ROBOMINERS DELIVERABLE D6.1

MINER PERCEPTION REPORT

Summary:

This report will give an overview of the possible sensing methods within the context of the mining scenarios presented in D5.1: operating and abandoned mines with known remaining unfeasible resources; ultra-depth; small deposits uneconomic for traditional mining.

The main challenges for the perception within the ROBOMINERS project are to perceive the environment with little or without visual cues, that is widely used and studied in ground and aerial robotics. The slurry underwater environment, as the most difficult use case, is therefore taken a basis for choosing sensors and sensor combinations for the task of following the ore body and mapping surroundings for localization.

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GLOSSARY

AEM: Airborne Electromagnetic. Geophysical method for mineral exploration and sub-surface imaging.
Backfilling: Method used during mining excavation for ground support. Mine tailings, soil or overburden are used to fill the excavated space created by mining operations.
Bench-and-fill: Mining method commonly used for orebodies with irregular ore zones and scattered mineralization. The ore is mined in slices, once every slice is mined the void is backfilled.
Borehole calliper: Well logging tool that provides a continuous measurement of the size and shape of a borehole along its depth.
COTS: Commercial off-the-shelf or commercially available off-the-shelf products.
Cross-section: Graphic representation of the geological features along a vertical plane.
CSMAT: Controlled-source Audio-frequency Magneto-Tellurics. Geophysical method for mineral exploration and imaging.
Dielectric permittivity: Physical property which characterizes the degree of electrical polarization a material experiences under the influence of an external electric field.
Drift-and-fill: Mining method similar to cut and fill, except it is used in ore zones which are wider than the method of drifting will allow to be mined.
Drill rod: Equipment for drilling deep holes, usually several rods are connected one after another to reach great depths.
Electrical conductivity: Material's ability to conduct electric current.
Electrical resistivity: Material's ability to resist electric current.
EM: Electromagnetic method. Geophysical method for mineral exploration and imaging.
ERT: Electrical resistivity tomography. Geophysical method for sub-surface imaging.
FMI-HD: High-definition Formation Microimager. Resistivity logger created by Schlumbereger for borehole investigation and imaging.
GNSS: Global Navigation Satellite System. Satellite navigation system that uses small satellites to pinpoint the geographic location of a user's receiver on Earth.
GPR: Ground Penetrating Radar. Geophysical method for sub-surface imaging. Applied also to mineral exploration.
GPS: Global Positioning System.
GR: Gamma-ray
Grade: Concentration of the desired mineral in the ore deposit.
Host rock: Rock surrounding the ore deposit.
IMU: Inertial Measurement Unit. IMU is an electronic device that measures accelerations, angular rate and the orientation.
IP: Induced Polarization. Geophysical method for sub-surface imaging.
IPB: Iberian Pyrite Belt
LIBS: Laser Induced Breakdown Spectroscopy. Spectroscopic imaging method.
LIDAR: Light Detection and Ranging. Remote sensing method.

Load Torque: Amount of torque constantly required for application and includes friction load and gravitational load. The torque is the measure of how much a force acting on an object causes that object to rotate.
Log: Record of the geological formation and characteristic encountered by the borehole.
LWD: Logging While Drilling. Exploration technique used in the oil and gas industry. Measurement of the formation properties during the borehole excavation.
MIP: Magnetic Induce Polarization. Geophysical method for mineral exploration and sub-surface imaging.
MMR: Magnetometric Resistivity. Geophysical method for mineral exploration and sub-surface imaging.
OEM: Original Equipment Manufacturer.
Ore: Rock or sediment that contains one or more valuable minerals.
Ore body: Accumulation of ore.
PCA: Principal Component Analysis.
PFTNA: Pulsed Fast and Thermal Neutron Activation. Technology for elemental analysis.
Raman: Spectroscopic technique for molecular analysis.
RFS: Radio Frequency Scanner.
ROBOMINERS: Resilient Bio-inspired Modular Robotic Miners.
Shrinkage stoping: Short-hole mining method which is most suitable for steeply dipping orebodies.
Sensing techniques: Technique for detection and acquisition of data. They include Geophysical investigation method and Spectroscopic techniques for geochemical analysis.
Slurry: Mix of solid particles suspended in liquid, usually water.
Solid-state-sensor: sensor without moving parts that have a high reliability.
SP: Self-potential. Electrical method for geophysical exploration and imaging.
SSC: Sediment host copper deposit.
SWD: Seismic while drilling. Techniques that merge the seismic data acquisition while drilling a borehole.
TDEM: Time-domain Electromagnetic method. Geophysical method for mineral exploration and imaging.
TRL: Technology readiness levels. Method for estimating the maturity of technologies.
Ultra-deep deposit: Ore bodies situated below 2.5 km.
UV: Ultraviolet. Electromagnetic radiation with wavelength from 10 to 400 nm
VIS-NIR: Visible–Near–Infrared spectroscopy. Spectroscopic technique for geochemical analysis.
VMS: Volcanic Massive Sulphide deposit.
XRD: X-ray powder diffraction. Analytical technique used for phase identification of a crystalline material.
XRF: X-ray fluorescence. Analytical technique used to determine the elemental composition of materials.

EXECUTIVE SUMMARY

This report will give an overview of the possible sensing methods within the context of the mining scenarios presented in D5.1: operating and abandoned mines with known remaining unfeasible resources; ultra-depth; and small deposits uneconomic for traditional mining.

To address the different scenarios, the deliverable will look at three tasks that are common to all the before mentioned scenarios. (1) The robot needs to navigate through the mine without global reference frame and create its own map and simultaneously locate itself. Thereof, sensors that can be used for mapping and localization are addressed and evaluated. (2) As a second task, the robot needs to be able to follow the ore vein in the mine. Meaning that it is important to evaluate sensors and methods that can be used to evaluate the properties of the excavated spaces to decide, which direction in the deposit the robominer should follow. (3) The excavated material needs to be evaluated as it is transported to the surface. As the transported ore would most likely be in a slurry form, sensors that can analyse/read the mineral content in this form will be studied.

The main challenges for the perception within the ROBOMINERS project are to perceive the environment with little or without visual cues, that is widely used and studied in ground and aerial robotics. The slurry underwater environment, as the most difficult use case, is therefore taken as basis for choosing sensors and sensor combinations for the task of following the ore body (selective mining goal) and mapping surroundings for localization.

The structure of the deliverable is the following:

- In the first section, an overview of the mining scenarios is given.
- An overview of sensors is given with pre-evaluations in section 2 following the before mentioned three mining tasks.
- In section 3, sensor studies made by WP1 and WP6 are demonstrated.
- In section 4, the proposed sensor list is narrowed down by the project consortium, considering the most challenging cases of the three mining scenarios. As a result, a short list of sensor modalities is proposed, that will be studied and tested within the ROBOMINERS project.

A large proportion of the proposed sensing methods will be evaluated in a laboratory environment using ROBOMINERS partners' facilities, and the most promising methods will be field-tested in a relevant environment. Considering the applicability in the harsh mining conditions, sensors availability in the project resources and reasonably achievable TRL level, a selection of technologies, highlighted in this document, will be applied on the final prototype.

1 PERCEPTION FOLLOWING THE MINING SCENARIOS

One of the main challenges to operate within an environment with unknown spatial and physical properties, that poses limitations for using optical clues for mapping and localization, is to combine multi-modality sensing for locomotion and mineral detection. Ground robots traditionally rely on sensors such as sonars, vision, GPS (Global Positioning System) or LIDAR (Laser Imaging Detection and Ranging), underwater robots almost always use sonars and vision if visual cues are available. Those traditional sensors mostly fail in an underground mine, in particular a slurry-filled environment. GPS signals are not available for global localization. Slurry and dust impede sonar or radar and LIDAR signal propagation as well as vision. Therefore, the ROBOMINER has to rely on other cues which might convey information from the environment.

The following section describes the work process that the ROBOMINERS platform will be conducting in different working scenarios. A short overview of the scenarios in context of challenges on perception is given in Section 2.1 based on D.5.1 (Hartai et al. 2020). After the overview, a list of possible sensing methods is described in section 2.2, following the logical order of mining tasks.

1.1 MINING SCENARIO OVERVIEW

The envisioned ROBOMINERS technology will be applied where traditional mining is ineffective, wasteful or hindered by serious obstacles. Considering the possibilities and the potential advantages of the new technology to traditional mining, the following geological and mining scenarios were set up:

- Operating and abandoned mines with known remaining unfeasible resources;
- Ultra-depth;
- Small deposits uneconomic for traditional mining.

These scenarios are discussed in details in Deliverable 5.1, titled “Review Document Giving Scope and Examples of Deposit Types of Interest” (Hartai et al. 2020).

1.1.1 Operating and abandoned mines with known remaining unfeasible resources

In Europe there are numerous ore deposits where operations were stopped because remaining resources could not be exploited economically. In such cases, application of the ROBOMINERS technology can be based on existing geological knowledge and technical facilities. A special advantageous case is when the ROBOMINERS technology can be coupled to an adjacent, operating traditional mine, supplying ores of alternative quality.

Example for the scenario: Neves-Corvo

The Iberian Pyrite Belt (IPB) extends to about 230 km in E-W strike through Southern Spain into Portugal. Most abundant metals produced from the IPB are copper, lead, zinc, silver and gold. Neves-Corvo is a Cu-Zn ore deposit is located in the western, Portuguese part of IPB. It is a volcano-sedimentary massive sulphide (VMS) deposit, formed from the Late Devonian to the Carboniferous. Ores are hosted by rhyolite dominated volcanic, volcaniclastic and sedimentary complex.

Typical ore bodies of the deposit are lenses of polymetallic Cu-Pb-Zn massive sulphides with additional Sn mineralisation that formed at or near the seafloor. Ore minerals are intergrown, often replacing each other formed by a multistage hydrothermal process, resulting complex textures. Shape of the ore bodies was also influenced by gravity-driven mass transport processes and subsequent low-angle thrusting and asymmetric detachment folding. The geology of the deposit is summarised in details in the reports of the H2020 project CHPM2030 (Schwarz et al. 2017; Ramalho, Matos, and Carvalho 2019).

Primary targets of the operation are a number of massive sulphide ore lenses linked by zones of thin discontinuous mineralisations in a shallow NE dipping zone. Seven major massive sulphide bodies are located at Neves, Corvo, Graça, Zambujal, Lombador, Semblana and Monte Branco. Geometry of the ore lenses is well known from mining and exploration (Figure 1). They are relatively flat, extensive in two dimensions (600-1200 m × 500-700 m) and their thickness varies from 50 to 90 m. The lenses are accompanied by stockwork zones in the footwall host rocks, mostly rich in copper as well as the bottom part of the lenses.

ROBOMINERS technology would be able to exploit economically the thin mineralised bodies between the major lenses, which are relatively well-explored between Corvo, Zambujal, and Semblana deposits. ROBOMINERS automated stopes could be developed and serviced from the existing and operational underground haulage, hoisting, ventilation and energy supply systems. The extracted product could be composited with the traditional mine products in a certain point of the processing flowsheet in on-site ore processing facilities.

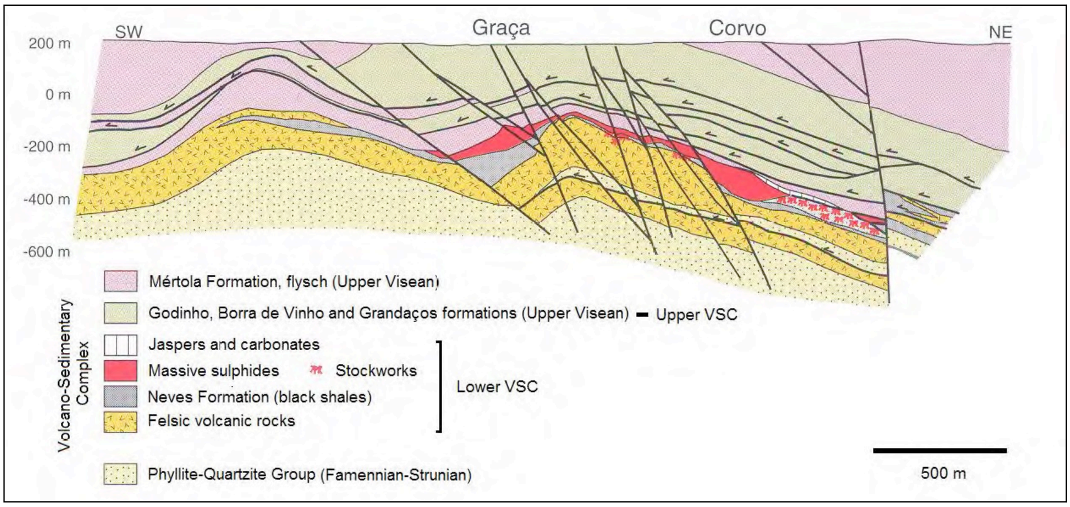

Figure 1 Neves Corvo general geological section, adapted from adapted from Relvas et al., 2006 (Schwarz et al. 2017)

The adopted mining methods in Neves-Corvo and possible application of the ROBOMINERS technology

During the 25 years of continuous mining in the Neves-Corvo mine, various mining methods have been developed and tested. Geology and geotechnical considerations and the geometry of deposit resulted in modifications in the mining methods. The geometry of the high-grade zinc and copper zones within the deposits can be very complex. The mining methods should be adapted to the present conditions.

Drift-and-fill method is implemented in the areas where the mineral deposit thickness is less than 10m. Following completion of a drift it is tightly backfilled with hydraulic sand fill or paste fill before the drift alongside is mined. When a complete 5 m high orebody slice is mined and filled, the back of the access drive is “slashed” down and mining recommences on the level above. In the areas with sufficient thickness (more than 20 m in vertical thickness) and continuity, bench-and-fill mining method is applied instead. Bench-and-fill stopes are also accessed from a footwall ramp, with footwall drives driven along strike in waste at 20m vertical intervals. Upper and lower access crosscuts are driven across the orebody to the hanging wall contact. Adjacent stopes are extracted in sequence. Initially, the so-called primary stopes are extracted up to 120m long. The stopes are normally mined in an up-dip direction. The primary stopes are normally filled with cement paste fill and subsequently tightly filled with hydraulic sand fill. After the backfill process for each of the bench-and-fill stope is finished, the back of the former drilling level is slashed out to establish a new mucking level for the next stope above.

In order to take advantage of the high strength massive sulphide zinc ore and reduce the costs with the similar recovery rates of bench-and-fill mining method, optimized bench-and-fill mining method was developed and introduced. This method is bottom-up with transverse stopes being accessed from footwall ramps and crosscuts. Initial extraction of the primary stopes is followed by backfilling and extraction of secondary stopes between the already mined and backfilled primary stopes. The primary and secondary stopes are of 15m width and 20m height with a variable length depending on the width of the orebody. After the primary and secondary stopes are extracted, the operations in the next level above can be commenced (Figure 2).

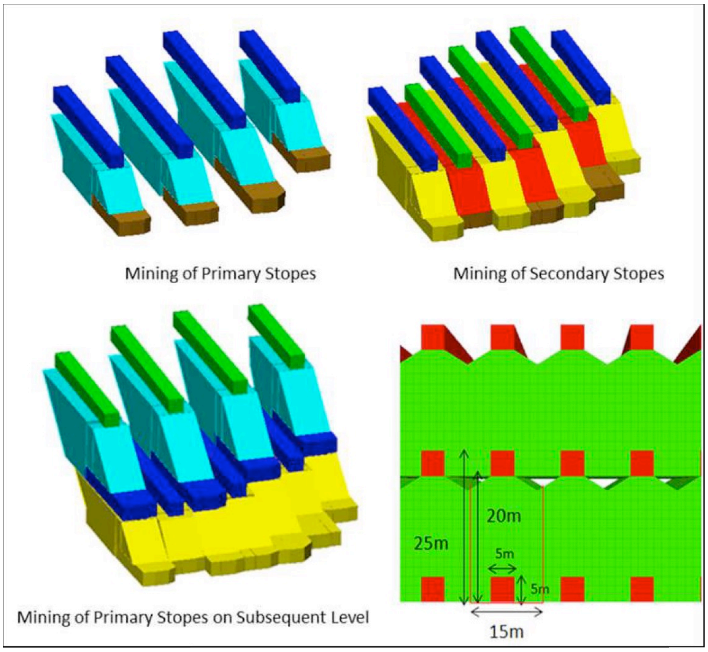

Figure 2 The current optimized bench-and-fill mining method at Nerves-Corvo (Wardell Armstrong International 2017)

The other variations applied in the mine are mini-bench-and-fill (MBF) and the sill pillar mining method. The MBF mining method is a hybrid method which can provide higher productivity compared to the drift-and-fill mining when the orebody thickness is between 10-15 m. The sill pillar mining method was also developed to extract the ore remaining in sill pillars between up-dip mining panels (Wardell Armstrong International 2017). As it was mentioned before, there are some zones connecting the already developed deposits, which demand high operating costs for extraction and are not economic to be extracted with the traditional mining methods explained (Figure 3). These deposits could be rather small deposits with less economic application of methods such as mini-bench-and-fill mining or drift-and-fill mining method.

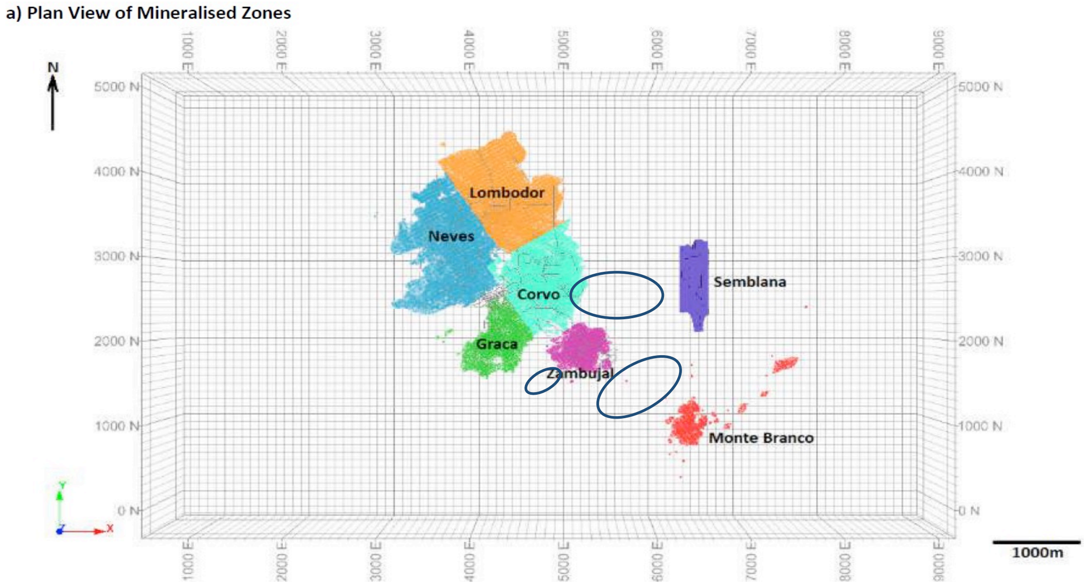

Figure 3 The zones lying between previously developed mining regions for application of ROBOMINERS technology (blue circles) (Wardell Armstrong International 2017)

1.1.2 Ultra-depth

Ore bodies are considered to be 'ultra-deep' when situated below the level of traditional mining (ca. 2.5 km). However, depth limits of mining depend on several factors including geothermal gradient, rock mechanical properties and fluid transport conditions. In the EU, the deepest operating mine is about 1400 metres deep (Pyhäsalmi in Finland), so practically every deposit below that level can be regarded as fitting to the ultra-depth scenario.

Exploration data of deep level ore bodies are very limited or lacking as these were not potential targets of the mining, and extrapolation from near-surface geological models is not straightforward. Even if there is an indication of the existence of such ore bodies, reaching the accuracy of knowledge on geometry and quality appropriate for initiating the mining requires significant additional exploration work. At specific deposit types, geometry and position of a probable continuation can be predicted. For example, if a stratiform deposit known in the basement at the shallow edges of a basin, it may be found also in tectonically subsided inner parts within the same succession.

Example for the scenario: Kupferschiefer, Fore-Sudetic Monocline

The Central European Basin System developed in the end of the Variscan (Hercynian) orogenic period extends from Silesia (Poland) to the eastern part of England. The Permian sediments of the sea filling the basins contain dominantly bituminous marly shale. This is known as a horizon enriched in several metals (mainly base metals), named Kupferschiefer (copper shale) after its German outcrops with deposits mined from the medieval age. The horizon lies on white and red coloured, barren sandstone, and is covered by the Zechstein limestone or dolomite. The mineralisation is known as a sediment hosted copper (SSC) type. The main metals are Cu, Pb and Zn in small grained (20–200 µm) sulphide minerals, but V, Mo, U, Ag, As, Sb, Hg, Bi, Se, Cd, Tl, Au, Re and PGE are also enriched. The magnitude of the original enrichment is some 100 ppm in general, but local secondary ore forming processes extending the mineralisation also to the under- and overlying formations produced higher grade disseminated and replacement style deposits. Although these deposits are of various size and quality, the formation itself is persistent and continuous with a thickness of 0.3–4 m across the continent.

Ongoing tectonic processes positioned the Kupferschiefer horizon to various levels. Outcropping deposits are exhausted mostly. Currently, there are operating mines producing copper and silver ores in Upper Silesia, Poland, situated in the area of the Fore-Sudetic Monocline (Figure 4). The mined levels are between 900 and 1400 metres, but a considerable part of the known resources lie deeper. Beds of the Fore-Sudetic Monocline dip towards NE at a slight angle of 1–6 degrees, and the occurrence of the succession was confirmed also beneath the Polish Lowlands in the North, in 2000–4000 m depth.

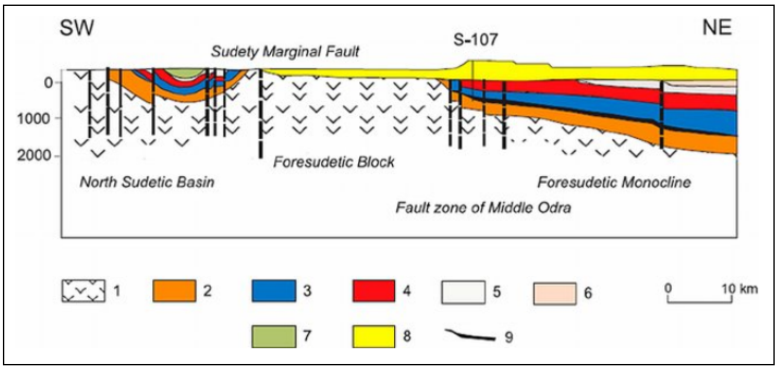

Figure 4 A geological cross-section across the North Sudetic Basin (the old copper ore basin area), Fore-Sudetic Block and the Fore-Sudetic Monocline (the LGOM Copper Ore Basin). 1: Crystalline basement, 2: Rotliegendes, 3: Zechstein, 4: Bunter Sandstone, 5: Muschelkalk, 6: Keuper, 7: Upper Chalk, 8: Cenozoic formation, 9: ore deposit. Source: (Bauer, Puła, and Wyjadłowski 2015)

The thickness of the most enriched shale layer with 5–11wt% Cu content) is generally 0.4–0.6 m, max. 1.7 m. Detailed data on the explored ultra-deep sections of the ore deposit are not public (or only partly available) but considering the distribution of the known ore bodies, the potential resources of copper and silver ores are very large. Application of ROBOMINERS technology could extend the mining economically toward these ultra-deep levels.

The adopted mining methods in adjacent mines and possible application of ROBOMINERS

The first adopted exploitation method in the copper mines of the region began in 1967 with a longwall mining system. The extracted regions were either caved behind or filled with dry backfill. However, this mining system was not efficient. The relatively low dip angle of the orebody and its thickness also enabled application of room-and-pillar mining system with rockbolt support in the year after (Figure 5). The first implementation of room-and-pillar system was done in Lubin mine. However, initial stability issues such as rock falls in the roof led to modernization of the system (Janowski et al. 1996).

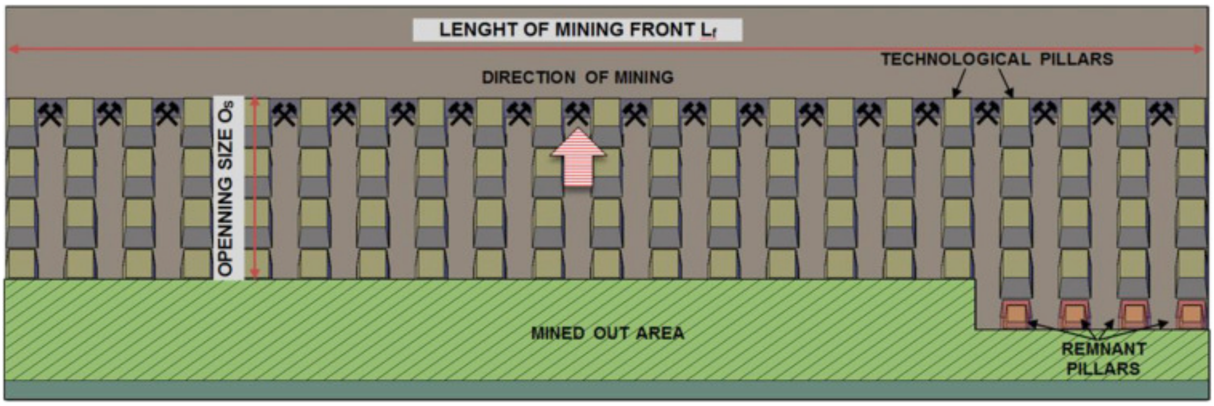

Figure 5 A sketch of the mining method used in KGHM copper mines (Fuławka, Pytel, and Mertuszka 2018)

The strength of rock is quite variable in different regions; however, investigations show a moderate to high compressive strength in the latest working areas (Polkowize mine with average UCS = 80-160 MPa – Rudna and Lubin mine with an average UCS of 60 MPa). The relatively deep mining conditions (up to approx. 1200m depth) and the hard brittle rocks in the mining regions has led to mining hazards. The induced seismicity as a result of overstressing of the rock mass is regarded as the most evident consequence. The stiff rock mass contributes to the accumulation of strain energy, which in turn triggers strong tremors.

In case such accidents are predicted with the increasing depth of the mines, adaptations to the mining system (pillar design) might be necessary. In addition, the use of backfill and destressing by the so-called group blasting are considered. Expanding the active mining regions to deeper recently explored areas requires more robust mining strategies. Ultra-deep mining (> 2.5 km) is mainly experienced in gold mines of South Africa. The so-called sequential grid mining has replaced longwall mining in many deep mines of South Africa. This mining method is designed on the basis of Control of Energy Release Rate. Besides, modifications in the support systems with higher energy absorbing properties are necessary. High support resistance pre-stressed elongates are successfully applied in deep South African mines.

In spite of all the aforementioned measures, there are still a high extent of risks associated with deep mining which cannot be avoided, as long as working personnel are involved in the mine workings. Thus, automated mining is obviously an important step towards increasing the safety in such conditions and enabling the extraction of deep orebodies. The current mining access developments can be a great advantage in facilitating opening the new mine workings for the ROBOMINERS to begin operation and follow the ore deposits. The same mining principles should also be adopted for ROBOMINERS to provide them with a safe working environment.

1.1.3 Small deposits uneconomic for traditional mining

Veins, crosscutting the host rock are the most common forms of mineralisation. Vein fillings can display high concentrations of useful metals, but mostly in relatively small volumes embedded in barren host rock. From the early civilisations, such veins were ideal targets, so a large number of vein type deposits were explored and mined. The current mining requires larger volumes to be cost-effective, thus large-tonnage, lower-grade deposits became more economic like vein-like bodies.

In Europe, there is a huge number of deposits which were abandoned, or never mined because of the development of the mining technology. However, if the investment and operational costs could be significantly reduced, potentially by applying the ROBOMINERS technology, the deposits supplying small volumes of high-grade ores or mineralisations of special composition can become viable.

Example for the scenario: United Downs project, Cornwall

Cornwall in South-west England is famous as a traditional mining region producing tin, copper, tungsten ores and some additional mineral resources. The mining declined and remaining mines were closed at the end of the 20th century, but still there are significant registered resources, and exploration activity – aimed partly on reopening of abandoned mines – did not cease. Strongbow Exploration holds owns mineral rights in the region including the United Downs area, located approximately 8 km east of South Crofty Mine in the mining district Gwennap, the richest copper producing region in the world in the 18th and early 19th centuries.

In April 2020, Strongbow Exploration reported the discovery of a new zone of a high-grade copper-tin mineralisation located in a previously unmined area between the historic United Mine and Consolidated Mines at United Downs (Figure 6). It is a 'semi-massive' sulphide deposit that has been intersected in a drill hole at around 100 m depth with grades of 7.46% Cu and 1.19% Sn over a drilled interval of 14.7 metres. The crosscut was oblique; therefore, the true thickness must be much less than this length. The main mineralised structures in the nearby mines trend ENE and dip steeply to the north.

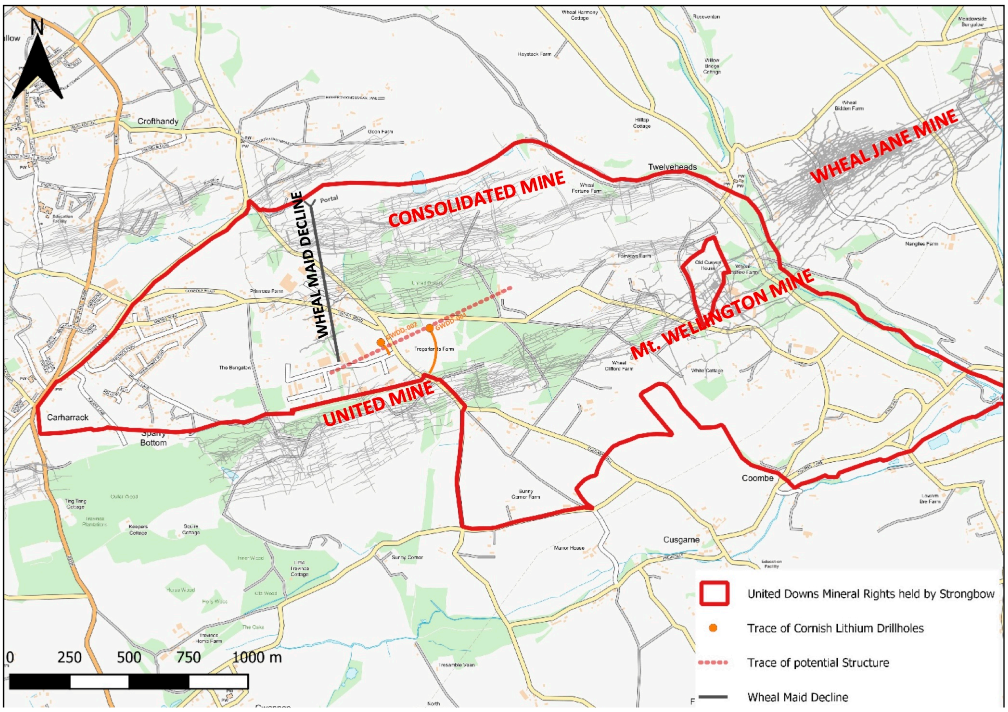

Figure 6 United Downs area showing location of the Wheal Maid decline and likely orientation of the newly discovered deposit. Source: ("Cornish Metals," n.d.)

If this is a tabular vein similar to other lodes of the area, a zonation can be expected. At the nearby South Crofty Mine, copper-tin-zinc-tungsten mineralisation hosted within the Devonian metasediments can be regarded as analogy of the crosscut vein. The deposit passes into tin mineralisation at depth as the mineralised vein-like structures pass into the underlying granitic host rock, which was encountered at United Downs between 300 and 600 m and again at 700 m vertical depth. Even if so, it probably will prove to be too small for conventional mining. However, it would be ideally suitable for robotic extraction by the ROBOMINERS technology, using ore-following methods. Dewatering, a common demand in the mines of Cornwall causing environmental problems could be also avoided.

The adopted mining methods for narrow vein deposits adjacent to United Down and possible application of ROBOMINERS

The vein geometry and the rock mechanical properties of the vein (deposit) and the hosting rock constitute the main factors. Due to the variability of geometry in narrow-vein deposits, the adaptability of the mining method is of crucial importance. Besides, the mining method should enable minimal dilution. In cases where the minimum stope width is smaller than the vein width, some dilution must be expected. Above all, an efficient and safe mining requires careful geomechanical investigations to provide the stability of stopes and development openings.

The mining methods implemented for Wheal Jane mine as one of the adjacent mines to the explored deposit was a combination of shrinkage, open and sub-level stoping (Figure 7). In the steeply dipping regions, shrinkage stoping method was initially being applied. However, they are not cost-effective compared to sublevel stoping and a large amount of mined ore which is piled cannot be extracted over a long period of time. Besides, high dilution of material can be expected where weak side walls exist. The sublevel stoping (longhole-based) method is commonly applied in areas with wider and more continuous steeply dipping veins, where the sidewall rocks are strong. The method was initially applied in Cornwall at Wheal Jane in 1979 and at South Crofty in 1982 (Figure 7).

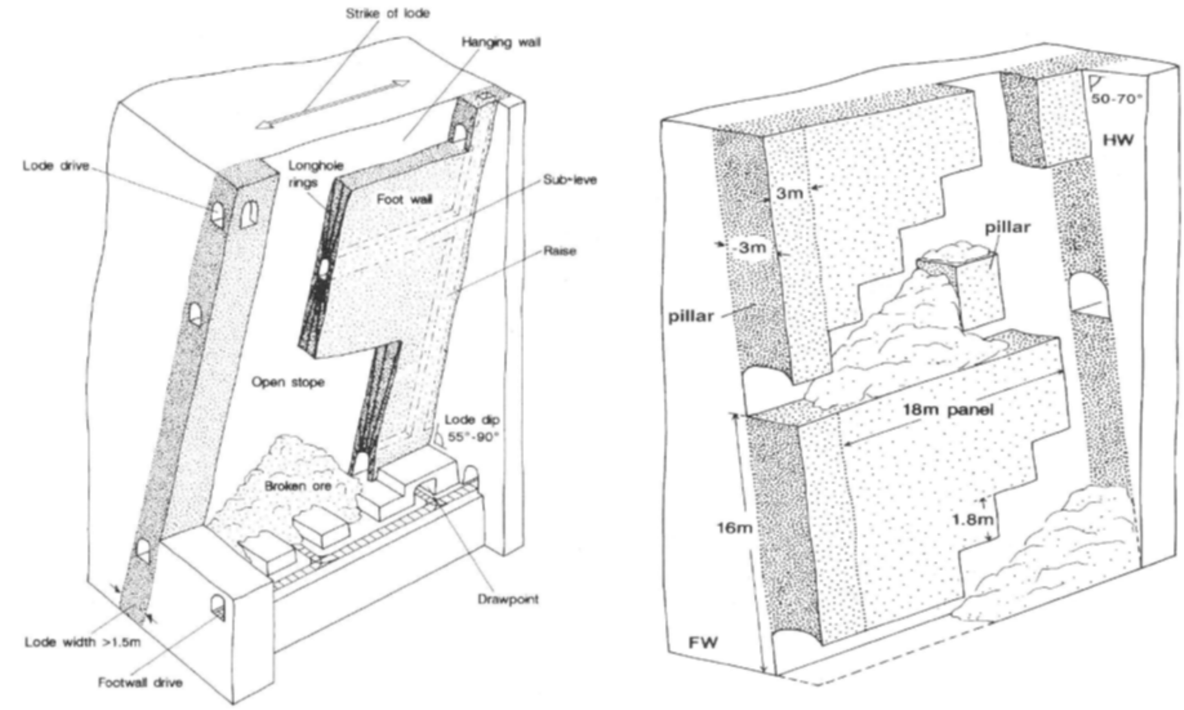

Figure 7 Right: Schematic block diagram showing semi-shrinkage stoping at Wheal Jane mine (Dominy et al. 1998) Left: Schematic block diagram showing sub-level stoping at South Crofty mine (Dominy et al. 1998)

An inherent disadvantage of sublevel stoping is possible dilution from the wall and roof rocks. This could happen where the ore boundaries are irregular or the hosting rock is unstable. To decrease such negative impacts, overbreaking of the rock must be avoided by efficient blasting. Besides, where necessary application of rock and cable bolts should be considered as a method of supporting the hanging wall. Introduction of backfill into the stopes is another supporting method that can be applied. As for Wheal Jane mine, supporting pillars were being left in random positions depending upon the local ground conditions and mineralization. In general, sublevel stoping mines enjoy from a safer extraction environment mainly due to the fact that they are non-entry methods.

Since there are a lot of unknown parameters regarding the shape, extent and the mineralization of the new explored mineral deposit (United Downs), ROBOMINERS technology can be of high advantage for this possibly small ore deposit. This technology can be applied without the necessity of dewatering the nearby closed mines. It can begin exploration and extraction from the pre-mined regions. In addition, ROBOMINERS are specifically efficient mining tools, as they can minimize dilution during extraction, which is quite common in stoping of narrow veins. The high flexibility of the ROBOMINERS concepts can be very beneficial in avoiding the extraction of unwanted low grade surrounding rocks (Dominy et al. 1998).

2 PERCEPTION OF MINING TASKS

ROBOMINERS project will be investigating perception methods in order to deliver solutions for a simple but robust perception, localisation and navigation techniques in underground environments where conventional sensing techniques are likely to fail (i.e. in slurry, dust, rock rubble). The base of evaluation of possible sensing methods must therefore look at following criteria:

- Applicability in air, water, dusty air, unclear water and mud (slurry etc.);
- Availability of the device regarding the project time and budget;
- Requirement of modifications to the sensors;
- Robustness in line with an underground mining environment;
- Ability to (as much as possible) allow continuous perception and continuous data transfer

The proposal of possible sensing methods will look at three main tasks, that are common to the three mining scenarios proposed by D5.1.

- Mapping and localization – a key challenge in the robot's perception point of view. The possible sensors applied should be able to provide information both about the surrounding environment and geophysics for localization purposes where visual perception is hindered.
- Excavation – task, where information from drilling would allow to follow the orebody. At the same time, information regarding the rock hardness and the awareness of the surrounding rock hardness would allow to evaluate the safety of the operation.
- Ore slurry sensing – after excavation, the evaluation of the particulate matter (ore) in the slurry would give an overview of the ore richness.

A fourth unlisted sensor related task of the robominer can be self-awareness. The internal measurements of the robominer modules can be included into the three up-mentioned tasks and could give important information regarding performance and help to reduce system related risks (e.g. breakage of tools, overloading limbs etc.). The self-awareness will be addressed within the development stage of the robot prototype.

The following sub-sections searches for possible sensing modalities for the proposed methods. It must be noted that the list of possible modalities is not final in the following sections. Additional sensing methods could be added into the list later within the project or left out in case of inapplicability becomes evident. A short-list of sensing techniques that will focused on within the ROBOMINERS project is discussed in section 4.

2.1 MAPPING AND LOCALIZATION

Automation in mining industry has made localization and continuous tracking possible using various methods ranging from radio-frequency identification to inertial navigation (Thrybom et al. 2015). Obstacle avoidance and mapping in mining industry mostly rely on visual cues implementing LIDAR, cameras etc. that have been used in automation and teleoperation of mining machines (Peinsitt et al. 2019). Limitation of using optical sensors in the ROBOMINERS poses a challenge and opportunity to develop new localization methods.

For localization, the robot could use proprioceptive sensing (inertial measurements) and exteroceptive sensors (tactile, temperature, pressure, geophysical and any other environmental/geological parameters that can be measured). Moreover, these measurements will be used to map the mined orebody, refine the mine model in real-time and plan the miner actions. For that, an overview is given of possible methods that could separately or in combination, introduce new ways for mapping, localization and navigation in visually deprived mining environments.

2.1.1 Overview of geophysical methodologies

Geophysical methods are used in mineral exploration for geological mapping, and to identify geological environment favourable for mineralization, i.e. to directly detect, or target, the mineralized environment (Dentith and Mudge 2014).

Contrary to the geological view of the environment that focus on the variation of the bulk chemistry, the geophysical view revolves around the changes in the physical properties within the rock. Several methodologies are currently applied for the exploration of mineral deposits. Each methodology relies on particular physical properties of the investigated area. The four main groups of geophysical methods are: (1) gravity and magnetic methods, (2) radiometric methods, (3) electrical and electromagnetic methods, and (4) seismic methods.

Gravity and magnetic methods

The variations in Earth's gravity and magnetic field are at the base of the gravity and magnetic methods. The physical properties considered are the rock density and magnetic susceptibility. These methods are widely used for airborne detection of mineral deposit as it allows to cover big areas. Downhole gravity measurements are used to target highly magnetic mineralization. In the last years, the technology development helped the diffusion of this type of instrumentation, leading to the improvement of depth resolution of gravity measurements (Geng, Yang, and Huang 2017). Gravity and magnetic map differ significantly, as they represent different physical characteristics of rocks (Dentith and Mudge 2014).

Radiometric methods

The radiometric methods measure naturally occurring radioactivity in the form of gamma-rays. The main sources of this type of radiation are the mineral species containing radioactive isotopes of uranium (U), thorium (Th) and potassium (K). Therefore, it is a method strongly linked to geochemistry. Beside the stratigraphy correlation between drill holes and γ-logging, the current technology allows the detection of hydrothermal altered areas and weakly radioactive mineral (Dentith and Mudge 2014).

Electrical and electromagnetic (EM) methods

Electrical methods can be either passive, using fields within the Earth, or active, with the injection of artificial and controlled current into the ground. They rely on the contrast of the electrical properties of the rocks (conductivity and resistivity) and the subsurface. The electrical conductivity is affected by several parameters, such as: presence of water, porosity, groundwater salinity, temperature, pressure and the amount of conducting minerals in the rock. This wide range of properties make electrical conductivity a perfect clue for the individuation of different mineral deposit (Kemna et al. 2012). These include the resistivity method, the induced polarization (IP) method and the self-potential method (SP)

(Dentith and Mudge 2014). While the SP method measure the natural potential of the subsurface, the resistivity an IP methods depend on the injection of the current (direct current or low-frequency alternating currents) into the ground. The resistivity method discerns in the electrical properties of the ground the horizontal and vertical discontinuities. It is also used for the detection of anomalous electrical conductivity measurement due to three-dimensional bodies. The IP method use the determination of the capacitive characteristic of the soil, or rather the capacity of rocks and minerals to accumulate charges by the injected current to locate the areas where the conductive minerals are disseminated (Kemna et al. 2012).

EM methods use the electromagnetic induction as principle. The behaviour of the EM field will then be controlled by the electrical conductivity (important for low-frequency geophysical exploration), the dielectric permittivity (fundamental for ground-penetrating radar measurements) and the magnetic susceptibility (Zhdanov 2010). Airborne EM measurements for geological mapping are increasing following the technological development of the technique.

Other magnetometric methods are the magnetometric resistivity (MMR) and the magnetic induced polarization (MIP). These use an injected low-frequency alternating current into the rocks, and are used to localize highly conductive or weakly conductive targets in a conductive host. Magnetometric measurements are affected by the presence of external magnetic field (Dentith and Mudge 2014).
The EM methods includes as well the radio (10 kHz to 30 MHz) and the radar (1 to 1000 MHz) methods (Figure 8). The EM field at these frequencies spread as a wave through the medium. Ground-penetrating radar is a method that use radar pulses to map the subsurface. Even if the range of penetration is limited due to the high frequency used, GPR has shown in comparison to other methodologies a remarkable resolving capability (Dentith and Mudge 2014). Finally, Terahertz and millimetres waves reflectance imagers (see figure 24) could also be applied to follow conductivity contrasts with a relatively small (centimetres to decimetres penetration depth).

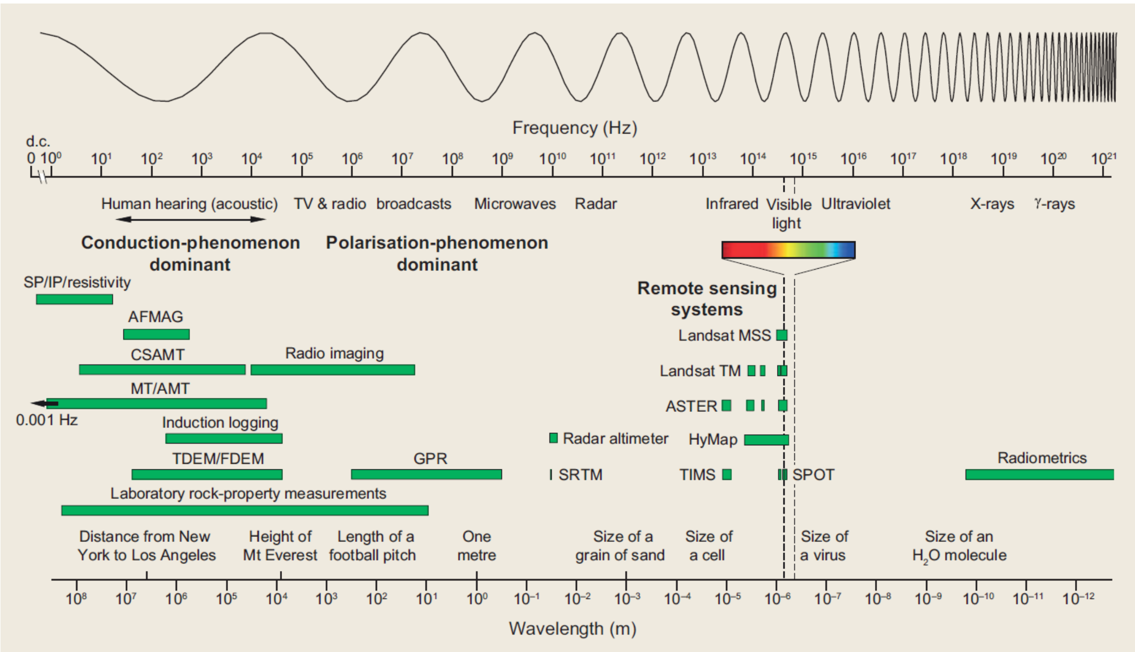

Figure 8 Frequency bands used by the various geophysical methods. From (Dentith and Mudge 2014)

Seismic methods

The seismic methods are active methods that uses elastic waves to investigate the subsurface. The two main survey types are the seismic reflection survey and the seismic refraction survey. The first one use waves reflected at elastic discontinuities and it is most efficient in areas with geological boundaries that are sub-horizontal and laterally continuous. Seismic refraction is based on the deflection of the waves when they encounter the bedrock's discontinuities. Even if this type of survey provides less detailed information, the accuracy for the boundary position is superior to a reflection survey. Tomography seismic is used to determine the elastic properties of the ore body between drill hole intersections (Dentith and Mudge 2014). To be mentioned is the passive seismic imaging, that using ambient noise tomography and reflection tomography creates high resolution images of the subsurface (Ramm, de Wit, and Olivier 2019). The geophysical surveys mentioned so far cannot be applied to all types of mineral deposits. From (Airo 2015) and (McQueen 2005) we have an overview of the elements and factors that influence the geophysical expression of the mineralized system:

1. Composition of the ore deposit and the contained elements. This influences the density, magnetism, electrical conductivity, and radioactivity properties of the rocks.
2. Form of the ore deposit (e.g. size, shape, orientation, depth; ore mineral distribution and texture). All these factors play a role in the high/low contrast of the received signal.
3. Associated geological structure. Most of the mineral deposits are structurally controlled; therefore, a knowledge of the structural interrelationship and stratigraphic units is essential for mineral exploration.
4. Associated host rocks. The association of ore types with a particular host rock assemblage broadly reflects the geological environment and processes that have formed the ore.
5. Non-ore element component. Chemical alteration of host rocks may produce detectable geophysical signatures if it produces minerals having anomalous physical properties. Extensive fluid-related alteration of the host rocks may have a significant effect on geo-physical signatures as well.

The applicability of the geophysical methods in the exploration of different mineral deposit is listed in Table 1 (developed from (K. FORD, n.d.), (Dentith and Mudge 2014) and (Airo 2015)):

Table 1 Applicability of the geophysical methods in the exploration of different mineral deposit. G: Geological framework, D: direct targeting

Geophysical method / Ore deposit	MAGNETIC				ELECTRO-MAGNETIC				ELECTRIC		GRAVITY				RADIOMETRIC				SEISMIC	
	Air		Ground		Air		Ground		Ground		Air		Ground		Air		Ground		Ground	
	G	D	G	D	G	D	G	D	G	D	G	D	G	D	G	D	G	D	G	D
Magmatic ore deposit																				
Orthomagmatic Cr-Fe-Ti	🟢	🟡	🟡	🟡	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟡	🔴	🟡	🔴	🟡	🟡
Orthomagmatic Cu-Ni-Fe-Pt	🟢	🟡	🟡	🟡	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟡	🔴	🟡	🔴	🟡	🟡
Carbonatite-alkaline intrusion related	🟢	🟡	🟢	🟡	🟡	🟡	🟡	🟡	🟡	🟢	🟢	🟡	🟡	🟡	🟢	🟡	🟢	🟡	🔴	🔴
Magmatic-hydrothermal																				
Pegmatite	🟢	🟢	🟢	🟢	🟡	🔴	🟡	🔴	🟡	🟡	🟢	🟢	🟢	🟢	🔴	🟡	🔴	🟡	🟡	🟡
Greisen	🟢	🟢	🟢	🟢	🟡	🔴	🟡	🔴	🟡	🟡	🟢	🟢	🟢	🟢	🔴	🔴	🔴	🔴	🟡	🔴
Porphyry	🟢	🟢	🟢	🟢	🔴	🔴	🔴	🔴	🔴	🟢	🟡	🔴	🟡	🟡	🟢	🟢	🟢	🟢	🟡	🟡
Epithermal	🟢	🟢	🟢	🟢	🟢	🟡	🟢	🟢	🟡	🟢	🟢	🟢	🟢	🟢	🟡	🟡	🟡	🟢	🔴	🔴
Skarn	🟢	🟢	🟢	🟢	🟡	🔴	🟡	🔴	🔴	🟡	🟢	🟢	🟢	🟢	🔴	🔴	🔴	🔴	🟡	🔴
Iron Oxide Copper-Gold (IOCG)	🟢	🟢	🟢	🟢	🟢	🟡	🟢	🟢	🟡	🟢	🟡	🟢	🟡	🟢	🟡	🟢	🟡	🟢	🔴	🔴
Hydrothermal deposit																				
Vein associated deposit	🔴	🔴	🟡	🟢	🔴	🔴	🟡	🟢	🟢	🟢	🔴	🟡	🟡	🟡	🔴	🔴	🟡	🟡	🔴	🟡
Volcanogenic Massive Sulphide (VMS)	🟢	🟢	🟢	🟢	🟡	🟢	🟡	🟢	🟡	🟢	🟡	🟢	🟡	🟢	🟢	🟡	🟡	🟡	🟡	🟡
Sedimentary exhalative (SEDEX)	🟢	🟡	🟢	🟡	🟡	🟡	🟡	🟡	🔴	🔴	🟡	🟡	🟡	🟢	🟢	🔴	🟡	🔴	🟡	🟡
Mississippi Valley Type (MVT)	🟢	🔴	🟡	🔴	🔴	🔴	🟡	🟡	🟡	🟢	🟡	🟡	🟡	🟢	🟡	🔴	🔴	🔴	🟡	🟡
Stratiform Sediment hosted Copper (SSC)	🟢	🟡	🟢	🟡	🟡	🟢	🟡	🟢	🟢	🟢	🟢	🟡	🟢	🟡	🔴	🔴	🔴	🔴	🟡	🔴
Orogenic gold	🟢	🔴	🟢	🟡	🟡	🟡	🟡	🔴	🔴	🟡	🟡	🔴	🟡	🔴	🟢	🟡	🟢	🟡	🟡	🔴
Sandstone hosted uranium-vanadium	🟢	🔴	🟢	🔴	🟢	🟢	🟢	🟢	🔴	🟡	🟡	🔴	🟢	🔴	🟢	🟢	🟢	🟢	🟡	🟡
Sedimentary deposits																				
Bauxite	🟡	🟡	🟡	🟡	🔴	🔴	🟡	🟢	🟢	🟢	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🟢	🟢
Placer	🟡	🟡	🟡	🟡	🟢	🟡	🟢	🟡	🟢	🟡	🟢	🟢	🟢	🟢	🔴	🔴	🔴	🔴	🟡	🟡
Banded Iron Formations (BIF)	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟡	🔴	🟡	🟢	🟢	🟢	🟢	🟡	🔴	🔴	🟡	🟡	🟡
Ironstone	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟡	🟡	🟢	🟢	🟢	🟢	🟡	🔴	🟡	🔴	🔴	🔴

G: Geological framework D: direct targeting

Applicability of geophysical method: 🟢 Highly effective 🟡 Moderately effective 🔴 Generally Ineffective

2.1.1.1 Following wall structure, ore sensing, global perception, mid-to-long range sensing

As ROBOMINERS mining scenarios (section 1.1) include parameters that are different from the ones of conventional mining, it is required a new approach to mining design. Considering that in the first phase of the mineral exploration a prospection map of the deposit is realized, the main challenge is to have a robot miner capable to detect and direct the excavation path towards and inside the deposit autonomously. As the target scale, compared to the prospection area, is smaller, the number of geophysical methods that can be used will decrease. As example in Fig. 9 are shown the areas and the line lengths sampled by different surveys costing the equivalent of a single 300 m deep diamond drill hole (Dentith and Mudge 2014).

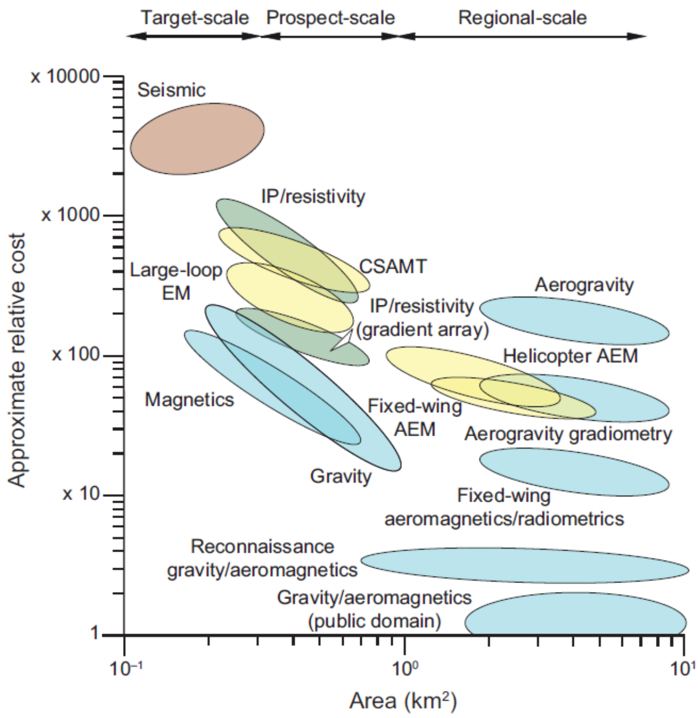

Figure 9 Approximate relative areas sampled by geophysical surveys costing the equivalent of a single 300 m deep diamond drill hole. AEM– airborne electromagnetics, CSAMT –controlled source audio-frequency magnetotellurics, IP – induced polarisation. From (Dentith and Mudge 2014)

The mid-range perception sensors are to be installed on the robot-miner in support to the selective mining and the general investigation of the deposit. These sensors will specifically assist the robot in following the wall structure and the ore detection.

For directional drilling (cm to m ahead) it is necessary to have a more refined model to identify a continuous direction of the ore body. For example, the geometry structure of vein-type deposits is known for being extremely variable in the shape and distribution of the ore, mineralogy and texture, require a new sensing and selective mining approach. Moreover, also the structural framework plays an important role on the distribution of the ore (Chauvet 2019).

2.1.1.2 Following wall structure

Tunnelling imaging for stability and geological mapping is a common practice in the mining and oil industry. This type of technique includes several combinations of methods: resistivity and conductivity, sonic, XRF, NMR, and gamma ray.

The first Logging while drilling tool (LWD) was introduced in 1983, with single spacing, single frequency and on depth of investigation (Rodney and Wisler 1986). Since the 80s there has been a constant progress in the development of this technology. Nowadays LWD technology with directional antennas and azimuthal measurement can determine vertical and horizontal resistivity, dip angle and azimuth. Thanks to the azimuthal resistivity measurement, the area near the wellbore can be defined with a 3D model (Bittar et al. 2009).

LWD (Figure 10) is also used to reach the geological target into complex environment with geo-steering to control the drill toll. (Shao et al. 2013) This technique could be adapted to the robot miner as the data are acquired by tools placed in the drilling assembly, and they can be transmitted in real-time on the surface or stored in a downhole memory and downloaded later.

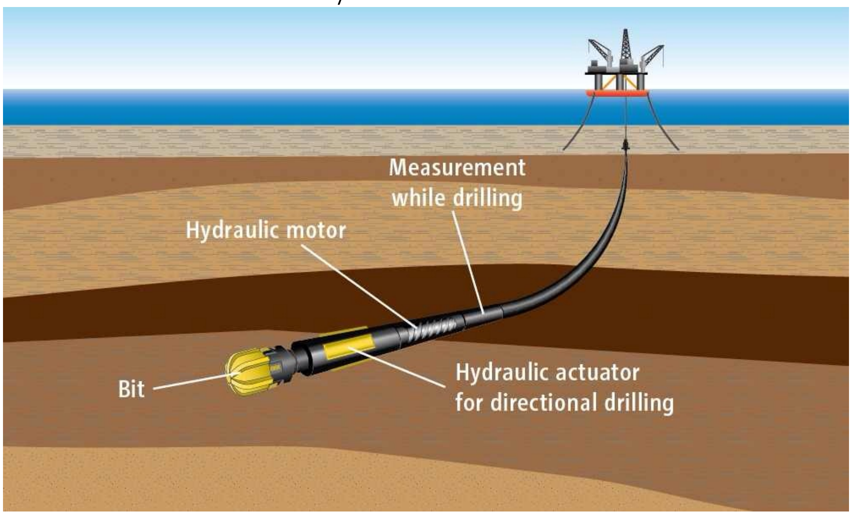

Figure 10 LWD representation (image from ("European Copper Institute" n.d.))

Resistivity and Conductivity measurements

The most common resistivity survey applied to LWD is the self-potential method (SP), which measure the natural potential of the rocks without current injection. Resistivity measurements can also be applied for lateral logging using low-frequency currents (Darling, 2005).

Sonic measurements

Sonic measurements consider the transit time of compressional sound waves in the formation. Rock strength and integrity information are provided as well with full waveform sonic (FWS) and acoustic televiewer. In Figure 11 are displayed the log from Kakatiya borehole KTK736. The acoustic scanner amplitude is plotted with the gamma ray, density counts and average amplitude. The variation of the rock strength and the unit boundaries are recorded thanks to the contrast of the acoustic impedance between the tunnel wall and the drilling mud (Zhou and Guo 2020).

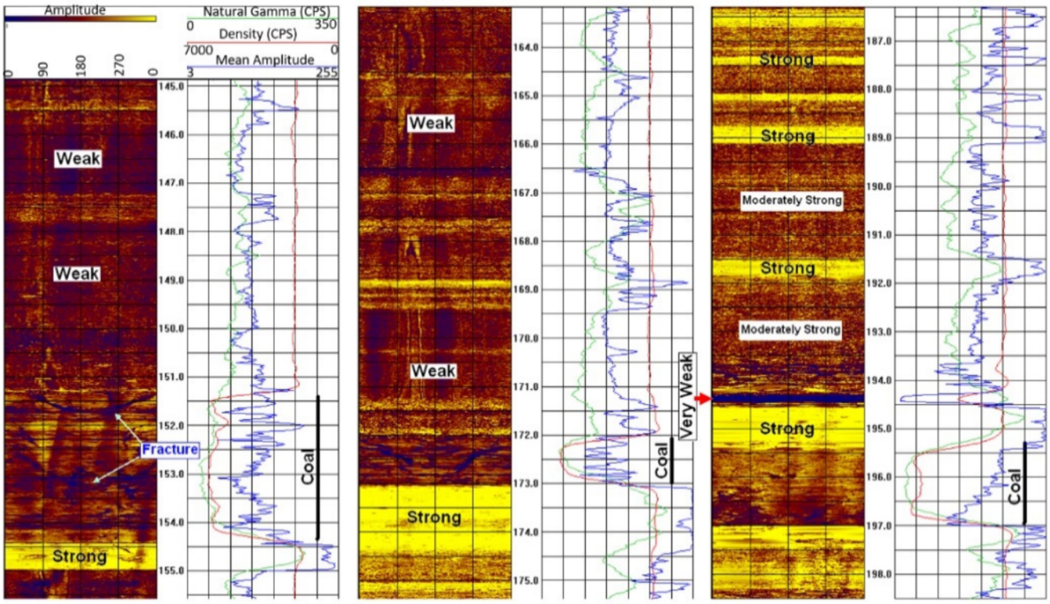

Figure 11 Log from Kakatiya borehole KTK736. The acoustic scanner amplitude is plotted with the gamma ray(green), density counts (red) and average amplitude(blue). In the acoustic scanner the dark colour represents weak strata and light colour strong strata. From (Zhou and Guo 2020)

XRF measurement

X-ray fluorescence techniques are well-developed for mineral analysis, mining, and process control. The low limits of detection (about a few ppm for most elements) is the main advantage of these techniques along the ability to measure simultaneously the concentration of up to 40 elements.
Usage of XRF measurements was studied by TalTech in relation to localization, described in section 3.1.

Gamma-ray measurements

This method measures the natural radioactivity present in the rock. The three main elements considered are uranium, potassium, and thorium. The relative contribution of these elements can be used for the determination in the formation of the presence (and proportions) of certain minerals (Darling 2005).

2.1.1.3 Ore sensing

The main geophysical sensors considered for targeted ore sensing, to be installed on the robot miner, are ERT/IP and GPR.

Electrical resistivity tomography and induced polarization (ERT/IP)

The ERT method permit the mapping in the subsurface of the electrical resistivity distribution. The electric potential distribution is measured with the injection of an electric current in the ground (Dahlin 2001; Loke et al. 2013). The geometry choice of the electrode distribution influences the depth of investigation, the spatial resolution, and the robustness top the electrical noise.
The IP method, often combined with resistivity measurements, measure the chargeability of the rock. (Sumner 1979; Evrard et al. 2018).

According to the development of the design of the robot miner, three different options for ERT/IP investigation have been studied:

1) an electrode plaque or hand positioned in the front and controlled by the mechanical arm that will position and move it on the front wall. The electrodes will be helped with “pogo pins” for a complete adherence to the rock wall.

2) a resistivity logging device to employ in case of use of drilling and blasting method for the production (see in section 2.2.3,Figure 17), the current is sent through the wall into the surrounding rock by the lower electrodes which are in contact with the wall. Electrical signals are then measured through the upper electrode.
3) the robot-miner can be used as a logging device itself when equipped with electrodes. The distance between electrodes will influence the distance into the formation that will be seen. If the robot has more module it will be possible to combine the distance between the electrodes and therefore increase the depth of investigation.

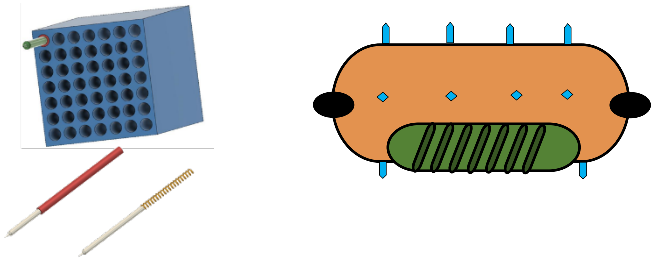

Figure 12 (left) Plaque prototype (right) The robot miner equipped with electrodes along its body (Stasi et al. 2020)

When the current is injected by the plaque or the logging device the electrode on the robot-miner body can work as receiver. With this configuration we can increase the depth of investigation and the area considered Figure 13.

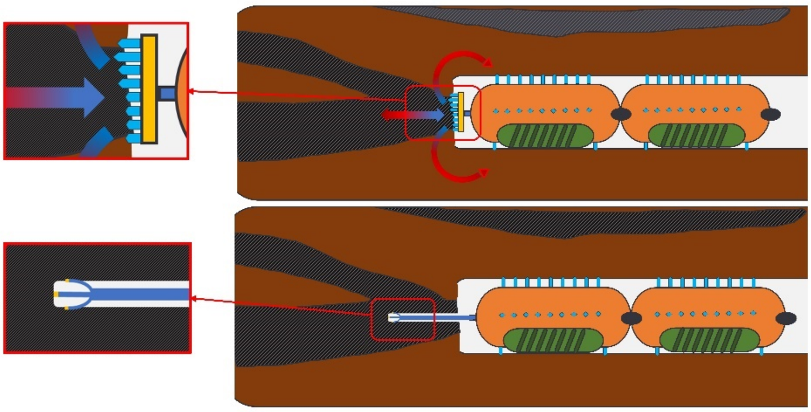

Figure 13 Detecting ore with the electrodes (Stasi et al. 2020)

Geological radar detection

Geological radar detection method is based on the difference in wave impedance between the target body and the host rock. The electrical conductivity of the measured rock has a large effect on the maximum effective depth of penetration. It can detect the geological structure, lithology, strata, and water distribution (Figure 14).
The depth of penetration has been improved thanks to systems using real-time sampling and pulse compression technology (Francke and Utsi 2009).

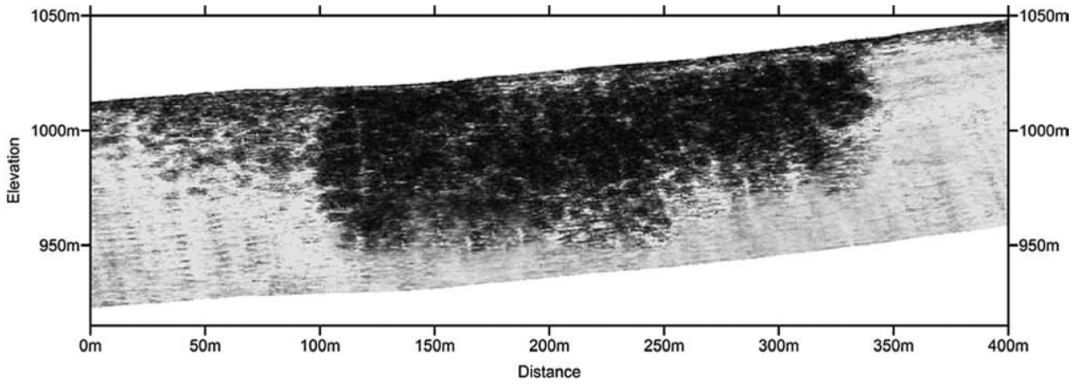

Figure 14 GPR profile of an iron ore (dark region). From Francke and Utsi, 2009

2.1.2 Bioinspired touch sensors

Mammals use tactile whiskers to guide behaviours like navigation, locomotion, exploration hunting and social touch (Grant, Breakell, and Prescott 2018). In robotics and bioinspired sensors development, there are several examples in literature of bioinspired whiskers for flow sensing (Tuna, Jones, and Kamalabadi 2014; Beem and Triantafyllou 2015; Eberhardt et al. 2011; Ristolainen, Tuhtan, and Kruusmaa 2019; Valdivia Y Alvarado, Subramaniam, and Triantafyllou 2012) and tactile sensing (Lepora 2016)(Wijaya and Russell 2002)(Hua et al. 2016)(Ju and Ling 2014).

On the robominer, such sensors could give insights on surface roughness, flows around the robot when submerged, help to detect walls and objects during locomotion. The main challenge in applying such sensors lays in the toughening for mining environment with high risk of wear and tear.

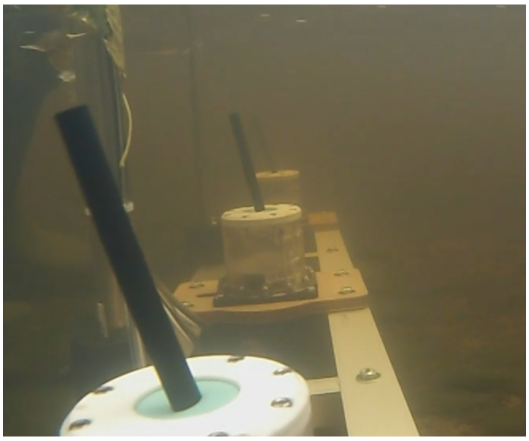

Figure 15 Bioinspired flow sensors used for flow classification (Ristolainen et al. 2018)

2.1.3 Solid-state-sensors

Solid-state sensors (sensors without moving parts) can be applied and modified for ultrahigh-dependability and continuous operation in high pressure/vibrations/temperature environment. Due to the small size and high energy efficiency, solid-state sensors could be applied on various modules of the robot, giving a comprehensive ambient awareness around the robot and cues for localization. Also, the solid-state sensors can give a state estimate of the performance of different robot parts and tools.

List of possible sensors is shown in Table 2, that identifies possible candidates following the main criteria proposed in Section 2: applicability in air, water, mud; implementation possibility within the project resources; need of modifications.

Table 2 List of proposed solid-state-sensors for ROBOMINERS

Sensor type	Applicability in air?	Applicability in water?	Applicable within the project?	Working principle	Sample applications	Available off the shelf?	Will work without modifications?	Relative price in 5-point scale
Temperature	●	●	●	Thermocouple / PN junction	Internal state, ambient changes in the temperature	●	●	1
Pressure	●	●	●	Deflecting diaphragm	Robot submerged or not, system leakages of the robot hull, internal feedback from hydraulic muscles	●	●	1
Sonars	●/x	x/●	●	Sound waves	Detection of solid in mud/water at close range, obstacle avoidance	●	●	1
Vibration - IMU	●	●	●	MEMS	Dead reckoning, surface irregularities, impact detection, drilling sensing, traction control, proprioception	●	●	3
Ultrasound proximity sensors	x	●	●	Sound waves	Obstacle avoidance	●	●	1
Magnetic field	x	x	x	Hall effect	Changes in the magnetic field for clues in localization	●	x	1
Humidity	●	x	x	Thermistor or capacitor	Changes in the mine ambient humidity	●	x	1
Gas sensors	●	x	x	Resistance change	Changes in the air mixture in the mine	●	x	1
Conductivity	x	●	●	Conductivity	Changes in the soil, mud, mining water and clue generation for localization from walls and surfaces of the mine	●	x	1
pH	x	●	●	Potential difference	Changes in mining water properties, pH of slurry	●	x	1
Turbidity	x	●	●	Scattering of light	Changes in the water properties when moving through water	●	x	2
Time of flight sensors	●	x	●	Infrared	Distance from obstacles, detection of obstacles	●	x	1
Current sensors	●	●	●	Hall effect	Internal state of actuators, slippage control, force control	●	●	1
Hydrophone with acoustics beacons	x	●	●	Sound waves	Localization with beacons, could be deployed from the robot	●	●	1
Camera with visual beacons	● (if clean)	● (if clean)	●	Optics	Surface mapping, wall shape if 3D cameras are used	●	●	1
Thermal camera	●	x	●/x	Infrared camera	Thermal changes around the robot in air	●	x	5
Radiation	●	●	●	Geiger counter	Changes in the radiation flux in the mine	●	●	1
UV camera with UV light	●	●	●	Optics	Fluorescent ore or rock detection	●	●	1

● - yes | x - no

The final decision concerning solid-state sensors that will be applied within the ROBOMINERS project, will be made in section 3.

2.2 EXCAVATION

2.2.1 Monitoring while drilling (rock mass recognition and tool wear)

With appropriate sensors, the inner hydraulic/fluid lines can be taken for measuring pressure/force acting on the drill string. Increasing depth leads to increasing frictional resistance of the drill bit and drill rod. This results in artificially higher measured force and torque.

More precise measurements can be conducted with a load/torque cell at the very top of drill rod. This is not affected by any frictional forces, but it needs careful implementation to measure unadulterated values. Data, which is to be used by the robot controller can either be sampled at fixed time steps (e.g. 10 kHz) or at specific depths. (Klaic et al. 2018) shows measured drill parameters for a certain time interval.

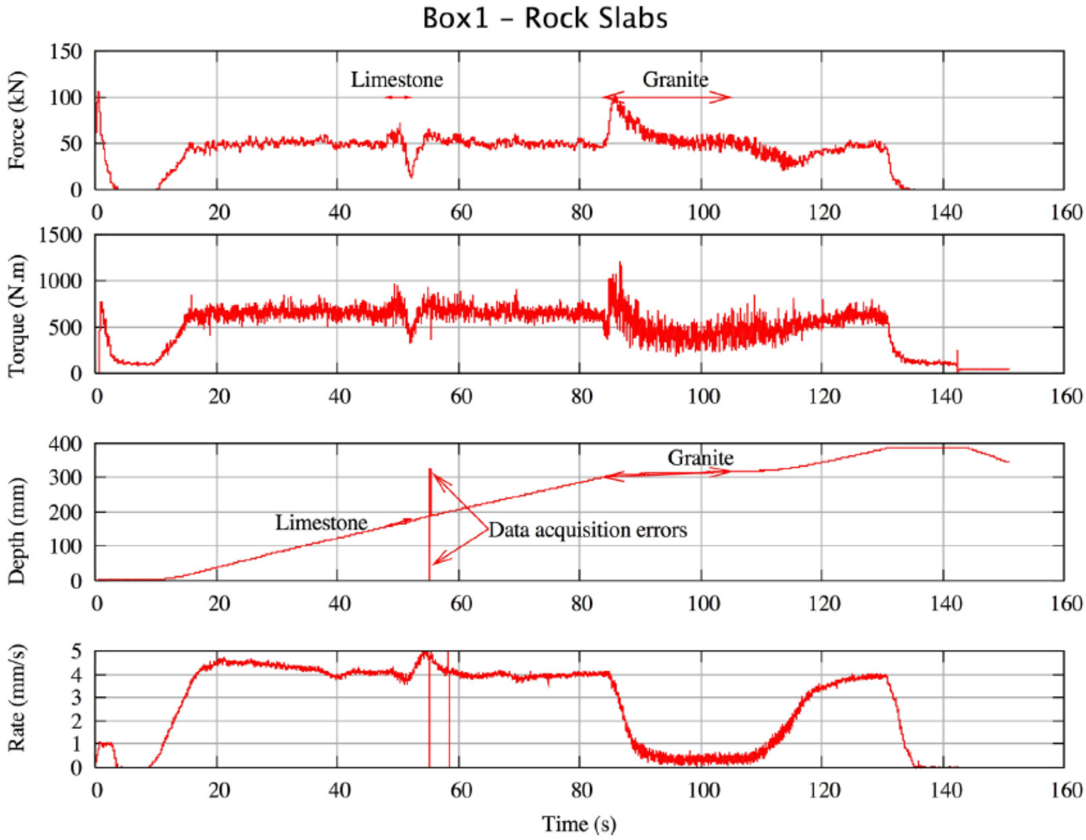

Figure 16 Measured drilling parameters over time (Klaic et al. 2018)

Safety, performance and productivity are highly influenced by tool wear. Tool wear is a result of frictional force between tool and the rock to be cut. Monitoring the tool wear is an immensely elaborate task due to the fact, that rock is brittle, highly non-homogeneous and has anisotropic material parameters. Scattering of those properties is an additional factor, which complicates the tool wear measurement. However, monitoring the tool wear in real time is desirable in fully automated drill rigs, because maintenance can be cut down sharply. Vibration sensors can provide the basis for proper tool wear measurement. This requires calibration work in terms of experimental tests with different rock types and conditions (Klaic et al. 2018).

2.2.2 Drill cuttings (debris) analysis

Rock drilling technologies most likely include a fluid based flushing system. The water/air flushing takes over several tasks: cooling, lubrication for wear reduction, rinsing out the drill cuttings (debris) of the drill hole. The drill cuttings are fine distributed particles and can be collected for further analysis. With a flexible funnel, the material can be collected and flushed into a storage/analysis toolbox. Depending on the applied analyses, the water-debris mix is can be separated with a filtering system. LIBS or RFS are possible technologies to be used for analysing the drill cuttings. The collector tool's design varies with the sensing method (dry-wet-slurry, moving-stationary).

To analyse drill cuttings and/or excavated ore continuously during excavation/initial transport, on-line analysers can be used which are becoming increasingly common in the mining industry. An on-line analyser uses technologies such as X-Ray Fluorescence (XRF) (IMA-Engineering, n.d.), Pulsed Fast and Thermal Neutron Activation (PFTNA) or spectroscopy (PANanalytical, n.d.).

Using laser scanning technology, it is possible to perform continuous particle size measurement materials in a dry environment, for example while material is on a conveyor belt. Such technology could be implemented in the robot miner when deployed in a dry environment (Thurley 2011).

2.2.3 Drill hole sensor

Analysis of material deposits and distribution behind the rock face can be done by electroconductivity measurements inside the drill hole, using a terameter. Current is sent through the well wall into the surrounding rock by the lower electrodes which are in contact with the well wall. Electrical signals are then measured through the upper electrode. A customized terameter for actual robot with similar design to a COTS tetrameter (see Figure 17) needs to be developed.

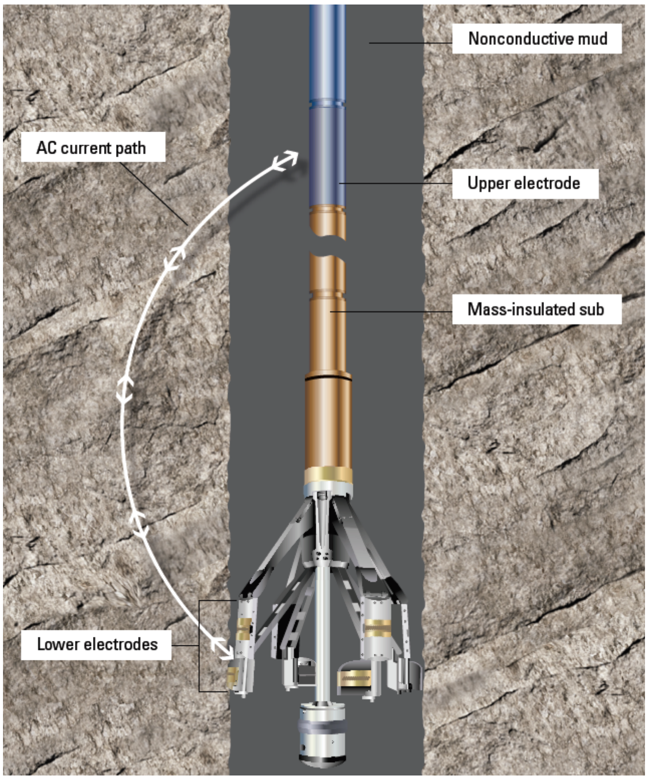

Figure 17 FMI-HD High-definition formation microimager (Schlumbereger, n.d.)

Sensor technology from the Oil & Gas industry i.e. Logging While Drilling (LWD) technology. LWD allows, depending on the layout of the sensor array, to measure a vast range of parameters such as, but not limited to, Gamma Ray (GR), Borehole calliper, Resistivity, Sonic (density), Imaging and Seismic While Drilling (SWD). Although readily available, LWD technology will most likely need to be miniaturized to allow at the envisaged scale of the ROBOMINER.

2.3 SLURRY SENSING

In an ore extraction process, done from a fixed installation (drilling platform) or a mobile driller (robotic miner) the concentrate of the ore can be mixed with water and then pumped to facilitate transport over a long distance to a facility where it can be further processed. At the end of the pipeline, the solid material is separated from the slurry and the water is recycled in a loop or processed. This water is usually subjected to a waste treatment process before disposal or return to the mine.

To monitor the physical and chemical properties of slurry in the ROBOMINERS system several in-stream technologies are available apart from the more common “solid-state” sensors monitoring parameters such as pressure and temperature (see Table 3). Slurry density for instance can be measured using several technologies such as dynamic actuators (turning fork, compression), magnetic and ultrasonic sensors. The volumetric flow rate of a slurry in a pipe can be measured using Doppler ultrasonic sensors, and viscosity could be measured using solid state pressure sensors and a calibrated pipe interval (using differential pressure) (Bamberger and Greenwood 2004). The particle size distribution of a slurry can be determined using laser diffraction/reflectance or ultrasonic methods (Optical Low-Coherence Reflectometry). On-line sensors for particle size measurements using these technologies are commercially available off-the-shelf (COTS). The mineral composition of slurries can also be analysed on-line using similar technologies as mentioned for the drill cuttings analysis, i.e. using XRD, XRF, gamma absorption/scattering, LIBS, neutron activation, fluorescence, etc. (Cheng et al. 2017; Khajehzadeh, Haavisto, and Koresaar 2016, 2017).

2.3.1 Slurry system physical properties sensors

Monitoring physical properties of slurries is a routine measurement in many industrial fields like dredging, mining and agriculture (see (Heywood 2000) for an extensive review). The main properties looked after are the slurry density, pressure and flow rate. Many COTS sensors exists for in-stream slurry sensing, i.e. for measuring slurry properties directly, in real- time, on or in the transport pipe (examples shown in Figure 18).

Previous neutron-neutron density meter has been replaced during the last 20 years by ultrasonic sensors (acoustic impedance) that allow non-intrusive measurements on large pipes and on high density slurries. Other methods includes dynamic conditions density measurement (an actuator exerts a force with a known value and frequency onto the slurry, while an accelerometer measures its resulting acceleration), this technique being less sensitive to the slurry composition (Bamberger and Greenwood 2004).

Doppler slurry flow meter measures flow from outside the pipe using by transmitting a high-frequency acoustic signal (hundreds of MHz) that travels through the pipe wall and into the flowing material. The signal is then reflected back to the sensor from solids or bubbles in the slurry. If the slurry is in motion, the acoustic echo return at an altered frequency proportional to the flow velocity (Bareš et al. 2014).

Slurries produced by a drilling and crushing system can have mean particle sizes from ~0.01um to 5mm. Non-invasive methods also exist to measure particle size distribution, like Ultrasonic backscattering measurement (Greenwood 2012) (easily couple with Doppler flow measurement) and Optical Low Coherence Reflectometry (OLCR) (L. Randall 2004). This last technique measures the 180° coherent backscatter of light (e.g. LED broadband source incident on the heterogeneous medium). Dynamic changes in particle size and concentration in the slurry may be extracted from the OLCR decay profiles.

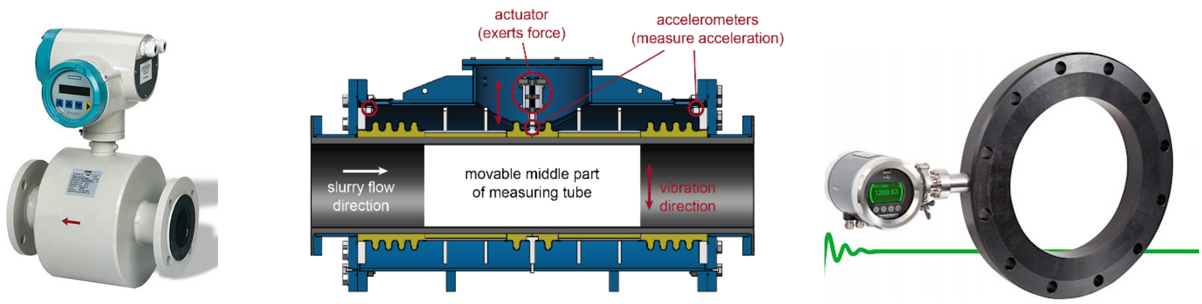

Figure 18 COTS slurry flow and density meters: from left to right: magnetic flowmeter (RSHydro), non-nuclear density meter principle (Alia Instruments), and ultrasonic flow meter (Rhosonic).

Table 3 List of available sensing techniques to determine the physical parameter of a mining slurry

Sensor type	Applicability in air	Applicability in water	Applicable within the project timeline	Working principle	Sample applications	Available off the shelf	Does it work without modifications	Comment	Relative price in 5-point scale
Magnetic flow meter	x	● (in-stream)	x	AC magnetic pulses	metallic ore detection, flow meter	●	●	Well known technique	2
Ultrasounds meter	x	● (in-stream)	●	Ultrasound pulses, Doppler effect	Slurry density meter, flowmeter, particle size	●	●	Well known technique	2
Density meter	x	● (in-stream)	x	Pressure exerted on slurry pipe and measured via accelerometers	Slurry density meter, flowmeter	●	●	Well known technique	4
Particle size sensor	x	● (in-stream)	x	Optical Low Coherence Reflectometry	Slurry diagnostics (particle size distribution)	●	x	Well known technique	3
Temperature	x	● (in-stream)	●	Diode bandgap	Slurry temperature	●	●	Well known technique	1
Pressure	x	● (in-stream)	●	MEMS diaphragm	Slurry pipe pressure, viscosity	●	●	Well known technique	1

● - yes | x - no

2.3.2 Sensors for chemical and mineral composition of the slurry

Real-time monitoring of physical and basic chemical properties (point 2.3.2.2) of mining slurries is already a common process in mining ecosystems. Commercial instruments and setups are already available and can be adapted relatively easily to a robotic platform. However, detailed mineralogy or minor-trace elements chemistry is usually performed by discrete sampling and lab analysis. Only relatively low TRL systems have been developed to adapt those analytical techniques to automated measurements that can be performed on site and sufficiently fast to be considered as real-time. Such advanced measurements are nevertheless key if we consider a robotic platform that must perform selective mining using on-board decision processes. This is especially true in mining scenarios of complex deposits were high value critical raw materials are concentrated in specific mineralogical phases or assemblages.

Amongst those advanced techniques, non-destructive, or quasi-non-destructive spectroscopic methods are the most promising, because they usually do not require a physical sampling or pre-processing of the material. In ROBOMINERS, we thus consider the whole range of wavelength available for spectroscopic techniques applied to minerals and geochemistry, from Gamma Ray radiations up to the

Terahertz domain. For this report, we will categorize them in 3 groups: laser techniques, reflectance/fluorescence techniques and high-energy wavelengths techniques.

Table 4 List of available spectroscopic sensing techniques to derive geochemical or mineralogical parameters of a mining slurry

Sensor type	Applicability in air	Applicability in water	Applicable within the project timeline	Working principle /EM Spectrum part used	Sample applications	Available off the shelf	Comment	Unconventional things you can learn from data	Relative price in 5-point scale
LIBS	•	• (via flow cell or in the slurry stream)	• (lab+field prototypes)	Laser/optics UV to near infrared	Chemical composition (extracted ore - slurry)	x	Many designs exist in literature.	„Big data" treatment possible (thousands of analyses /s). Trace elements detection	4
Time-resolved close-range Raman spectroscopy	•	• (via flow cell or in the slurry stream)	x (lab test maybe possible)	Laser/optics UV to near infrared	Mineralogy (extracted ore - slurry)	• (e.g.: Timegate spectrometer)		Fluorescent "free" Raman spectra on ore and clays (slurry diagnostics). Precise mineralogy	5
VIS-NIR reflectance spectroscopy	•	• (via flow cell or in the slurry stream)	• (lab+field prototypes)	broadband source/optics Near to mid-infrared	Mineralogy, including clay content	• (needs adaptation)	Many designs exist in literature.	If distributed (many sensors: Could provide slurry composition profiles in the pipe	2
UV fluorescence spectroscopy	•	• (via flow cell or in the slurry stream)	•/x (laboratory test)	UV-VIS source/optics Deep UV to visible	Mineralogy	• (needs adaptation)	Many designs exist in literature. can be coupled with VIS-IR sensors	Specific minerals can be fluorescence-activated using specific bacteria in the slurry	2
XRF Spectroscopy	•	•	• (laboratory test)	crystals/ scintillator X-Rays	Chemical composition (extracted ore - slurry)	• (needs adaptation)		If distributed (many sensors: Could provide slurry composition profiles in the pipe	4
Gamma-Ray spectroscopy	•	•	• (laboratory test)	crystals/ scintillator Gamma-Rays	Mineralogy, including clay content	• (needs adaptation)	better penetration depth than optical techniques or XRF	Fast screening of radioactive ore	3
Neutron activation	•	•	x	Neutron source crystals/ scintillator Gamma-Rays	Mineralogy, trace elements	x (working prototypes exist)	Need neutron source /radioactive hazard (regulations!)	Fast and sensitive technique for trace elements in the slurry	4
Terahertz reflectance spectroscopy	•	• (only very close range – reflection)	• (laboratory test)	Bolometer, pyroelectric detectors Gigahertz to terahertz radio waves	conductive material content	x (low TRL technique, especially in reflection setups)	Very fast technique, better penetration depth than optical techniques or XRF	Unconventional method, fast screening of metallic ore possible	4

• - yes | x - no

2.3.2.1 Laser-based spectroscopic techniques

Laser-induced breakdown spectroscopy (LIBS):

LIBS is a very interesting atomic emission technique for real-time monitoring of slurries. The technique uses a high-energy pulsed laser beam on the surface of a sample to produce a plasma. The plasma emission is then collected and coupled into a spectrometer for analysis to identify and quantify the chemical elements in the sample (Fabre 2020) (see Figure 19). LIBS have many attractive features, such as simultaneous multi-element detection, the ability to detect all elements, simple or no sample preparation. It has been already used as a competitive approach to monitor slurries using flow cells in mining (Khajehzadeh, Haavisto, and Koresaar 2017) and metallurgy applications (Kaski, Häkkänen, and Korppi-Tommola 2003). LIBS typically achieve fast and sensitive analysis, with micro to milliseconds analytical time per single laser shot and detection limits ranging from ppm to ppb. Caveats includes poor signal repeatability and complex plasma physics, so quantitative lab-quality measurements are a challenge, but qualitative and semi-quantitative measurements are possible and is totally relevant for ROBOMINERS selective mining application.

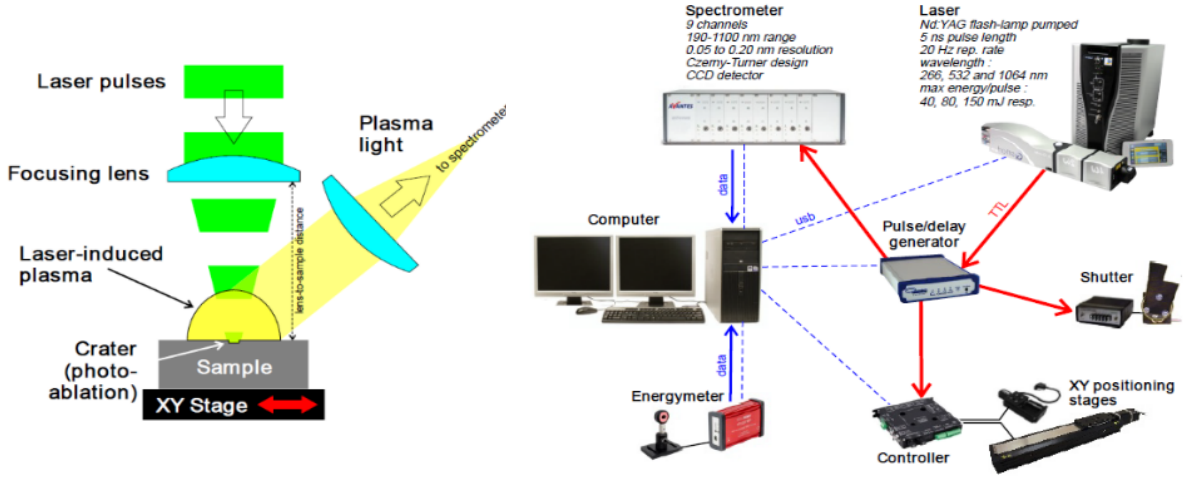

Figure 19 (left) Principle of LIBS. Spectral analysis of the laser-induced plasma light provides in seconds the chemical composition of the target. The XY stage is required only for line and area scanning. (right) Example setup of a laboratory LIBS mapping instrument at University of Mons -Belgium) (optics not shown). (Baele, Papier, and Tshibangu 2018)

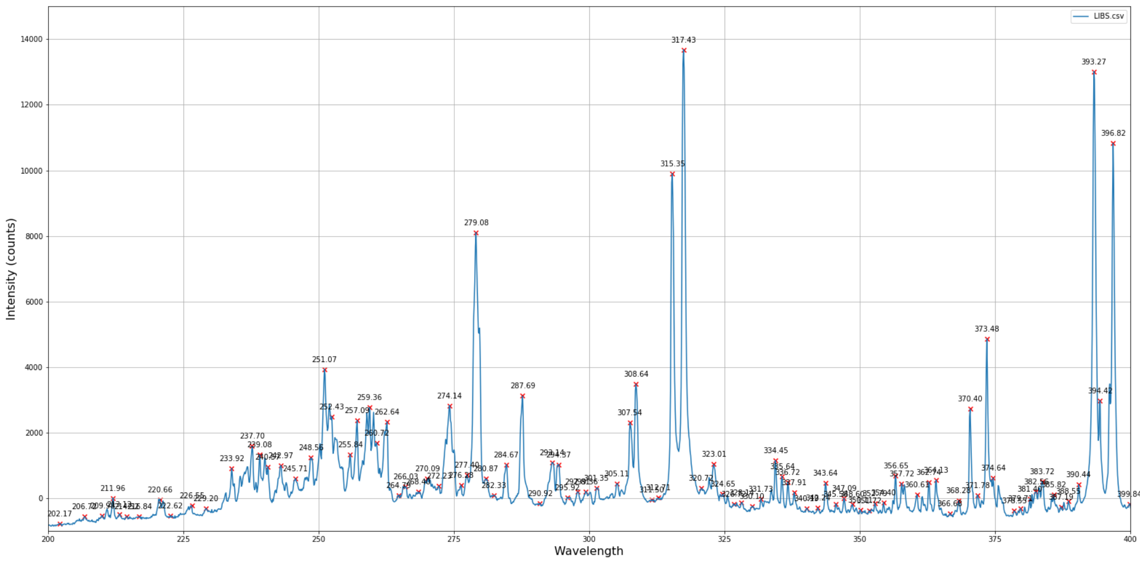

Figure 20 Portion of a LIBS spectrum (Copper carbonate – ROBOMINERS instrument prototype), the multitude of sharp peaks allows very specific identification of atomic elements.

Raman (time-resolved) spectroscopy.

Raman spectroscopy is a powerful molecular analytical tool to identify minerals and chemical in solid and liquids. Raman is a light scattering technique, whereby a molecule scatters incident light from a high intensity laser light source. Most of the scattered light is at the same wavelength as the laser source (Rayleigh Scattering), however a small amount of light (typically one photon in 10^{-6}) is scattered at different wavelengths, which depend on the vibration modes of the chemical bonds of the analysed material. This is called non-elastic scattering or Raman Scattering (Hazle et al. 1990).

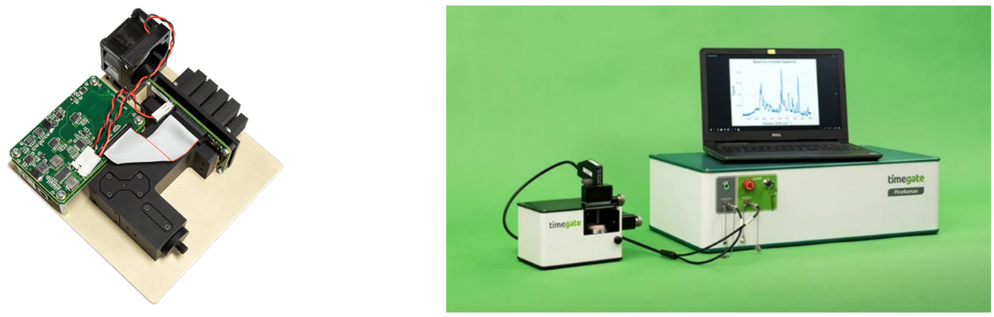

Figure 21 (left) an example of an OEM Raman spectrometer (Wasatch photonics); (right) the first commercial time-resolved Raman spectrometer (Timegate Instruments)

Raman spectra can be acquired in seconds on geological material (specific minerals or rocks), through an optical window (no contact needed) and constitute very specific fingerprints of the nature of the material, even in amorphous or crypto-crystalline forms(Burlet and Vanbrabant 2015). Unfortunately, laser-induced native fluorescence, while also interesting for the identification of some mineral species, often overwhelms completely the Raman signal. However new developing techniques like deep UV Raman (Hooijschuur et al. 2015) and time-resolved Raman spectroscopy helps separate the Raman scattering from the induced fluorescence and are thus extremely promising techniques, although still very expensive compared to current alternatives.

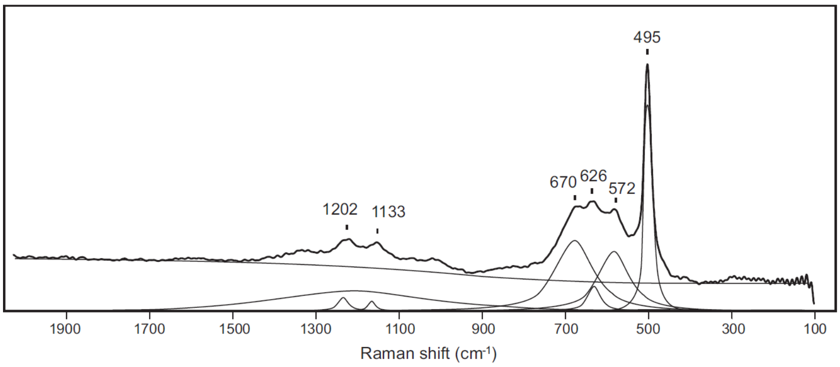

Figure 22 example of a Raman spectra acquired on a cobalt oxide ore (heterogeneity). (Burlet et al. 2011)

2.3.2.2 Reflectance/fluorescence-based techniques.

UV fluorescence spectroscopy.

Fluorescence spectroscopy uses a beam of light, usually UV light (UV lamp, LED, even laser) that excites the outer electronic layers of atoms, especially free-radical of organic compound and clays, and causes them to emit light; typically, in the visible or near infrared spectrum. Many minerals display fluorescence spectra, like aragonite, apatite (rare earths), calcite, fluorite, scheelite, willemite, and zircon (Bowles 1980). Developing techniques in bio-assisted (ex: bacteria assisted) mining are also promising for UV spectroscopy (see : H2020 Tarantula project- https://h2020-tarantula.eu/). Because fluorescence spectroscopy is a robust and fast technique, it can provide valuable information to a robotic platform, moreover, as it is relatively inexpensive, detectors can be multiplied on the platform (slurry composition profile).

VIS-NIR reflectance spectroscopy.

Visible and near-infrared spectroscopy is the baseline technique in optical spectroscopy. Using a broadband light source (ex: halogen light, white LED+NIR LED) the reflectance spectrum of the slurry mixture can be acquired. While the resulting spectrum will probably not contain any sharp and specific absorption peak, monitoring the global shape of the spectrum (corresponding to a "colorimetric" inspection of the slurry) can provide a good proxy of the composition of the extracted material, especially if the VIS-NIR absorbance spectrum (or more simply the colour) of the ore is different of the host rock. Like the fluorescence sensors, it can also easily be multiplied on the miner to compensate for spatial heterogeneities in the extracted slurry.

Figure 23 Examples of inexpensive miniature spectrometer that can be used to multiply UV-VIS-NIR reflectance and fluorescence drilling slurry measurement on the robotic platform: (left) ocean Insight STS; (right) Hamamatsu micro series.

Terahertz reflectance spectroscopy.

Terahertz (time-domain) spectroscopy (by transmission or reflection) is a relatively new and unexplored technique when considering its applications in applied mineralogy and mining. It uses a strong (hundreds of milliwatts to one watt in COST systems) Gigahertz to Terahertz electromagnetic wave as excitation source. At these frequencies, the electromagnetic waves share properties between optical domain light and radio-waves, with the wavelength sufficiently small to be steered or reflected with optics (ex: Teflon lenses, gold coated mirrors) and also able to penetrate some materials depending of their dielectric constant (Miao et al. 2017). An example of application is the detection or imaging (using fast bolometer-based detectors (Catapano and Soldovieri 2019) conductive material or ore behind a non-conductive cover of a few centimetres. While the terahertz signal is quickly absorbed by water molecules, the development of stronger sources and sensible detector might allow an in depth inspection of slurries through opaque windows where classical spectroscopy techniques are strictly limited to the surface of the slurry in contact with an optically clear window.

Figure 24 example of a commercial Terahertz detector (left) and source (right) that can be used in a reflection configuration for slurries (sub) surface analysis. (source: Terasense Group)

2.3.2.3 High-energy wavelengths techniques.

XRF Spectroscopy.

X-ray fluorescence (XRF) is the emission of characteristic "secondary" (or fluorescent) X-rays from a material that has been excited by high-energy X-rays or gamma rays. XRF spectroscopy allow slurry elemental "bulk" analysis (up to a few millimetres depth can be analysed). Using an energy dispersive X-ray detector (EDX) that does not require liquid nitrogen cooling, and miniaturized X-Ray tube(s) such as those used in portable XRF equipment, this technique can be integrated on a robotic miner platform. This type of instrument is commonly used for portable screening applications, such as sorting scrap metals, and characterising mining slurries (Khajehzadeh, Haavisto, and Koresaar 2016). On the other hand, light elements (especially Lithium) cannot be detected, and important matrix effects render quantification difficult without ore-specific calibration (like with other elemental techniques).

Gamma-Ray spectroscopy and neutron activation/scattering.

Gamma-ray spectroscopy is a rapid and reliable radiometric method of analysis of Uranium and/or Thorium bearing ores. Gamma-ray spectrometers have been used for many years by well logging and airborne surveys, they can record energy radiation emitted by naturally-occurring radioactive elements (^{40}K,^{232}Th,^{238}U) (Mero 1960). Neutron-activation, using a radioactive neutron source, and followed by gamma-ray spectral analysis, can also detect bulk abundance of elements such as Ca, H, Cl, S, and Mg. These techniques present the unique advantage of being non-invasive "bulk" chemical analysis, not limited to the surface or sub-surface analysis of the slurry stream. They also target very specific elements that can be used as mineral assemblage proxies to achieve selective mining.

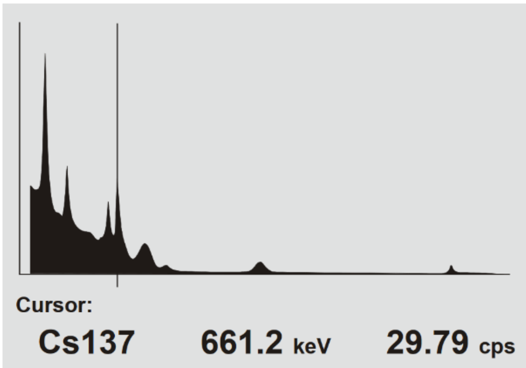

Figure 25 (left) portable gamma-ray instrumentation to be evaluated during ROBOMINERS (Gamma Surveyor from GF instrument; (right) typical gamma ray spectrum on a sedimentary rock (source GF instrument manual).

2.4 GROUND TRUTH SENSORS

In order to validate the performance of ROBOMINERS perception, ground truth sensors need to deploy in the testing and development phase. In cleaner environments they would also help to add situational awareness to the overall mining operation with the robominer.

Immediate surroundings

The miner can be operating in a variety of different environments: dry, damp, and submerged. Of these the simplest for sensing the environment is the damp environment, where the presence of water suppresses dust, and visual sensors – optical cameras – can provide detailed images of walls, roof, and floor, both forwards and backwards. A set of cameras would be required for all-round vision. The most important imaging would be forward, to the working face, and rearward, to the already mined tunnel. The primary purpose of these cameras would be to assess the tunnel stability, and for this purpose a live video feed to the control room will be necessary, to allow real-time photogrammetric data processing which would give a changing 3D model that can indicate whether action is required to stabilise roof or walls.

If the tunnel is dry, or if the miner is submerged in water, there is likely to be a significant amount of dust or suspended particles which could obscure the camera views. In these cases, if the amount of dust or turbidity is not excessive, there is technology that can sense reflection time of laser pulses to eliminate reflections from dust particles, so a pulsed laser could replace continuous lamp illumination as the light source, but would require additional software to eliminate the spurious reflections.

In conditions of extreme turbidity, optical systems would be replaced by scanning sonar to give accurate 3D models. The quality of these would be lower than from optical videos, as there would be no colour rendering, but they would give overall 3D information on the wall and roof configuration.

Equipment status monitoring and control

The forward-looking cameras can be used to supply auxiliary information to the control-room operators on the positioning and operation of drilling and other equipment, including placement of explosives or focussing of alternative rock-fragmentation technology (plasma, ultrasound, cavitation, etc.).

The 3D scanners would give the x-y-z coordinates of a proposed blasthole collar allowing the accurate length of hole to be calculated and drilled so that the bottom of all the holes are all on the same plane. So that a straight a rockface as possible is produced.

3 EXPERIMENTAL PERCEPTION FOR ROBOMINERS

The list of possible sensing techniques is broad as shown in section 2. Possible applicability of all these sensing methods would not be achievable within the project resources. Therefore, a calculated decision must be made. The focus of the perception methods of the robominer lays on the three proposed scenarios given in section 1.1. Each of them proposes distinct requirements for the perception. List of them is given below:

- Operating and abandoned mines with known remaining unfeasible resources – flooded mines, small access points meaning small size of sensors, hazardous environment e.g. rock fall would need ruggedized and protected sensor heads.
- Ultra-depth – high pressure environment, high temperature environment, rock composition accuracy both for ore vein following and rock stability (safety).
- Small deposits uneconomic for traditional mining – rock composition accuracy both for ore vein following and rock stability (safety).

A decision on the sensing techniques to explored and developed further in WP6 must therefore be evaluated according to the following points:

- applicability in air (0 to 5):
  - 0 – not applicable
  - 5 – air with high particular matter
- applicability in water (0 to 5):
  - 0 – not applicable
  - 5 – mud, slurry
- Applicable within project resources (0 to 5);
  - 0 – not doable within the project,
  - 5 – applicable right away)
- Availability without modifications (0 to 5);
  - 0 – not available
  - 5 – available without modifications needed
- Relative price (5 to 1);
  - 1 – high price
  - 5 – low price
- Measurement speed (with processing) (1 to 5);
  - 1 – slow
  - 5 - fast
- Energy efficiency (1 to 5);
  - 1 – requires significant amount of energy
  - 5 – vey energy efficient
- Applicability in/on:
  - Lab (1 to 5)
  - In field (in relevant environment) (1 to 5)
  - Final prototype (1 to 5)

The following evaluation will be done following each of the tasks. Methods that were ruled out in the section 2 will be not evaluated here. There are some overlaps in the tasks, therefore some methods are shown in multiple sections below. The evaluation was done by the consortium with participants from WP1, WP2, WP3 and WP6.

3.1 SENSORS FOR MAPPING AND LOCALIZATION

For locomotion, sensors that were considered are given in Table 5. Perception methods, that could be applied up to the prototype level are highlighted in green.

Table 5 Sensors proposed for mapping and locomotion

Sensor type	Applicability in air?	Applicability in water?	Applicable within the project resources	Availability off the shelf / requirement of modifications	Relative price	Measurement speed (including processing)	Energy efficiency	Total score	Applied in: lab, field, final prototype
ERT/IP	0	5	5	4	2	4	4	**24**	5-5-4
GPR	5	2	3	4	3	4	4	**25**	4-4-3
XRF	5	2	5	3	4	2	2	**23**	5-5-3
Terahertz reflectance spectroscopy	5	2	1	2	4	5	4	**23**	5-1-0
Temperature	5	5	5	5	5	5	5	**35**	5-5-5
Pressure	5	5	5	5	5	5	5	**35**	5-5-5
Sonars	0	4	3	5	2	5	4	**23**	5-5-2
Radar	4	4	3	4	3	5	4	**27**	5-5-2
Turbidity	0	5	4	4	3	5	4	**25**	5-5-3
Current sensing	5	5	5	5	5	5	5	**35**	5-5-5
Hydrophones	0	5	5	5	4	5	4	**28**	5-5-4
IMUs	5	5	5	5	3	5	4	**32**	5-5-5
Camera	3	3	5	3	3	4	4	**25**	5-4-4
LIDAR (ground truth)	4	0	5	3	3	4	4	**23**	5-5-4
Passive seismic (external)	5	5	4	5	3	5	-	**27**	5-5-5
Bioinspired touch sensors	3	4	3	3	3	4	4	**24**	5-4-3

3.2 SENSORS FOR EXCAVATION MONITORING

The evaluation of excavation awareness and monitoring sensors are given in Table 6. Perception methods, that could be applied up to the prototype level are highlighted in green.

Table 6 Sensors proposed for excavation

Sensor type	Applicability in air?	Applicability in water?	Applicable within the project resources	Availability off the shelf / requirement of modifications	Relative price	Measurement speed (including processing)	Energy efficiency	Total score	Applied in: lab, field, final prototype
Load/torque cell	5	5	5	3	4	5	4	**31**	5-5-5
Vibration sensor / tool wear monitoring	5	2	3	2	4	5	4	**25**	4-4-3
IMUs	5	5	5	5	3	5	4	**32**	5-5-5
Thermal imaging	3	0	5	3	3	4	3	**21**	5-4-2

3.3 SENSORS FOR SLURRY SENSING

The evaluation of possible slurry sensing methods is given in table below. Perception methods, that could be applied in the final prototype are highlighted in green.

Table 7 Sensors for measuring slurry properties

Sensor type	Applicability in water?	Applicable within the project resources	Availability off the shelf / requirement of modifications	Relative price	Measurement speed (including processing)	Energy requirements	Total score	Applied in: lab, field, final prototype
Magnetic flow meter	5	4	5	4	5	5	**28**	5-4-2
Ultrasounds meter	5	3	4	4	5	4	**25**	2-2-3
Density meter	5	3	5	3	5	3	**24**	1-2-1
Particle size sensor	5	4	3	2	5	4	**23**	4-3-1
Temperature	5	5	5	5	4	5	**29**	5-5-5
Pressure	5	5	4	5	5	5	**29**	5-5-5
LIBS	3	5	3	3	5	3	**22**	5-5-4
Time-resolved close-range Raman spectroscopy	3	1	2	0	3	4	**13**	3-0-0
VIS-NIR reflectance spectroscopy	4	5	3	4	5	5	**26**	5-5-5
UV fluorescence spectroscopy	3	5	3	4	5	5	**25**	5-5-5
XRF Spectroscopy	4	5	4	3	3	3	**22**	5-5-3
Gamma-Ray spectroscopy	5	5	5	3	3	4	**25**	4-3-0
Neutron activation	5	0	5	3	5	4	**22**	0-0-0
Terahertz reflectance spectroscopy	4	1	2	2	4	3	**16**	4-0-0

4 CONCLUSION

Considering the possible scenarios and the varied tasks that the ROBOMINERS platform should perform, a large list of possible sensing methods was considered, balancing robust, well-establish sensing with more recent, or unconventional technologies. A large proportion of these techniques will be evaluated in a laboratory environment using ROBOMINERS partners' facilities, and the most promising methods will be field-tested in a relevant environment (corresponding to one of the mining scenarios). Finally, considering the evaluation criteria's based on the applicability in the harsh mining conditions, their availability in the project resources and reasonably achievable TRL level, a selection of technologies, highlighted in this document, will be applied on the final prototype. As a summary, a Venn diagram in Figure 26 gives an overview of the possible ROBOMINERS perception methods to be studied forward in the project.

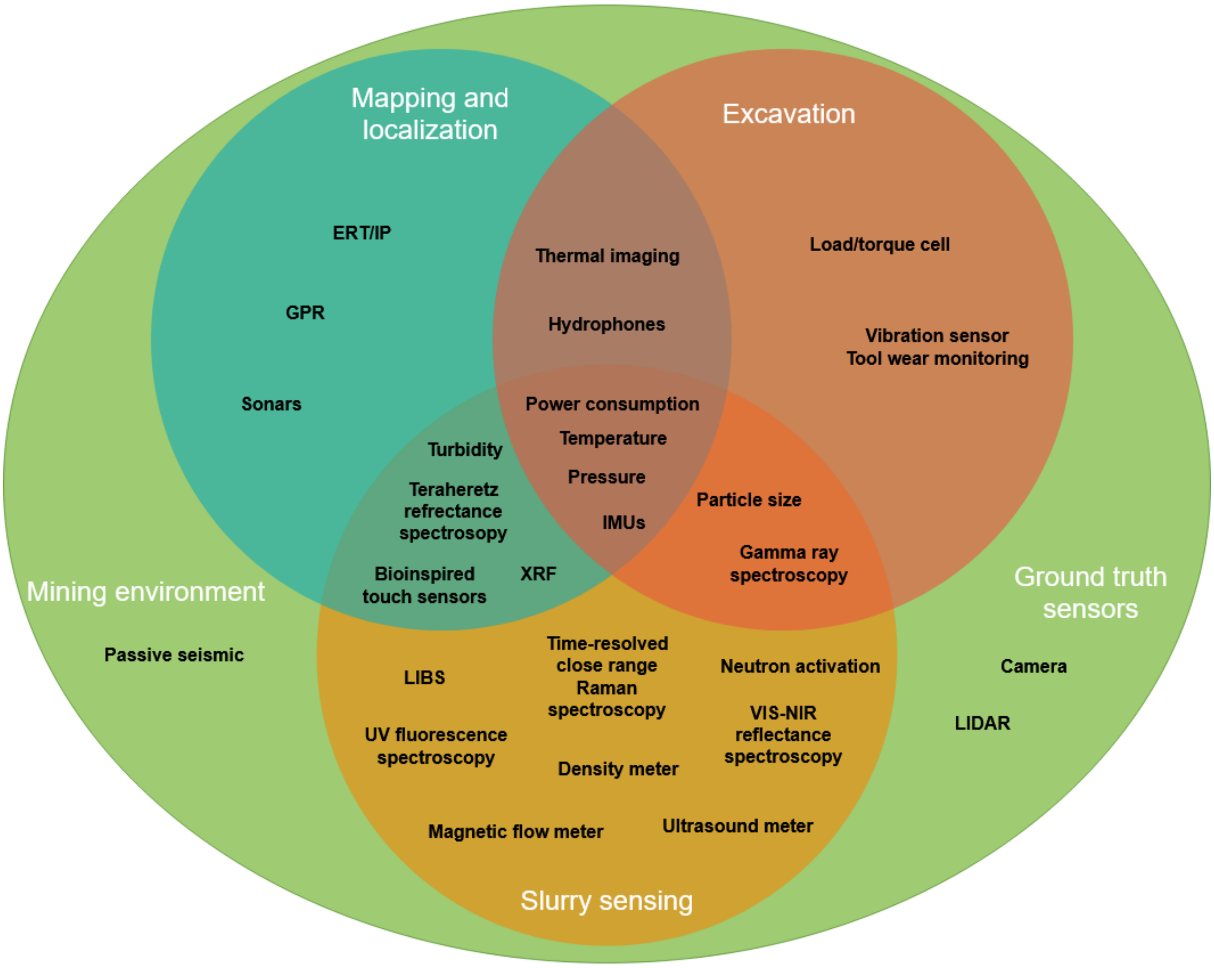

Figure 26 ROBOMINERS perception methods VENN diagram

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