. The thermal resolution and high-zoom visual camera excel at safety-critical fire detection and infrastructure inspection, while the Mavic 3M's multispectral array delivers insight into vegetation health and environmental compliance. Their shared RTK precision, autonomous flight capabilities, and compact deployability enable cost-effective, repeatable monitoring regimes that minimize personnel exposure to hazardous site conditions.

In conclusion, the use of modern monitoring techniques, combined with a comprehensive approach to data analysis and interpretation, is essential for ensuring the stability of slopes in mining areas. The integration of these systems into the overall management framework contributes to improved safety conditions, increased operational efficiency, and the sustainable development of mining activities.

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Annex 1 Required Geodetic and Geotechnical Instruments and Methods for Dump Monitoring

Instrument / Method	Action	Description	Availability / Relevance
High-resolution topography	Accurate Assessment of Surface Displacement	Provide high-precision spatial data about the geometric displacement of points on the tailings dump over time	Yes / Yes
	Assessing Slope Stability	Determines surface trends	
	Monitoring Leachate and Water Influence	Has an indirect role in determining movement trends which may be correlated with rainfall/leachate patterns. Can identify drainage blockages or pooling.	
	Detecting Waste Body Settlement	Assess dump stability	
	Validation and Refinement of Models	Acts as a ground-truth reference for testing the accuracy of parametric models	
	Integrated Risk Management	Identifies at-risk surface zones	
	Environmental Protection	Monitor potential seepage or environmental contamination pathways through displacement patterns. Detect cover failures or leachate escape routes. Highlights erosion or runoff changes.	
	Cost Efficiency	May miss underlying causes	
Total stations	Accurate Assessment of Surface Displacement	Monitor movement of targets placed on the landfill surface.	Yes / Yes
	Assessing Slope Stability	Points along slope for monitoring the signs of progressive failure. Supports early warning through trend forecasting	
	Monitoring Leachate and Water Influence	Establishes movement trends based on precipitation/leachate buildup	
	Detecting Waste Body Settlement	Track differential settlement across the landfill	
	Enhanced Predictive Capabilities	Offer periodic snapshots of ground movement	
	Validation and Refinement of Models	Time-series data used to compare predicted vs. observed behaviour	
	Early Warning System Development	Robotic total stations are used for rapid displacement detection.	
	Integrated Risk Management	Captures localized displacements, which might indicate risks such as slope failure or seepage	
	Cost Efficiency	May miss underlying causes	
	Environmental Protection	Monitor potential seepage or environmental contamination pathways through displacement patterns. Detect cover failures or leachate escape routes. Highlights erosion or runoff changes.	
GNSS monitoring stations	Accurate Assessment of Surface Displacement	high-precision surface movement detection. Track horizontal and vertical displacement.	Yes / Yes

	Assessing Slope Stability	Points placed along slope for monitoring the signs of progressive failure. Supports early warning through trend forecasting	
	Detecting Waste Body Settlement	Track differential settlement across the landfill	
	Validation and Refinement of Models	Time-series data used to compare predicted vs. observed behaviour	
	Integrated Risk Management	Historical displacement trends from archived GNSS data	
	Cost Efficiency	Selective high-precision GNSS reduces need for dense instrumentation, though may miss underlying causes	
	Environmental Protection	Monitor potential seepage or environmental contamination pathways through displacement patterns. Detect cover failures or leachate escape routes. Highlights erosion or runoff changes.	
Continuous / Real-time geodetic measurements	Enhanced Predictive Capabilities	Offer real-time or periodic snapshots of ground movement. Tracks movement acceleration trends.	No / No
	Early Warning System Development	For rapid displacement detection.	
	Cost Efficiency	Reduces need for over-instrumentation	
Photogrammetry	Accurate Assessment of Surface Displacement	Identifies terrain changes in shape and elevation over time.	Yes / Yes
	Assessing Slope Stability	Deformation photogrammetric mapping is used to quantify changes in slope geometry	
	Detecting Waste Body Settlement	Assesses long-term subsidence.	
	Enhanced Predictive Capabilities	Drones used for high-resolution deformation maps.	
	Validation and Refinement of Models	Acts as a ground-truth reference for testing the accuracy of parametric models. Time-series data used to compare predicted vs. observed behaviour.	
	Integrated Risk Management	Captures localized displacements, which might indicate risks such as slope failure or seepage. Historical displacement trends from archived photogrammetric data.	
	Cost Efficiency	Fast and low-cost coverage of large areas, though may miss underlying causes.	
	Environmental Protection	Monitor potential seepage or environmental contamination pathways through displacement patterns. Detect cover failures or leachate escape routes. Highlights erosion or runoff changes.	
Terrestrial LiDAR	Accurate Assessment of Surface Displacement	Scans terrain changes in shape and elevation over time. Provide high-precision spatial data about the geometric displacement of points on the tailings dump over time.	No / Yes
	Assessing Slope Stability	Deformation mapping is used to quantify changes in slope geometry.	
	Monitoring Leachate and Water Influence	Has an indirect role in assessing movement trends correlated with rainfall/leachate patterns.	
	Enhanced Predictive Capabilities	Offer periodic snapshots of ground movement based on high-resolution deformation maps.	

	Validation and Refinement of Models	Acts as a ground-truth reference for testing the accuracy of parametric models. Time-series data used to compare predicted vs. observed behaviour.	
	Integrated Risk Management	Captures localized displacements, which might indicate risks such as slope failure or seepage. Historical displacement trends from archived LiDAR data.	
	Environmental Protection	Monitor potential seepage or environmental contamination pathways through displacement patterns. Detect cover failures or leachate escape routes. Highlights erosion or runoff changes.	
Inclinometers	Accurate Assessment of Surface Displacement	Helps in understanding the behaviour of the dump by fitting measured data to models based on physical, geotechnical, or empirical parameters. Measure subsurface horizontal displacements.	Yes / Yes
	Assessing Slope Stability	Identify slip surfaces.	
	Enhanced Predictive Capabilities	Automated readings detect precursor movements	
	Early Warning System Development	Automated readings help detect internal destabilization	
	Cost Efficiency	Strategically placed, reduce over-instrumentation. Models without data validation risk inaccuracies.	
Piezometers	Assessing Slope Stability	Measure pore water pressure, indicating risk of slope failure.	Yes / Yes
	Monitoring Leachate and Water Influence	Track internal fluid pressures.	
	Enhanced Predictive Capabilities	Monitor pore pressure build-up (a key failure trigger).	
	Early Warning System Development	Automated readings help detect internal destabilization	
	Cost Efficiency	Strategically placed, reduce over-instrumentation. Models without data validation risk inaccuracies.	
	Environmental Protection	Simulate environmental impacts and devise containment strategies. Assess hydraulic gradients that might threaten containment.	
Temperature sensors	Assessing Slope Stability	Contribute indirectly to overall landfill stability	Yes / Yes
	Monitoring Leachate and Water Influence	Affect biological activity and leachate and gas generation, contributing indirectly to overall landfill stability	
	Detecting Waste Body Settlement	Affect structural material integrity which contributes to overall landfill stability	
	Enhanced Predictive Capabilities	Establish a correlation between temperature values and ground movement	
	Validation and Refinement of Models	Hypothesize or simulate conditions and responses based on tailing dump temperature values	
	Integrated Risk Management	Affect biological activity, leachate and gas generation and structural material integrity, all of which contribute to overall landfill stability	
Humidity sensors	Assessing Slope Stability	Contribute indirectly to overall landfill stability	Yes / Yes

	Monitoring Leachate and Water Influence	Measure precipitation levels. Affect biological activity and leachate and gas generation, contributing indirectly to overall landfill stability	
	Detecting Waste Body Settlement	Affect structural material integrity which contributes to overall landfill stability	
	Enhanced Predictive Capabilities	Establish a correlation between humidity values and ground movement	
	Validation and Refinement of Models	Hypothesize or simulate conditions and responses based on tailing dump humidity values	
	Integrated Risk Management	Affect biological activity, leachate, structural material integrity, and hydrological conditions, all of which contribute to overall landfill stability	
Geophone	Assessing Slope Stability	Can measure ground velocity or ground acceleration. Detect ground motion by analyzing the returning seismic waves	Yes / Yes
	Monitoring Leachate and Water Influence	Assessment of subsurface geology and identification of features like underground layers and water	
	Detecting Waste Body Settlement	Seismic waves are partially reflected due to changes in material properties (such as density and elastic modulus), allowing subsurface structures mapping	
	Cost Efficiency	Minimise infrastructure set-up costs	
Strain gauges	Assessing Slope Stability	Detect stress in geosynthetics or retaining structures.	No / Yes
	Validation and Refinement of Models	Hypothesize or simulate conditions and responses based on tailing dump characteristics. Validate internal stress response.	
	Early Warning System Development	Help early detection of displacements and deformations	
	Cost Efficiency	Strategically placed, reduce over-instrumentation. Models without data validation risk inaccuracies.	
	Environmental Protection	Simulate environmental impacts and devise containment strategies. Ensure barrier integrity.	
Extensometers	Accurate Assessment of Surface Displacement	Helps in understanding the behaviour of the dump by fitting measured data to models based on physical, geotechnical, or empirical parameters. Track vertical settlement within the landfill body.	No / Yes
	Detecting Waste Body Settlement	Measure layer-specific settlement.	
	Validation and Refinement of Models	Hypothesize or simulate conditions and responses based on tailing dump characteristics. Validate internal stress response.	
	Early Warning System Development	Help early detection of displacements and deformations	
	Cost Efficiency	Strategically placed, reduce over-instrumentation. Models without data validation risk inaccuracies.	
	Environmental Protection	Simulate environmental impacts and devise containment strategies. Ensure barrier integrity.	
Settlement plates	Accurate Assessment of Surface Displacement	Track vertical settlement within the landfill body.	No / No
	Detecting Waste Body Settlement	Quantify vertical displacement at various depths.	

	Validation and Refinement of Models	Hypothesize or simulate conditions and responses based on tailing dump characteristics. Validate internal stress response.	
	Cost Efficiency	Strategically placed, reduce over-instrumentation. Models without data validation risk inaccuracies.	
Leachate level sensors	Monitoring Leachate and Water Influence	Indicate hydrodynamic changes in the waste body.	No / No
	Environmental Protection	Simulate environmental impacts and devise containment strategies. Ensure barrier integrity	

Annex 2 Comparation between LiDAR and photogrammetry

The choice between LiDAR (Light Detection and Ranging) and photogrammetry largely depends on the environment to be scanned, budget, and the desired end result. While both technologies create 3D models, they use fundamentally different methods: LiDAR uses active laser pulses to measure distances, while photogrammetry relies on the overlay of 2D photographs to reconstruct geometry.

Key Differences

Feature	LiDAR	Photogrammetry
Data Source	Active (Own Laser)	Passive (Ambient Light/Photo)
Vegetation	Penetrates canopy (sees ground)	Sees only top of foliage
Vertical Accuracy	Very high, even in complex areas	Good, but depends on surface texture quality
Visual Details	"Dry" point cloud, often without true colors	High visual realism (real photo textures)
Lighting Conditions	Works at night or in shade	Requires good, constant lighting
Costs	Expensive equipment, fast processing	Affordable equipment, intensive processing

Choose LiDAR if:

- You need a digital terrain model (DTM) under forests or dense vegetation.
- You measure thin or complex objects, such as power lines or fine metal structures.
- The project requires high absolute accuracy in low-contrast areas (e.g., uniform paved roads).

Choose Photogrammetry if:

- The priority is visual context (color maps, photorealistic 3D models for presentations).

- The budget is limited; you can use a standard drone with a high-resolution camera.
- The area to be scanned is open, with no vegetation blocking the view of the ground.

Many modern surveying projects (including mining waste dump monitoring) use a hybrid approach, combining the structural accuracy of LiDAR with the visual realism of photogrammetry to create ultra-detailed, true-to-life 3D models.