illuMINEation
THE FUTURE OF MINING

DATA ASSESSMENT FOR SAFE ZONE CLASSIFICATION

This Deliverable D4.1 presents an overview on available data from existing sensors used in mining operations and evaluates potential analytical methods to extract information for safe zone classification.

Identifier:	illuMINEation_D4.1_MUL_Data assessment for safe zone classification
Work package:	WP4
Document status:	Final
Dissemination level:	Public
Keywords:	Digitalization, data analysis, safe zone classification.
Abstract:	This deliverable is a report on available data from existing sensors which are, or can be used in mine operations. Data from those sensors will be assessed and possible analysis in terms of safe zone classification will be presented.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 869379.

Document history:

Version	Date	Reason of change
V1.0	06.08.2021	1st Draft
V2.0	17.08.2021	2nd Draft
V3.0	25.08.2021	3rd Draft
V4.0	27.08.2021	Final Draft
V5.0	31.08.2021	Final Draft with integrated comments from review

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Disclosure Statement:

This document has been produced by consortium partners of the *illuMINEation* Horizon 2020 project, funded by the European Union's Horizon 2020 research and innovation programme under grant agreement No. 869379. The content of this document, the information contained herein and the views expressed are those of the authors and do not necessarily reflect the official opinion of the European Union. Neither the European Union institutions and bodies nor any person acting on their behalf may be held responsible for the use which may be made of the information contained.

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Executive Summary

This deliverable will contribute to the general objective defined for work package 4 in the framework of the illuMINEation project, which is the classification of underground and surface mining areas with respect to assess the potential risk for personnel, critical mining infrastructure and equipment. Therefore, new and existing digital monitoring methods for observing rock mass stability, underground atmosphere, ground water, critical mining infrastructure (tailing storage facilities) as well as position and status of mining equipment and personnel will be implemented during the project. As a first step, to achieve the pre-set goals, real time monitoring data from existing sensors have to be investigated on their availability and be evaluated for their further use in the project. This report is closely linked to Deliverable D3.1 (Low-cost sensor options for mining applications). Data from existing sensors strongly depend on the degree of digitalization and deployed monitoring systems in respective mines. Due to this strong variance in data availability, this work not only focuses on existing data from project use cases, but also on data perceived as being generally provided from a variety of different monitoring systems available on the market.

In order to derive meaningful information for safe zone identification, large data sets have to be analysed in a subsequent step. Therefore, an assessment on the analysis of such data will be performed in terms of how to analyse it and derive meaningful information regarding safety status based on real time monitoring data. Subsequently, the extracted information will be used to assess the potential risks within mines. Zones with different safety status can be designated ensuring a safe mining operation. A great potential in the data analysis for safe zone classification lies in the development of the Industrial Internet of Things (IIoT) platform. All monitoring and position data as well as already analysed data is stored and therefore readily available for complex interlinked data analysis to derive even more additional and meaningful information. This allows for an improved judgment on safety status based on real time monitoring data. To achieve these goals, the aim is to develop intelligent algorithms for analysing those massive data sets for their defined purpose.

In case of geotechnical and environmental monitoring, novel rock bolts that are equipped with low-cost sensors will allow to measure bolt deformation due to changing stress conditions as well as atmospheric parameters. Due to the low-cost nature, these “sensorised” rock bolts will be installed throughout the mine, hence, forming a comprehensive mine-wide monitoring network. Concepts of how to analyse such data in terms of rock mass behavior, changes in rock mass conditions, support functionality and effectiveness are presented in this deliverable. Moreover, important parameters that influence the safety of the underground work environment such as temperature, humidity, air pressure, or the occurrence of harmful pollutants can be monitored, and knowledge of the mine ventilation system could be derived. All data acquired by these sensor-equipped rock bolts will be used to assess and designate the safe zones. In addition, options for positioning and tracking of personnel and equipment on local or global basis are investigated, accompanied by further improvements of current systems from Epiroc, and the development of new concepts using existing technologies. Via this approach, hazardous situations that are potentially caused by interactions between machinery and humans, i.e. machine-machine or machine-human collisions, can be avoided. Positional information in connection with the zone classification based on the intelligent rock bolt data analysis will form the backbone of the safe zone concept.

Drones, equipped with various sensors and devices, will act as agile inspectors of the underground environment. Inaccessible areas can be inspected and important information transferred to the IIoT platform.

In all ongoing or completed surface mine operations, monitoring of the environmental impact caused by mining activities is essential. In the framework of the project, a sensor system will be developed and tested that allows to measure ground water conditions, ground water table

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and air quality parameters. Thereby, additional knowledge in environmental impact of mining can be derived. Furthermore, mathematical models will allow to predict the propagation of potential pollutants. Monitoring and subsequent data analytics results will be used and transferred into safety status information in order to support the classification of mining areas according to the illuMINEation safe zone concept.

Structural failures of tailing storage facilities, if occurring, pose a serious risk to human life and may cause a major impact on the environment. For this very reason, an absolute safe operation must be ensured, if possible also via improved designs of such facilities accompanied by comprehensive monitoring of the storage structures. To achieve these important requirements, a method to automatically analyse massive amounts of monitoring data will be developed. This approach will help to significantly improve the assessment of various safety factors and parameters connected with risk assessment methods deployed to safely operated and manage tailing storage facilities.

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1 Introduction

1.1 Purpose of this Document

The purpose of this document is to report on available data from existing sensors in a typical highly mechanized mine. This includes data from already implemented systems in mines as well as data from existing sensors, which potentially will be integrated in the framework of the illuMINEation project and therefore will be useful to achieve pre-set goals in terms of safety. Based on the data assessment, an evaluation of data usage and analysis, for classifying mining areas with respect to a safety status, will be performed.

1.2 Scope of this document

This document is structured into four main subchapters for each of the tasks that are participating towards developing the Safe Zone Concept as part within WP4. As a first step the potential resulting from digitalization will be discussed. Simultaneously, this chapter also presents a short general introduction, and is subdivided into three main parts. In the first part, the challenges and needs of the industry, especially as defined by the “USE CASES” of the project, will be outlined. The second part summarizes how data is acquired and which methods are applied to deal with the aforementioned challenges and needs (Deliverables D2.1 and D3.1). A critical discussion about the methods and their shortcomings will also be included. In the last part, a solution to overcome some critical points, and further advantages of future developments within the scope of the illuMINEation project, will be covered.
In the 2nd subchapter, the available data from existing sensor and their usage in the project will be assessed. The content includes (a) an overview of data already available from existing sensor systems, and (b) additional sensor data which will become available based on developments in the course of this project. Furthermore, the reasons and advantages of the additional data are discussed and outlined.
The 3rd subchapter deals with the analysis of the assessed sensor data, and will provide an overview on how information can be extracted from such sensor data and how it can be transferred and translated into valuable safety status information of individual mining areas. A description of necessary information to fulfil the main goal of the task, i.e. classifying mining areas with respect to a safety status, will be presented. Furthermore, in this part potential information generated by data analysis and their applications will be identified and analytics methods required to reach the defined achievements will be presented. Finally, findings will be concluded and a future outlook will be given.

1.3 Related Documents

This document is based of general safety and monitoring requirements of underground mines which are described in: Deliverable **D2.1 Requirements of the mining industry.**
Additionally, the report on available sensors for potential use in the project is strongly linked to: Deliverable **D3.1 Low-cost sensor options for mining applications.**

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2 Data availability and use in different utilization scenarios

2.1 Intelligent rock bolts for geotechnical & atmospheric monitoring

Generally spoken, the purpose of mining is to extract minerals from the earth's upper crust in order to cover the world's demand of different raw materials and mineral resources. In order to be able to run a mining operation in a successful manner, it must be ensured that safe working conditions are established and that mineral extraction is economical and sustainable. However, this is a challenging task when operating in a natural environment like mining, due to its complexity and multitude of influencing factors. Especially in underground mining the prevailing conditions are governed by such a natural environment and determined by designs of the mine and artificial control measures. Key success factors of safe mining operations are to ensure, on the one hand, stable ground condition and on the other hand, a safe atmospheric underground environment. Hence, it is essential to monitor the ground conditions by determining the current condition state and to track their changes using monitoring systems.

2.1.1 Potential of digitalization

2.1.1.1 Environmental Monitoring

In an underground mine many factors are influencing the atmosphere which may be harmful to humans, and potentially affecting the health of mining personnel. Hence, ventilation systems are commonly installed in order to control the underground environment and to ensure safe atmospheric conditions within the mine. The main purpose of mine ventilation is to provide fresh air for personnel working underground and to remove toxic, combustible or asphyxiating gases that are inevitably produced by various mining activities. Such gases are produced by machinery with combustion engines or toxic fumes are created during blasting. Depending on geological conditions, hazardous gases may also be of natural origin as they are contained within the rock mass and released during mining. Moreover, harmful or combustible dust may also be raised by moving machinery, too high or improper ventilation throughput and airflow, from cutting or drilling operations or from air pressure waves after blasting. Another function of mine ventilation is to regulate air temperature, ensuring reasonable levels and safe working conditions for operating personnel (e.g. avoiding freezing or dangers to suffer from heat stroke). Proper temperature control is also crucial to sustain high productivity levels of the work force which may be affected by extreme temperature or by legislative requirements to reduce working time. Cooling or heating of intaking air may be necessary in mines which are located in extreme climatic settings, or in areas where heat flux from the rock mass increases with increasing mining depths, or in mining locations that are affected by high machinery activities. First and foremost, it must be an absolute priority of the mining industry to facilitate a harmless atmospheric environment throughout the mining infrastructure in order to ensure safe working conditions. Secondly, gas, dust and temperature levels are regulated by European and national legislation that are defining threshold limits for safe workspace conditions which must not be exceeded.

As previously pointed out, mine ventilation is deployed to control atmospheric conditions in underground mines where needed. Because of the complexity of large underground mining infrastructure, the installation and maintenance of proper ventilation systems may be a rather challenging exercise. Furthermore, the continuous extension of the mine results in a dynamic growth of the systems with the effect of influencing the overall ventilation performance. Airflow rates and directions are key factors in controlling the underground environment. This is usually done using stoppings, sealings, air locks, ventilation doors, active or passive regulators, air ducts, air crossings, auxiliary fans and main fans. Due to its complexity, a good understanding

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of the underground mine ventilation system is necessary in order to assess the overall ventilation performance and to continuously optimize the ventilation design. Additionally, the environmental conditions in underground workings must be regularly monitored, essential to ensure safe working conditions for the mine personnel.

Nowadays, monitoring of the underground environment is undertaken by specifically skilled ventilation engineers on a mine-wide basis at several control points via mobile measurement equipment. Fixed installed sensors are frequently deployed at critical airway locations that are providing real time information, measuring gas, dust and temperature levels. Moreover, in many mines underground personnel are encouraged to use carry on devices or devices installed on machineries, capable of measuring different gas concentration, which will alert them as soon as certain gas levels are exceeding predefined threshold values. In this way, people are informed about changing atmospheric conditions, allowing them to immediately evacuate the affected area. A main purpose of ventilation surveys is the analysis of the overall ventilation system. Based on surveys, knowledge of the ventilation network and its effectiveness is gained and information for an optimized ventilation design can be derived.
Such ventilation surveys commonly assess airflow velocity and direction, but may also include measurements of pressure drop, leakage determination, fan performance analysis and other parameters. Other surveying methods like pressure drop measurements need precise measurement equipment, they are more elaborate and often require at least two people.

Conventional environmental monitoring and ventilation surveys performed by ventilation engineers is highly labour intensive with many person hours are required to perform all the needed measurements. Besides this major disadvantage, the measurements are performed only at certain airways and the measurement frequency is rather low. Therefore, rapidly changing environmental conditions cannot be properly monitored, which is essential when sudden events like gas outbursts or fire events are to be detected. Hence, mobile gas measurement devices should be carried by the mining personnel, which, unfortunately is often not the case as they are rather unwieldy. As previously pointed out, systems with fixed installed or mobile measurement stations have already been implemented, capable of delivering real time data about environmental and ventilation conditions within the mine. However, their installation is commonly limited to only a few strategic locations. Especially in mines where ventilation systems are dynamically controlled and steered to the currently required demand (so-called ventilation on demand), real time data acquisition is an absolute prerequisite. A major advantage of such real time data availability is that it allows for a short reaction time to set measures and adjust the ventilation system performance. The novel concept of illuMINEation to use rock bolts as carrier of environmental sensors will be a highly valuable contribution to already existing monitoring systems. Via the utilisation of readily available low-cost sensors, the density of measuring and data acquisition locations can be substantially increased throughout underground mine infrastructure. This will allow to comprehensively monitor environmental conditions and their changes in all areas of the mine and in real time. Furthermore, various factors that influences the ventilation system may be monitored on a mine-wide basis. Additionally, locating and tracking the spreading path of gas emission will be made possible due to a dense sensor installation pattern.

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2.1.1.2 Geotechnical Monitoring

Observations of changing rock mass conditions during the advancing mining progress throughout an entire mine life forms an integral part in every mining operation, resulting in a large variety of monitoring methods and systems which have been developed and evolved over time. According to Brady and Brown (2006) the need for rock mass monitoring is based on four main reasons, which are:

- The recordings of geotechnical parameters and their changes in planning phase;
- its function as an early alert system providing data for judging excavation stabilities to ensure safe mine operation;
- for validation and assessment of design parameters; and
- to check the implementation, effectiveness and impact of ground control measures.

A wide portfolio of different methods is commonly used to fulfil the above listed requirements. Measurements of deformation, convergence, stress and strain changes, seismicity and micro seismic events, wave propagation velocities as well as visual observation of the rock mass conditions and many others are covered by those systems. This effort is taken to gain knowledge of the response behaviour of the rock mass due to mining activities and the effectiveness of set ground control measures, resulting in an iterative design optimization and process (observational method). The main objective is to ensure safe and stable ground conditions by assessing their local and regional stability for safe, economic and sustainable mineral extraction. However, shortcomings of currently established monitoring approaches are that visual inspections of all mine openings are practically impossible on a weekly or even daily basis and that documented monitoring data is mostly rather sparse and dependent on local rock mass and stress conditions. As a result, data collection, processing and analysis are rather slow and heavily dependent on experience. Judgements and interpretations are necessary in order to get an overview of ongoing rock mechanics processes, such as stress redistributions, rock fracturing, instabilities etc. Moreover, the evaluation of data requires a fair amount of time. Consequently, information and knowledge lag behind ongoing mining activities. The availability of mine-wide, real-time rock mass monitoring data, as it can be delivered through the dense installation of sensor equipped rock bolts, as it is planned in the illuMINEation project, offers potential to overcome at least some of the latter issues.

The list of requirements on modern monitoring system to fulfil their defined purpose is quite extensive. Information should be provided in all areas of the mine at high accuracy, with good spatial coverage rather than punctual, and with small temporal intervals in order to track changes in ground conditions, as well as their rate, and time dependency. Especially, in the assessment of local stability, spatial and frequent monitoring is needed. Therefore, beginning instabilities can be detected quickly, with the effect that mining personnel is made aware of potential rock fall hazards and appropriate control measures can be established at an early stage. Local instabilities often arise from issues related to controlling the regional stability regime. Depending on the speed of the mining operation, regional changes in ground condition are commonly evolving slowly over extended time periods. Therefore, robust monitoring systems, capable of providing consistent data over long time periods are essential when assessing the regional stability in a mine. Moreover, to guarantee successful mine-wide application, a system should be designed for easy and fast installation at low costs, with automatically or semi-automatically bolt installation, which can withstand the harsh conditions of the underground environment. Additionally, efficient data handling, including a consistent accumulation, transfer and automatization of the data analysis, will play a key role in managing massive datasets and for extracting valuable information from the data.

As already pointed out, frequently used monitoring methods have some specific disadvantages, which have to be considered in design and application of those systems. For example, conventional LIDAR (Light imaging, detection and ranging) scans can provide spatial deformation through generating a cloud consisting of millions of survey points. Fixed-stationed

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LIDAR devices are also able to accurately detect deformation and deformation rates at millimetre scale. (Gelinas *et al.*, 2019) However, in case of periodic measurements, stationing of the device, scanning, data transmission and analysis of massive data sets is always required (Gelinas *et al.*, 2019). Due to these facts, such periodic monitoring methods are labour intensive and time consuming in scanning and analysis of the acquired data. Moreover, measurement devices are expensive and monitoring intervals are large and discontinuous. But a major advantage is that these LIDAR devices can be mounted on remote controlled equipment like drones, allowing to scan inaccessible or hazardous areas. In such applications, accuracy may decrease to the centimetres range (Jones *et al.*, 2020). On the contrary, commonly used multiple rod extensometers can provide highly frequent and accurate information of displacements, however installation is time-consuming, the information is limited to a single measuring line and the system is inflexible in respect to location changes.

Now, the main idea to overcome many of these critical aspects during the illuMINEation project is to make use of regularly installed rock bolts, which are connected to the rock mass and are linked to its deformation. Such bolts will be installed with strain gauge to measure the deformation of the rock bolt. However, the concept to make use of rock bolt as a carrier for measuring devices is not new, in fact even dating back to the 1960's. These systems are useful in the investigation for instance of the rock mass behaviour, support-rock mass interaction of different rock mass types and different bolt systems, monitoring support effectiveness and support state etc. (Mueller, 1978). But, usually bolts equipped in such a manner are expensive and due to this they are not installed densely and systematically throughout the entire mine. Therefore, new intelligent rock bolts will make use of methods in the application of low-cost measuring equipment, which has only insignificant impact on the price compared to "normal" rock bolts commonly installed. Furthermore, the process of handling and installing these bolts is equivalent to current standard procedures, and hence, no changes to procedure or equipment will have to be made, with the effect that the mining process is not disrupted. Therefore, an efficient installation process has to be ensured considering that hundred-thousands of bolts are installed in larger mines in a single year.

2.1.2 Data availability and their use in the illuMINEation Project

2.1.2.1 Environmental Monitoring

In case of environmental condition monitoring, digital systems have already been developed, capable of providing real time information of the subsurface atmosphere. Such existing monitoring data could be integrated into the safe zone concept. During the illuMINEation project, rock bolt heads will be equipped with available low-cost sensors. However, there might be some limitation to be considered, when installing sensors on rock bolt heads. Due to limited space at the rock bolt head and lack of permanent long-term power supply, only "small sensors" without high power consumption are feasible to be installed on every single rock bolt. To overcome this issue, a separate sensor box will be developed in the project, which can carry a number of different additional sensors for monitoring of the underground environment. This box will be designed for sensors characterized by higher energy consumption like electrochemical gas sensors. A sensor box - bolt head interface will ensure a fast installation process on any single rock bolt located in selected areas where monitoring is required. On the one hand, the usage of low-cost sensors enables a dense installation pattern but on the other hand a compromise between sensor accuracy, precision, sensitivity and sensor price has to be made. For instance, defined threshold limit values of some gases are set at very low levels. Due to this fact, special sensors are needed to quantify or even detect such low concentration levels. Here lies the strength of the sensor box, which can individually be designed on the special monitoring needs of certain air ways of mining areas. Admittedly, a customized designed box provides a great opportunity for a dense installed environmental monitoring system. Especially in mines, where real time monitoring is not yet performed, or in mines where existing digital systems can be extended. A general problem of fixed installed sensor data is that their value detection is limited just to a single point. For example, gas

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concentration may not be distributed equally over a whole cross-section and therefore only a cut-out can be tracked. In addition, logged values of air velocity sensors may not be representative, because of their linkage to the excavation boundary where special flow conditions are dominant.

If it would be possible to connect fixed-installed or carry on gas measurement devices with the underground communication system, such data could be transmitted to the IIoT platform and subsequently analysed. Thereby, larger areas could be covered due to its mobility and changing environmental conditions would directly be detected in the vicinity of personnel increasing their safety.

Additionally, conventional ventilation and environmental survey data should also be integrated into the IIoT platform. Such data will be helpful in the understanding of the ventilation network and therefore provide essential information during the analyzing process. Moreover, conventional environmental monitoring should be used to validate values of digital sensors installed on the rock bolts.

The following table summarizes all possible data that is potentially available in the framework of the illuMINEation project. The column "Location Concept" describes the location of the sensors which can either be integrated into the sensor box, or directly mounted on the rock bolt head. Further detailed information of different sensors is described in Deliverable D3.1. The table also includes two ratings defining the importance during the analysis in terms of the safe zone concept as well as estimated availability of reliable sensor data for analysis in the project. The rating reaches from one to three, where one describes highest importance of needed data availability to be integrated in the analysis of safe zone concept and three the lowest. The column "Data availability" assesses the availability of reliable sensor data, which might become available in the framework of the project. A rating of three means that data from sensor won't be available or reliable for further usage and, vice versa, one estimates that data will available and reliable for use. For instance, the data availability of the air velocity measurement was estimated with three. However, sensors reliably measuring such a parameter are principally available, but installation is restricted to excavation boundaries, where special air flow conditions are prevalent, with the effect that no meaningful data for analyzing of the overall air flow in an airway could be provided.

Table 1 Rating of Data availability and their importance for safe zone classification integration.

MEASURED PARAMETER	LOCATION CONCEPT	SAFE ZONE CONCEPT	DATA AVAILABILITY
AIR VELOCITY	Sensor Box	1	3
AIR FLOW DIRECTION	Sensor Box	1	3
GAS SENSOR: NO_X	Sensor Box	1	1
GAS SENSOR: CO_2	Sensor Box	1	1
GAS SENSOR: H_2S	Sensor Box	1	1
GAS SENSOR: CO	Sensor Box	1	1
GAS SENSOR: SO_2	Sensor Box	1	1
GAS SENSOR: H_2	Sensor Box	1	2
GAS SENSOR: CH_4	Sensor Box	1	2
DUST SENSOR	Sensor Box	1	2
HUMIDITY	Bolt Head	3	1
TEMPERATURE	Bolt Head	2	1
BAROMETRIC PRESSURE	Bolt Head	3	1

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2.1.2.2 Geotechnical Monitoring

It has to be mentioned, that a similar concept has already been successfully tested by Sun *et al.*, 2019. Small clusters of rock bolts equipped with ultrasound sensors have been used detecting the load and displacement changes of the rock bolt. The researchers demonstrated, that ground conditions monitoring through clusters of rock bolts can be more reliable and meaningful, instead of using single measurements.

A similar approach by monitoring clusters of rock bolts is used in case of the illuMINEation project. But on the contrary, a completely different, novel and powerful overall concept of intelligent rock bolts will be implemented. Data from a densely installed geotechnical monitoring network will become available through sensor instrumented rock bolts, measuring the bolt deformation. On the bolt itself, a polymer-based strain gauge is printed on the rod, determining the longitudinal deformation of the bolt via a sensor in the bolt nut. In addition, a communication unit connected to the wireless communication network of the underground mine will transfer measurement data to a central infrastructure. At this point, the data is collected and combined with other information for the mine and transmitted to the IIoT platform. The data is then readily available for immediate automatized analysis, providing information for the mine personnel and supporting staff in decision making. The availability of such rock bolts can make an essential contribution to temporal and spatial monitoring of changes in rock mass conditions in areas where they are used, without adding much additional costs.

However, also additional data from existing monitoring systems within the mines, can be included in the analysis, ranging from 3D-optical target measuring, 3D laser scanning, seismic and micro seismic monitoring systems, installed rod or tape extensometers to stress change measurements. Such data can be used to cross-check data reliability of the new installed monitoring system and can be integrated in the overall data analysis in the frame work of the safe zone concept.

Possible data analysis conducted in the framework of the project, will strongly depend on the capability of the rock bolt transmitting necessary data for different analysis applications. Hence, particular analysis of rock mass condition and bolt functionality needs certain data, which has to be delivered by sensors. Therefore, some initial requirements of the rock bolt sensor functionality need to be defined. The following Table 2 presents five different development stages of available data, which already is or might become available during the project. The special need of data for further analysis related with the development state will be discussed separately in the next chapter.

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Table 2 Different development stages of geotechnical rock bolt sensor and requirements for data analysis

DEVELOPMENT STAGE	DESCRIPTION OF ROCK BOLT SENSOR FUNCTIONALITY
STAGE 1	Rock bolt sensor is able to record if the bolt has experienced deformation
STAGE 2	Rock bolt sensor is able to determine if experienced deformation is related either to compression or tension
STAGE 3	Rock bolt sensor can provide deformation data to distinguish between elastic, plastic or failed rock bolt state
STAGE 4	Rock bolt sensor is able to measure the magnitude of deformation along the tendon with reasonable accuracy
STAGE 5	Rock bolt sensor is able to capture the magnitude of deformation with high accuracy, comparable to commonly installed extensometer, and high data resolution of deformation distribution along the tendon is provided

2.1.3 Data analysis and information extraction regarding safe zone classification

2.1.3.1 Environmental Monitoring

In comparison to the analysis of geotechnical sensor data, the information extraction regarding safe zone classification for environmental monitoring is much easier in terms of judging on critical safety states. The reason for this is that safe working space conditions are already defined by European and national legislation, defining the maximum concentration of harmful substances present in a working environment. Such threshold limit is usually structured into 2 stages. The first stage defines the maximum allowable average concentration over a whole working shift and in the second stage, alert values are set defining a certain concentration level where personnel has to immediately leave their working place. Therefore, it is necessary to not only monitor the underground environment but also to track the position of personnel within the mine. Environmental data acquired at different locations will be compared to threshold limit values on a real time basis, resulting in the identification of zones with different environmental conditions and potential hazards. However, how accurate the areal extension of safe zones can be determined will depend on the installed sensor density. The closer environmental sensors are installed relative to each other, the more precise extensions of critical areas can be located.

An improved understanding of the underground ventilation model is an important tool in terms of advanced data analysis for identifying safe zones. Data from existing surveys could be implemented creating an extended ventilation model. Such survey data can contain information of air velocity, air volume and air flow direction at several airways. Moreover, useful information of the ventilation system could be extracted by making use of gas spreading in the mine that is produced by blasting events or mine machinery. Sensors will track the increase of gas concentrations time dependently as a function of the source distance. Based on the elapsed time between sensors, which recorded an increase in certain gas concentrations, the air flow direction can be determined. If the absolute distance between sensors is known, air velocity can be estimated by back calculation. Moreover, relative statements may be deducted in case of air flow volume of merging air ways by observing reductions of gas concentration after intersections. Figure 1 illustrates the sudden increase of gas concentration after a blasting event as a function of time at several monitoring stations. The apparent decreases of the concentration level after intersections, where fresh air is added, is also visualized. Such

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analysis would allow to overcome difficulties of air flow sensors installed on intelligent rock bolts. Furthermore, an improved understanding of the underground ventilation systems can be achieved. This allows to set control measures more efficient to improve the safety of the underground environment.

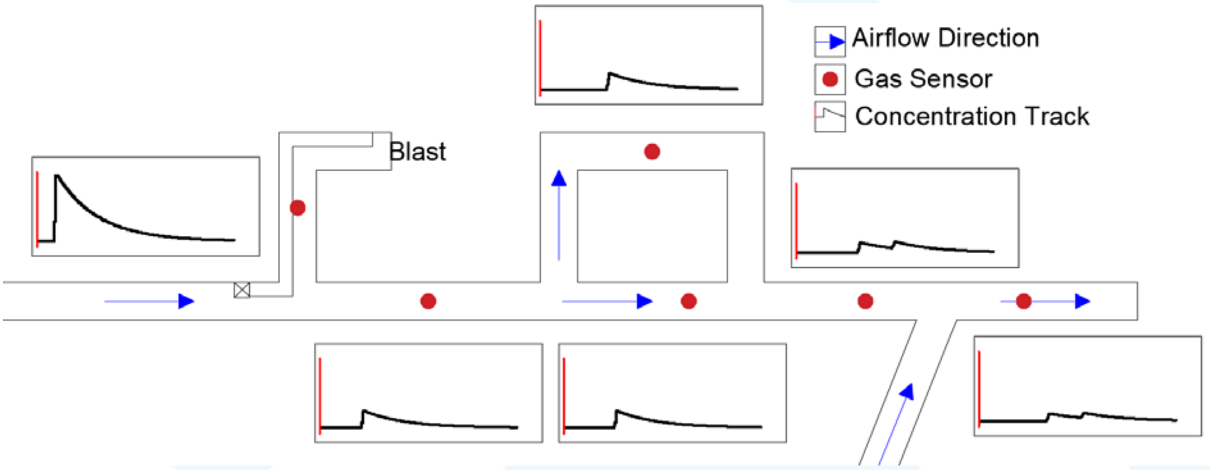

Figure 1 Time depended gas distribution in airways after a blast

As already pointed out, the strength of data analysis lies in the combination of generated information via sensors and a thorough understanding of the entire ventilation network. Such information is especially needed in case of fire events. Fires in underground mines represent a major danger, producing high level of toxic gases which can rapidly distribute through the whole mine. Fire events must be identified and located as quick as possible, and fast reaction time is crucial in order to set required measures for evacuation of persons to safe areas such as rescue chambers, fresh air intakes, mine exits, etc. Furthermore, escape routes strongly depends on the location of personnel and evacuation through contaminated air ways should be avoided whenever possible. In case of sudden events, predictive safe zone classification could be an opportunity to decrease the reaction time ensuring a safe and quick evacuation of staff. First of all, growing fires could be detected through a punctual increase of temperature and gas concentration within the dense sensor network. Merging this information with information of air velocities and flow direction of the ventilation system, time-depended emission spreading could be forecasted. Therefore, predictions when and in which air ways toxic gases will increase, could be made. Such an analysis provides the basis for a dynamic safe zone classification, informing about when a certain zone will be expected to become unsafe. One application of such information is to immediately regulate the ventilation system to minimize the effect of toxic emissions. The effectiveness of set measure could again be monitored using the sensor network and cross checked to validate the forecasts. Another application is by making use of personnel positioning within the mine as it is described in section 2.2. The determination of the location of mine personnel in combination with the information extracted from the predictive safe zone classification allows to define optimized individual escape routes. Subsequently, those findings must be immediately communicated to each single person via portal systems like mobile phone. In case artificial ventilation system regulation and atomized escape route finding is applied simultaneously to minimize the risk of fire events, complex situation may arise. Therefore, it is essential to know the impact of control measures in terms of fire emission spreading through airways, precisely in advance. Based on set control measures and forecasts of their system impact, escape routes have to be adopted quickly, due to changed ventilation conditions, ensuring a fast and safe evacuation.

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2.1.3.2 Geotechnical Monitoring

The utilization of intelligent rock bolts offers considerable chances and opportunities. In the following chapter potential improvements are outlined and discussed. These points were derived in a preliminary study concerning the possibilities of the intelligent rock bolts. Accordingly, the outlined applications provide initial "ideas" of what could be done with the data gained from the bolts. Further theoretical investigations and analyses are necessary to verify, whether these ideas can also be implemented in practice on a regular basis. Besides the proof of application, latter investigations also point out the demand on the readings taken from the bolt in respect to type of data, position of data collection along the bolts, accuracy of data and sampling rate as it is defined in Table 2.

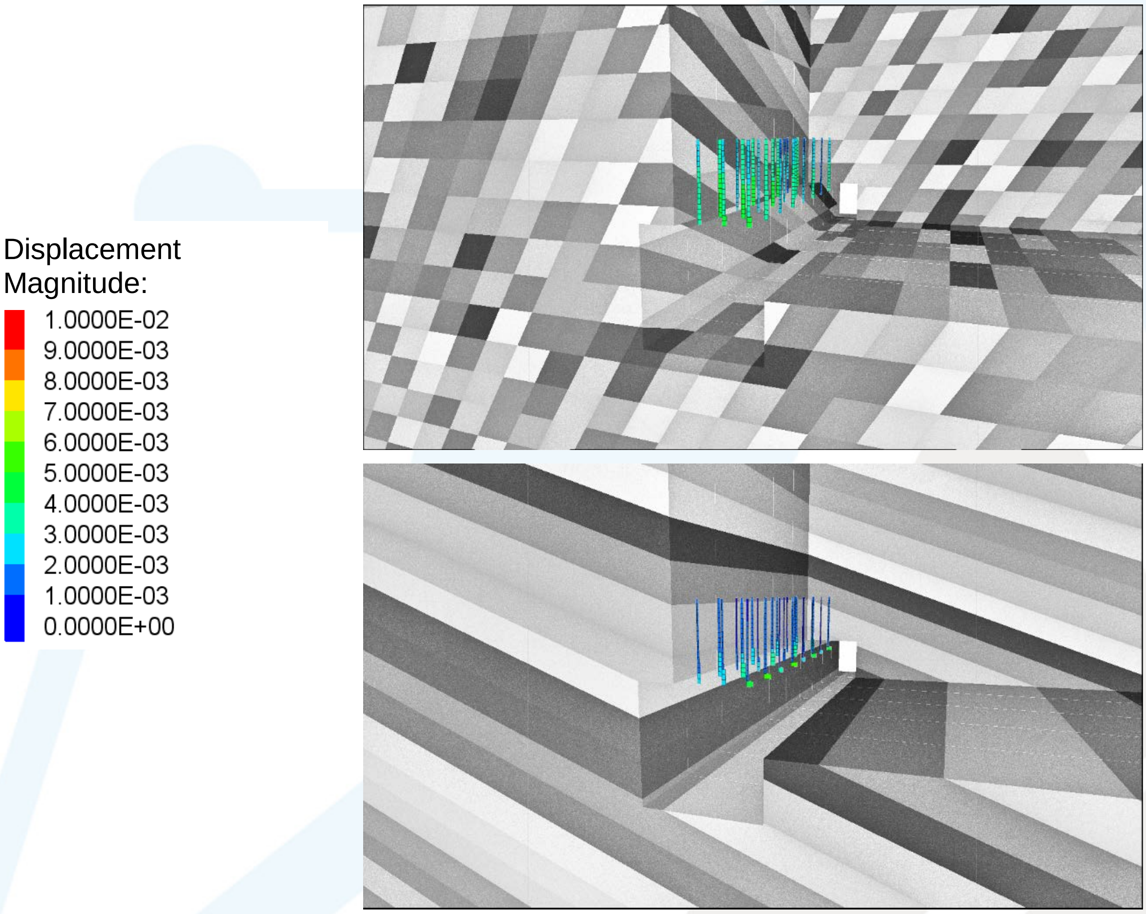

Figure 2 Displacement distribution of rock bolts for laminated rock mass (bottom) and blocky rock mass (top)

A big opportunity in the usage of intelligent rock bolts lies in the low-cost availability as well as the simple installation of the sensor equipped rock support system. As already pointed out, many geotechnical monitoring systems face the issue, that their observations are either punctual but with consistent temporal interval or vice versa with spatial information but over larger time intervals. Furthermore, the observation of areas with monitoring system is often only limited to areas, which have been either identified as critical during the design process, or where intense changes in the ground conditions become apparent.

Due to possible mine wide application of intelligent rock bolts, changing conditions in all areas of the mine, even in places where deformations have not been predicted or expected, may become recognizable in an early phase, enabling quicker and more efficient reaction, while also observing the effectiveness of these mitigation measures in real-time. Deformation data and its analysis will act like a medical thermometer for the whole mine. Through regional real time monitoring critical areas can be detected. Data analysis will support the engineers in

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judging the ground condition changes and their causes. Based on the identified causes, related measure like changes in stope design, mining sequencing, panel layout etc. or symptom related measure like increasing rock support can be implemented and monitored in order to ensure safe ground condition for working personnel. Furthermore, the analysis of the mine wide intelligent rock bolt response monitoring system could be included into the practical action plan for the mine management.

This leads to fulfilling one of the key aspects of any monitoring systems, which is gaining experience and knowledge in the behavior of different rock mass types. (Brady & Brown, 2006) Essential for such understanding is the description of the rock mass itself linked to information in the response behavior of the rock mass due stress changes in the underground environment caused by mining activities. A common method for standardized describing and rating of rock masses is classification methods, based on the rating and visual inspection of rock mass structure combined with laboratory testing and empirical studies, mechanical parameters describing the rock mass behavior are found (Marinos & Hoek, 2000). Shortcomings of such methods are, that the rating is subjective to a certain extent, and they are often applied for rock mass types, they have not been designed for.

Intelligent rock bolts provide the opportunity to overcome such difficulties, by objectively measuring and judging the rock mass based on bolt deformation. However, different rock mass types show different failure mechanisms resulting in different deformation characteristics as a function of the direction and magnitude of the principal stresses to the excavation (Marinos, 2012). Because the availability of low-cost intelligent rock bolts enables dense installation patterns of such bolts, the vision is to detect specific rock mass with specific deformation patterns by analyzing the values of every single rock bolt installed in the mine. This allows to identify the characteristic deformation patterns more reliably and enables the opportunity to characterize different rock mass types based on their deformation characteristics. Figure 2 illustrates the different deformation distribution along the rock bolt for different rock mass types in a 3DEC simulation. The goal is to analyze such different deformation behavior, which is related to stress magnitude, principal stress direction, anisotropic behavior of the rock mass as well as excavation size and shape. Due to this, information of the rock mass behavior as well as changing stress field may be derived. By making use of different drift orientations in same characterized rock mass types, analyses of the principal stress field orientation may be possible based on the deformation pattern analysis. In dependency of the rock mass deformation, information of stress magnitudes relative to each other probably can be derived. How the different rock masses react in terms of deformation rates, magnitude and deformation distribution related to support measures and mining activities will also be analyzed to gain knowledge of the rock mass behavior and extract parameters describing its mechanical properties strongly linked to the information of the rock mass type. Regional changes of stress redistribution may be determined by areal ongoing deformation of rock bolt clusters. For instance, in case of a support drift in an upwards sublevel stoping operation, a nearby support drift will be first subjected to the virgin stress state. During the passing of the stope front, high stresses and a changed stress field orientation will act on the drift. Finally, after the stope has passed surrounding rock mass may be fractured changing the ground conditions and the drift will be subjected to a low stress field as it is visualized with an ABAQUS simulation in Figure 3. The vision is to detect such behavior in terms of deformation measurement and gain information of the rock mass behavior by making use of dynamically ongoing processes in an underground mine. Such analyses will require an advanced development stage of 4 or 5 as it was defined in Table 2.

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Figure 3 Regional changes in stress distribution of the maximum principal stress at a drift during a simplified mining operation

Data will be analyzed to make statements in terms of bolt functionality, by knowing the bolt deformation, their mechanical parameters and the mode of action of the different bolt systems. Hence, information of the bolt state, distinguishing between elastic, yielding or failed status, as well as the current build up reaction force, will be extracted. In terms of safety and support functionality, information of the rock bolt integrity is essential which will be provided by the sensors. Failed rock bolts will reduce the support capacity and its functionality. For example, the failure of cement grouted rock bolts often cannot be visually detected, although still providing some residual reaction force. If numbers of rock bolts in certain areas have failed and cannot be detected, the support functionality is restricted and instabilities will put working staff in danger. Additionally, analysis of the support capacity state will be performed leading to an optimized support design. As a result, over or under design of the support system will be determined allowing the installation of an ideal numbers of rock bolt as required. Such rock bolt system can be designed on demand for all varying geological condition and stress levels in all areas of the mine. All acquired information can be integrated into the judging process of the safety status in the mining areas and will require at least stage 3 development. (Table 2)

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Another important application is provided by back analysis of such massive data sets. Due to continuous measurements of rock mass responses related to design and its changes within the mine (e.g. panel, stope or simply the rock support design), the effectiveness of design measures can be assessed. Based on information, new design criteria for different mining methods and rock support systems for varying rock mass characteristics could be derived. Rock mechanical design is often either based on numerical or semi-empirical methods. Numerical simulations are commonly very sensitive to certain mechanical input parameters and in most cases, initial pre-assumptions such as homogeneity and isotropy for rock mass are not applicable. Scale effects are usually neglected and mechanical input parameter are extracted from subjective rock mass classification systems. Using continuum mechanical approaches, failure along natural discontinuities and of intact rock are rarely considered (Elmo *et al.*, 2016).

The development of the intelligent rock bolts is an ongoing process, with many great opportunities. At the same time a range of further developments need to be implemented for full-scale deployment of the subject technology. To fulfill all of those described visions, many demands on the intelligent rock bolt are made in order to advance the development. Such requirements have to be defined in cooperation with the mines as end-users of the technology, including required data accuracy, logging frequency, deformation distribution resolution along the tendon, reliable long-term functionality in an underground environment, reliable results for different rock bolt systems as well as easy installation and data transmission to analyze the acquired data. In the framework of the illuMINEation project, field tests with use case partners under real mining conditions will be performed. During these tests all described relevant system components will be checked and their functionality analyzed, leading to an iterative design process. Nevertheless, successful analysis of rock bolt deformation data is strongly depended on the understanding of underlying rock mass deformation, characteristic rock mass failure and support rock mass interaction. Further research on these aspects has to be conducted, where comprehensive data analyzes from the mine wide and real time monitoring system will contribute to an improved understanding resulting in a wide field of applications.

2.2 Positioning / tracking of equipment & personnel

Reliable and robust tracking of the position of equipment and personnel in the mines helps to improve the work place safety and allows to optimize various mining process for best possible operational efficiency. The position of equipment and personnel will contribute to a safety-classification of the mining areas under the Safe Zone Concept, together with intelligent rock bolts, environmental monitoring, tailings dam stability and inspections conducted via drones. The Safe Zone Concept is based on the classification of individual mining areas into safe (green), risky/critical (yellow) and dangerous/unsafe (red) zones, all implemented via the IIoT Platform, and accessible by mine personnel for visualization on e.g. via tablets, mobiles, etc.
The sensors already installed on the mining equipment will together the emitrace® vision system from Retenua provide data for the classification, as well as with novel use of low-costs sensor solutions where applicable.

2.2.1 Potential of digitalization

There is a need of knowing the position of the equipment in the mine to plan for maintenance, operational control, work dispatch, traffic planning and blast planning. The need to know the position of personnel in the mine links to all these actions but most importantly, a safe working environment must be ensured.

The position tracking of equipment and personnel can be divided into a global context and a local context. The global context shows the equipment and personnel in the entire mine, typically visualised in a 3D-representation of the mine. This is typically used for work dispatch

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and preparing for blasting by evacuating all personnel from the mine. Mines such as Boliden use Epiroc's partly owned Mobilaris system as one global positioning tool.

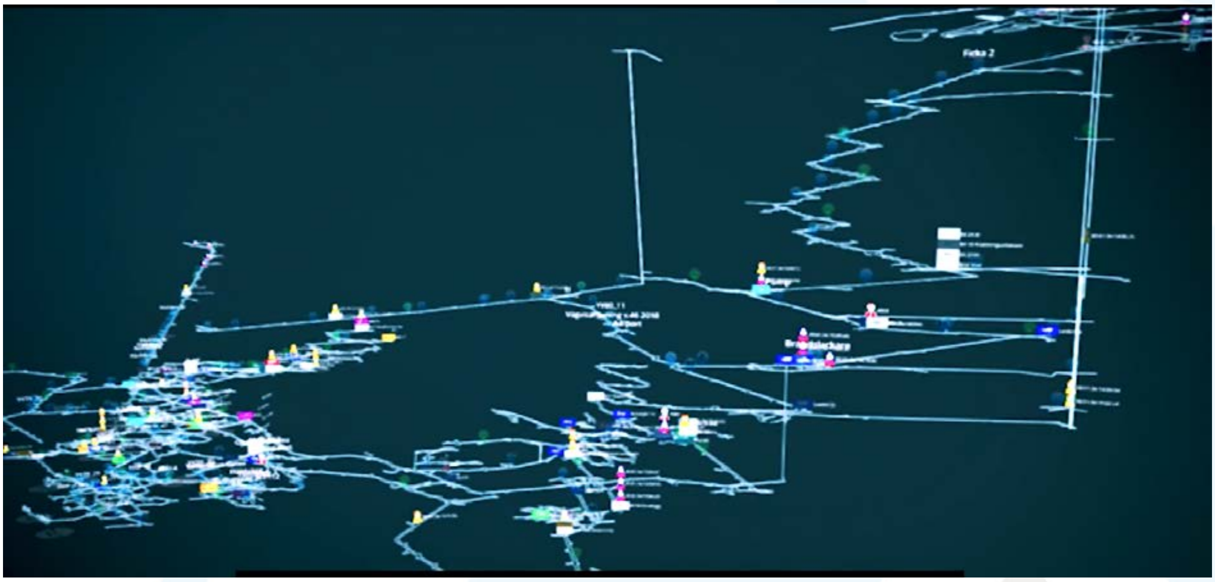

Figure 4 Boliden Kristineberg Mine visualized by Mobilaris : https://www.mobilaris.se/traffic-awareness/

To be able to determine the positioning of equipment and personnel in a global context, technologies such as UWB, BLE, LTE, NFC, RFID, 4G/5G or WIFI are commonly used. All these technologies require some communication infrastructure with access points at certain distances. Until the installation of these access points are made in newly developed areas within the mine, these areas are blind spots in respect to tracking of equipment and personnel. It is also not possible to establish access points in areas of active development and blasting activities due to the high potential of destructing the infrastructure.

Positioning in a local context relates to the detection around a mining vehicle, to warn the operator or trigger signal to the vehicles control system that an obstacle is approaching. The obstacle can be another mining vehicle, a person, a car or any other bulky infrastructure object such as pumps or electric cabinets.

On Epiroc's loaders there are sensors installed that are required for autonomous driving, such as articulation sensor, odometer sensor IMU, cameras and laser scanners. The laser scanners are capable of detecting anomalies in the driving route and triggers a signal to the control system to stop the vehicle if necessary. The autonomous loaders are operated in restricted automation areas where no humans or normal cars are allowed to enter for safety reasons. The loaders position in a global context is visualized by Epiroc's TMS (Traffic Management System) and the position can be picked up by any system via an OPC UA API. Dusty environments are a challenge for the laser scanner, since the visibility for the laser arrays is degraded, making the system unusable under severe conditions. Similarly, for the cameras mounted on the loader, a dusty environment reduces the visibility for the tele remote operator. There is the need to make the system more reliable and robust for the challenging underground environment characterised by high level of dust and, as for all mining sensors, they also need to be able to handle high humidity or rain, corrosive environment, vibrations, darkness etc. Moreover, there is also the need for an operator assistance system monitoring the surroundings to detect obstacles such as humans and other vehicles, in order to prevent collisions and accidents, thus making the surroundings safe for continuous operation.

At present, a common way to create safe work zones in mines is the use of light curtains. Those devices prevent people and other vehicles to enter the safe zone where the mine truck

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and loaders are autonomously working. The light curtains are connected to a safety system controlling which vehicles have entered the safe zone. The safety system prevents unauthorized people or machines to enter the area, and if needed will automatically shut down the operation in the specific area. Machine positions are determined using odometers, laser scanners, IMU:s and articulation sensors. Wi-Fi is used as the communication link between machines and the safety system and to transfer the machine's location to the traffic management system.

2.2.2 Data availability and their use in the illuMINEation Project

2.2.2.1 Evaluation of the emitrace® sensor system

When a mine truck is travelling in main areas of the underground mine, it can be manually operated, operated by tele-remote or autonomous. In all situations it is crucial to monitor the surrounding to prevent the machine from colliding with other machines or humans. Even for manually operated vehicles, an operator assistance system is of great importance that will warn the operator in case of an obstacle. In a mixed traffic scenario, it is also of important to know what kind of object the truck is approaching. The object ID will determine the logical functions of the control system in the truck, i.e. the truck detects another mine truck going upwards in the ramp could result in that the mine truck drives to the side and allows the full truck to pass. Or the mine truck detects a personnel transport truck and slows down as they both safely pass each other. Or the mine truck detects a human and either slows down or comes to a complete stop.

A sensor system like emitrace® could monitor the surroundings and give feedback in respect to the types of vehicles it detects, or if humans are approaching the machinery. Moreover, it would allow for a better flow of traffic, prevent collisions and hazardous situations for humans in the mine environment.

emitrace® is a machine vision system designed for positioning and tracking personnel and selected equipment or infrastructure from mobile machinery in industrial work environments. Its primary task is to detect patterns of reflective markers on high-visibility clothing worn by workers in order to detect the presence of workers in the vicinity of machinery. For that purpose, the camera is placed at a suitable spot on a mobile machine where it monitors a specific risk zone in the surrounding of the vehicle in order to detect the presence of humans. Upon detection of a person, alarm signals can be used for alerting a vehicle operator by visual or audible means, or to provide information for a vehicle control system. In addition to detecting workers, the camera system is also able to detect specific objects or items of infrastructure if marked with a reflective pattern of predetermined pattern.

The detection method of emitrace® builds upon infrared camera technology customized to detect reflective markers in industrial environments. The application of the sensing method for the task of detecting workers around machinery is therefore suitable for environments where the use of high-visibility clothing with reflective markers is mandatory, as it is commonly the case throughout the mining industry. Furthermore, using active infrared illumination in combination with the high reflectivity of the work garments, emitrace® offers a solution to the issues encountered by conventional camera systems characterized by decreasing performance when deployed in low-light conditions.

As part of the illuMINEation project, emitrace® will be evaluated for the task of human and equipment detection and positioning in underground mining environment. The objective is to understand the advantages and limitations of the solution as well as to explore applications where the technology can be used for.

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For that purpose, experiments will be carried out to assess or carry out the following tasks:

- Evaluation of maximum detection range and zone coverage with one camera device.
- Assessment of the influence of environmental factors (mainly water and dust).
- Evaluation of the influence of ambient light conditions on detection performance.
- Integration of the camera system into the vehicle's Rig Control System (RCS) and execution of vehicle behavior patterns upon detection of a person.

Figure 5 emitrace® mounted on an Epiroc vehicle.

Figure 6 Epiroc MT42 and emitrace® visualization of near vehicle Safe Zone. Note that in T4.1 only 1 emitrace® placed on the front will be evaluated, giving limited radius of detection around the truck

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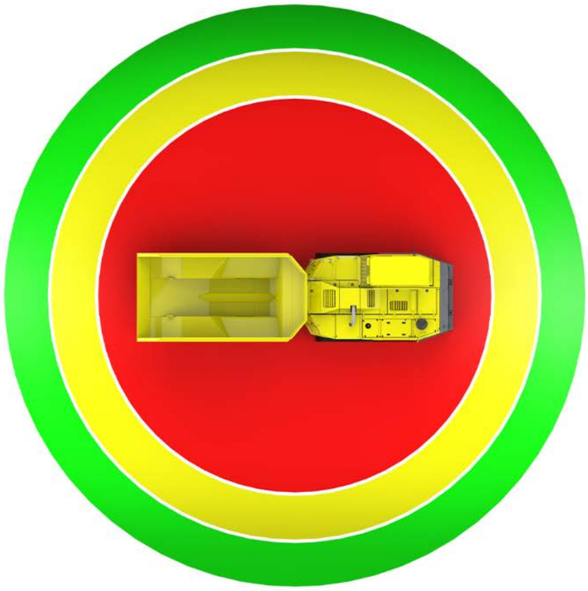

Figure 7 Top view of Epiroc MT42 and emitrace® visualization of near vehicle Safe Zone. Note that in T4.1 only 1 emitrace® placed on the front will be evaluated, giving limited radius of detection around the truck.

2.2.2.2 Conceivable principles for wireless detection

In general, there are several different methods for detecting objects within a conceivable distance, differing in various characteristics, such as in terms of general-purpose (actually for distance detection, or originally for data transfer purpose, with the additional side effect of giving distance information), accuracy, supported range and reflection behavior ("going around bends/objects"), energy consumption, feasibility/ availability/ economic aspects, etc.

Major techniques in this context refer to smartphone technologies and related wireless devices and technologies (cf. smart devices/internet of things, such as in automobility applications (e.g. in tunnels), or to name a specific application: to support locating missing things, e.g. keys using a detectable keychain device). In this regard, several technologies are well-known as established in the context of these smart-related applications, with further information correspondingly given in pertinent literature. Those technologies are:

- Wi-Fi (Wireless Fidelity; cf. WLAN)
- Bluetooth
- NFC (Near-field communication)
- UWB (Ultra-wideband)
- Sub-gigahertz (LoRa, LongRange)
- SDR (Software-defined radio)
- GSM (Global System for Mobile Communications; ref. telecommunications)

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2.2.3 Data analysis and information extraction regarding safe zone classification

2.2.3.1 emitrace® machine vision system

In a typical use case, the emitrace® machine vision system is placed on a mobile machine where it continuously monitors a specified risk zone in the vicinity of the vehicle. Reflective markers are detected and their 3D location is estimated. The system then estimates the likelihood by analyzing the observed reflective pattern whether it is associated with a person wearing high- visibility clothing. The data are provided to the vehicle system or can be made available for integration into higher-level data gathering information systems including:

- 3-dimensional position and velocity estimates of individual reflectors as well as tracked objects relative to the vehicle;
- A unique object ID for every tracked object.

The availability of this type of data enables a vehicle control system to initiate preventive measures to avoid collisions with workers or specific infrastructure. In addition, based on the detected location of workers or objects, the data allows for a dynamic classification under the safe zone concept. This prevents unexpected interference, allows for a better predictability of the traffic flow and improved work planning / scheduling in the mining operation.

The vehicle control system will respond to the human detection data provided by emitrace® in following ways:

- If there is a detection at a 'long' distance, flashing headlights and acoustic signals (e.g. honking the horn) on the mine truck will aim at raising the human's awareness.
- If there is a detection at a 'short' distance, the mine truck will slow down accompanied by similar visual and acoustic warnings as described above.
- If there is a detection at a 'danger' distance, the mine truck shall immediately come to a full stop.

The signals can also be transferred to and processed by the illuMINEation IIoT-platform to inform about human presence in active work areas. In case of a "danger zone" detection / situation, the area can be classified as unsafe zone and other personnel are immediately informed. In the event, another vehicle is detected that is not planned to enter a certain area, the zone can also be classified as dangerous since the vehicle is not recognised by in the IIoT monitoring application.

2.2.3.2 Concepts for position determination in underground applications

Common positioning methods typically used above ground are based on GPS, which are, due to the shielding from the required satellites, obviously not applicable in underground applications. Thus, different approaches are needed to detect the positions of objects (either personnel or mobile devices/machinery) in such underground environments.

A general prerequisite in this context is the fact that the structure of the underground building in focus is known to the deployed positioning system, i.e. the tracks, passages and connections that exist are known. Hence, only positions within this defined layout are possible.

In principal, there are two different overall concepts to be considered: (1) whether an object is generally within a certain section (e.g. somewhere in a particular stope, or along a certain track, but without detailed knowledge about the actual relative position), or (2) the more or less exact positioning of an object, i.e. where it actually is located in relation to its surroundings. These two overall concepts are schematically depicted in Figure 8 below.

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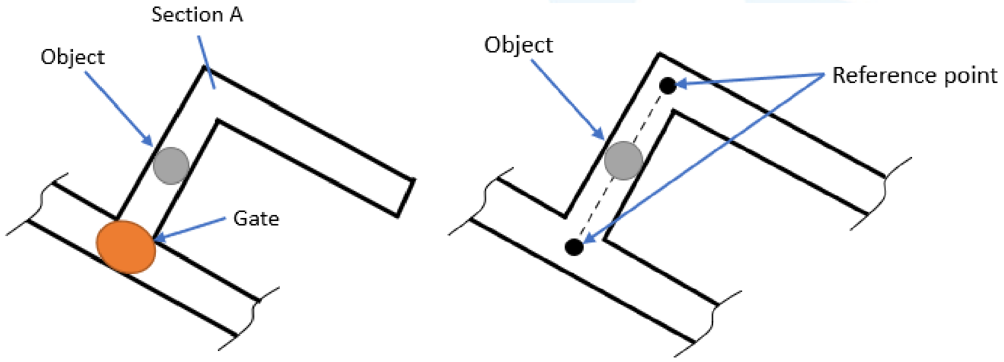

Figure 8 The two general concepts of positioning an object within an underground structure, gate-based (left; determining the object as inside section A) and reference-point-based (right; via determining the distances to the two reference points)

2.2.3.3 Gate detection

Especially the first concept, where objects are detected via passing gates in order to inform if it is inside or outside of a particular area, is already well establishes in several (underground) applications. This gate concept is commonly implemented via tags to determine personnel or machinery passing gate detection points. With this approach, critical areas can be monitored in a relatively simple way, as the determination of actual positions tags passing the gate is not required.

Problematic with this simple setup is to detect in which direction an object is passing the gate. This shortfall can be overcome via a relatively minor enhancement by sequentially arranging two gate sensors along a track, as shown in Figure 9.

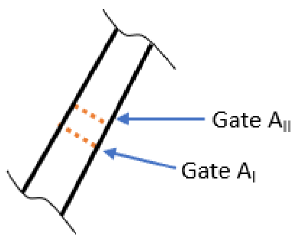

Figure 9 Two gate sensors forming an enhanced gate

If an object applied a gate-tag is passing A_{I}-to-A_{II}, then the object is determined inside the section behind A_{II}. And the other way around, by passing A_{II}-to-A_{I} the object is determined in the section in front of A_{I}.

Via this dual-gate-detection setup, intersections can be monitored to determine in which direction an object is leaving an area (see Figure 10.

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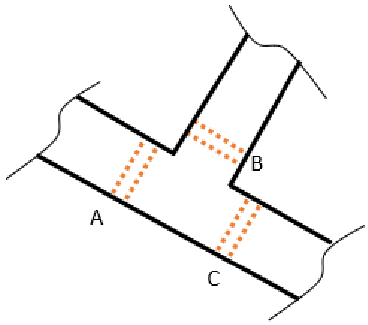

Figure 10 Gates at an intersection

Consequently, by applying such gates at several intersection points, the determination of objects within sections is principally made possible, as visualised on a branched system in Figure 11 below.

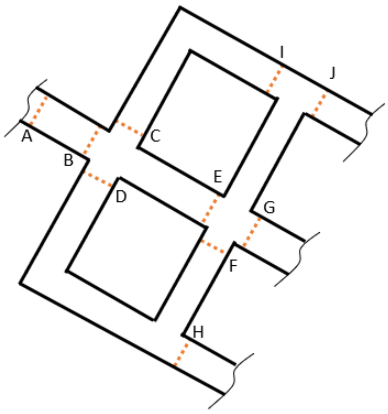

Figure 11 An exemplary branched system applied with gates (A-J)

Thereby, objects are detectable as within two specific gates only via the information of passing them. Accordingly, this concept is also applicable in three dimensions, e.g. at shafts and similar vertical connections.

The technique for detection at via gates does not require accurate position determination or long-range detection (of several dozen meters). However, it would be beneficial to detect a passing in the form of a more-or-less virtual curtain. In this form, the two gate detectors can be placed close to each other whilst covering the cross-section of the track and without overlapping of the two sub-gates within a particular gate (cf. Figure 9 and Figure 10).

Furthermore, specific (critical) gates may be additionally surveyed via a motion detection sensor, and if needed even via an additional camera system. Such a setup may be of benefit in entrance areas or at restricted areas in order to detect:

a. Objects that do not carry a tag are still identified as the motion sensor / camera would detect it but the gate alone would not. Consequently, a return message can be issued in this case in order to inform or warn the operator.
b. On the other hand, if motion is detected in parallel to a tag passing the gate, the process is categorised as ok and normal by the system, as a registered object is then

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considered as entering/leaving the section according to the descriptions as given above.

Thus, this somehow redundant system of a gate in combination with an additional motion sensor/camera can be of advantage in these terms of monitoring certain areas of interest (e.g. at entrances or points where tags may be removed (such as at residency areas)) – whilst keeping the additional effort for implementation relatively low in contrast to more complex systems of full position tracking, as described in the following subsection.

2.2.3.4 Relative object positioning

A different approach, in contrast to the simple gate detection, is concerning the positioning of objects relative to multiple fixed points with defined spatial position.

This principle is generally based on triangulation, but in this specific context of known surroundings, the detection can be reduced to bi-angulation. This approach is understood as detecting the position only via distances to two (instead of three) fixed points, also referred to as anchor points. This principle is illustrated in Figure 12, showing the positioning of an object along a track using this principle.

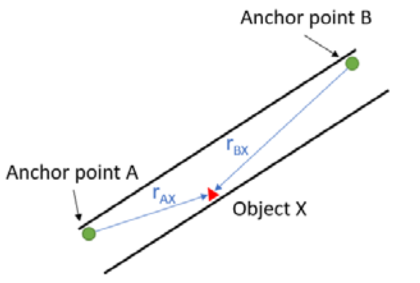

Figure 12 Relative positioning via distance determination to two fixed anchor points

By determining those two distances (r_{AX} and r_{BX}) relative to the anchor points (A and B), the position of the object (X) inside of the known mine layout can be determined at a sufficient accuracy. The use of such anchor points is further shown in Figure 13, deployed on a similar branched mine layout as previously outlined (cf. Figure 11).

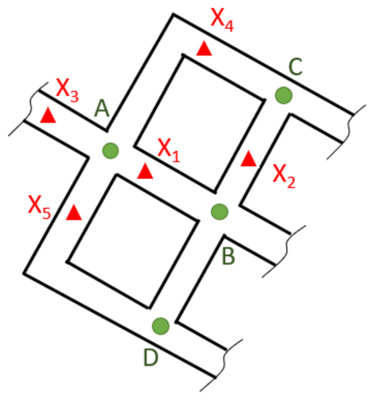

Figure 13 An exemplary branched system applied with anchor points (A-D)

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The scheme of this positioning principle depicted in the above figure highlights several different cases:

a. The case X_1/X_2: Simply resulting from the distance towards A and B / B and C, respectively; as between them, due to A-to-X and B-to-X both smaller than A-to-B.

b. The case X_3: Resulting from the distances towards A and B, but with B-to-X larger than A-to-B, thus with the object not between A and B, but rather in front of A, as shown.

c. The case X_4/X_5: Such cases may require additional anchor points, but in most situations reflections of distance detections are possible. Hence, the distance of D-to-$X_{(5)}$ is in some form principally possible to be detected, although with some degree of uncertainty. As the distance from A-to-$X_{(5)}$ is definitely resulting in a more accurate form, the position of X_5 between A and D is made possible with the reference distance set towards A. Similar applies for X_4, where the distance detection of C defines the reference value, whereas the distance determination to A gives a more uncertain result.

The technique for distance determination between two points is generally more complex than the simple gate detection as described before. To determine the distance between two points, that is between the anchor point (known position) and the object acting as slave point (position unknown and to be determined), several principles have to be applied, as already addressed in subsection 2.2.2.2.

Deployment of the so-called ultra-wideband (UWB) technology has significant potential for bi-angulation in underground applications as, in contrast to other technologies, it is already used for position determination and costs per device (anchor points and slave points) are relatively low. Detection ranges of a few dozen meters are fully feasible in line of sight situations, although some limitations of the detection around corners, such as in “shadows of objects”, are likely. In operation mode, an anchor point detects a device in its range and ping it to determine its location. Therefore, the slave device is not permanent in full sending mode, only if responding to the ping of the anchor device.

For fully position determination, integration anchors need to be hard-wired and positioned in relation to the surroundings as fixed points. Furthermore, slave devices installed on objects with energy supply are required. Commonly, power supply is available on mobile machinery by default. Alternatively, small UWB devices similar to key-less entry devices may be carried by underground personnel. Moreover, new generations of mobile phones are already equipped with UWB technology. Such devices can therefore be used for positioning of personnel carried by underground staff.

The Near Field Communication (NFC) technology are an inferior option when compared to UWB as their detection range is rather limited. On the other hand, advantageous is that NFC tags installed on objects do not require additional energy supply. In underground application, NFC may be deployed in the gate detection method at defined points, for instance when passing ventilation doors.

Another possible application for gate detection of personnel is to make use of GSM technology. GSM may be interesting, as to detect persons carrying a phone, lacking UWB technology. Even tough WiFi, Bluetooth and NFC are commonly switched off by the user, mobile phones are usually not set to airplane mode. Therefore, a receiver could theoretically detect the GSM signal of a proximal mobile phone passing it. In case of GSM, no additional software on the device is required. As long as the mobile phone transmits a GSM signal, any device may be detected.

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2.3 Environmental monitoring

Environmental monitoring is extremely important for the mining industry. The observation network is often highly developed both in terms of the number of measurement points and their spatial distribution. The main two tasks fulfilled by the observation network are the assessment of the impact of mining on the groundwater quality, the environment in general and the assessment of potential water hazards to the mining infrastructure. Due to the extensive area of mine workings and the even greater range of influenced groundwater table due to mining activities, measuring points can be distributed within an area of hundreds of square kilometres. The purpose of this project task is to create a device that allows for the automatic collection of data on groundwater quality as well as the level of the water table. The acquired information is subsequently transferred to an IIoT platform for data storage / management, processing and visualization. In addition to groundwater quality monitoring, the illuMINEation team will attempt to develop a surface air quality monitoring device. Data from the aforementioned devices will provide a basis for monitoring and analysing the impact of the mine and their infrastructure on the surrounding soil and water environment.

2.3.1 Potential of digitalization

The mining industry sees the need to increase both, the frequency of measurements and the spatial distribution of measurement points in the monitored areas. Such actions are necessary to fully understand how a mine affects the environment and are needed to react quickly to possible pollution occurrence. With a dense network of observation points, it is easier to identify a potential source of contamination and thus find a way to prevent it. Unfortunately, it should be remembered that making manual measurements is a rather time-consuming exercise. Moreover, when increasing the number of measurement points, a reduction of the frequency of observations at already existing points is often required. To avoid such a decrease of the measurement frequency, additional personnel would need to be employed, hence, generating additional costs. The solution to optimize this work is to use automatic logging devices, which unfortunately are rather expensive. Therefore, mining companies still prefer manual measurement, although to a limited extent.

The idea of the illuMINEation project is to developed automatic measuring devices at relatively low-costs, thanks to the use of components and sensors that are already available on the market and in common use, e.g. in the automotive or robotic industry. Such components are often cheaper than dedicated solutions, and the quality of measurements do not substantially differ from professional equipment. The currently used devices are insufficient due to the limited service life (corrosive effects of water, seepage of sediments) or high costs (e.g. heavy-duty pressure measuring devices used in the oil industry). Lowering the costs of measuring equipment would allow mining companies to increase its number and use it over a larger area or in a higher density mesh. The combination of increasing the number of used devices and automating measurements at a higher frequency will allow to meet the needs of the mining industry and translate into better monitoring of the impact of its activities on the environment, including quicker response time to potential hazards. The installation of data transmission modules (WiFi, LoRa) in devices would make it possible to receive measurement data almost in real time.

2.3.2 Data availability and their use in the illuMINEation Project

Referring to the currently conducted manual readings, the number of parameters received during automatic measurements will not change, leading to an unchanged data structure. However, the amount of data will significantly increase due to the already mentioned increased frequency of measurements and number of devices. The sensors installed in the device will collect information about the depth of the groundwater table, water temperature, pH and

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electrical conductivity. Additional information attached to such a data set will be the reading time and spatial coordinates of the respective device. The measurement of the water table will be carried out via a pressure sensor. The readings of the water pressure at the time of installation at a known water depth will serve as a reference point. Subsequent readings will then allow to determine fluctuations of the groundwater level due to water pressure changes relative to the reference value. In the case of measurements of hydrostatic pressure in the observation well, it is necessary to "clean" the obtained pressure values from the influence of the atmospheric pressure (pressure of the water column and the air column, which add up). In order to compensate the atmospheric pressure, it is necessary to use an additional logger that measures this pressure in the area of the observation wells. If it is expected that the pressure is be compensated on the fly and the "cleaned" data is directly sent from the measuring point, the barometric sensor would need to be mounted in the piezometer housing. Similarly, air quality sensors (like PM 2.5, PM 10 or some gas sensors) could be mounted together with the barometric sensor. The second possible solution to compensate atmospheric pressure, currently used in measurements, is via a pipe connecting the water column pressure logger with the atmospheric air. However, in the case of loggers installed at a depth of several hundred meters below the ground level, this solution has a high risk of failure.

At present, it is difficult to specify the exact type of sensors that will be used in the discussed device. There are several possible solutions on the market. The proposed device will most likely be based on the Arduino platform or some other similar solutions such as RaspberryPi. There are currently few sensors dedicated to the Arduino platform that will be tested in the course of illuMINEation, but there is also the possibility to adapt other sensors accordingly.

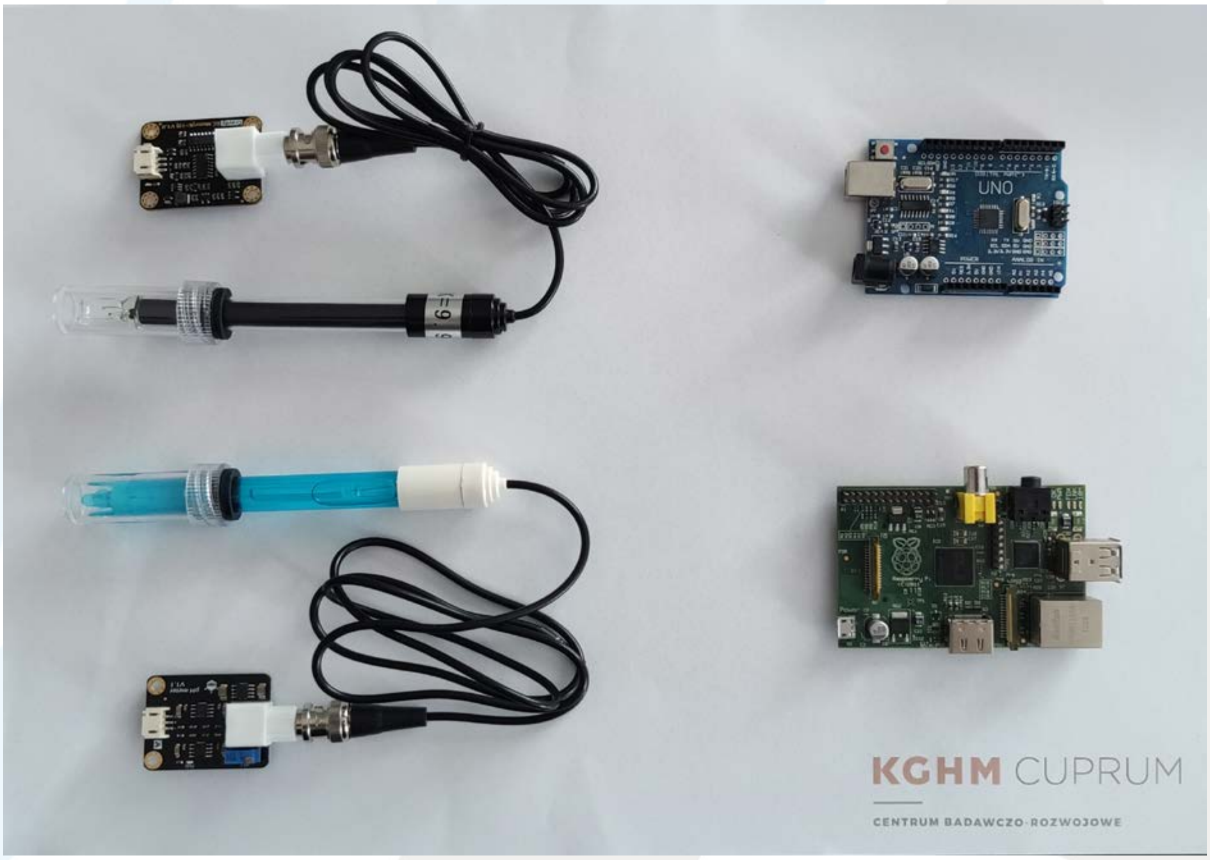

Figure 14 Sensors and microcontrollers. Upper left – electrical conductivity sensor, lower left – pH sensor, upper right – Arduino Uno, lower right – RaspberryPi

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Immediately after conducting the measurements, the acquired data will be wirelessly sent to the IIoT platform where it will be collected and stored. Another option is to install a card reader or memory module to collect and store data directly in the device. This way, potential data loss can be avoided in case of weak GSM, WiFi or LoRa signal reception due to i.e. bad weather or interferences.

2.3.3 Data analysis and information extraction regarding safe zone classification

The data collected by the aforementioned device, after appropriate processing, can be easily used to classify the mine's surroundings into safe or potentially endangered zones. Each measurement point will have its geographic coordinates defined in the database, allowing to easily create maps of water or air quality in mining areas. In combination with other spatial data, such as a digital terrain model, it will be possible to predict the migration of pollutants from the source along slopes or along watercourses. Rapid identification of the spread of pollutants in the groundwater environment on the basis of automated observations will allow for reliable forecasts of the migration of polluted water by using software for mathematical modelling of groundwater flow in pore centres. This will allow mining companies to react quickly and to focus their operation and mitigation activities to effected areas. Data visualization in the form of a two-dimensional map should be sufficient to assess the situation in the mining area.

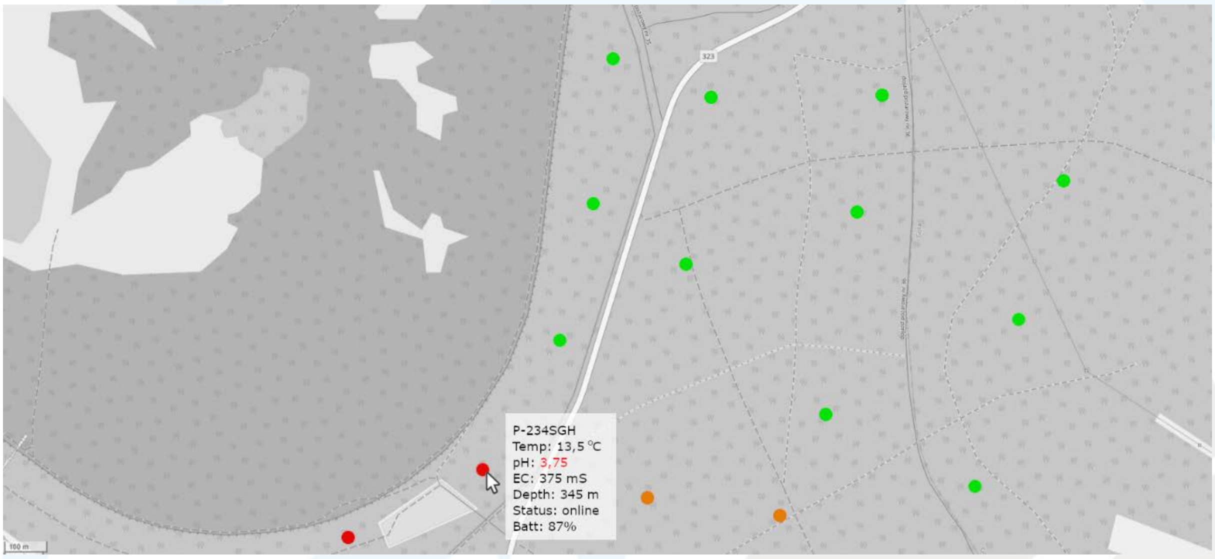

Figure 15 Example of data visualization

Measurement points represented by coloured dots can show, for example exceedances of the pH or EC value, thus indicating areas with an increased risk of contamination. Using such data will also allow to produce other types of maps, such as heat or contour maps, which may for example depict a too rapid lowering of the water level. In this way, monitoring personnel can easily identify sensitive places where undesirable phenomena are occurring.

2.4 Tailings dam stability

Tailings represent the uneconomic waste material created as part of the mining process, mineral processing and refining. This material is commonly stored in large embankments, so-called Tailings Storage Facilities (TSF) or Tailings Dams. They pose a significant risk to the surrounding environment and nearby communities when not properly monitored and managed. Potential TSF failures can lead to hazardous situations like fatalities, missing people,

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compromised transport infrastructure including roads, bridges and railways, illness, river pollution, damage and contamination of flora and fauna, power disruption, utility damage, drainage contamination, flooding, water contamination, mudslides and spills or lost homes. Therefore, there is an essential need in designing and operating TSFs in an absolute safe and responsible manner. One essential part of the illuMINEation project focuses on improving Tailing Storage Facility safety by implementing Machine Learning (ML) algorithms into data analytical processes.

2.4.1 Potential of digitalization

Commonly, TSFs are spatially extensive geotechnical structures, occupying a significant amount of space. When designing such structures, detailed geotechnical investigations are required and therefore, large amount of data has to be collected and analyzed prior to the construction process and, subsequently, continuously during the operation and maintenance of the TSF. Nowadays, collecting and storing massive data sets can easily be handled with modern database systems. However, the analysis of such a large amount of data is still a challenging task. Furthermore, there is a need to examine the data by qualified and skillful engineers. Unfortunately, it is practically impossible to screen and scrutinize all the data and analyze every trend manually. The reality also shows that usually only anomalies are analyzed is a more thorough manner. These aforementioned shortcomings can be overcome by the implementation of a “thinking” algorithm which supports the engineer to analyze big data set and therefore, will be a great step forward when it comes to safety and management of these structures.

Nowadays, many geotechnical projects are considering a risk and reliability-based design. This approach takes into account many different design scenarios and data variability. It assesses the risk of taking some decisions which represent a whole spectrum of the results. For the carried-out risk analysis, not only the investigation data is needed but also the detailed numerical calculations for many different scenarios and whole probability spectrums of data must be considered. Such calculations have to be done automatically and the processing unit should be able to draw the conclusion from all different scenarios.

In summary, when it comes to TSF design there is a need to implement the “thinking” computer algorithms supporting engineers, designers and managers to analyze the problems in a more detailed way. Due to an intelligent data analysis, a more colorful and broader view will be made possible. Such an approach will help to minimize the risks and allows to propose appropriate countermeasures already at a very early stage, thereby avoiding potential failure processes.

2.4.2 Data availability and their use in the illuMINEation Project

The data, which will be used in the illuMINEation project will be provided by an already existing and operational TSF structure situated in Poland, the Zelazny Most Tailings Storage Facility (ZM TSF). ZM TSF is the largest tailings storage facility in Europe, owned by KGHM Polska Miedz. Its construction began in 1974, and its operation on February 12, 1977. It occupies an area of 14 km^2 with a maximum dam height of 45 meters.

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Figure 16 Zelazny Most Tailings storage facility

The solutions developed in the framework illuMINEation will be based and tested on real data. Therefore, engineers will test the performance of the "thinking" algorithm and, additionally, compare those results with their own knowledge and experience. The project includes the analysis of different kinds of data sets including, ground investigation data, laboratory data, monitoring data and data from the maintenance department.

2.4.3 Data analysis and information extraction regarding safe zone classification

The project activities comprise several blocks according to the schema below and depicted in Figure 17:

- Creation of a database system with frontend application to control and visualize the data and the analysis results (reddish color);
- laboratory data analysis block (blue color);
- field data analysis block (turquoise color);
- monitoring data analysis block (yellow color);
- calculation and risk analysis block (light green color);
- spatial distribution of data block (dark green color).

Assessing risk and reliability will support the estimation of potential risks under the illuMINEation safe zone concept. The data will be analyzed towards making statements on the factor of safety with results visualized with combined information from the risk assessment. Thereby it will be made possible to determine the locations which are potentially unsafe or where only limited data is available and further investigation are needed. Such an approach will also help to notice dangerous phenomena that might occur in the future. In summary, the "thinking" computer algorithms will be implemented to analyze the raw data sets and moreover collect data to draw conclusions based on the multilevel, and different scenarios approach.

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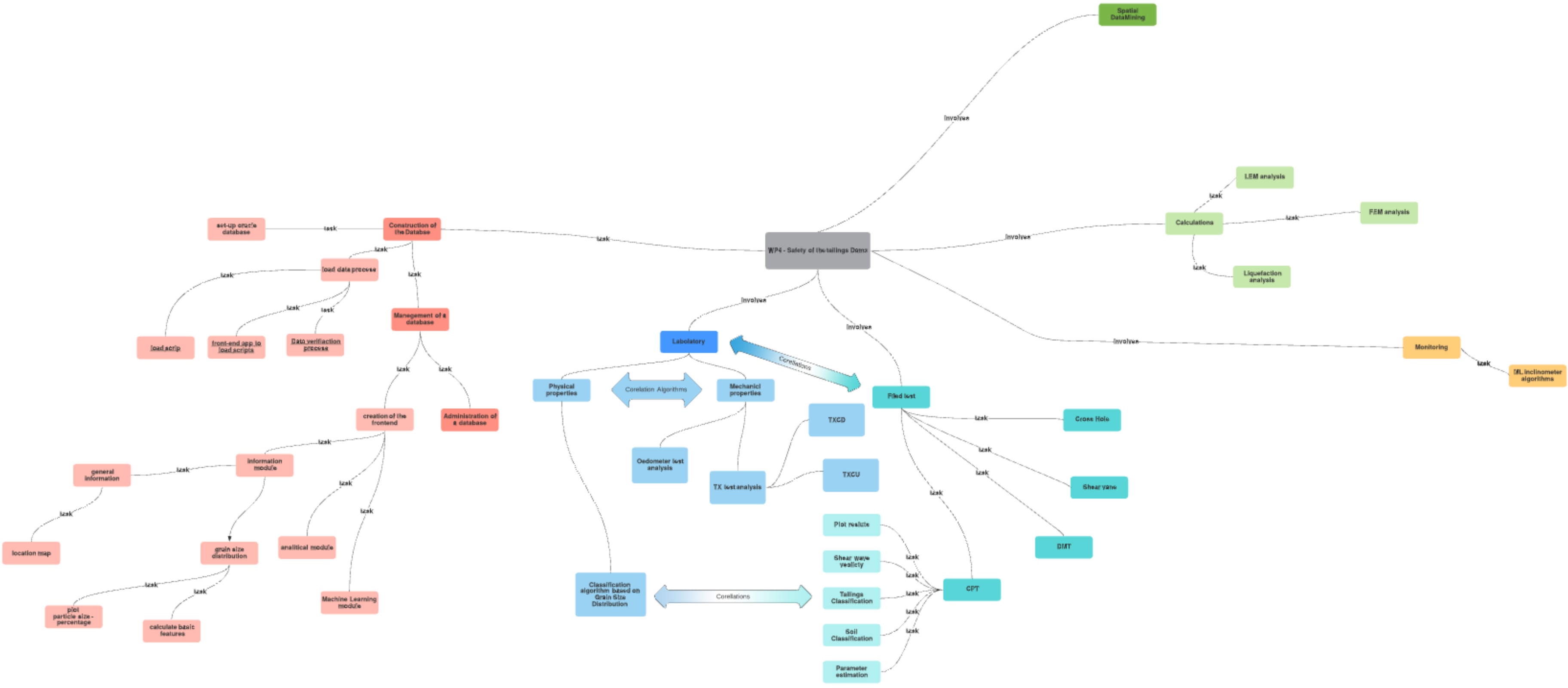

Figure 17 Project block plan

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2.5 Drones as Agile Inspector and first response unit

The mining industry targets the integration of drones in application scenarios related to the inspection of production areas, like underground tunnels. In these cases, the inspection task includes the deployment of an aerial platform, endowed with a sensor suite: a) to autonomously navigate along the tunnel and collect mine oriented valuable information (images, gas levels, lidar scans, etc.) and b) to autonomously act as datalink range extender of the mines‘ WiFi network to a vehicle. In a later stage, the collected data will be used from the mine operators for further analysis to determine the status of the inspected area.

2.5.1 Potential of digitalization

The mining sector envisions that a further mine digitization, as well as increased utilization of robotics and automation, will contribute to safer mines, fewer emissions to air and water and higher efficiency of mining operations. Overall, the deployment of drones can have a high impact on decreasing the time needed to inspect areas after blasting, since the autonomous drones could directly enter the areas of interest. In this manner, human exposure to dangerous environments (e.g. blind openings, areas after blasting, etc.) will be reduced. In an initial project task, this capability will be studied and the drone will be deployed in structured and unstructured environments for acting as emergency first response unit for further investigation of e.g. air quality, the existence of a fire in the mine etc. In a subsequent task, the utilization of drones as data link range extender will be investigated. WiFi, LTE, or other network connectivity are affected by the position of the mining vehicles in the underground mines, such as end of tunnels/stopes or when the mine machine works close to a mining face. Drones integrated to the machines could serve as data link range extender and relay the data to the network further back in the tunnel. Such data-mule drones will operate in the form of having network relaying mobile nodes that could be deployed either after an emergency or in production areas with no fixed communication infrastructure available. Finally, both cases will be demonstrated in Epiroc’s testing facilities.

2.5.2 Data availability and their use in the illuMINEation Project

Figure 18 The drone equipped with IMU, RGB camera, and 3D lidar.

The drone will be equipped with IMU, RGB camera and lidar scans as depicted in Figure 18. Additionally, the integration of gas sensors onto the drone will be evaluated. The collected information such as detecting personnel or objects in the tunnel, visual feedback from the environment, lidar scans and gas level can be shared with the operator. The dataset contains synchronized raw data measurements from all the sensors in a Robot Operating System (ROS) message format and the dataset contains data stored in ROS bag[1]. This file format is used for storing, processing, analyzing and visualizing ROS message data such as text, images, positions, orientations, etc. that are published by sensors through ROS topics. Measurements from each sensor are grouped under the related topic and namespace, such that a generic message structure can be represented as follows.

[1] http://wiki.ros.org/Bags

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```
dataset_id
├─ sensor_id_1
│  └─ data
├─ sensor_id_2
│  └─ data
├─ sensor_id_N
│  └─ data
├─ sensors_tf
└─ clock
```

N corresponds to the number of sensors, while the time synchronization of all sensors measurements within a bag file is established using timestamps and clock topic[2]. Each sensor topic in bag file has the following structure with a corresponding timestamp:

```
sensor_id
├─ header_length
├─ header_data
├─ data_length
└─ data
```

The data will be stored on the drone while an on-board algorithm can be used to analyze the collected data for example to detect personnel online. The data will be shared with the IIoT platform.

2.5.3 Data analysis and information extraction regarding safe zone classification

The collected data from onboard sensors of the drone can be used in the IIoT platform for safe zone classification such as detecting personnel in the underground tunnels or gas level of the environment. To this end, the drone will be equipped with sensors studied in the course of illuMINEation for positioning, collecting images and lidar scans from the environment. Additionally, the drone can be equipped with other sensors if they are compatible to the drone solution from aspects of power consumption, weight, connectivity, etc. such as e.g. gas sensors to measure gas level in underground workings.

[2] http://wiki.ros.org/Clock

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3 Conclusions

3.1 Intelligent rock bolts for geotechnical & atmospheric monitoring [Safe Zone 1]

In the scope of this Deliverable, available data from different sources including their potential usability for the illuMINEation safe zone concept have been assessed. Both, geotechnical and environmental monitoring is discussed.

Appropriate environmental conditions are crucial in order to ensure safe working conditions for underground personnel. Current efforts in this field include conventional ventilation surveying methods and digital surveying methods. Within the frame of the illuMINEation project, additional data from the developed and installed sensor network will become available. One of the key goals is to merge all mentioned data into one robust IIoT platform for subsequent analysis. Later on, such data will be analyzed and transferred into statements concerning the safety status of different mining areas. Some ideas for data analysis have been presented, including the comparison of sensor data with legislative threshold limit values, the mine ventilation system analysis and an approach for forecasting gas spreading. However, a more detailed analysis of such considerations is needed to avoid conceptual errors and to detect possible shortcomings, including an assessment of their reliability and usability. Nevertheless, installation of a high density of environmental sensors can positively contribute to a safe working environment.

In the case of geotechnical sensors, the continuous inspection of altering ground conditions using intelligent rock bolts can be beneficial for rock mechanical applications. On the one hand, an improved understanding of the rock mass behavior and an attempt to describe those with mechanical parameters will contribute to an optimization in the mine design. On the other hand, the reaction of the rock mass related to changes in rock mechanical designs will be tracked and adjustments consequently can be made in case unwanted trends are observed. Furthermore, the functionality of measures to control the ground conditions with rock bolt support can be monitored. This allows to assess the effectiveness of the deployed support system and to deduct the number of rock bolts that are required to ensure stable ground conditions in different mining areas. The approach will lead to positive effects and a safe and economic ground support design on demand. Finally, the extracted data regarding rock mass behavior and support effectiveness in combination with continuous observation provides valuable information. The gained knowledge, together with the individual experience of the engineer will help to evaluate the regional as well as the local ground stabilities in all mining areas, ensuring a safe, sustainable and economic mining operation.

The concept of illuMINEation's novel intelligent rock bolts will contribute to a permanent monitoring system, spatially distributed throughout underground mining operations. The main ideas lie in the equipment of conventionally installed rock bolts with low-cost strain gauges that are monitoring bolt deformation. Easy installation, equipped with data transmission and the lacking need of excessive maintenance are a prerequisite to guarantee a successful mine wide application. However, there are still open questions in setting the requirements for such systems to fulfill the envisaged variable needs.

Based on the deformation data of the rock bolts, continuous areal and temporal monitoring of changing rock mass conditions will be possible. Measures in mine design and support design, as well as their effectiveness can be evaluated when analyzing data from the intelligent rock bolts as part of an iterative optimization process, resulting in a design and support on demand system.

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Extracted information provided by the intelligent rock bolts represents a new way for optimizing the mine and ground support design, and for assessing rock mass related stability for safe mineral extraction.

3.2 Positioning / tracking of equipment & personnel [Safe Zone 2]

Tracking and determining the position of machinery and personnel in underground environment is crucial for ensuring a safe mining operation. Furthermore, equipment positioning enables efficient and safe maintenance, traffic and blast planning as well as an improved work dispatch and operational control. To meet safety requirements for personnel and machinery, the emitrace® sensor system of Retenua AB provides a great opportunity for deployment in underground environment. Equipping machinery with this sensor system allows to detect other vehicles and humans in its vicinity to avoid collision and hazardous situations for personnel working underground. emitrace® makes use of reflective markers detection as it is usually present on high-visibility clothing. Additionally, mounted markers on infrastructure and obstacles within the mine can also be individually captured. Furthermore, information of detected markers could be provided to the IIoT platform and integrated into the safe zone concept.

Another need is to track vehicles and humans in underground mining operations by making use of existing low-cost technologies, which can be implemented on rock bolts. The determination of personnel and machinery position is an integral part of a safe zone concept and is strongly connected to areal classification based on the analysis of environmental and geotechnical sensors. Due to the analysis of such data, areas will be classified regarding their potential risk. Mine management and staff working underground have to be informed in which classified areas humans are located. Such information could be provided by making use of the presented systems.

3.3 Environmental monitoring [Safe Zone 3]

The proposed solution will not only have a significant impact on the environmental monitoring in areas with active mining operations, but rather also in post-closure and rehabilitation areas. Reducing the costs of measuring devices and their full automation will allow for a significant increase in the range and density of observation networks in mining areas. This will lead to increased safety in the mine's surroundings and will allow for faster detection and prevention of undesirable phenomena such as contamination of groundwater or air. Additionally, constant monitoring of the groundwater table at high measurement frequency will also allow for a better understanding of occurring phenomena related to rock mass drainage, i.e. subsidence or the correlation of water table fluctuations with seismic events.

3.4 Tailings dam stability [Safe Zone 4]

Tailings Storage Facilities (TSF) are very large and sensitive geotechnical structures. There are many issues to be solved by the engineers. Subsequently, there is a need to create analytical tools to help the working staff to perform better maintenance and design. This outcome will only be made possible when having a clear understanding of the processes that might occur in order to be able to eliminate the potentially negative ones. To conclude, all of these actions are aimed at providing safer operation, maintenance and design of TSFs.

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3.5 Drones as agile inspector and first response unit

Drones operating in underground mine tunnels will provide access to unreachable and dangerous environment, while being used as a data-mule for connecting vehicles to the communication network. The data collected from drones such as visual feedback and gas level will reduce human presence in the risky areas.

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4 References

Brady, B.H.G. & Brown, E. (2006) Rock Mechanics For Underground Mining. *Chapman and Hall*, 1993.
Elmo, D., Moffitt, K. & Carvalho, J. (2016) Synthetic rock mass modelling: experience gained and lessons learned. In: *50th US Rock Mechanics/Geomechanics Symposium*.
Gelinas, L.P., Falmagne, V., Bedard, B. & Matte, O. (2019) Advanced geotechnical monitoring technology to assess ground support effectiveness. In: *Proceedings of the Ninth International Symposium on Ground Support in Mining and Underground Construction*, pp. 59–74.
Jones, E., Sofonia, J., Canales, C., Hrabar, S. & Kendoul, F. (2020) Applications for the Hovermap autonomous drone system in underground mining operations. *Journal of the Southern African Institute of Mining and Metallurgy*, 120(1), 49–56.
Marinos, P. & Hoek, E. (2000) GSI: a geologically friendly tool for rock mass strength estimation. In: *ISRM international symposium*.
Marinos, V.P. (2012) Assessing rock mass behaviour for tunnelling. *Environmental & Engineering Geoscience*, 18(4), 327–341.
Mueller, H. (1978) Studies on measuring bolts and other measuring elements to determine rock behaviour.
Sun, Z., Wu, K.T., Kruger, S.E., Levesque, D., Gagnon, D. & Quenneville, Y. et al. (2019) A new paradigm in ground support monitoring through ultrasonic monitoring of clusters of rockbolts. In: *Proceedings of the Ninth International Symposium on Ground Support in Mining and Underground Construction*, pp. 75–84.

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