ADOPTION OF SPACE LASER BEAM ROCK ANALYSIS TECHNOLOGY FOR TERRESTRIAL MINING APPLICATIONS WITH A FOCUS ON BLOCK CAVING MINING SYSTEMS: CONCEPTUAL DEVELOPMENT.

by

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ORIGINALITY STATEMENT

I, Bakytzhan Sadyrbayev, hereby declare that this submission is my own work and to the best of my knowledge it contains no materials previously published or written by another person, or substantial proportions of material which have been accepted for the award of any other degree or diploma at Nazarbayev University or any other educational institution, except where due acknowledgement is made in the thesis.

Any contribution made to the research by others, with whom I have worked at NU or elsewhere is explicitly acknowledged in the thesis.

I also declare that the intellectual content of this thesis is the product of my own work, except to the extent that assistance from others in the project's design and conception or in style, presentation and linguistic expression is acknowledged.

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ABSTRACT

The block caving mining system is the most economical underground mining system known today, and its popularity in the mining industry continues to increase. The block caving mining system can be described as the preferred mining system of the future, as it lends itself to automation. One of the most laborious tasks in block caving operation management is monitoring dilution at drawpoints. This task is currently manually handled by a geologist. Monitoring dilution manually at drawpoints is labor-intensive, time-consuming, and depends on the experience of geologists. In 2011 the National Aeronautics and Space Administration (NASA) introduced a laser beam rock analysis system via ChemCam on its Curiosity rover deployed on Mars. This device based on Laser-Induced Breakdown Spectroscopy (LIBS) heats the rock to about 10 000°C by the infrared laser beam and then analyzes laser plasma created from the molten rock. The technology is currently enhanced and is deployed on Mars via SuperCam on the Perseverance rover which is landed on Mars on 18th February 2021. It is hypothesized that the LIBS can be adopted for terrestrial underground mining applications for dilution monitoring at drawpoints in block caving operations. This application will increase the precision of the measurements, remove the labor-intensive and time-consuming use of geologists at drawpoints, reduce the block caving mining system's costs and increase the safety of the operation. In this thesis, a conceptual model for the application of LIBS space technology for dilution monitoring via a mobile robot is developed.

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1. INTRODUCTION

The recent discoveries of new orebodies often occur at depths, and they are generally low-grade ore deposits. In such conditions, the block caving mining system can be applied for economically feasible ore recovery. This view is supported by Laubscher (1994) who stated that caving is the most cost-effective underground mining process if the drawpoint dimensions and working equipment are suited to orebodies that will be caved and the extraction level could be preserved throughout the mine's lifespan. But with greater depth come new challenges such as higher in-situ stresses, high temperature, and many more, which lead to health and safety issues as well as ventilation costs and other hazards such as rockbursts. These problems can be solved by full automatization of the mine, which is already partly done by the implementation of automated LHDs (Albanese and McGagh, 2011). However, sampling processes still occur manually by geologists causing production delays, since heavy equipment cannot enter drawpoints when geologists are present.

Innovations in the elaboration and implementation of modern laboratory rock composition analysis technologies are constantly accompanied by a surge in demand and the use of novel instruments in the field. An analytic device for regular elemental analysis on-site, with specifications, such as small and compact size for personal usage, ease and speed of operation, high performance, and stability to be used in a range of conditions where different types of rocks must be examined, has been pursued in developments for the mining industry.

Various laboratory analytic methods have been converted into handheld instruments for on-site chemical analysis, such as XRF, optical spectrometers, Raman spectrometers, and LIBS. In the last decades, interest in LIBS spectrometers has increased dramatically. This seems to be a new solution to the problems faced by the scientific community when analyzing the composition of materials. It provides fast and high-quality rock analysis, and it has been shown from the ChemCam that this is possible even at a distance of 7 m.

Handheld LIBS analyzers are now applied in developed countries for sample evaluation purposes at different stages of the mining industry production. However, it is still manually operated by geologists and in cases of high-risk environments, such as drawpoints in block caving mines, there is a strong need for automation of this process. Currently, with advances in robotic technologies, the mining industry needs new opportunities for solving its problems. The block caving mining system, as the most adapted to automation, can be a starting point for 100% autonomous mines of the future.

1.1. Problem Definition

The traditional ore sampling techniques in block caving operation is deemed:

Dangerous: to collect samples, geologists must each time enter drawpoints that are subject to high rock stresses, which, in case of poor ground support, may result in failures and rockbursts. Mining operations tend to become deeper each year, thus there is a high risk of more accidents as the stresses and temperature increase with depth.

Labor-intensive: in traditional sampling processes geologists are required to travel from one drawpoint to another, covering considerable distances per shift. Another problem is that personnel must carry the samples in their bag, which requires physical strength and energy.

Time-consuming: taking samples at drawpoints requires at least 30-40 minutes per drawpoint and up to 24 hours for an entire undercut level. Due to the fact that heavy equipment cannot enter drawpoints while geologists are present, the sampling process is delaying the production. Samples must be prepared before they can be analyzed, and this process requires additional time and effort. Moreover, the sample must be sent to a laboratory, which is usually located far from the mining site, to determine the composition of the sample, which requires additional time.

Shortage of technical skills: In recent decades, the mining industry has become less popular among young people, despite the increasing demand for metals. In the future, the mining industry will feel a strong shortage of qualified personnel such as geologists, geotechnicians, surveyors, etc.

Inaccurate: results of traditional sampling processes are mostly influenced by geologists' experience. The grade control process might be seriously affected if geologists take samples that they might consider to be a higher grade. This would provide skewed analysis results for drawpoints.

1.2. Objectives of the thesis

1.2.1. Main objectives

The main objective of the thesis is to solve the problem of monitoring dilution at drawpoints in mines with the block caving mining technique. To reduce work delays associated with the presence of a geologist at the extraction level, as well as to avoid risks associated with the health and safety of geologists. Understanding that the deeper the block caving mine is, the greater the risks associated with the safety of personnel, the main goal of this thesis is to automate the drawpoint inspection process.

1.2.2. Specific objectives

The specific objective of the thesis is conceptual development for the application of space laser beam rock analysis to detect dilution at drawpoints in block caving mining operations. This thesis focuses on the transition from the traditional manual sampling to an automated LIBS-based robotic system capable of sampling and analyzing rock composition. To achieve the final goal of the thesis, the following specific objectives are set out:

1. To conduct a thorough literature review to understand the current grade control process in block caving operations;
2. To define the applicability of LIBS spectrometer to grade control process in block caving;
3. To develop a 3D model of an autonomic robotic system suitable for sampling in block caving and on which a LIBS spectrometer can be installed;
4. To prepare requirements and technical specifications for the robot needed to fulfill the mining requirements.

1.3. Hypotheses of the thesis

It is hypothesized that the use of LIBS spectrometer in a robotic configuration system, will improve grade control at drawpoints and, therefore, overall production of block caving mines. The conceptual development of a robotic system will address several existing challenges occurring during the drawpoint monitoring process in block caving mines by:

1. Performing continuous sampling of drawpoints under hazardous conditions, which is currently done by geologists;
2. Undertaking rapid determination of rock composition with improved accuracy

3. Reducing the amount of time spent for sampling each drawpoint;
4. Eliminate the components of the grade determination process associated with sample preparation and sample delivery to the laboratory.
5. Increasing safety of the operation by removing mine site personnel from the hazardous areas.

1.4. Scope of Work

In light of the fact that global development requires an increase in mining operations, the future of mining is closely tied to the deepening of mines and the increase in productivity. Block caving is one way to solve this issue. The monitoring of drawpoints is a critical part of any caving operation. As the depth of the block caving mines increases, the industry is faced with a new set of problems, such as increased stress and temperature, which pose serious health and safety concerns for workers as well as economic challenges. In essence, it raises the issue of automating processes that are currently performed manually.

For the replacement of geologists in the deepening mines, knowledge of the state of the art of block caving operations and traditional sampling processes is crucial. It is also necessary to find alternative sampling approaches for accelerating the sampling process. This will be achieved through a comprehensive literature review. Once an alternative approach has been found, the possibility of automating it will be investigated. It will be decided what parts of the system will be required and a design will be made for the automated sampling system. This design will serve as the basis for building a 3D model of the automated sampling system. With this model of the sampling system, a 3D simulation will be produced in a small part of the mine that represents the extraction level of the block caving operation.

Limitations. Conceptual development of the alternative to traditional manual sampling in block caving mines is presented in this thesis. Thus, the 3D conceptual model of the automated sampling system will be built on a computer using Blender software and the building of the model in real life is not considered. Software development for the automated sampling system is not considered. Moreover, this thesis will not include any laboratory tests for the compositional analysis of rocks.

2. LITERATURE REVIEW

2.1. Block caving operation

The mining industry has been extracting deposits with low grade ores, located at depths in recent years (Crowson, 2011). Block caving is a mining system where a block of unsupported ore fractures under gravity, allowing it to be extracted via already built draw points. The orebody is undercut at the bottom using traditional extraction techniques, and, subsequently, allowing the ore column to fracture and the rock mass to unravel under gravity (Figure 1). The overlying ore begins to fracture and cave as fractured ore is extracted from the ore column (Brannon, Carlson and Casten, 2011).

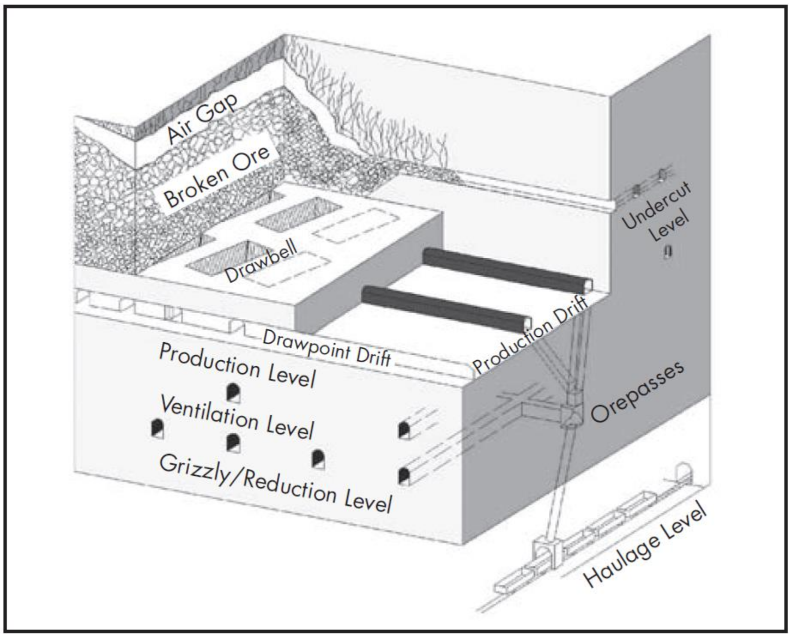


Figure 1. Example of block caving system (Brannon, Carlson and Casten, 2011)

After thoroughly revising cave mines, Laubscher (1994) developed a set of 25 parameters that must be considered before any cave mining operations commence, which is being used by practitioners in the field. Massive, relatively flat-dipping or porphyry-type orebodies which lend themselves to a long-term, massive caving, are the most common targets for the caving method. Ground conditions must allow for the building of mine openings and the proximity of required infrastructure in order to exploit the ore body. One of the two most common layouts for extraction levels is shown in Figure 2.

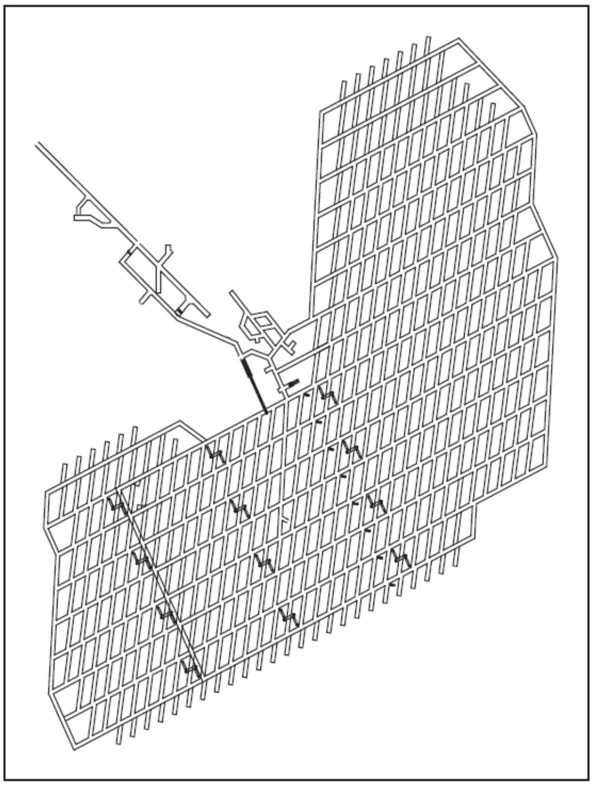


Figure 2. The Henderson mine's extraction level plan (Rech, Keskimaki and Stewart, 2000)

2.2. Mine automation and robotics

The increase in global demand for mineral resources and the decline of high-grade and shallow orebodies, pushes mining engineers to more optimized exploitation of remaining ore deposits (Osanloo, 2012). Due to the lack of new discoveries, the mining industry is forced to extract lower-grade orebodies at depths. In order to meet potential mineral demand, Moss, Klein and Nadolski (2018) claim that block caving is the only mining technique that can be adapted to massive low-grade orebodies at depths. Due to expanded processing capacities caving activities are becoming a feasible production alternative for massive open pit mines which are move toward their final economically extractable limits (Hustrulid and Kvapil, 2008). Mines in the future are expected to produce up to 160,000 t/d, demonstrating the transformation of caving mines toward "rock factories" able to such high production, next potential development is for mining depths to be increased when new "super caves" are formed below open pit mines. This development is expected to continue as technology increases the ability to handle problems in deep mines such as in-situ stresses, temperature, etc. (Brannon, Carlson and Casten, 2011)

In recent years, underground mining has been moving towards the adoption of equipment automation, due to greater health concerns of personnel, limited space, and high risks (Albanese and McGagh, 2011). Albanese and McGagh (2011) claim that the increase of production to meet the world's expected continued rise in commodity requirements is one of the industry's most urgent challenges, and automation of mining processes is a technical leap forward that will help to solve it, automation also tackles the immediate need to keep a suitably trained workforce on hand at remote mine sites. To avoid worker and machine interaction problems, automated machinery works in isolated locations, but when staff is present for rock breakage at hang-ups, drawpoint sampling, or other tasks, all automatic machinery is turned off.

2.2.1. Advantages of block caving

When a mine has achieved its peak production rate, the mine's operational costs are usually very small, with only a minimum supplementary infrastructure needed to maintain the big production rate (Brannon, Carlson and Casten, 2011). Generally, block caving is the cheapest of all underground mining methods, which is the best advantage of this mining method over other underground mining methods, and in case of an overall operational cost, block caving could compete with open pit mining. Also, mines operating with block caving system require an easier ventilation system compared to other underground mining methods.

After analyzing the activities of the most efficient mining companies all around the world that use caving methods, Kuzmin and Uzbekova (2006) concluded that block caving mining system is the cheapest and most efficient underground mining method today, but the use of block caving, like other systems with caving, is excluded when the surface above the deposit cannot be subsided. However, Laubscher (2011) stated that in environmentally vulnerable regions, block caving with a much smaller surface crater, caused by subsidence, benefits over huge open pits, and even during caving operations, the crater of a caving mine can be filled with a waste rock if needed. Eventually, the rehabilitation costs after cave mining closure would be significantly lower than for a huge open pit.

2.2.2. Disadvantages of block caving

The block caving mining system takes a long time for pre-production development, usually 5–10 years, depending on the amount of time required to getting initial access, because all of the construction stages and infrastructure must be in place before caving can begin, considering this, Brannon, Carlson and Casten, (2011) reasonably conclude that the upfront capital, required before a return on investment can be realized, is significant.

Cave mining is considerably more complicated than a pit or even other underground mining techniques, according to Moss, Klein and Nadolski (2018), with a significant difference in the level of risk related to the restricted grade selectivity relative to the draw process, the often inaccurate orebody information, initial capital needs and the long development time.

Production rock blockages caused by oversize and hang-ups, according to Baiden (2016), result in production delays, dilution and recovery problems, and possible safety problems in their clearance. Moreover, the demolition of these obstructions, regardless of their nature, carries a risk to all those involved.

For block heights above 500 meters, predicting production grade for each drawpoint is dependent on how broken rock is moving in the direction of the drawpoint in relation to surrounding rocks as well as on the ore reserve's initial grade distribution (Moss, Klein and Nadolski, 2018). Since the ability to predict how the ore breaks and moves to the drawpoints is minimal, this poses a serious danger.

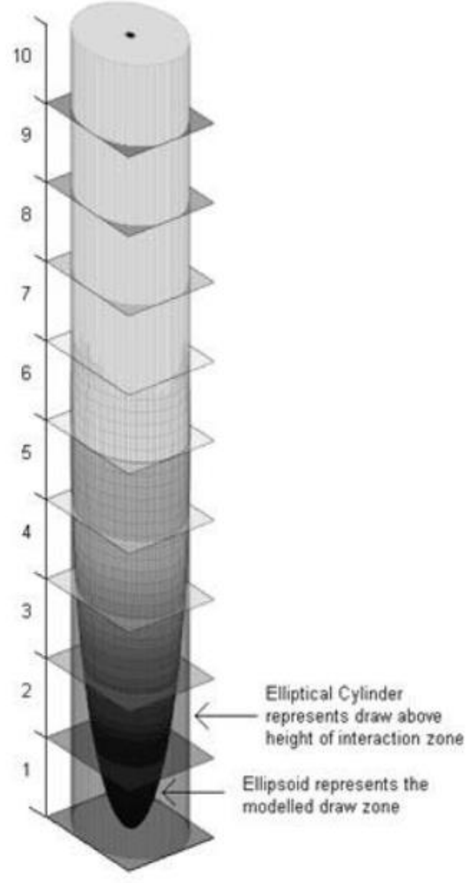


Figure 3. Example of draw column caving process. Numbers from 1 to 10 are represent each drawing zone with height of 20 m (Stewart, Allman and Hall, 2010).

2.3. Dilution control in block caving operations

The mining industry, especially in caving operations mainly used for the mining of medium to lower grade mineral reserves, is concerned about ore recovery. In comparison with other underground mining systems dilution in caving operations is a more complicated process, which leads to a higher percentage of waste and a higher cost of refining because the grade of the product sent to a plant is decreased as dilution increases. Dilution is the result of adding waste rock to ore that is going to a processing plant, and it is attributed largely to the mining of waste contained in the orebody, waste mining at the boundary between the ore and waste, and imprecision in waste classification (Dagasan, 2018).

Dilution control is a challenging job that requires a big amount of time and effort for solving, this view is supported by Diering *et al* (2018) who investigated dilution cases in the Palabora mine operated by the block caving method. According to Mubita (2005), by looking into excellent mining examples of the past and via effective grade control, draw point monitoring, and appropriate mine design, the aim of minimizing dilution is to increase revenue. These, on the other hand, necessitate collaboration among production engineers, surveyors, mine planners, geotechnical engineers, and geologists on a multi-disciplinary basis.

In mining operations, grade control systems are used to separate ore from waste. Optimized mine layout and draw management techniques are important for both decreasing dilution and increasing mineral recovery (Bull and Page, 2000). The majority of the field personnel believe that keeping an equal speed of draw at each draw point is optimal and that measuring the weight of a rock recovered from each draw point and adjusting schedules for the draw is critical to prevent dilution (Heslop, 2010). Those tasks are usually accomplished by the use of special programs. A successful quality management system prevents dilution and correctly determines the weight and content of the material going to be processed (Dagasan, 2018).

2.4. Grade control in underground mines

Monitoring of drawpoints aims at preparing info on the quality of the material that will be recovered from drawpoints. The monitoring system might be able to provide either continuous or periodical ore grade measurements and it is specific to the ore type and mine requirements (Quinteiro, Larsson and Hustrulid, 2001). Visual, density based, and sampling and assay based are the three categories of estimation that can be classified based on the methodology used for monitoring (Quinteiro, Larsson and Hustrulid, 2001). During the scope and exploration stage of mine development, primary grade analysis is performed. Information obtained from primary grade analysis is used at the mine planning stage (Laubscher, 1994). The term “grade control” is referred to analyzing the ore grade at drawpoints, and it is used for monitoring drawpoints.

According to Booth *et al* (2004), the visual estimation approach works by visually distinguishing between ore and waste, in cases where the color, form, or texture of the sample could be used to distinguish ore from waste. The ore and waste distinguishing in Perseverance mine are based on a comparison of angularity and color of the rock, because darker and more angular ultramafic ore is readily isolated from rounded ultramafic footwall and light colored and stronger hangingwall gneiss. Those estimations were done with an observation error of 1 in 42 (Booth *et al,* 2004).

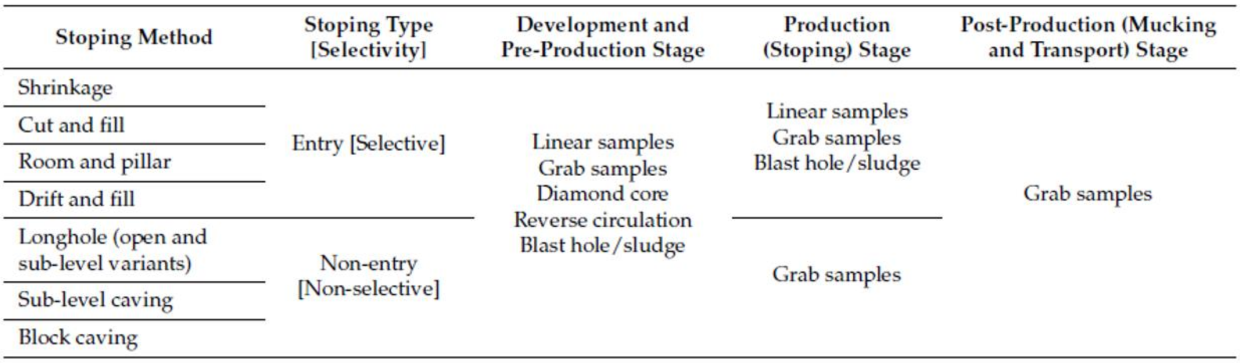
In the mines where the density of ore and waste differs considerably, the density-based approach is applied for grade control. According to Quinteiro, Quinteiro and Hedstrom (2001), a density-based approach has been used by LKAB mines to monitor draw points depending on the material's mass, which is filled into the buckets of LHD. The hydraulic pressure in the LHD bucket's hydraulic cylinders is detected by a load sensor, which transforms the hydraulic pressure value into the mass value. Subsequently, the ore-waste ratio in the LHD bucket is measured using the bucket weight reading. For various bucket sizes, the mass of 100 percent waste and 100 percent ore inside of a totally full scoop is calculated, then the load sensor records bucket weights. Using all this information a special program computes the percentage of waste and ore inside the bucket (Nordqvist and Wimmer, 2014).

While sample preparation and assaying technology have vastly improved, sampling methods for grade control in underground mines have remained unchanged (Storrar, 1981; Dominy *et al*, 2009). Manually taken in-situ chip and channel samples, as well as grab samples, are the most popular methods. Channel or chip samples, aside from the sum of work that must be done, are simple to collect, and they are comparatively inexpensive to obtain. The variability of each assay is smoothed out by the possible big quantity of samples that take part in estimation, which results in a high skewness and a significant number of low-grade assays. Usually, it means that the samples are not representative and complicates the evaluation process. Grab sampling is aimed at evaluating and comparing the extracted ore's grade at the drawpoint with the expected grade, and forecasting the grade of mill feed (Dominy, 2010).

2.4.1. *Sampling in block caving: grab sampling*

Grade control, dilution behaviour, and approximate drift results are all addressed by a drawpoint monitoring system. Most mines currently rely on mill grade data to optimize draw control because of lacking an effective monitoring method of drawpoint (Shekhar, Gustafson and Schunnesson, 2016). To increase ore recovery and control dilution, so far as the flow of fragmented rock at drawpoints is not uniform, continuous drawpoint monitoring is necessary. Dominy (2016) discusses a series of case studies in the underground mines in which annual financial waste is attributed to inappropriate sampling before preventive changes are implemented, ranging from $2 million to $12 million US dollars. Wrong and incorrectly applied sampling techniques, wrong sampling, and assaying processes, and low to no quality assurance/quality control at all are major problems. The goal of sustainable mining in caving methods cannot be achieved without first adjusting the mine's current draw management technique (Shekhar, Gustafson and Schunnesson, 2016).

Table 1. Types of sampling for various underground mining methods upon mining production stages. (Dominy et al, 2018).



Stoping Method	Stoping Type [Selectivity]	Development and Pre-Production Stage	Production (Stoping) Stage	Post-Production (Mucking and Transport) Stage
Shrinkage	Entry [Selective]	Linear samples Grab samples Diamond core Reverse circulation Blast hole/sludge	Linear samples Grab samples Blast hole/sludge	Grab samples
Cut and fill				
Room and pillar				
Drift and fill				
Longhole (open and sub-level variants)	Non-entry [Non-selective]		Grab samples	
Sub-level caving				
Block caving				

Usually, grab sampling at draw points is used in block caving mines with a similar purpose like different sampling methods used in many underground mines, that is monitor grade over time period (Ross, 2012). To avoid over dilution, when a drawpoint gets closer to the ending of its operation, the amount of sampling is known to grow, and if it is necessary the drawpoint will be closed (Brannon, Carlson and Casten, 2011). Geologists sampling manually all drawpoints by the grab sampling method. Grab samples can be used when the plant results are not matched the expected grade, with the purpose of grade control at active drawpoints, but samples are not substantial when reconciliation is positive (Dominy *et al*, 2018).

The issue of representativity has long been a source of dispute among persons actively engaged in the discipline. The grab sampling method at drawpoints concentrates on the rocks that are broken into small pieces and can be collected manually and placed in the sample bag (Dominy *et al*, 2018). When samples are not taken among the bigger fractured rocks, that is important in cases when ore has a proven tendency to increase grade in the smaller fractions, there is a bias. In order to spread sample distribution, geologists can draw a grid to the surface of the rocks at draw points, showing where samples will be collected (Ross, 2012).

2.4.1.1. Disadvantages of grab sampling

Grab sampling from draw points theoretically is problematical, according to Dominy (2018): since geologists appear to sample the fines too much or take out bits that seem to be high grade; surface sampling of mound would not allow for the testing of content inside the mound; during haulage, high and low grade ore can possibly be separated at the drawpoint; there is typically an association with the bigger fractions being concentrated or degraded in the substantial portion of the meaning; even with massive samples, the error produced when calculating the grade of the ore reserve is apparently to be significant.

Figure 4. Example of manual sampling at draw point (Dominy et al, 2018).

Fourie and Minnitt (2016) found the "in-stope sample discard process" in the gold mines of Witwatersrand, where geologists had a tendency to selecting what they thought was a better-looking sample. A positive "waste discard bias" and therefore better analysis results for draw points are possible from such waste discard and selective collection of mineralized rocks. The waiting times of more than 24 hours are required for mine sampling conducted using traditional techniques by geologists, creating delays in the productional process on mining or exploration sites and therefore rising costs of operation and production, and there is a search for emerging technology that addresses the mining industry's costs mitigation needs (Rifai *et al*, 2017).

Although grab sampling is troublesome in mines with block caving, it does provide the mine managers with the knowledge that helps them to make some solutions for further operation if the grade seems to be deteriorating. Safety and health concerns, in addition to the laboratory's ability to analyze samples in a timely manner, constrain the amount of sample obtained. To meet health and safety requirements, forthcoming very massive caving activities would necessitate a new method of sampling at the production stages of mine life (Dominy, 2018). To meet the requirements of large caving mines, a quicker and more effective sampling would be needed due to the increased amount of draw points (possibly up to 1000) and increase in the usage of automated vehicles (Ross, 2012).

2.5. Spectroscopy: laser induced breakdown spectroscopy

Rapid measurement of the concentration of valuable metal in the field during the various stages of mine production is one of the revolutionary innovations, whose implementation will be a significant leap forward (Rifai et al, 2017). The rock sample mineralogy (e.g., sphalerite, chalcopyrite, pyrite, etc.) can be determined using current technologies for direct inspection of solid samples, such as infrared spectroscopy, but the elemental composition cannot be measured (De Benedetto *et al*, 2002). Although X-ray fluorescence (XRF) has been applied to determine the composition of specific samples (e.g., iron, copper, etc.), it is still insufficient for quantifying gold concentration since its detection limits and sensitivity are poor (Hall, Buchar and Bonham-Carter, 2011). Portable XRF is not sensitive sufficiently for the detection of gold in the range of ppm, demanded by the industry, and is affected by interaction with iron and zinc, resulting in false gold values.

LIBS, or laser-induced breakdown spectroscopy, is considered to be a perspective technology for conducting rapid and on-site elemental analyses (Grant, Paul and O’Neill, 1991). LIBS is an emission spectroscopy-based optical diagnostic process, which atomizes the surface and generates plasma by directing a moderately strong laser stream upon a specimen. Subsequently, the chemical compound of the sample is determined by spectrally analyzing the light produced by the plasma, which makes it possible to precisely define the elemental concentration of all specimens (Cremers and Radziemski, 2006).

Analyzing ore samples by LIBS has been elaborated for a long time and the majority of these studies were focused on identifying mineral types (Rifai *et al*, 2017). Grant, Paul and O’Neill (1991) conducted research on the application of the LIBS technology for iron ore analysis, including multi-elemental semi-quantitative and qualitative analysis of iron in samples. The first move toward the application of LIBS to rock samples with the purpose of finding the gold concentration was done by Rifai *et al* (2017) and Harhira *et al* (2017). They demonstrate that LIBS technology can find out gold in the ppm diapason and established the evidence of analyses of gold in powdered and synthetic samples.

Initial efforts to create a moveable capability for LIBS outside of the laboratory environment focused on compacting the elements of a laboratory device into a small-sized box or portable moveable lab which can be transferred to the sampling location and powered by an external energy supply (Yamamoto *et al*, 1996). The first rucksack LIBS concept had a fiber optic cable that retrieved the laser and transmitted the light to a handheld stick (DeLucia et al, 2005). This field-portable LIBS device had the spectrometer, data processing hardware, and control apparatus all built in the rucksack configuration. Chargeable, very compact, small size facilitated handheld LIBS apparatuses looking like a cordless drill in a shape, shown in Figure 5, that could be used on the sampling site for several hours by anyone with only a piece of basic knowledge, have been produced and released a short time ago by many commercial manufacturers (Senesi, Harmon and Hark, 2020).

Figure 5. Examples of handheld LIBS apparatuses (Senesi, Harmon, and Hark, 2020).

2.6. The chemcam instrument: key features

The ChemCam instrument is a part of the Curiosity Rover, which was deployed on Mars in 2011. The ChemCam is the abbreviation for Chemistry and Camera. This instrument uses a combination of the spectrograph, laser, and camera to determine soil and rock composition (Wiens, n.d.). ChemCam tool can:

- provide visual aid during rock core drilling;
- determine the structure and depth of rock's weathering;
- assess the composition of pebbles and soils;
- chemical elements' concentration can be measured;
- identify the type of rock being analyzed.

According to Wiens (n.d.), all these operations can be done from a distance of 7 m.

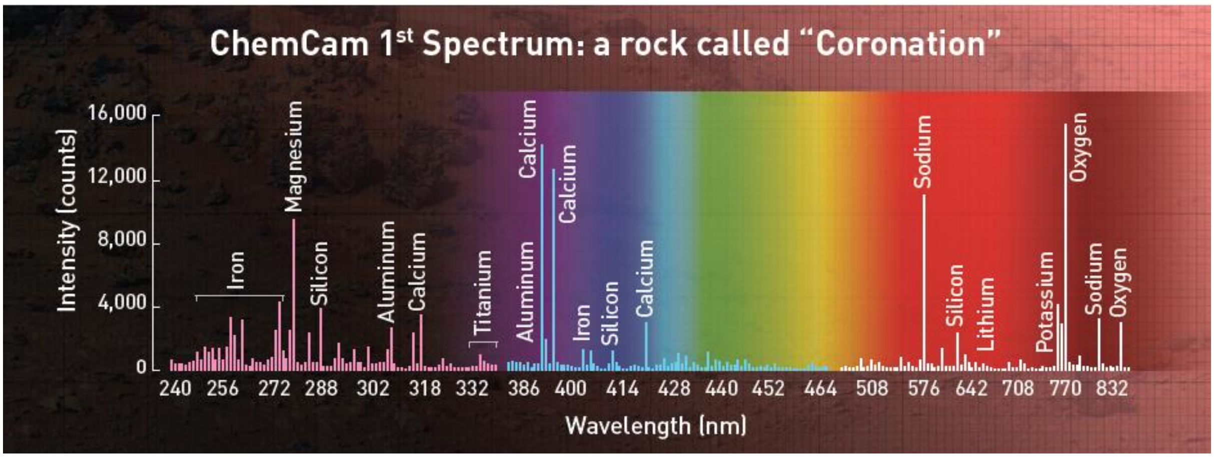


Figure 6. The first LIBS analysis performed by ChemCam from a distance of 2.6 m (Melikechi et al, 2013).

ChemCam's opportunity to apply LIBS to find out almost all chemical elements is a crucial advantage. According to Melikechi et al (2013), the analysis does not necessitate the preparation of samples, which is the greatest advantage of the LIBS tool over others. Laser pulse removes all dust from the surface of the sample by hitting the rock 30-50 times overall. Only tens of microseconds are required for full LIBS analysis (Melikechi *et al*, 2013).

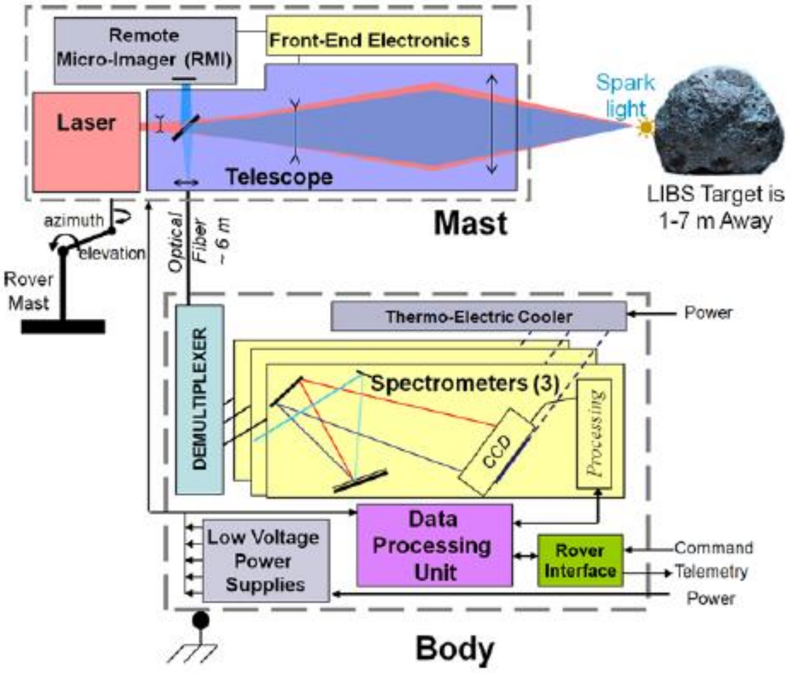


Figure 7. ChemCam's overview (Wiens et al, 2012)

2.7. Application of libs instrument to sample analysis

In the mining industry, elemental analysis and material recognition are crucial because the entire productivity of mines depends on this information. Information about potential mineral-bearing zones can be provided by geological exploration. Mineral detection costs are substantial, and identification loss is not uncommon (Bellie *et al*, 2021). As a result, a more thorough and precise investigation is needed to determine the available elements. Lots of instruments and methods, such as Raman Spectroscopy, XRF, XRD, and many more have been utilized.

Individual laboratories started developing LIBS-based equipment in the early 1980s for special purposes. Production of commercial LIBS equipment started in the 1990s (Radziemski and Cremers, 2013). Currently, developed countries use LIBS as the modern and robust approach for quantitative and qualitative contents study (Bellie et al, 2021). LIBS provides a number of benefits for on-site and instant applications, including the ability to detect multiple chemical elements' spectral lines together in a brief period of time and without the need for the preparation of samples. A LIBS spectrum can be recorded in only a couple of milliseconds. LIBS device modules can now be miniaturized, and the process can now be used in the field, thanks to advances in laser and photonics technology (Harhira *et al*, 2017).

The discovery of elements and minerals takes a lot of time, capital, technological and labour resources in mining exploration. If nothing concrete and valuable is discovered, attempts do not produce positive results. Furthermore, the mineral discovering equipment is cumbersome, and at usually challenging mining topography, a simpler device that is compact and lightweight, reliable, environmentally safe, and fast with the simplicity of design and file transfer to computers working remotely is a huge boom when the mining industry will access it (Bellie *et al*, 2021). However, the LIBS device poses hazards to workers, as discussed by Cremers and Radziemski (2013), such as skin or eye damage, and aerosols produced during the heating of rocks by laser, which should be handled with care.

2.8. Drawpoint automation

Mines operating by block caving mining system are very suitable for automation. Of specific interest for automation are the drawpoints areas. A robot system built by Penguin Automated Systems that can operate safely in drawpoints blocked by rock is an excellent example of block caving mine automation. Baiden (2016) in his paper described an application of this robot system at Codelco's Andina Mine in Chile. This robotic system consists of two robots, one of them has geospatial scanners and cameras onboard, allowing operators to remotely identify the causes of rock blockages and show them to the blast operators through cameras (Figure 8).

Figure 8. Robot system developed for geospatial mapping (After Baiden, 2016).

The second robot has a robotic arm that can drill and load explosives into the "keystones", that originally caused the rock blockage and then blast them (Figure 9).

Figure 9. The robot system built by Penguin Automated Systems with extended arm for hang-up removals (After Baiden, 2016).

3. RISK MANAGEMENT

3.1. Overview

Risk identification and risk management analysis were performed so that the thesis project could achieve its main and specific objectives. Tables 2 and Table 3 describe risk probability and risk severity respectively, which are necessary for risk management analysis.

Table 2. Probability of risk.

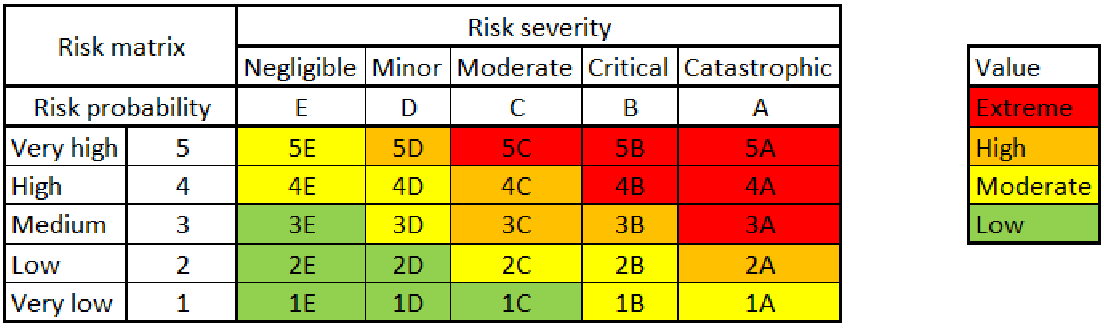
Risk probability	Description
Very high	Expected in most cases
High	A risk incident is more likely to occur during a project
Medium	May occur at some point
Low	It is unlikely that this would happen under normal circumstances
Very low	Can only occur in rare conditions

Table 3. Severity of risk.

Risk severity	Description
Catastrophic	It is impossible to complete the tasks, thus the project is closed.
Critical	Project delays, changing the objectives of the project may be necessary.
Moderate	It is necessary to consider the risks since the project schedule may change.
Minor	The project schedule was not delayed by the minor impact
Negligible	Impact is insignificant

A qualitative risk examination was conducted on the current project using the two Tables 2 and 3 to produce the risk matrix shown in Table 4.

Table 4. Matrix of risk assessment



Risk matrix		Risk severity				
		Negligible	Minor	Moderate	Critical	Catastrophic
Risk probability		E	D	C	B	A
Very high	5	5E	5D	5C	5B	5A
High	4	4E	4D	4C	4B	4A
Medium	3	3E	3D	3C	3B	3A
Low	2	2E	2D	2C	2B	2A
Very low	1	1E	1D	1C	1B	1A

Value
Extreme
High
Moderate
Low

3.2. Risk assessment and risk control

Potential dangers include negative effects on project progress, well-being, or the mental health of the student. Probability and consequences were intersected to calculate the risk level. The probable dangers were summarized, and several solutions were proposed for risk reduction and elimination, as shown in Table 5.

Table 5. Risk assessment and risk control

Risks	Description	Level of risk	Risk control
Stress	Working a lot or having personal problems	2B Moderate	Proper time management, making and sticking to a schedule, and constant communication with loved ones
Eye disease	As a result of constant laptop use, vision becomes impaired.	4C High	Eye exercises, regular breaks while working with the computer, and a healthy lifestyle
Cold-related illness	Cold weather that is characteristic of the Nur-Sultan city area creates the risk of illness.	4D Moderate	Wear warm clothes, exercise, eat healthy food.
Incorrect usage or miss of referencing	Unintended plagiarism	2B Moderate	Refer to the instructions provided in the MEA report
Data lost	Files are not saved, or computer suddenly shuts down	3B High	Turn on autosave in Word and periodically safe files in Blender software

3.3. Contingency plan

In case of unexpected project disruptions, it is possible to overcome them quickly if a contingency plan is in place. Identifying and analyzing risks can affect the project objectives. This is covered in the previous sections. Contingency plans are designed to handle moderate and high risks.

Stresses, sore eyes, and colds are all health problems. They can be prevented with exercise, proper nutrition, and timely rest. A daily schedule was developed that included time for rest, diet, going to the gym, and working on a project.

To avoid misuse of references that lead to unintentional plagiarism, the MEA report writing guidelines are taken as the basis for writing the thesis. The report covers all types of references and the proper use of references to the work of other authors.

To avoid losing data in the Word program, the automatic change saving function will be enabled. The Blender program has the quality of dropping out of the application without saving the data due to complex calculation processes. For this reason, it is necessary to manually save the model files after making changes and before starting the simulation.

4. METHODOLOGY

4.1. Required resources for the thesis

The equipment listed in Table 6 is crucial for completing established thesis tasks. Access to computer classes should be determined according to safety conditions during a pandemic. The Nazarbayev University Library or the supervisor should be contacted if access is restricted to academic websites.

Table 6. Required resources for thesis

Internet access	Access to internet is a requirement to read and download scientific papers
Access to scientific websites	Journals, papers, and scientific works can be restricted on a variety of scientific web sites. The university library or supervisor should be contacted in order to gain access to scientific websites
Access to library's study room	It is required to work in a focused environment in order to finish the thesis report.
Google Drive and flash drive	With Google Drive and flash drive, data can be stored in the cloud and on a secure device to prevent data loss.
Access to the computer classes	Having access to computer classes is essential since the pandemic situation and safety conditions need to be met during the visit.

4.2. Research process

This thesis will focus on reviewing the current state of drawpoint monitoring in block caving mines and search for improvement of the process by application of new technologies. An overview of the qualitative research will be presented in this chapter. The proposed qualitative research plan is shown in Figure 10.

This thesis is a conceptual development of a robot capable of replacing the geologist in deepening mines with a block caving mining system. A detailed explanation of the planned actions to achieve the project goals will be shown in the following sections of this chapter.

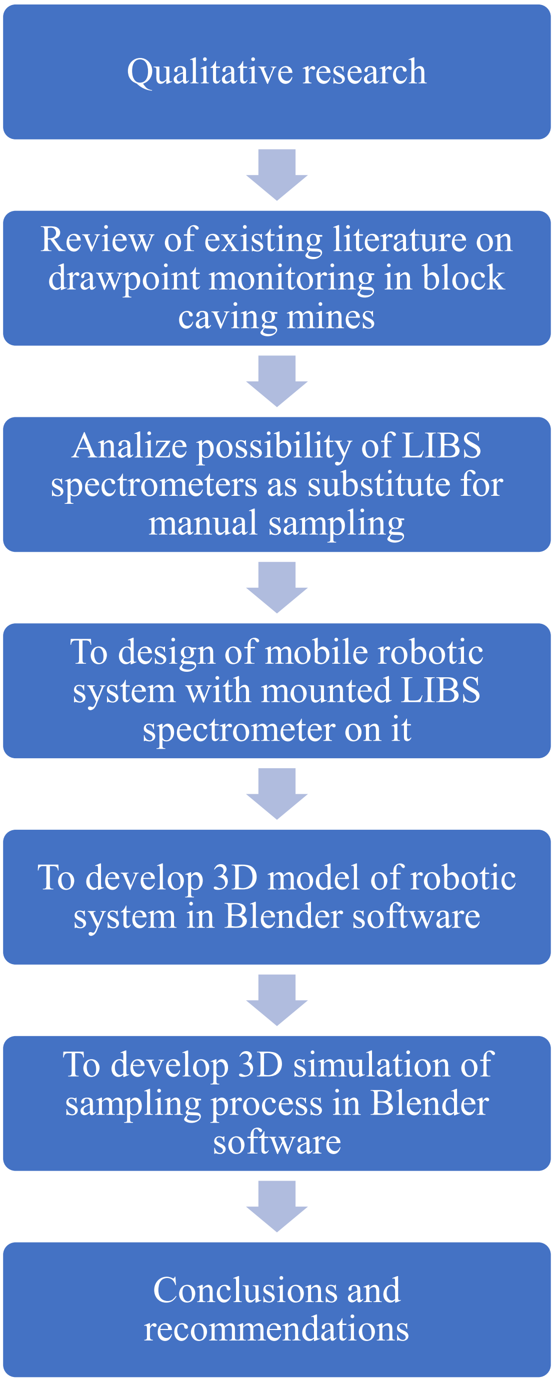


Figure 10. Methodology diagram of the proposed R&D.

4.3. Design of the robotic system

A robotic sampling system will be developed on the basis of the Curiosity Rover and be composed of two parts: mast and body units. Since the robot must be mobile, it will have wheels and an electric engine so there are no exhaust gases. The wheels must be specially selected to suit the underground conditions.

The mast unit contains:

- a laser to produce plasma;
- Remote Micro-Imager (RMI) for taking images of plasma;
- a geospatial sensor, so the robot can determine its position in the mine;
- a fiber optic cable to transmit obtained data to the spectrometer.

The body unit contains:

- an electric engine is required to make the robot mobile;
- a powerful processor, which will serve as the brain of the robot;
- a spectrometer for analysis of composition;
- a hard drive with a large amount of memory for storing data;
- a transmitter that will transmit the information to the surface;
- a powerful cooling system that will cool the computer and facilitate normal operation of the system at high temperatures in deep mines;
- a sound signal system and lights in front and back of the robot for safety precautions;
- a lithium-ion battery that should be removable so that it can easily be replaced with a fully charged battery at maintenance stations.

4.4. Building a 3D model of the robot

Blender software was used to make a 3D model of the robot with LIBS on it. Blender (Blender, 2002) is open-source software for 3D modeling and rendering program used to create computer-generated graphics and animations. Despite the fact that it is not developed as a simulation tool, it has a number of characteristics that make the construction of such an application easier.

The decision was made to choose low polygon modeling since this is a concept design. Low polygon graphics techniques mean that a mesh contains fewer shapes. Models with more polygons will appear more realistic. However, the fewer the polygons, the better the performance of the animation will be, and the computational resources will be reduced. Low polygon modeling doesn't result in a fully detailed model, but rather allows a stylistically geometric recreation of the desired model. It is typically used for concept drawing and design visualization.

Blender's most visible benefit is the great degree of visual details that could be accomplished on a real-time basis owing to complex mesh modeling and features like illuminating, texturing, and shaders. When modeling a robot's vision, the visual element is crucial because simulated pictures can be realistic enough to be analyzed using the same methods as real images (Echeverria *et al*, 2011). Blender does have the potential of employing multiple camera positions to track the simulation's progress, providing a general picture of the scene as well as views of each of the robots' cameras.

The main body, battery, and head are created from a cube mesh. The edges were edited using a "Convex Fillet" feature that makes the profile of the rover look smoother. The head is connected to the body via a cylinder-shaped mesh. There are several devices installed on the head that is done via adding cylindrical meshes and then some circular cuts and holes were made to give them a more realistic look. The small holes in the laser and camera were colored with red and light blue color, and the emission feature was turned on, which indicates that they are activated and working.

The wheels were made on side of the rover and then using a "mirror" feature copied on the other side. A suspension system is also made on both sides of the main body to connect the wheels with the body. The tires are made using a circular mesh with 16 slightly extruded faces to create a tire tread. The spokes that connect the hub and the wheel are cylinders with their middle part shifted to the side to give it a curved look.

The car headlights are cylinders with white color with "emission" functionality. The "Smooth" setting was turned on for all rover parts to polish the surface of the model and add more polygons to it.

4.5. Building a 3D model of extraction level

Creating a 3D model of the mine’s extraction level is necessary to show the robot during the sampling process. A small section of the mine with ore in drawpoints was modeled in Blender software to represent the extraction level of the block caving operations for this purpose. El Teniente mine's extraction level layout was chosen for the model as one of the most popular extraction techniques.

To create a mine model cube was shaped into the required layout using the button “E” to extrude and by rotating the face. This process is shown in Figure 11.

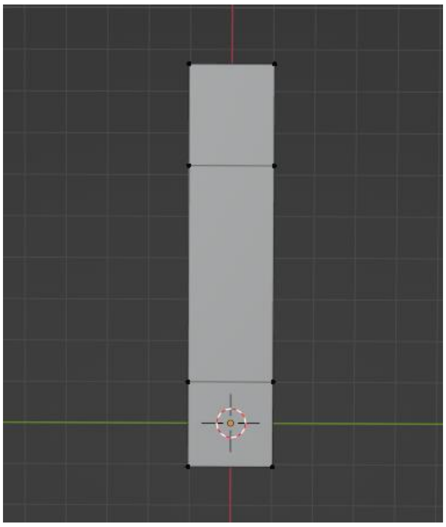


Figure 11. Shaping the cube into the needed layout.

By choosing the “Faces” button on the one of the sides of the cave we can show the entrance to the extraction level.

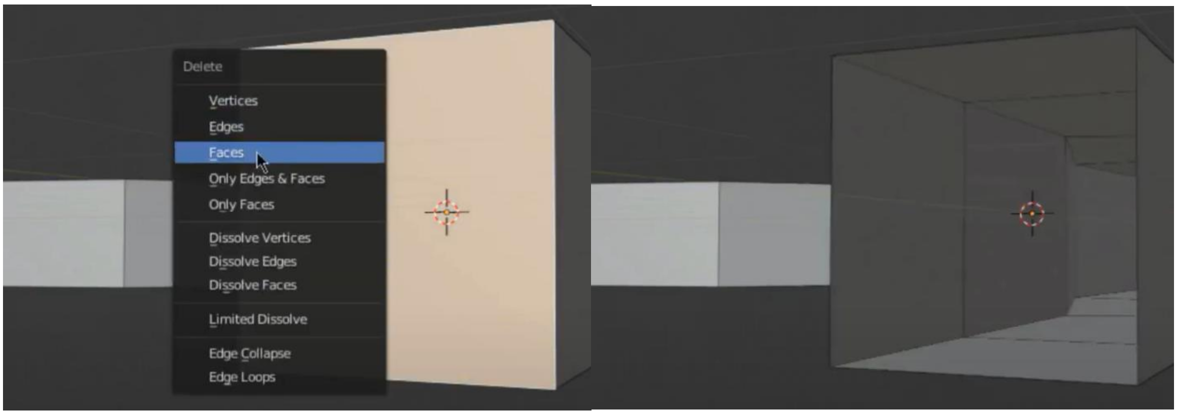


Figure 12. The modeling of extraction level.

By pressing the “R” button a cut was made in the middle of the model, for making our model look similar to a tunnel, the edges of that cut were chosen and drugged down. Now the model has a required tunnel shape with a height of 5.2 meters and a span of 4.7 meters.

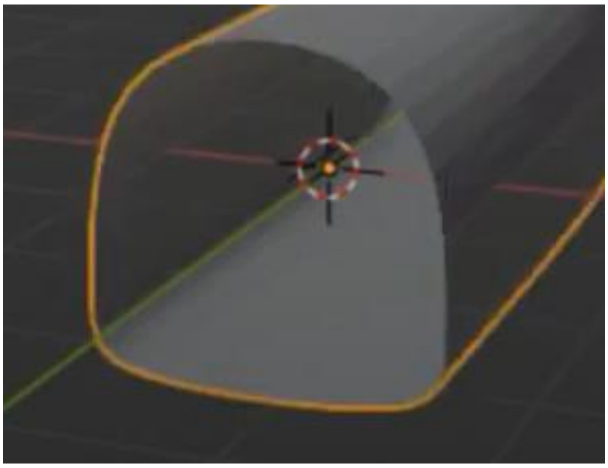


Figure 13. Giving the tunnel shape to the model.

Next in the “Texture Properties” section by pressing the button “Stucci” we made our tunnels' walls and roof look more realistic by adding fractal noise texture. Rather than being smooth, the walls and roof of the tunnel now resemble real-life mine tunnels.

Figure 14. Making the tunnel more realistic.

After preparing the model of the extraction level, the next step is a modeling of the pile of caved rock at the drawpoint. For this purpose, the “UV sphere” was chosen as the basis of the model.

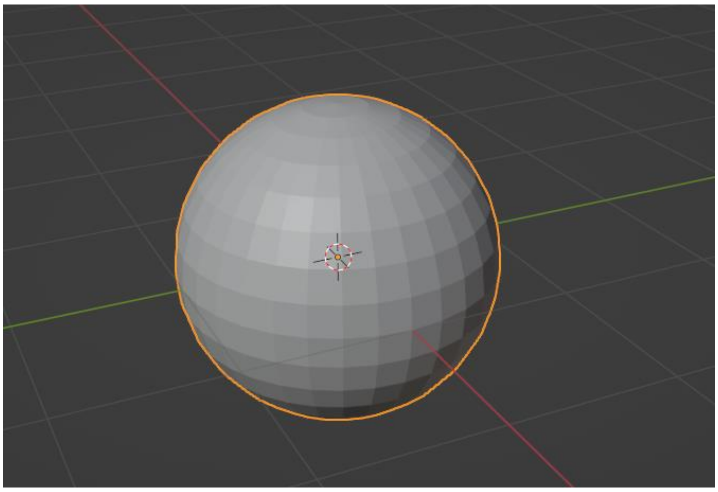
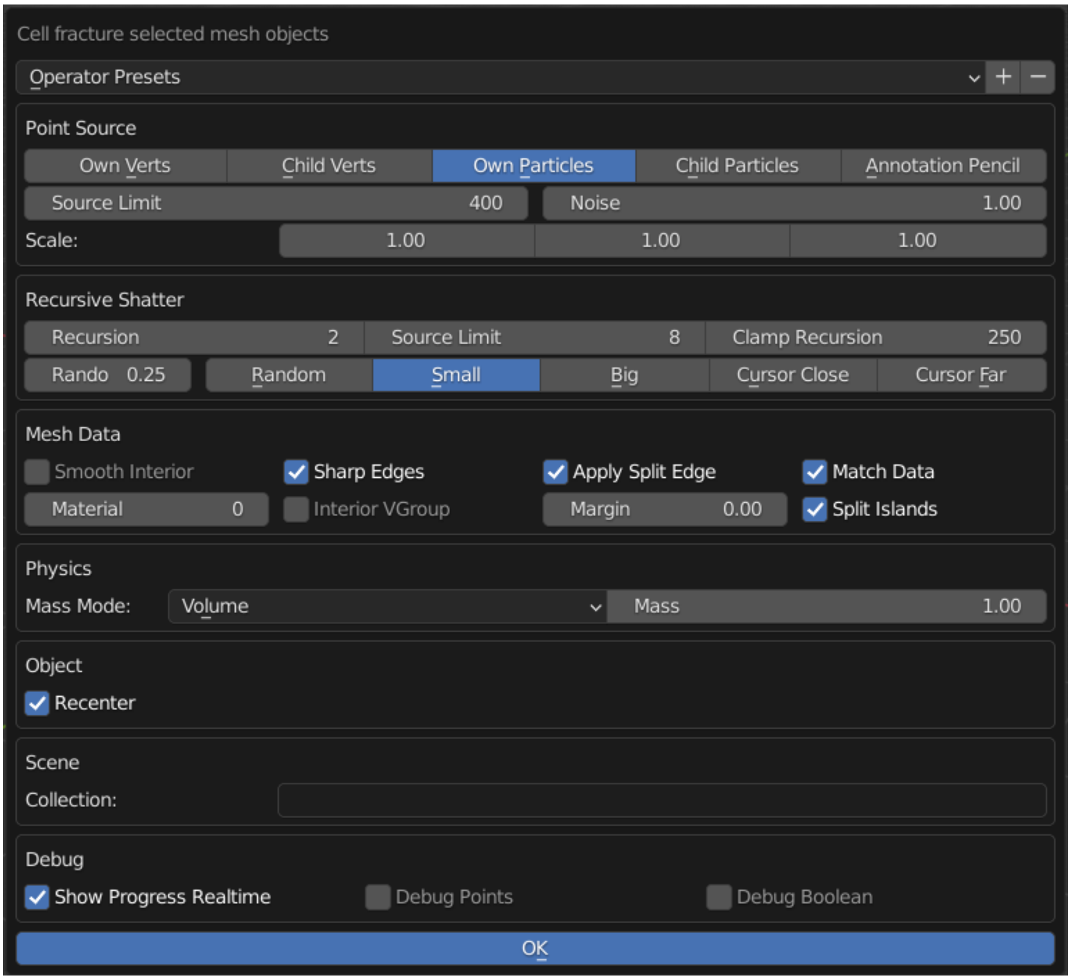


Figure 15. UV sphere.

Then we pressed the “F3” button and in the new window selected “Object - Quick Effects - Cell Fracture” mode, after which the window named “Cell fracture selected mesh object” appeared. In this window, the necessary parameters shown in Figure 16 were set.



Cell fracture selected mesh objects

Operator Presets

Point Source

Own Verts | Child Verts | [✓ Own Particles] | Child Particles | Annotation Pencil

Source Limit 400 | Noise 1.00

Scale: 1.00 | 1.00 | 1.00

Recursive Shatter

Recursion 2 | Source Limit 8 | Clamp Recursion 250

Rando 0.25 | Random | [✓ Small] | Big | Cursor Close | Cursor Far

Mesh Data

☐ Smooth Interior | ☑ Sharp Edges | ☑ Apply Split Edge | ☑ Match Data

Material 0 | ☐ Interior VGroup | Margin 0.00 | ☑ Split Islands

Physics

Mass Mode: Volume | Mass 1.00

Object

☑ Recenter

Scene

Collection:

Debug

☑ Show Progress Realtime | ☐ Debug Points | ☐ Debug Boolean

OK

Figure 16. Cell fracture selected mesh object window.

After all parameters were set, the software does the necessary computations and breaks the UV sphere into small fractures shown in Figure 17.

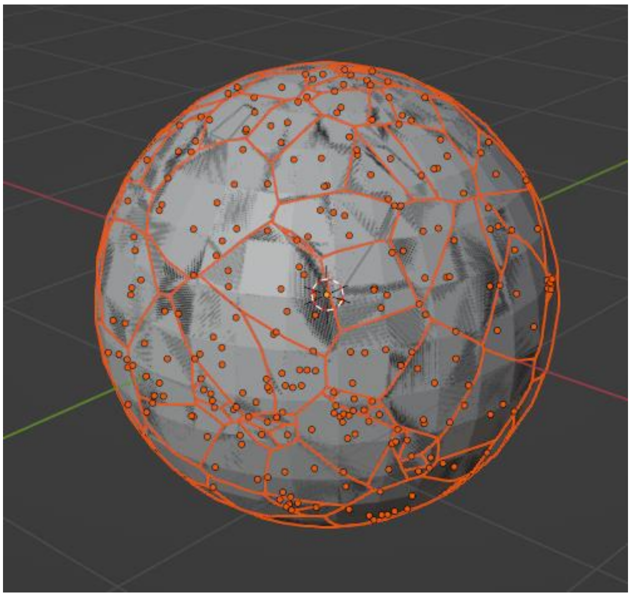


Figure 17. UV sphere broken into small fractures.

Then it is necessary to set up physical parameters, to give rock properties to the fractures of the UV sphere. Now the fractured UV sphere will fall on the plane underneath after pressing the “Space” button. Then it is needed to place simulated pile in the middle of the drawpoint.

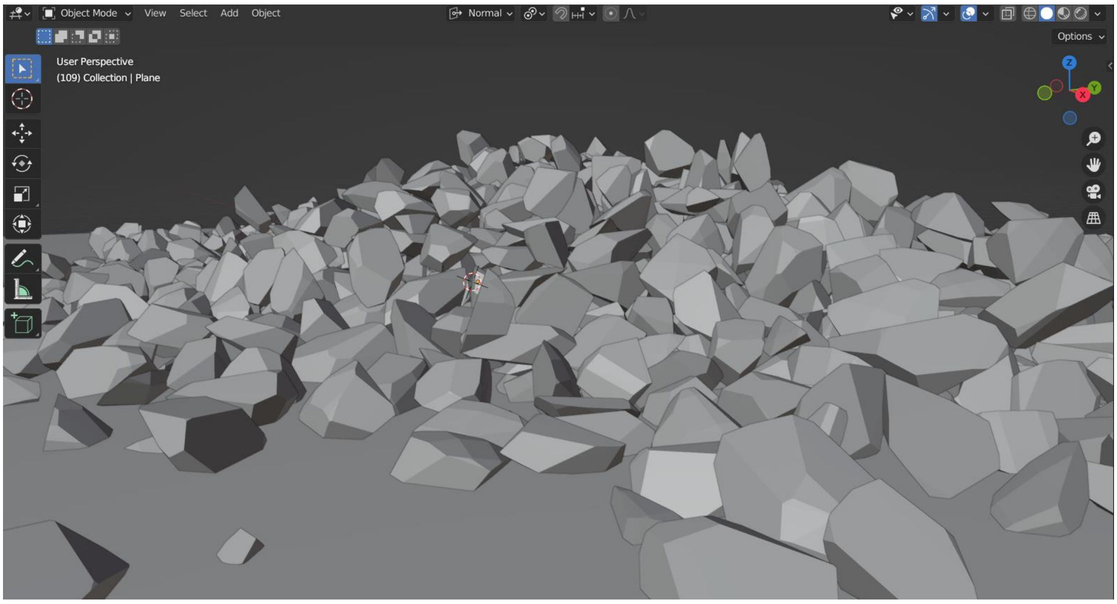


Figure 18. Simulated pile of rocks.

4.6. Developing 3D simulation of the sampling process

Simulation of a 3D model is a complex process that needs utilizing of Blender 3D software. To show the sampling process via the robotic system at the extraction level of the block caving mine first we need to build a 3D model of production drifts and drawpoints. Then inside of drawpoints, it is needed to put caved ore. The height of the wall is 5.2 meters, and the span is 4.7 meters. The robot must move inside of production drifts to drawpoints. In every drawpoint, the robot has to accompany sampling of the caved rock. This process will be shown by shooting a laser from the mast of the robot to the rocks in the pile. The laser was made using a long cylinder mesh with red color with an emission feature turned on. To modify it and make it more realistic a “Fog Glow” setting was activated in the “Composition editor” mode.

Each frame of a video is edited to create animation in Blender. Generally, the process involves setting a start frame and a finish frame. Blender enables automatic simulation of the model's and the camera's movement (which follows the rover).

The software renders the animation of the rover and the camera from the point at the initial frame to point at the last frame, and with 24 frames per second, 24 frames of the animation are transformed into a second of video. These steps were repeated for other animation clips.

5. RESULTS

The results will be given as an output of a 3D simulation of the sampling process by the robotic system.

The robot model was developed according to design specifications that were established after reviewing existing Mars rovers and the desired functionality of the rover. Several devices are mounted on the head: camera, laser, geospatial sensor, and RMI. The head part is connected to the body through a mechanism that allows up-and-down and 360-degree circular movement. A fiber optic cable and all the necessary electronics to make the devices work also will run through this mechanism.

The robot's body contains an electric engine, a computer with a powerful processor, a hard drive, a spectrometer, and a cooling system. A lithium-ion battery will be located in the rear part, which is replaceable if needed. On the top-middle part of the robot is a data transmitter that will be used to communicate with the surface and to transmit the results of the compositional analysis of rocks. A robot will also have lights on its front and back to light up the path and to indicate its location to others. Analyzing the Mars rovers, it was decided to put six wheels, three on each side for stability and maneuverability of the robot. Figure 19 shows the designed robotic system.

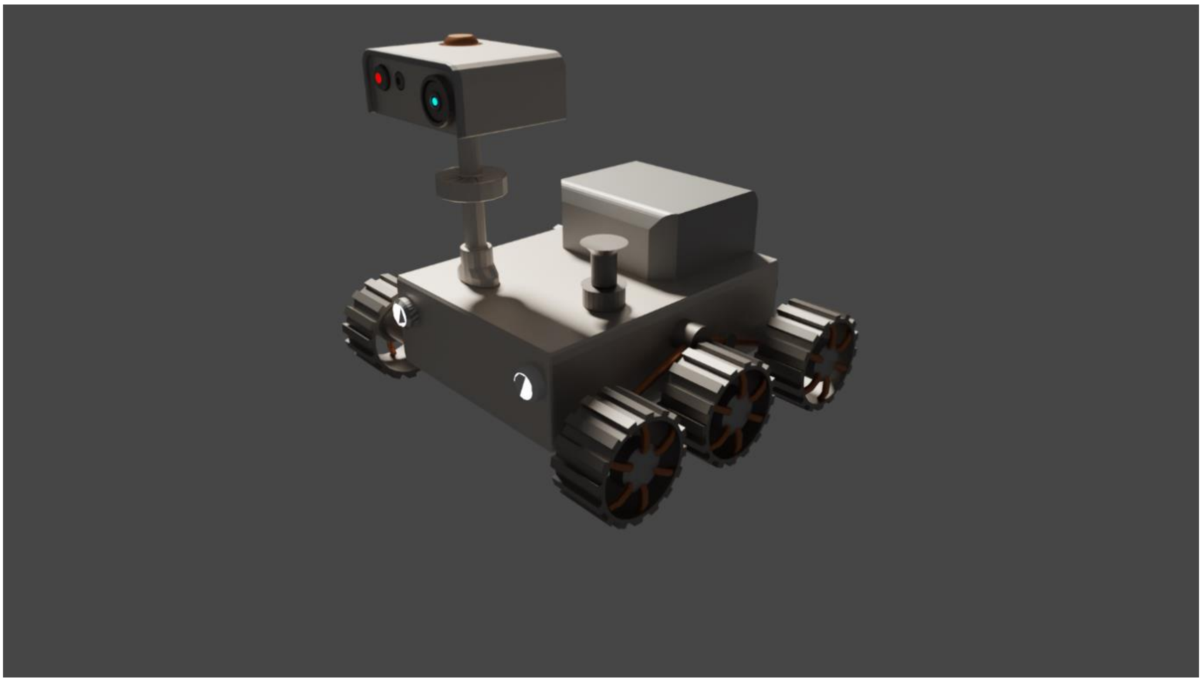
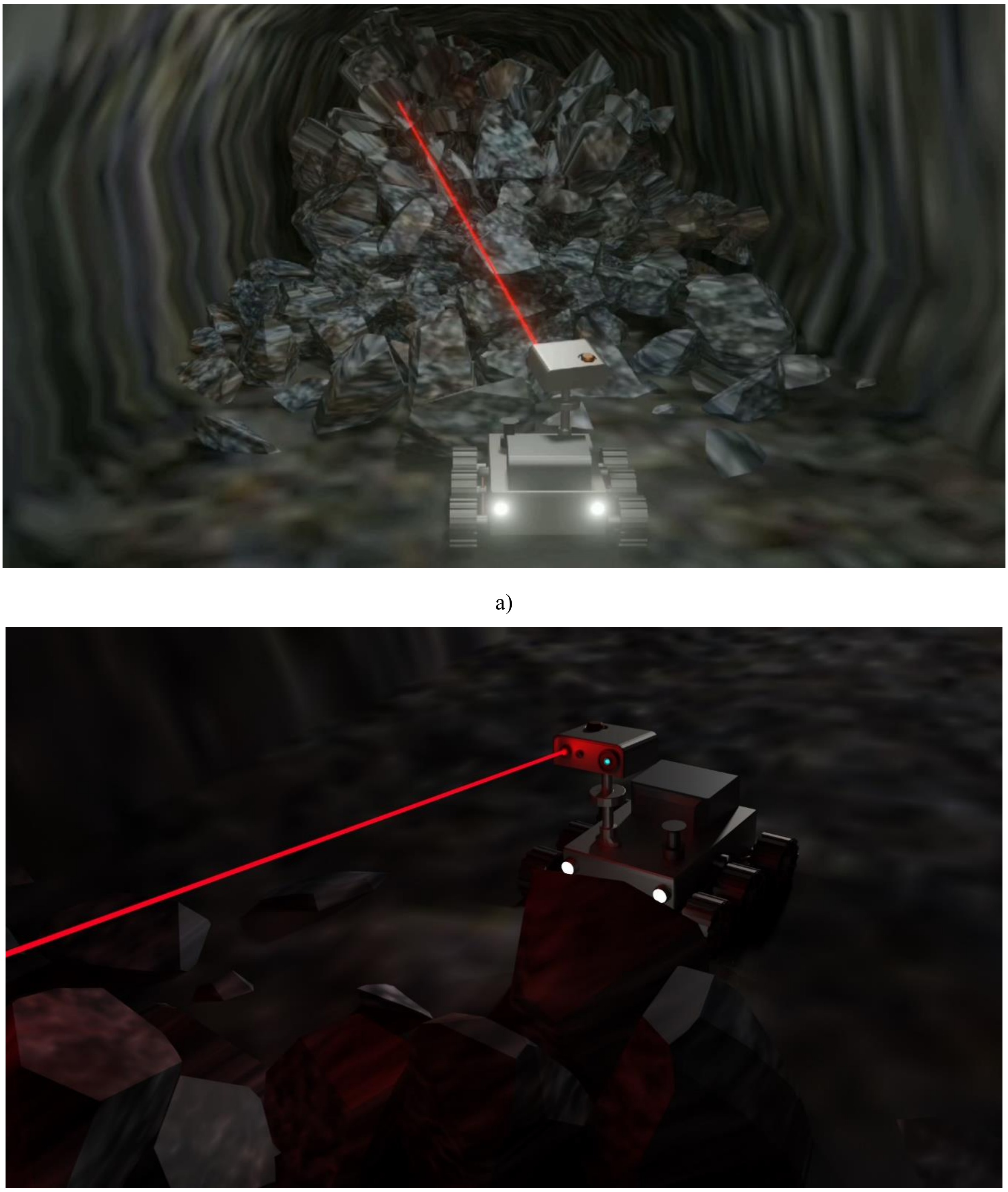


Figure 19. 3D model of the sampling robot system.

The robotic sampling system has dimensions of 1.5 m long, 1 m wide and 1 m high and weighs between 60 and 100 kg, depending on the parts installed (battery, device set can vary depending on specifications and price). In the drawpoint, which has a span of 4.7 m and a height of 5.2 m, the robot takes up little space and has plenty of maneuvering space. In Figure 20, the robotic sampling system can be seen directly in the drawpoint.

Figure 20. The robot system at drawpoint.

Once the robot comes to the drawpoint and reaches the pile of caved rock, the sampling process begins. A special program must be written for the robot’s sampling. In each drawpoint, the robot has to accomplish sampling by LIBS spectrometer imitating manual sampling by geologists. Using the same techniques as geologists the robot will shoot in special places of the caved stockpile by replacing the sampling grid on it. The robot takes samples every 1 m using a 1 m by 1 m grid. However, for each mine, the sampling grid will be set by the geological department according to the geological characteristics of specific mines. Striking several times, the laser heats the point on the rock surface up to 10 000°C in a matter of milliseconds. Produced plasma is transmitted through the RMI to a spectrometer, where the composition of the rock is determined. The sampling process is shown in Figure 21.



a)

b)

Figure 21. Sampling process by the robotic system: a) look from the back; b) look from the front.

After completing the sampling process at one drawpoint, the robot heads to the next drawpoint, and so on. The number of maximum drawpoint the robot can reach depends only on the capacity of the battery installed on the robot. Compared to a geologist for whom maximum drawpoint coverage is limited to the number of samples he or she could carry, the robot can take a more number of samples if it is provided with proper maintenance and timely battery replacement. The movement of the robot must be smooth and energy efficient. It is recommended movement from each drawpoint to the next opposite one. The computer of the robot has to always compute how much the robot can use the battery. If the charge is low, it has to go to the closest maintenance department where maintenance workers will replace the uncharged battery with a charged one. The robot traveling from the first drawpoint to the next one is shown in Figure 22.

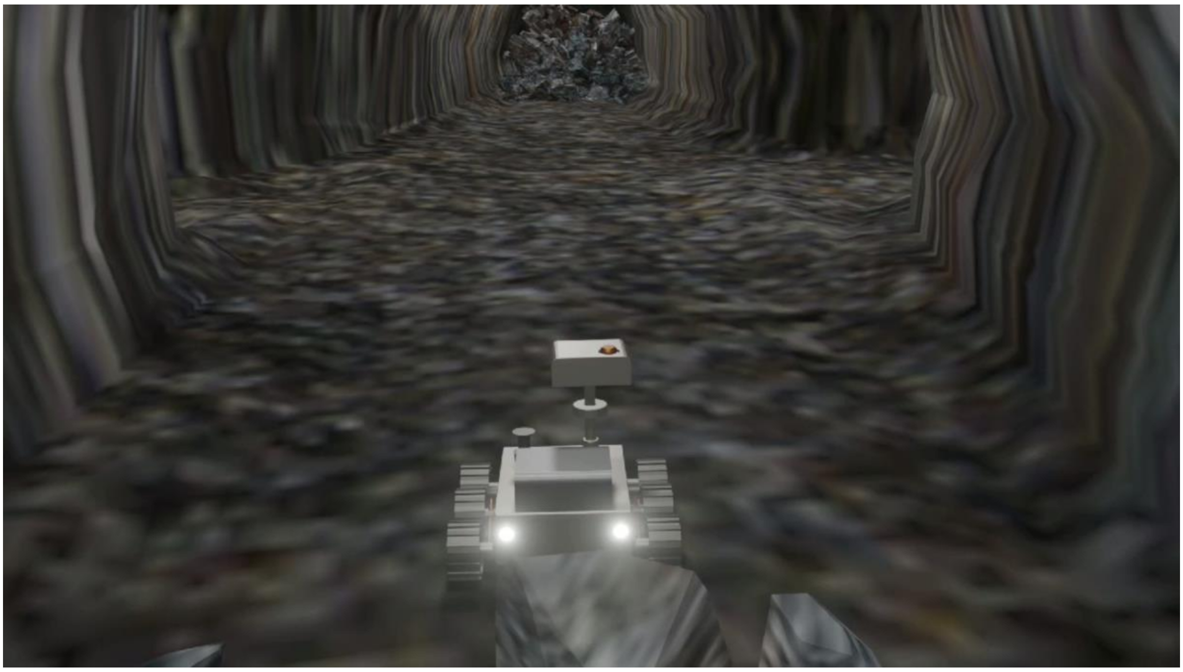


Figure 22. Robot traveling from one drawpoint to another.

As robotic sampling systems are moving machines with a powerful laser, they can pose a threat to mine personnel. A sound signal system and lights at the front and back of the robot will alert employees when the robot is approaching. This will help prevent injuries to workers. Due to the fact that each worker has a tracking device, a special program will be built into the robot's computer to prevent the robot from approaching the worker directly by stopping the robot when it notices a signal from this device.

The robotic system will have tubeless tires similar to those on the latest Mars rovers, to prevent tire blowouts. Underground mines often have rocks or puddles in drifts, so the wheel design will be useful for driving over them. To prevent dust or water from entering the system, the robot will be completely sealed, and all devices will be built into the body.

6. DISCUSSION

The results of this thesis have shown that a mobile robot with a LIBS analyzer installed onboard can replace a geologist in deepening mines with block caving. The robot can be used in hazardous conditions of drawpoints to obtain information on the composition of the caved ore in the pile. This sampling system is a possible solution to all problems stated in the problem definition part of the thesis.

Table 7. Comparison of geologists against robotic sampling system

Comparison parameters	Geologists	Robotic system
Time	When taking a grab sample to determine the composition of the rock it is necessary: first, the sample is taken from the drawpoint, second, lifted to the surface, third, sent to the laboratory, then prepared for analysis and, finally, compositional analysis is performed. This make takes several days or weeks.	The robot determines the composition of the sample in a few milliseconds.
Accidents	The safety and health of workers are of paramount importance. A person with a serious injury may never fully recover his or her legal capacity.	If a robot gets stuck under rocks, it can be dug out, and repaired if possible, or its parts can be reused in other robots. Having an accident with a robot is better than one with a human.
Capability of sampling	The amount of rocks geologists can carry, and their physical strength and energy limit the number of drawpoints they can sample.	A robot's sampling limit depends on its battery capacity and its proper maintenance.
Sampling error	Perhaps geologists choose to analyze rocks that look more like ore, based on their preferences and lack of experience.	Each time the robot takes samples, it follows the sampling grid programmed inside its computer at exactly the same spot at every drawpoint.
Infrastructure/skills requirements	Grab sampling experience is mandatory	To recharge and replace the robot's batteries, a space must be provided in the maintenance department and staff must be trained to maintain the system.

Small sections of the El Teniente mine were taken by geologist and robot to compare theoretically their sampling times. For each mine, the sampling grid will be set by the geological department according to the geological characteristics of specific mines. Consider, for example, that there are 25 samples per drawpoint. The geologist will take 30 minutes to collect 25 samples and draw the sampling grid. It will take the robot about one minute. A geologist will travel from one drawpoint to another in about 30 seconds at an average speed of 5 km/h. The robot's speed will be determined by its electric engine and can reach speeds of 15-20 km/h, so traveling will take less than 10 seconds. As a result, a robot will spend less than two minutes sampling two drawpoints, whereas a geologist will spend over an hour.

LIBS analyzers have proven their effectiveness in analyzing material composition over the past decades. LIBS analyzers can also be installed on LHD equipment. A prerequisite for this is that the equipment must be unmanned. The current technology allows the use of remotely operated equipment, which can be operated by a worker who is far away from the mine.

Hazards/risks that may be present or encountered when using LIBS in a mining environment, when mines are not fully automated:

- the robot could run over a person causing injury;
- gases produced by laser heating can have toxic elements in their composition;
- the laser can cause burns or eye damage if it hits a person directly.

A robotic system manufacturer will provide a repair warranty, and if the laser or other parts of the robot breaks down, it will send workers to fix the laser and the complex systems inside the robot. A training program for the mine's maintenance personnel at the manufacturer's company is also an option.

7. CONCLUSIONS AND RECOMMENDATIONS

7.1. Conclusions

This thesis defined current problems in the mining industry and especially in block caving operations. The current situation in metal markets shows that there is an increasing demand for metals and large open pit mines, which currently produce a big percentage of the metal market, are reaching their economic limits. The demand for mineral resources can be answered by mining massive, low-grade deposits deep underground using the block caving mining method. However, block caving requires further developments in terms of the health and safety of the workers and increasing productivity. Compared to all underground mining methods, block caving has a big advantage, such as high suitability for automation.

One of the problems of the block caving method is dilution control at drawpoints, which is a laborious task that requires qualified personnel. It is a high-risk task because the drawpoints need continuous inspection regarding safety issues such as rockbursts, weakening of support systems, and others. A possible solution for those issues can be an application of automated robots with LIBS analyzers for grade control at draw points. LIBS technology recommended itself as a future of determining the composition of materials. A fully autonomous robot designed specifically for sampling is a more suitable tool for geologists' duties. A robot programmed to take samples in the drawpoint, with a complete travel path and that will send the data to the geologist's department on the surface, is the ultimate goal of this conceptual development. The use of robots will allow to increase efficiency by reducing production delays happening when all automated equipment is turned off, because of waiting times caused by the sampling process at draw points.

This robotic system could work as part of future 100% automated mines that do not require the presence of personnel underground. In the early years, the robotic sampling system could work in tandem with the remotely operating LHDs, and with further advances in technology, it will be possible to control all automated mining systems using artificial intelligence (AI). This thesis is a good start to developing a dialogue that will lead to further research in mine automation.

7.2. Recommendations

Based on the results of this study, further development of the idea of automation of mines is recommended. It is recommended:

- Risk analysis for the use of LIBS in an underground environment. It is necessary to establish rules governing the precautions to be taken when a robot interacts with humans when used in a mine with personnel present.
- Cost-benefit analysis. A robot's individual cost as well as its use costs must be assessed.
- Use of LIBS for mud rush risk assessment at draw points. Because the LIBS can determine a large number of elements, even noble gases, and hydrogen, it can be used to determine the amount of groundwater in order to avoid fatalities and accidents associated with mud rushes.

With the further deepening of the mines, the presence of personnel underground becomes dangerous due to high pressures and temperature. In order to avoid injuries and fatal accidents, it is recommended to exclude human presence in the underground workings. Existing technologies already allow to partially automate mining processes, and mines with block caving as the most adapted to automation can be the beginning of full automation of all mining operations. Further improvements to the robotic system should be undertaken in order to satisfy high demands in the mining industry.

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