ROBOMINERS

ROBOMINERS DELIVERABLE D5.4

MINING ANALOGUES & UPSTREAM/DOWNSTREAM MINING PROCESSES

Summary:

This document describes the availability of State-of-the-Art technologies and methods from the mining industry for the main activities in a mining eco-system which can serve as analogues for underground robotic mining. The concept of keyhole mining aimed at by the Robominers project was used as a guide for the selection of suitable technologies and methods. Relevant analogues have been used as the basis for several "futuristic" conceptualisations for keyhole mining by robotic mining equipment.

Authors:

Tobias Pinkse, K-UTEC AG Salt Technologies
Robert Quensel, K-UTEC AG Salt Technologies
Sandro John, K-UTEC AG Salt Technologies
Benjamin Müller, K-UTEC AG Salt Technologies
Michael Berner, Montanuniversitaet Leoben
Stephen Henley, Resources Computing International LTD
Colin Morrish, Resources Computing International LTD
James Tweedie, Resources Computing International LTD
Milan Milanov, Resources Computing International LTD

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement nº 820971.

Title:	Mining analogues & upstream/downstream mining processes		
Lead beneficiary:	The PP that manages the document preparation		
Other beneficiaries:	Other PP the document is prepared for		
Due date:	Date in which the document is to be issued		
Nature:	Confidential/Public		
Diffusion:	e.g. all Partners, WP-partners		
Status:	Final		
Document code:	D5.4		
Revision history	Author	Delivery date	Summary of changes and comments
Version 01	Tobias Pinkse	04.04.2022	First complete draft
Final version	Tobias Pinkse	20.05.2022	Reviewed version

Approval status				
	Name	Function	Date	Signature
Deliverable responsible	Tobias Pinkse	Task leader	19.05.2022	
WP leader	Éva Hartai	WP leader	11.04.2022	
Reviewer	Éva Hartai	WP leader	11.04.2022	
Reviewer	Gorazd Žibret	Project partner	13.04.2022	
Project Coordinator	Claudio Rossi	Project Coordinator	25.05.2022	

Diffusion List		
Partner name	Name	e-mail
All partners -	-	ROBOMINERS_all@autolistas.upm.es

TABLE OF CONTENTS

EXECUTIVE SUMMARY

The purpose of D5.4 is to identify potentially useful and relevant analogues for robotic mining from the available State-of-the-Art technologies and methods used in the mining industry. The selection of relevant analogues has been guided by the keyhole mining concept proposed by the Robominers project. In a keyhole mining operation, the footprint for access to an underground mineral occurrence is kept as small as possible thus minimising impact on local surroundings and the environment. Relevant analogues have been used as the basis for several "futuristic" conceptualisations for keyhole mining by robotic mining equipment.

Considering the possible scenarios and the varied tasks that the ROBOMINERS platform should perform, a large list of possible analogues from the mining industry was considered. The State-of-the-Art technologies and methods for the main activities in a mining eco-system have been studied to select relevant analogues for underground robotic mining. These analogues have subsequently been used as a baseline or starting point for several conceptualisations for keyhole mining by robotic mining equipment. Potential analogues for robotic mining which are less suitable to act as inspiration for the keyhole mining concept have not been included in this report.

The proposed concepts are all elaborations of, or derivatives of, the Robominers prototype design in combination with technologies currently in use in the mining industry. This prototype will be designed and constructed during the project in accordance with the Grant Agreement. However, the concepts presented in this report are not intended to be further engineered and/or tested as part of the Robominers project. The presented concepts can be used by any follow-up study or industrial uptake project leveraging the findings from the Robominers project.

Section 1 provides and introduction to this deliverable and summarises mining scenarios with relevance for robotic mining, as investigated in Task 5.1 and delivered in D5.1. The introduction also provides a framework of the investigations performed as part of Task 5.4 including a listing of the main activities in a mining eco-system for which analogues have been sought. Relevant State-of-the Art technologies and methods, as well as conceptualisations of how to potentially apply these analogues, are subsequently presented in Sections 2 to 6.

Section 2 identifies and potential mineral exploration methods that can be used as part of the robot's sensing array. Section 3 examines potential analogues for mine development, i.e. the initial construction of a mine and a mining infrastructure, and includes a section on possible bio-inspired, mining layouts suitable to robotic mining. This sub-section is an elaboration on the work presented in D2.2 of the Robominers project. Section 4 focusses on analogues for mineral extraction, while Section 5 summarizes relevant underground support methods to secure stability of mined openings. In Section 6 the underground material transport methods potentially suitable for the Robominers keyhole mining concept are discussed. The report closes with conclusions and recommendations in Section 7. The references to publications and other literature are included in Section 8. References to websites are included in the report as foot notes at the appropriate position.

1 INTRODUCTION

This deliverable D5.4 documents task 5.4 as described in the Grant Agreement. Task 5.4 within Work Package 5 of the ROBOMINERS project relates to the research performed regarding “Mining Analogues & Upstream/Downstream Mining Processes”. This work package has been included in the project plan for the ROBOMINERS project in order to draw on experiences and technologies from current mining industry practices as a proverbial diving board for the development of an operational eco-system for robotic mineral exploration, extraction and (primary) processing.

The aim of Task 5.4. was to analyse existing engineering processes and technology solutions that are available from the various sub-sectors of the extractive industries, and establish what is “readily available, what would need to be adapted from other sub-sectors, and what is it that would require lower TRL research. This has the purpose of conceptualising possible operational eco-systems for robotic mining beyond the aim of the Robominers project itself, since not all the components of a mining process are within the scope of the project. In the Robominers project, only a prototype will be designed, constructed and tested in a controlled environment. This report takes the prototype design and places it in both ‘realistic’ and ‘futuristic’ scenarios based on the available SotA technologies in the mining industry. The presented scenarios are not deemed fully technically feasible at this time as they require significant development of the Robominers prototype. Nonetheless, they can act as inspiration for future developers of robotic mining equipment and eco-systems as the technology presented by the Robominers project is further developed in future studies and industry adaptation.

As such, this work package has been approached as a desktop study on the state-of-the-art (SotA) processes which hold potential for adaptation to a robot miner eco-system including upstream and downstream. This desk study has been performed not with the intention of providing a complete overview of the SotA in the ore mining and processing industries, as this would lead to a multi-volume ‘encyclopaedia’, but rather to provide an overview of technologies that the project group believe can play a significant role in the development of robotic explorer/miner equipment within the ROBOMINERS framework.

The work on Task 5.4 has been iteratively performed within the constraints of work packages 2 and 5. Early idea development within task 5.4 has fed the development of simulations and prototypes in work package 2 while, in return, the prototype concept has fed the conceptualisation of possible robotic mining eco-systems presented in this report.

The result of this desk study has been captured in this report, deliverable 5.4 (D5.4), and has been structured largely following the common processes in the development and execution of a mining operation which will be further elaborated in paragraph 1.2. Before looking at these processes, the introduction continues with a summary of three mining scenarios, which hold particular promise for the deployment of robotic explorer/miner equipment, that have been established in Task 5.1 of the ROBOMINERS project and extensively described in deliverable 5.1 (D5.1).

1.1 MINING SCENARIOS WITH RELEVANCE FOR ROBOMINERS

Following WP5 D5.1 (Hartai et al. 2020), also introduced in D6.1 (Burlet et al. 2020) and D2.2 (Henley et al. 2021) there are 3 possible mining scenarios presented by examples chosen from mining regions of Europe:

1. operating and abandoned mines with known remaining unfeasible resources (e.g. Neves-Corvo, Iberian Pyrite Belt, etc.)
2. ultra-depth (e.g. Kupferschiefer mines in Silesia, Fore-Sudetic Monocline, etc.)
3. small deposits uneconomic for traditional mining (e.g.United Downs, Cornwall).

The parameters of these scenarios are different from that of the traditional mining in several aspects. Benefits of the Robominers technology may come from access to ore bodies in dangerous environments or in unavailable positions, and from low material volumes to be mobilized and low environmental impacts.

1.1.1 Operating and abandoned mines with known unfeasible resources

Ore reserves are always smaller than the resources of mineralized rocks. However, resources can be classified as reserves, when new exploration is done, considering also technological, safety and economic reasons. The main targets of the Robominers technology can be those bodies of high specific value ores which are unavailable for traditional mining because of their (small) size or unfavourable position within a mined deposit complex which cannot be exploited using conventional mining techniques.

In Europe there are several deposits where mining was abandoned but which can still contain significant resources. Costs of reopening can be significantly decreased by using Robominers, avoiding large mass transports and decreasing environmental impacts (e.g., dewatering). Operating mines also have to face the problem of depleting their high-grade orebodies and, in consequence, decreasing their profitability. In such environments, Robominers can be coupled to existing facilities including mining, transport and ore processing infrastructure, reducing required investment.

1.1.2 Ultra-depth

There are several cases where mineral enrichments were indicated in deep drillings (e.g., during the drilling of hydrocarbon exploration wells) which cannot be rendered to mineral reserve because of the deep setting with high pressure-temperature conditions; therefore, further exploration data were not obtained. The exact depth from which ultra-deep zone can be counted depends on the tectonic and geothermal conditions and on the rock type. The deepest shafts of the world reach ca. 4 km in South Africa; in the EU, however, the maximum depth is ca. 1.4 km in Finland.

Exploration of the ultra-deep zone from the surface is a task where the usual confidence level of information on an ore reserve is hardly available even when investing huge efforts. Most advantageous situations are when continuity of the ore bodies can be predicted by the deposit model itself; such deposits are formed by the stratabound ores hosted by thick basin filling sedimentary successions, e.g., black shale formations with associated secondary enrichments in the over- or underlying strata. Robominers could access these ore bodies through boreholes and move forward continuously by analysing and monitoring the quality of the ore ahead.
In this scenario, Robominers technology has to be adapted to an environment which is very different from the near surface conditions and must cope with a low level of predictability in the ore body, where continuous exploration parallel with exploitation is a crucial task.

1.1.3 Small deposits uneconomic for traditional mining

Historical mining of Europe was based on several small vein-type ore bodies which are uneconomic on the scale of the modern mining industry. However, these deposits might still host considerable volumes of high-grade ore. There is an increasing need for forming a viable small-scale mining concept in Europe (Sidorenko et al. 2020).

Ore lodes often form thin, discontinuous segments of centimetre to decimetre thickness, but on larger scale, these are steeply dipping bodies which can be followed to several hundred metres horizontally and vertically as well. A vertical zonation is also typical with variable properties of the ore and of the

host rocks. In this way, lode sections tend to have specific compositions, including enrichment of metals which are not usually enriched in other ore types. If the Robominer can exploit such ore bodies keeping the dilution low by following the veins in small cross section shafts, then high grade ores or ores of special composition (including metals with high specific value) will be produced. In some cases, mining has to be performed in protected areas possibly without any surface impacts, e.g., under historical mining towns built over the ore bodies.
In this scenario, Robominers technology has to be implemented, minimizing the mobilized rock volume and the infrastructure, finding the most effective ways to minimize the costs and environmental impacts as well.

1.2 RELEVANT PROCESSES FOR ROBOMINERS

In order to attain the capability of using robotic exploration/mining equipment in the above mining scenarios a number of 'generalised' process steps, e.g. exploration, mine development, mineral extraction, etc., are normally deemed required for the development and execution of an ore mining and processing operation. These steps are not necessarily all required for any one particular mining operation, nor do they imply a particular state (i.e. 'wet' or 'dry') of the planned mine.
To elaborate on the latter, the common state of human-accessible mines is obviously dry to provide an environment in which a human can exist without, for example, breathing apparatus. However, the deployment of robotic explorer/miner equipment opens up the possibility to operate wet mines, i.e. flooded with (ground)water, brine and/or slurry ("drilling fluid").

Some potential advantages of a wet mining environment, i.e. a flooded mine, are:

- The possibility of re-opening abandoned mines which have been flooded since abandonment. Using a robotic mining system which can operate in a flooded environment avoids the need to pump an abandoned mine dry before production can be re-initiated.
- The possibility to use a robotic mining system as an extension into deeper areas in an existing dry mine without the need to dewater these areas. The support system for the robotic mining eco-system would be in a dry environment while the excavation by robotic miners can be in a flooded environment.
- The option to use the fluid in the flooded mine as a "drilling and carrier medium" for the mining process. This medium could be the ground water present in the host rock, but it could also be an engineered fluid or slurry which aids the excavation and material transport processes analogous to oil and gas drilling technology. In this case, the "drilling and carrier medium" surrounds the robotic miner, cools, and lubricates excavation and, driven by a pump, carries the excavated material into the robot. The fluid in the mine thus acts as a carrier medium for horizontal and vertical transport (hoisting).
- The option of using such an engineered, high density, fluid, or slurry to counter the lithostatic pressure in the mine and provide support to the mine openings analogous to the way a drilling fluid is used to keep a borehole open in the oil & gas industry. Alternatively, or in addition, an engineered fluid or slurry could also be pressurised, when a geological hydraulic barrier is present above the mining horizon, analogous to salt solution mining.

However, a clear disadvantage of a flooded mining environment is:

- Hydrostatic pressure may reduce mine stability and potentially increase underground opening support requirements in the case of rock types with low cohesion. This is of particular interest to the Robominers project as it is partly targeted at "soft rocks". Because of the neutral stress, confining effective normal stresses are relatively low compared to the differential stress in a dry environment. See e.g. (Sasaoka et al.,2016).)

A preference for a wet or a dry mining environment as a basis for work package 5.4 of the Robominers project was therefore not made. The report thus includes State-of-the-Art (SotA) technologies directly related to current ore mining practices from dry mines but also related to industries such as, oil & gas drilling, maritime dredging and solution mining which operate in flooded environments.
To aid future development of robotic miner systems, i.e. beyond the current phase of the ROBOMINERS project, the presented technologies will be illustratively applied in a robotic explorer/miner eco-system. These 'visions' are included in this report at the appropriate place, i.e. aligned with the presented SotA technologies. All the illustrations connected to these visions refer to a common model for the mentioned robotic eco-system which is presented as a 'Block Flow Diagram'(BFD) in Figure 1.

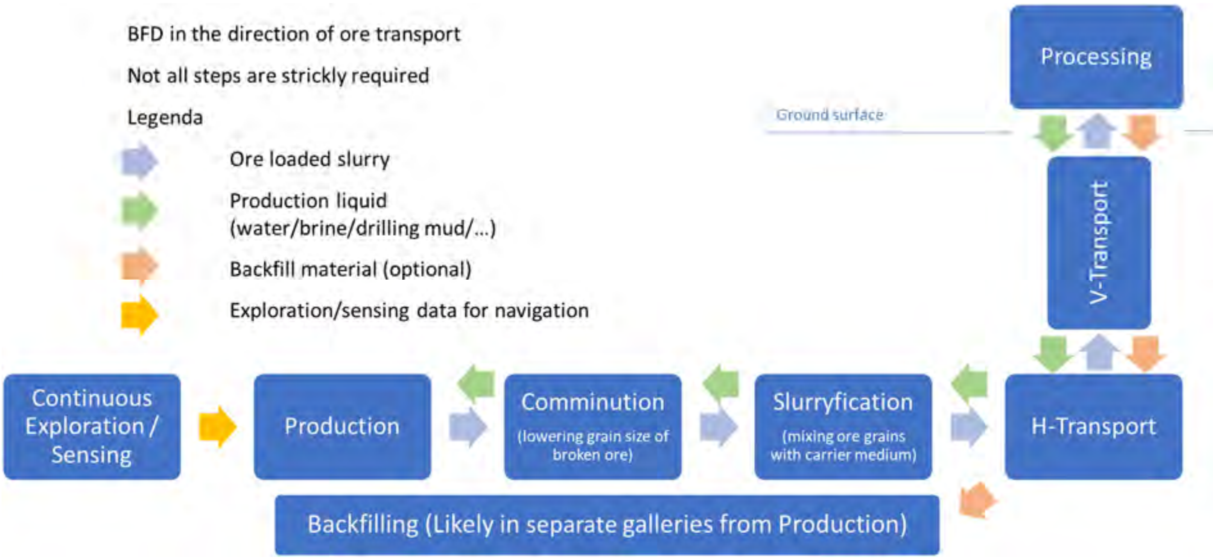


Figure 1: Block Flow Diagram (BFD) of envisaged ROBOMINERS Eco-System

The robominers eco-system presented in Figure 1 is largely based around 'wet' ore transport methods and any particular mine using robotic explorer/miner equipment will not strictly require all shown steps, however the general layout of this BFD is nonetheless very applicable as a reference framework for the visions presented in this report and will thus be used as such. The robot needs to be equipped with a range of mineralogical and chemical characterisation equipment that can continuously assess the quality of the ore as it is being extracted. In addition, the robot needs to be equipped with a plethora of sensors to enable perception and, subsequently, the ability to navigate autonomously.

The visions presented in the following sections cover several stages in the roadmap towards the ROBOMINERS long term vision of full autonomous deployment and operation of robotic mineral exploration and exploration equipment. For reference, several stages have been defined within this roadmap as presented in Figure 2.

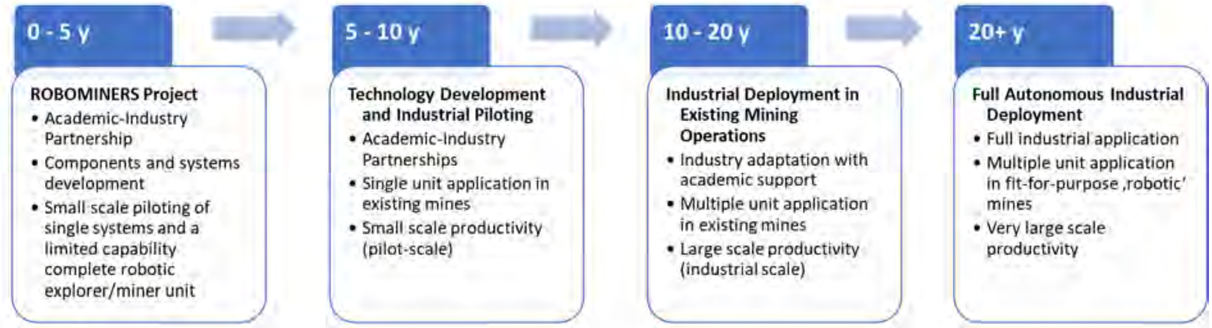


Figure 2: Generalised robotic explorer/miner development and deployment roadmap

The processes in the ROBOMINERS eco-system, see Figure 1, which are considered relevant for robotic exploration/mining from the desk study on upstream and downstream mining and processing analogues, are the following:

1. Mineral Exploration and Evaluation
2. Mine Development
3. Mineral Extraction
4. Underground Opening Support
5. Underground Material Transport and Hoisting

The corresponding SotA technologies which have been investigated during Task 5.4 are presented in the following sections bearing the terms used in the list above. The corresponding conceptualisations have been included in the appropriate sections and refer to the ROBOMINERS eco-system as presented in Figure 1 and the roadmap stages presented in Figure 2. References to publications such as books, scientific papers and alike are included in the text at the appropriate position and are provided at the end of the report in Section 8. Direct references to web pages are provided by footnotes at the appropriate positions in the report. All illustrations, unless otherwise stated, have been produced by the ROBOMINERS team.

2 MINING ANALOGUES : MINERAL EXPLORATION AND EVALUATION

2.1 EXPLOITATION TARGET IDENTIFICATION

The aim of this section is to summarize potential geological scenarios for optimal hosting of the ROBOMINERS technology. Without knowing the rate of efficiency and working performance of the equipment a series of preliminary assumptions should be made when selecting the most suitable mineral deposits for the technology:

- The deposit should preferably be
  - explored to the degree of indicated resource.
  - of high specific value, i.e. high USD/ton extracted
  - low hardness/rock strength and suitable rock structure to allow full-facing technology
  - it should be from minerals with easily detectable and assessed grade using real-time assaying/testing by on-site, built-in instrumentation
  - It should be preferably in brownfield areas, with suitable complementary surface and underground infrastructure.
  - Mineralization of a more 'discrete' nature as opposed to a disseminated style with gradational margins. An example of a preferred deposit style would be vein-hosted mineralization as opposed to a porphyry copper deposit.
  - High grade-low tonnage.
  - Containing minerals of strategic importance to the EU

  However, with the future development of the Robominers technology (i.e. beyond the Robominers project), several of aforementioned constraints could be overcome and become obsolete, enabling wider use of this technology.

- Specific metal value of the ore, other market conditions

  Specific metal value data from the available internet sources was collected to gather deeper knowledge of this parameter of the market. This is illustrated in Figure 3. It should be noted, that purely the metal price itself is not decisive, but at least many of the low-value commodity types can be excluded from the further investigations.

  The elemental composition may also be ambiguous to judge the value of the ore (like the difference in specific value of diamond versus graphite, both of them are elemental carbon minerals). The references for each price estimate are attached as Appendix 1. Naturally, the price estimates are sometimes far from the actual contract prices. Therefore, a colour coding was applied to show which price group the actual element belongs to.

  The price groups are per magnitudes i.e. 1-10, 10-100, 100-1000 and >1000 USD/kg metal. In the majority of cases the price information comes from the Chinese market, where we took the lowest published value at the moment of the search (June-July 2019).
  The data show, that apart from the six PGE elements (Pt, Pd, Rh, Ir, Os, Ru), a few other chemical elements, Au, Re, Sc, Rb, Ge, Lu) reach the >1000 USD/kg metal value.

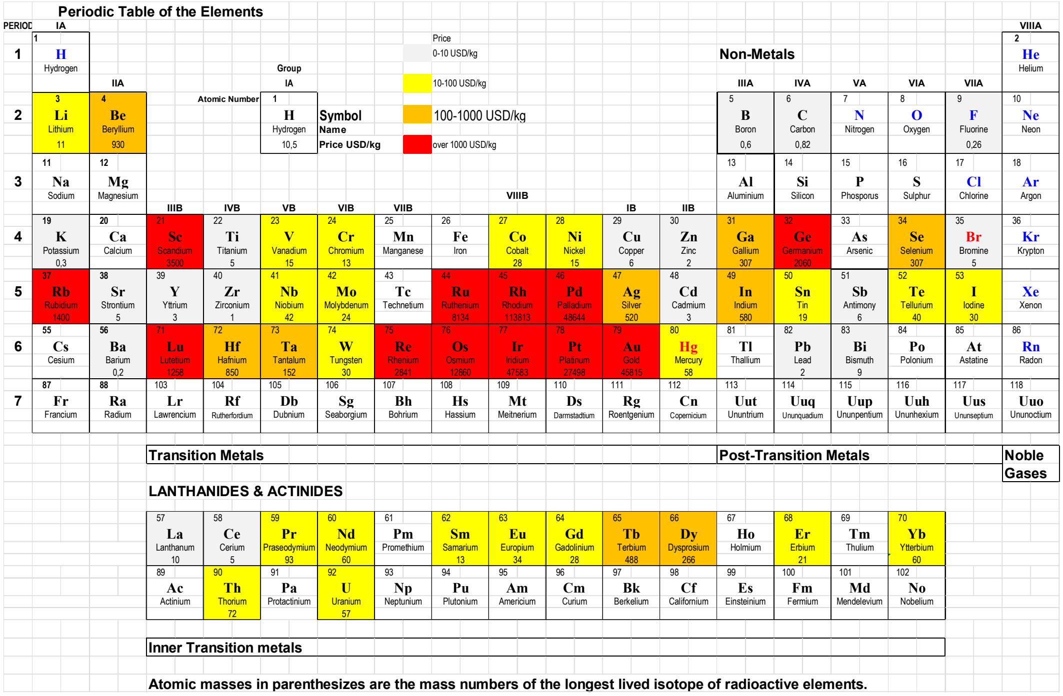


Figure 3: The approximate metal value of different elements, as appear in market quotes (for references see Annex 1.)

Furthermore, Figure 3 gives no information about the market size and offer/demand conditions of the elements and can this merely be used as an initial guide for selection of deposits befitting the ROBOMINERS technology.

Economic evaluation of polymetallic and complex ore extraction targets requires not only modelling of the target components but also of the penalty (deleterious) elements' distribution and concentration. The presence of such elements affects the downstream processes – additional stages of ore processing that may have to be established for leaching the penalty elements. If these technologies are not available, then the contaminants remain in the produced concentrate which narrows the potential market and negatively impacts the overall value of the ore.

Other market conditions that directly affect the prioritisation of the ROBOMINERS exploration targets is the EU strategy for the critical raw materials supply - ref (https://ec.europa.eu/growth/sectors/raw-materials/areas-specific-interest/critical-raw-materials_en). A recent example: In 2020 the European Commission launched the European Raw Materials Alliance (ERMA) to address challenges in the critical raw material supply and specifically to secure the supply of rare-earth elements (REE) used in in various high-tech applications including: smartphones; wind turbines; MRIs; hard disk drives; LEDs; electric motors and more. Whilst the EU is a global manufacturing leader for products like automotive traction motors and wind turbines, it does not produce any rare earth elements itself. Of its total rare earth magnet demand, 98% is met by Chinese imports[1]. The availability of other commodities that are currently primarily imported into the EU could be affected by new policies related to the Conflict Minerals Regulation. This specific regulation covers gold, tin, tungsten, and tantalum.[2]. This being the

[1] https://ec.europa.eu/growth/sectors/raw-materials/areas-specific-interest/rare-earth-elements-permanent-magnets-and-motors_en

[2] https://ec.europa.eu/trade/policy/in-focus/conflict-minerals-regulation/regulation-explained/

case, deposits rich in these commodities should be considered to be of particular interest when selecting mineral deposits for the ROBOMINERS technology.

2.2 CONTINUOUS GEOPHYSICAL EXPLORATION METHODS APPLICABLE TO ROBOTIC MINING

The potential exploration methods suitable for use in a robotic exploration/mining eco-system have been investigated extensively within work package 6, in particular as part of Task 6.1, and presented in D6.1. The information included in this section on continuous geophysical exploration methods applicable to robotic mining elaborates on the information provided in D6.1. This section thus describes geophysical exploration methods that can be applied continuously during or shortly before or after robotic excavation. The application of these methods can potentially support and optimise the mining procedures that will need to be devised for a robotic explorer/miner eco-system. Optimising the mining process can be envisaged to take place using decision making models which are supported by artificial intelligence. The prerequisite for the application and improvement of these continuous geophysical exploration methods is the performance of a preliminary exploration from the ground surface using common exploration methods which are in use today: e.g. exploration drilling, seismic, electrical and magnetic surveys, etc.

With regard to potential sensor technology for robotic mining covering the mineralogical, chemical and perception functions, the Robominers Deliverable 6.1, Miner Perception Report by Burlet et al. (2020) provides a detailed overview of the possible methods within the context of the envisaged mining scenarios. The main challenges for perception within the ROBOMINERS project are to “see” the environment with little or no visual cues, which are widely used and studied in ground and aerial robotics. The slurry underwater environment, as the most difficult use case, is therefore taken as the basis for choosing sensors and sensor combinations for the task of following the ore body and mapping surroundings for localization.

To avoid overlap between deliverable D6.1, Miner Perception and this deliverable (D5.4) on useful analogues from the mining industry, this report solely discusses the analogues for (near) continuous exploration methods that can potentially be used in robotic mining as shown in Figure 4, which presents the various geophysical methods that can be applied in robotic mining in a (near) continuous manner as used in a wide range of mining sectors today. The methods are divided into four categories: radar, seismic, geoelectric and exploratory drilling. The category *exploration drilling* is shown as the central element, as all other categories provide methods that are also used in the borehole, such as borehole geophysics and core logging. In the following sections, the individual categories are discussed, and the procedures are described.

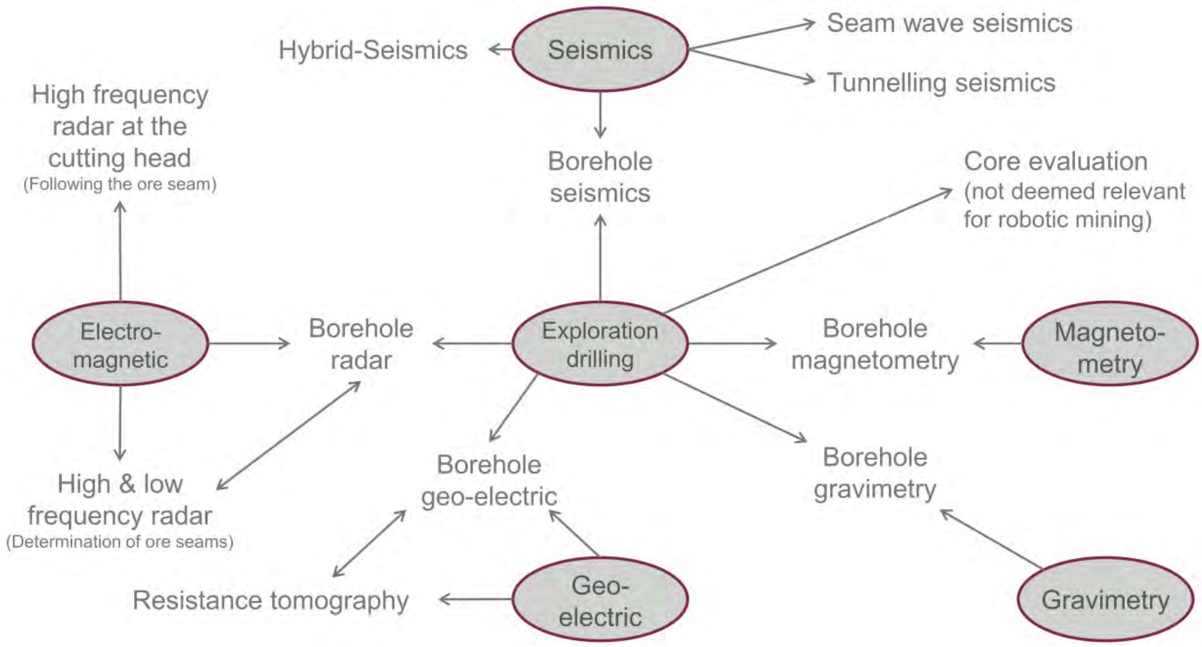


Figure 4: Potential geophysical and geoscientific methods for robotic exploration

2.2.1 Exploration drilling

Like in any other mineral program, exploration drilling is an inevitable pre-requisite for mine planning and development. In case of the Robominers the issue is even more complex, since the envisaged target ore bodies are most likely much smaller than those for traditional mining methods. Features, which help defining ore contours on-site, should be recorded during the exploration. Due to the smaller size of the targeted ore bodies, the resolution of data acquisition by exploration drilling should be higher than required for traditional bulk mining.

The Robominers technology requires drilling for both exploration and "mine development". The textbook "Drilling in Extreme Environments: Penetration and Sampling on Earth and other Planets" (Bar-Cohen and Zacny, 2009) covers terrestrial and extra-terrestrial drilling and excavation, combining the technology of drilling with robotics and offers many clues to what would also be required for robotic mining on earth. Robominers technology will need both vertical and horizontal boreholes to supply access and production tools to the active face. Such boreholes can be drilled with directional drilling technology, see Section 3.1.4. for details. Mud motors are widely used for such operations. In this technique a so-called screw pump or progressive cavity positive displacement pump (PCPD) is placed in the drill string to provide power to the bit while drilling as the drilling mud is forced through the PCPD. Semi-autonomous, fully automatic remote controlled blasthole drilling is a reality in Canada, Ontario, in the Hollinger open pit gold mine, operated by Newmont-Goldcorp using Epiroc's SmartROC D65 rigs[3]. Moving, set-up, and drilling the planned drilling pattern is automated, increasing both the working safety as well as availability of the drilling rig.

Using advanced materials, the development of a down-hole fluid hammer, innovative coatings of components, 3D printed sensors for monitoring has been the objective of upgrading holistic drilling

[3] https://www.epiroc.com/en-qa/newsroom/2019/important-milestone-in-surface-drilling

technologies that have the potential to drastically reduce the cost of drilling to large depths, 5 km or more and at temperatures as high as 250°C[4].

Extending the depth range, a challenging frontier is the zone of supercritical conditions. An international H2020 project in 2015-2018 (DESCRAMBLE) was performed with the objectives of demonstrating safe drilling to such depths, to reduce technical and financial risks, to upgrade reliability of pre-drilling geological information, as well as investigating co-production of minerals and chemicals. The objective was to reduce drilling costs by 28-60%. The demonstration drillhole was completed in the Larderello zone, historically Europe's first geothermal production field[5].

2.2.2 Seismic methods

Seismic methods use elastic properties of the rocks to transmit transverse and longitudinal waves and wave fields as information carriers, which are processed into planar or spatial images of the subsurface. The decisive parameters for wave propagation are the wave velocities in the different materials. The wave velocities are determined by parameters such as density, compression and shear moduli as well as porosity. The subsurface influences the propagation of seismic (elastic) waves through mechanisms such as reflection, refraction, diffraction, absorption and scattering.

The seismic waves are generated artificially, e.g. by explosives, hammer blows, vibrators, implosions, accelerated drop weights or airborne sound sources. The waves are recorded with geophones, accelerometers or hydrophones. Transmitter and receiver frequencies have to be adapted to the tasks before starting a measurement.

Seismics offers various methods that can be used in the borehole and at the excavation site. Depending on the method, it can be used within the excavation chamber to be mined as well as from neighbouring chambers that have already been excavated. Some methods, such as hybrid seismics and borehole seismics, can be applied shortly before or after mining for the preliminary exploration of the current or following mining chamber. Techniques such as tunnelling seismic can be done directly during mining for preliminary exploration. Procedures such as coal seam seismics can be applied just before, directly during or after mining for preliminary exploration.
In the following subsections, the individual seismic methods and their application are discussed.

Hybrid seismics

Hybrid seismics is a combination of reflection seismics and refraction tomography. The former deals with waves returning directly from the geological contacts, the latter with waves travelling along the geological contacts laterally. Both reflection seismics and refraction seismic dip wave tomography have undisputed advantages, but also disadvantages, when used individually, depending on the problem and the depth of investigation, as shown in Table 1.

[4] https://www.geodrillproject.eu/project
[5] http://www.descramble-h2020.eu/

Requirements/ measurement objectives	Reflection seismics	Refraction tomography
Resolution at shallow depths ('10 m)	limited	good
Resolution at greater depths ('40 m)	good	poor
Exploration depth	high	limited
Indicator for rock strength/ loosening/ permeability	poor	good
Detection of velocity inversions (hidden layers)	poor	good
Detection of fault and fracture zones	good	limited

Table 1: Advantages and disadvantages of reflection seismics and refraction tomography

The comparison on Table 1 suggests that the two methods should be combined, as the disadvantages of one method are offset by the advantages of the other. With current measuring instrumentation both methods can be run simultaneously. Complete information potential is reached by data processing of both methods together.

In addition to the greatly improved resolution, hybrid seismics not only map the subsurface structures in the manner of an X-ray image, but also simultaneously provides information about the rock strength and, thus, indirectly about the permeability down to depths of 400 metres. (Prinz et al. 2018, Frei 2015, Frei 2020) For the robotic mining eco-system as envisaged in the Robominers project, a shallow penetration depth and a centimetre-scale resolution of hybrid seismic data acquisition should be applied in order to effectively extract the targeted small-scale mineral occurrences.

Tunnelling seismics

Tunnelling seismics is a special seismic method used in tunnelling and mining. For some years now, exploration systems have been under development that make it possible to determine the location of geological hazard zones in advance of the tunnel/roadway excavation with the help of geophysical measurements during the excavation. The conventional systems use seismic methods, which are superior to other geophysical methods due to their long range and high resolution. They work according to the following basic principle: Seismic space waves (P- or S-waves) are initiated either near the lateral tunnel wall or at the tunnel face or joint. These are reflected or backscattered by geological heterogeneities and picked up by receivers placed around the tunnel and/or directly at the tunnel face or joint. Spatial imaging of the reflectors is achieved by reflection tomography or migration.

For the application in unconsolidated rocks, Sonic Softground Probing (SSP) was developed. This system uses a high-frequency P-wave vibrator and accelerometers, both of which are mounted in the cutting wheel of a tunnel boring machine. Seismic measurements are taken during drilling. SSP provides a reflection seismic image of P-wave reflectors up to a maximum of 100 m in front of the tunnel face.

In bedrock, the Tunnel Seismic Prediction (TSP) system is used along with other hazard zones prediction tools. This system uses up to 30 explosive charges placed in boreholes laterally in the tunnel wall as sources and two to four three-component accelerometers in boreholes. Explosive charges and receivers are arranged in profiles about 20 m to 50 m long on the side of the tunnel wall. The evaluation of the measurements consists of identifying reflections from fault zones in front of the face based on their travel time curves in the registrations of reflections.

In recent years, the Integrated Seismic Imaging System (ISIS) has been used primarily for tomographic exploration of the tunnel environment. The measuring system consists of a non-explosive seismic source (impact hammer or magnetostrictive sonar vibrator) which is attached to the side of the tunnel wall and initiates seismic waves there. These are then recorded by 3D geophones mounted in the tips of rock bolts (Lüth et al. 2004).

Seam Wave Seismics
Seam wave seismics is a special seismic method with the sources and receivers in a coal seam. The seismic velocities in the coal are lower than in the adjacent rock, therefore the seam acts as a waveguide and dispersive channel waves are formed. Coal seam waves are used in reflection and transmission measurements to determine the continuity of the coal seam and to plan further mining. The so-called Krey wave represents an important type of channel wave (Stolzenberger-Ramirez 2010).

Borehole seismics
Borehole seismics is a downhole geophysical exploration method used to measure the seismic wave field through geophones at specific depths, i.e. a through-transmission method. In these methods, the travel times of waves, starting from an excitation source in a borehole or at the ground surface, to geophones in a borehole are measured. In this way, conclusions are drawn about the density of the subsurface. In borehole seismic methods where the source is located at the ground surface, a distinction is made between two different arrangements:

1. The vertical seismic profile (VSP), where the source is located close to the borehole approach and the travel time to the geophones in the borehole is measured. If the source is close to the borehole, it is called the zero-offset VSP; otherwise, it is called the offset VSP.
2. The slant seismic profile (SSP), in which the sound source is located further away, resulting in a larger resounding area.

Other borehole seismic methods include the cross-hole seismic method (intermediate field seismic exploration), which can be used to record the stratigraphic conditions between boreholes and to detect cavities. In this method, the propagation time of elastic waves from an excitation source in a borehole to the measurement boreholes is obtained using geophones.

The BHC (borehole compensated sonic log) method is used in particular to determine the porosity of rocks is the ultrasonic method. Short sound pulses are transmitted from an upper and lower sound generator into the rock adjacent to the borehole. The waves travelling parallel to the borehole are deflected back into the borehole and picked up by receivers located between the upper and lower sonic generators.

In a Walk-Away-VSP, the source is moved on a profile away from the borehole and activated at (usually constant) intervals. Special data processing steps are required to separate the reflected wave field from the downward travelling wave field (down waves), which cannot be observed in surface seismics. Borehole seismics forms an important link between surface seismics and borehole measurements. (Martin 2000, Hiltmann 1998).

2.2.3 Electromagnetic methods

Georadar
Georadar (also known as rock or ground penetrating radar) belongs to the pulse echo sounding methods and works with electromagnetic waves in the high frequency range (10 MHz - 2.5 GHz). The measuring principle is based on the fact that short electromagnetic pulses with a length of a few nanoseconds are emitted into the subsurface by a transmitter. If the wave propagating in the rock medium hits an electrical discontinuity surface, part of the energy is reflected and radiated back to the receiver antenna. The signal is amplified, processed and registered by a control unit. From the measured propagation time of the signal from the start time to the arrival of the reflected wave, the depth of the detected reflector can be concluded if the propagation speed in the medium is known.

The high-frequency method can be optimally used in particular in high-resistance rocks with very low electrical conductivity. The electromagnetic waves are only slightly attenuated in these media, so that large exploration ranges of several decametres can be achieved. Various crystalline (e.g. granite) and sedimentary rocks (e.g. salt, limestone), with electrical resistances in the kilo- or mega-Ωm range, usually offer very good petrophysical conditions for the application of this method. Exploration ranges of up to 100 m can be achieved under favourable conditions.

Limiting factors for the successful application of the method are, in particular, clayey, clay-containing and thus cohesive layers or components in the rock that have a low electrical resistance. Due to the good conductivity, the electromagnetic wave is strongly attenuated in these media. Conductive layers have a shielding effect on the electromagnetic energy propagation and decisively reduce the maximum achievable depth of exploration. The same applies to heavily mineralised waters. Different measuring antennas can be used, which have different penetration depths and resolving power due to the frequency used.

The radar method achieves a high resolution (in the dm to cm range) and can still show indications for objects smaller than the resolving power, which an experienced geophysicist can use for evaluation. In this case, the spatial contour is no longer completely mapped, but, for example, pipelines, tunnels or cellar walls can be recognised as diffraction elements and also as continuous diffraction hyperbolas in an aerial representation. The main prerequisite here is a contrast between the dielectric constant of the objects and the surrounding rock.

Possible applications of georadar:

- Structural reconnaissance from the roadway (course of geological units such as seams, fault areas, etc.).
- Roof radar - safety measurements for occupational safety before possible roof detachment or delamination of strata from the roof

The geophysical method georadar can be applied both at the mining face and in boreholes. The guide horizons determined by georadar in the preliminary exploration can be used for mining. Using high frequency georadar equipment on the cutting machine allows it to orientate itself in relation to the guide horizons for selective mining. (Hiltmann 1998)

Induction logging (IL) / Dual induction logging (DIL)

The induction log is another electromagnetic method carried out in open and in plastic-cased boreholes. A particular advantage of the measurement method is that no electrically conductive medium (drilling fluid etc.) is required in the borehole.

It is possible to structure the borehole profile together with other borehole measurement methods on the basis of different specific conductivities of the surrounding rock. The determination of the true electrical resistivity of the rock using correction diagrams is considered a prerequisite for further quantitative interpretation (porosity). For the calculation of water saturation, a determination of the dielectric constant for rock packages is carried out. (Hiltmann 1998)

2.2.4 Geoelectric methods

The methodological concept of geoelectrical resistivity methods is that in general the measured horizontal or vertical distribution of the specific electrical rock resistivity is transformed into lithological-structural information. This allows an analysis of the layered structure or the delineation of geogenic or anthropogenic structures and anomaly zones with differences in conductivity. As a rule, the interpretation is based on a layer model (true resistivity) of the subsurface, which is derived from the measurements (apparent resistivity) with the help of appropriate inversion algorithms. The prerequisite for this is sufficient resistivity contrasts between the complexes to be delimited from each other.

As a special variant of the geoelectrical methods, geoelectrical tomography to a certain extent combines depth sounding (VES) and mapping of conventional configurations and provides a 2-dimensional depth section of the subsurface with the help of modern 2D inversion software. The high information density guarantees a higher reliability, especially in case of small-scale variations of the conditions. (Hiltmann 1998)

The geoelectric methods can be applied both at a rock face and in a borehole. The geoelectric borehole methods are described in the following subsections:

Spontaneous Potential (SP)

SP logs are used to qualitatively determine the electrical resistivity of formation waters (groundwater salinity), to estimate clay content and to interpret facies changes. (Hiltmann 1998)

Focusing electrical resistance measurement (FEL)/ Dual Laterolog (DLL)

The measurement of the specific electrical resistivity with focussing electrode systems with screen electrodes under the designations Laterolog-3, Laterolog-7 or Dual Laterolog have a higher vertical resolving power and a greater depth of investigation (penetration depth) compared to conventional resistivity measurements. With negligible infiltration, the measured value provides the true electrical sheet resistivity (Rt).

The most modern type of focussed resistivity measurement is the combination of 2 laterolog systems with large and small depth of investigation. The deep penetrating system provides the rock resistivity (Rt) and the shallow system the resistivity of the infiltration zone. Preferred conditions of use are low mud resistivity (salt mud) and relatively high formation resistivity (Rt > 50 Ωm).

Generally, electric borehole methods are used to structure the borehole profile together with other measurement methods based on characteristic resistivity values and resistivity changes, as well as to determine the true rock resistivity using correction diagrams with the aim of a quantitative interpretation, to determine porosity and water saturation. Electric borehole measurements can only be used in open (uncased) boreholes. (Hiltmann 1998).

Microlaterolog (MLL)

Micro-resistance measurements have a lower depth of investigation due to the small electrode distances and are used to evaluate the near borehole area. The micro-resistance measurements are used as a qualitative porosity and permeability indicator. The depth of investigation is 3 - 5 cm and the vertical resolution is 2 - 5 cm. The focused micro-resistance measurement according to the laterolog principle is called microlaterolog. The vertical resolution is about 5 cm and the examination depth up to 10 cm. Microresistivity measurements are used to detect thin layers and inhomogeneities, detect fractures and determine the specific electrical resistance of the infiltrated area near the borehole. (Hiltmann 1998).

Other geoelectrical Methods

Some methods can be applied also in excavated tunnels, to increase penetrating range. For example: VES with different arrays of electrodes; resistivity mapping with various arrays; Mise-à-la-masse method; etc. The mise-a-la-masse method is a geoelectrical method that uses a conductive area in the subsurface as a current supply electrode. The method was originally developed to map ore deposits (Kauahikaua 1980).

2.2.5 Gravimetry

Gravimetry deals with the gravity of the earth. It belongs to geodesy as well as to geophysics. While geodesy deals with questions of the earth's surface parameters(?), especially the determination of the earth's outer gravity field and the setting-up of a global network of measured points as a reference system, geophysics takes more interest in the density distribution in the earth's interior. A measured deviation from the 'normal' distribution of gravity allows researchers to draw conclusions on sub surface density inhomogeneities.

Adequate mathematical modelling methods allow quantitative statements on the geometry and density contrasts of the disturbing bodies. Those can be, for example, magmatic intrusive bodies, lithologic boundaries, sedimentary basins, changes of crust-thickness or inhomogeneities or other causes within the earth's crust or the upper mantle. In applied geophysics, gravimetry is applied for the exploration of near-surface layers, for example in hydrocarbon exploration, in the exploration of deposits of metallic and non-metallic raw materials, in hydrogeology, in foundation soil and environmental surveys.

Gravity is measured with gravimeters. It can be determined absolutely – for example with the help of pendulums in drop? experiments or, today, with so-called superconducting gravimeters (Meyer, 2022).

The ROBOMINERS consortium did not find this method suitable for robotic mining, because the interpretation of results will be too complicated. However, it is mentioned at this place to show it was also considered as one potential method.

2.2.6 Magnetometry

The magnetic disturbing field is defined, like in gravimetry, as a deviation of the measured values from a normal field, the latter being basically a dipole field called International Geomagnetic Reference Field (IGRF). In small-scale surveys, often simply an empirically determined regional field is deduced, calculated from, for example, existing measured values.

The cause of magnetic field anomalies is sub surface magnetized disturbing bodies, often composed of basic or ultra-basic rock like gabbro, diorite, basalt, serpentinite and the like. The strongest disturbing fields are found over deposits of magnetite and pyrrhotite. The magnetic susceptibility, which is the relevant physical parameter for magnetization, can vary by many decimal powers (unlike the corresponding parameter 'density' in gravimetry), thus very different magnetic field anomalies can be found. It is, however, impossible to identify a certain type of rock directly by the strength and form of the magnetic anomaly it generates.

Magnetic field is measured in three directions (axes). This is why interpreting magnetic anomalies is much more complicated than gravimetric anomalies. Their form depends strongly on the geographical and magnetic latitude: more precisely, the inclination of the magnetic field vector at the site of the measurement. Measurements are also affected by the dip of the disturbing bodies and the strike direction of the measuring profile.

The interpretation of magnetic anomalies is usually again done with the help of model calculations. In former times graphic methods were also very important: i. e. adequate geometric values are read off the gradients; with the help of evaluation diagrams, it is possible to determine the parameters of the generating disturbing bodies, like depth, width, and dip (Costabel and Noell 2022). Since robot parts are made from para- and diamagnetic materials, they can disturb the measurements of magnetic fields, so this method was not considered as of highest priority for ROBOMINERS.

3 MINING ANALOGUES: MINE DEVELOPMENT

Mine development is defined within this report as the collection of processes that achieve access (for personnel and equipment) to and prepare a deposit for mining. After the exploration phase which also includes the analysis and assessment of its economic potential, a final investment decision can be made for the initial development of a mine, according to the mine development project and obtained extraction permit. In most cases, the work that needs to be done during mine development before any ore extraction is very extensive and capital intensive.

For example, this work comprises the construction of an required infrastructure, above ground mining site, shaft sinking or tunnel (drift) construction to reach the deposit, the development of the main underground infrastructure (near the shaft-bottom/drift-bottom) such as: workshops, electrical switching gear rooms, primary processing equipment, transport hubs, etc.; the excavation of the first tunnels (headings) into the deposit from where the planned extraction panels or blocks can be reached and construction of ore purification systems and mine waste storage facilities.

The initial mine development can take up several years during which, usually, only a negative cash-flow is possible because no ore is being excavated, processed, and brought to the market. As such, optimising mine development is a major driver for the ROBOMINERS project which aims at simplifying the processes involved and, consequently shorten the time and lower the investment needed for the mine development process. This section discusses several analogues from the mining and civil engineering industries that can potentially contribute to this aim and concludes with a presentation of some mining layouts that are particularly suitable for robotic mining.

3.1 DRILLING TECHNOLOGY

The aim of the ROBOMINERS project is to create robotic miner technology that can eventually be delivered to an underground mineral deposit via one or more large diameter boreholes. (ROBOMINERS 2019). As such, the ROBOMINERS technology could be considered as 'keyhole mining', analogous to Laparoscopy, or keyhole surgery, a surgical procedure which uses a special surgical instrument called a laparoscope to look inside the body or to perform certain operations (Knott 2018). By designing a modular robotic miner which can be transported through a borehole and self-assemble once at the bottom, it is possible to develop an underground mine without the need for elaborate and costly mine development process involving, for instance, shaft sinking, underground workshops, etc.

Drilling technology is widely used in many industries for sub-surface exploration, investigation, and extraction/production. Some examples include: in the mining industry for exploration, production, and transport purposes; in the geothermal, oil and gas industry to reach reservoirs hundreds or thousands of metres below the ground surface, in the civil industry for geotechnical assessment and the construction of piles, in the salt industry to reach deep brine aquifers or reach rock salt deposits for solution mining and lastly to drill water wells for agriculture and/or consumption. Drilling technology is therefore a highly developed and wide field of engineering which holds many cues for the ROBOMINERS technology. To assist future developers of robotic miner technology, a simplified overview of the current state-of-the-art drilling technology is presented in the following figures and paragraphs. This information has been collated from several industry handbooks (e.g. Finger et al., 2010; Devold, 2013) and available online as university courses.

3.1.1 Basic of drilling a borehole applied to robotic miner technology

When the available drilling technologies from the previously mentioned industries are used as a means to provide access to a mineral deposit for a robotic miner/explorer, the basic steps illustrated in Figure

5 will most likely be necessary based on the state-of-the-art. For a sense of scale, the depth of conventional drilled borehole using rotary drilling is from a few hundred to several thousands of metres. The sizes of the pipes, i.e. casing, used to stabilise the drilled borehole range typically from7" (178mm) to 13-5/8" (346mm) for a typical deep oil/gas/brine production wells. Larger diameters drill equipment and casing sizes (up to 24" (508 mm)) are available for staggered well completions such as shown in Figure 5. Rotary drilling of boreholes is aided by the use of a drilling fluid which will be explained in Section 3.1.2.

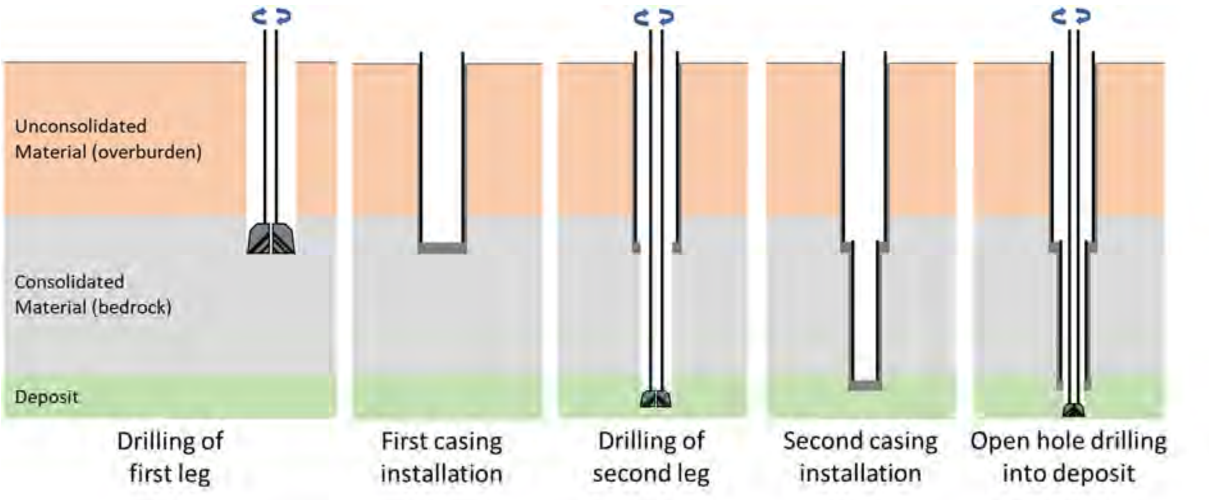


Figure 5: Basic steps in drilling a borehole

In the first step a large diameter hole is drilled or excavated going through topsoil and unconsolidated overburden material. To maintain a stable drill hole during this stage often a length of pipe is first driven, or piled, before any drilling starts. Once the consolidated overburden is reached, the borehole can be cased by inserting a pipe into the borehole and cementing it in place. This is shown in the second picture in Figure 5. For the next leg of the borehole a smaller diameter drill bit is used which fits through the now cemented first casing. Depending on the depth of the deposit, either the second leg reaches the deposit, as shown in the third picture, or the process of installing and cementing a casing is repeated several times, each time reducing the drill bit diameter, to reach large depths. In Figure 5, right hand illustrations, the second leg does reach the deposit and the second leg of casing is cemented like the first. Once the final cementation is completed, the borehole is now stable, and the deposit can be accessed.

Regarding the drilling process itself, several types of drill bits can be used depending on rock strength and type. The most common types of drill bit used for full-size conventional drilling are shown in Figure 6. Whereas the roller cone types bits (first two drill bits shown in Figure 6) have moving parts, they are more prone to failure but are able to cut through hard fractured rocks. The two bits on the right do not have any moving parts which makes them more durable. The first of these non-moving-parts drill bits is a polycrystalline-diamond compact (PDC) cutter and the second is a diamond impregnated drill bit. Although the technology of producing PDC and diamond impregnated drill bits has advanced in recent decades, they are still less capable of drilling into very hard rock formations. Each of the shown drill bit types thus have their own application area and the well design in combination with the geological conditions determine which of these is used in practice. (Finger et al., 2010)

Figure 6: Common drill bit types: (from left to right) Milled tooth roller cone, insert cone roller bit, polycrystalline-diamond-compact (PDC) cutter, full size diamond impregnated drill bit (Finger et al. 2010)

3.1.2 Drilling fluids

While drilling a borehole, the rock formation being drilled through is being cut, sheared and ground creating small fragments of rock. These rock fragments need to be transported away from the drill bit. In most conventional drilling processes used in mining and oil & gas drilling, a drilling medium is used. This can be a gas or a liquid, whereby the latter is more common for deep boreholes as the fluid creates a static pressure on the borehole wall and the reservoir thus increasing borehole stability. The common word for drilling fluids is “mud” as the first drilling fluids used were a simple mixture of water and clay. Nowadays drilling fluids, or mud, are more sophisticated and contain three principal components:

- Base liquid: oil, fresh water or brine.
- Active solids: clays and polymers to manipulate the viscosity of the mud by creating a colloidal suspension.
- Inert solids: rock fragments created by drilling and/or added barite increase the density of the drilling mud which aids the borehole stability and, in petroleum drilling, can balance the pressure in a reservoir avoiding a so-called blow out when a gas reservoir is reached.

The drilling mud is pumped down the drill pipe, through the drill bit, thus cooling it and taking rock fragments away from the cutting face and returns by flowing up the annular space between the drill pipe (drill string) and the borehole wall. A reverse flow of the drilling mud is also possible but rarely used in conventional drilling. (Finger et al., 2010) These two flow path alternatives are illustrated in Figure 7.

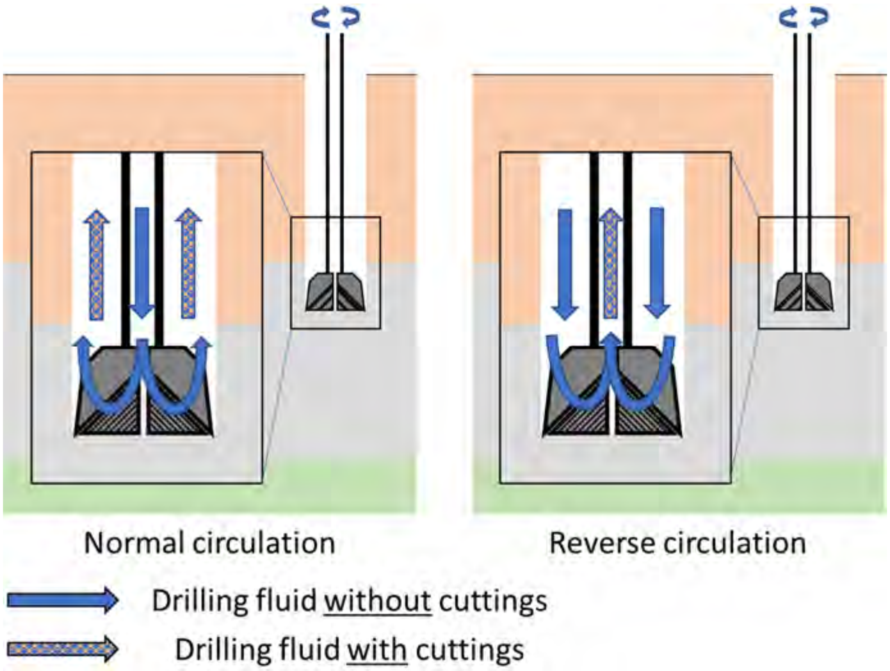


Figure 7: Normal and reverse circulation in a borehole during drilling

3.1.3 Underreaming

When a borehole is created using the processes described in the previous sections, the resulting open hole diameter in the deposit will be rather small compared to the expected size of the robotic miner. Even when this miner is modular and can self-assemble at the bottom of a borehole from a series of smaller parts, enlarging the diameter of the open hole section may be necessary to provide space for the self-assembly. This can be achieved using so called 'underreamers'. The basic functioning principle of an underreamer is that it holds cutting device which is retracted while travelling down the borehole but which can be extended once in the open hole section. By extending the cutting devices while rotating the underreamer, the borehole diameter can be enlarged up to typically 50%-75% of the original bore hole diameter. (Jones et al. 2009; Schlumberger 2021). The underreaming process is illustrated in Figure 8.

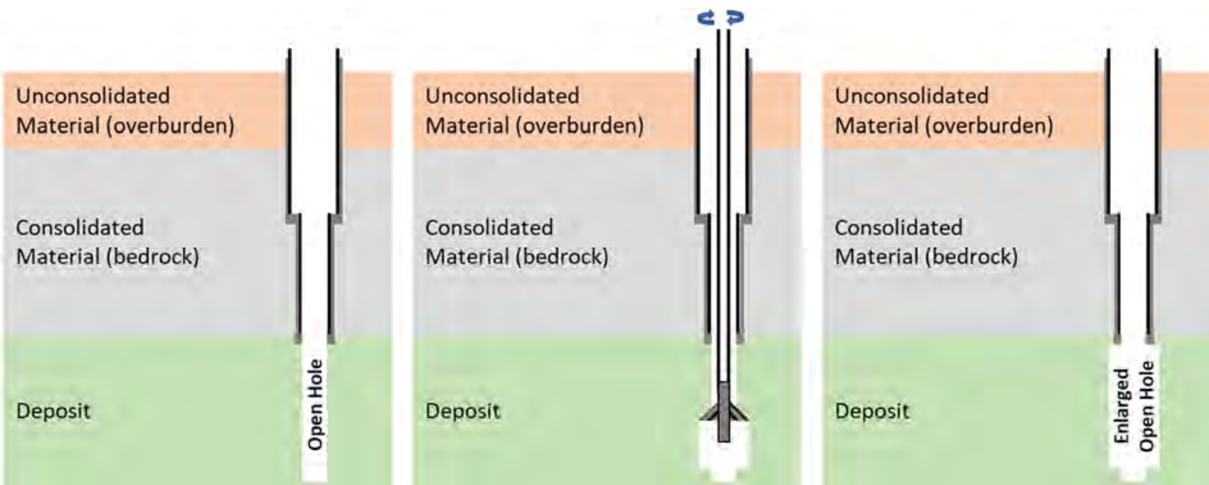
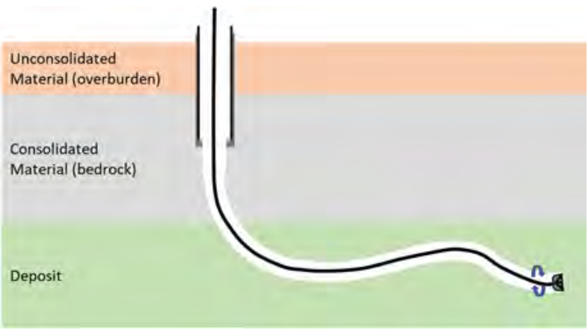


Figure 8: Underreaming an open hole section of a borehole using an underreamer

3.1.4 Directional drilling and side-tracking (branching)

Directional drilling, in other words, 'steering' the track of a borehole in a predetermined direction stems roots back to the 1920's when wellbore surveying tools were introduced in the oil drilling industry. These tools allowed drillers to observe the actual track of the wellbore rather than assume it was vertical. Initially, techniques were used to keep the well track as vertical as possible, however later these techniques were also used to deliberately deflect the well track to reach hard-to-access oil reserves. Directional drilling provided remedial solutions for common challenges during drilling such as crooked well tracks, 'side-tracking' around stuck pipe and relief wells to kill blow-out (an uncontrollable outflow of oil or gas from a well). Today, directional drilling technology allows for the precise hitting of 'target' reservoirs at the right approach angle to optimise oil or gas production. Sophisticated drilling assemblies are used to drill complex geological structures guided by 3D seismic data and petrophysical data acquired during drilling. (Mantle 2014). In exploration, mining and geotechnical work, directional drilling and branching is also used to 1) Minimise costs when multiple orebody intersections are required, 2) allow a single collar drill location to provide multiple holes in environmentally and/or spatially constrained locations.

The basic processes of directional drilling and sidetracking (branching) are illustrated in the following illustrations (Figure 9) which are based on information mainly available as industry brochures and alike from the major manufactures or industry associations (e.g. ICOTA 2005).



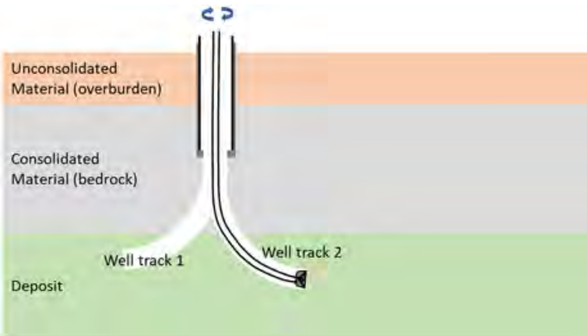


Figure 9: Directional drilling (left) and side-tracking (right)

3.1.5 Link to Robominers

The subjects introduced in this section on drilling technology can be linked to the Robominers project in several ways which will be discussed in this section. The first link to a robotic mining eco-system refers to reverse circulation of drilling mud in the borehole as described in Section 3.1.2. Although reverse circulation is not commonly used in the mining and oil & gas industries, it can potentially be of great interest for robotic miner applications. Circulating the rock cutting through the drill string firstly allows for a controllable and sufficient flow velocity which keeps the rock cuttings in suspension by selecting the right combination of rock cutting device and drill string diameter. In this case, reverse circulation prevents clogging up the drill bit or the borehole when the flow velocity is lowered when the borehole diameter increases, for example, when soft or fragmented rock is encountered. A further advantage of reverse circulation for robotic miner applications is the possibility to use inline cuttings analysers, for instance, determining the grade of the ore, without the risk of contaminating the rock cuttings with material from other strata being drilled through.

Drilling fluid/mud technology is a good analogue for the ROBOMINERS project regarding the potential transport of excavated ore as a slurry. The basic principles for transporting excavated ore fragments vertically in a borehole during normal circulation are illustrated in Figure 10.

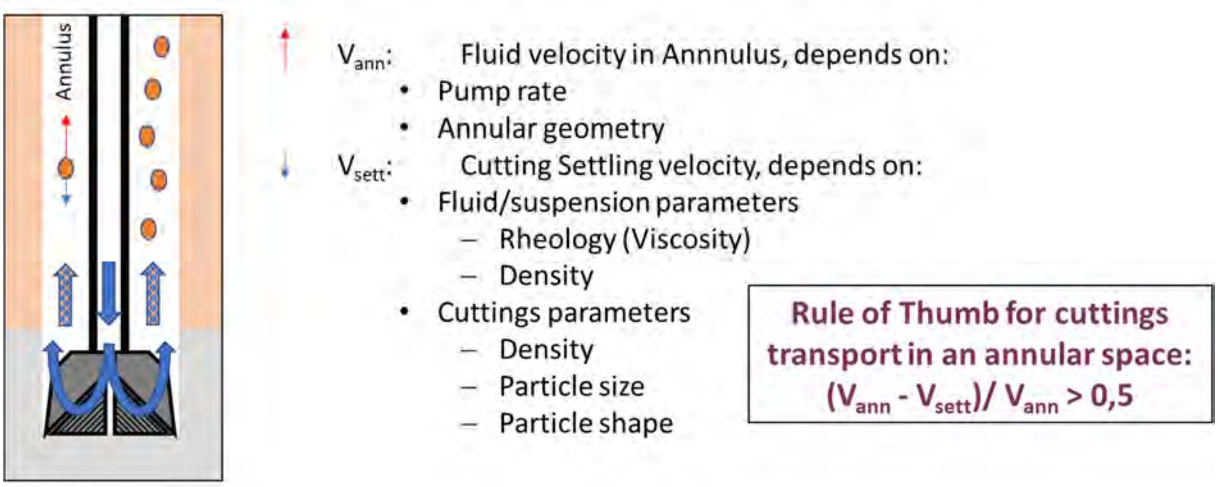


Figure 10: Cuttings' transport in an annulus during normal circulation of drilling fluid

A rule of thumb, used in the oil & gas industry for cutting transport, can be used as a guide for designing hydraulic hoisting systems for a robotic miner environment. By using reverse circulation, an optimal pipe diameter for the hoisting system can be selected based on fluid, suspension and cutting parameters determined from laboratory and pilot testing of overburden/ore material sourced from exploration.

Another link to the Robominers project can be made with regards to the subject of underreaming as discussed in Section 3.1.3. In a robotic explorer/miner eco-system, the underreaming technology allows for the creation of a space in which a robot can "self-assemble by sequentially lowering the robot in modules through the narrow borehole into the space created by the underreamer and self-assemble. Modularity and self-assembly are critical for the envisaged robotic explorer/miner eco-system. As such it is further discussed at this point.

Modularity and Self-Assembly

Modularity is a key enabler for re-configurability. Re-configurability is an important enabler as it allows fault tolerance and flexibility to adapt the robot's size, power output, functionalities and reach to a wide range of different scenarios. Nowadays, this topic is still a subject of academic research and examples of concrete applications (TRL>3) are still lacking.

In a modular robot it is possible to assemble the components in a number of ways to suit a variety of purposes. The main advantage of modular robotics arises from the ability to reuse hardware to perform multiple functions, adapting its morphology with available modules to accomplish a specific task while adapting to environmental changes. Inspired from the flexibility, adaptability and self-organizing properties of multicellular biological systems, roboticists have striven to create self-organizing machines that adapt. This is achieved, e.g., by the use of Evolutionary Algorithms (see, e.g., the pioneer work of D. Floreano and S. Nolfi). The characteristics of reconfigurable modular robots are mainly dependent coupling, powering, reconfiguration, communications, locomotion, degrees of freedom (DoF), size and control. Think "Transformers" :)

Modular robots can be homogeneous, where all modules are the same or heterogeneous, meaning they are composed of different kinds of modules. It has been shown that although the tendency has been to build auto-reconfigurable robots, many manually configurable robots have appeared in recent years. Self-reconfigurable robots seem to have general purposes, while manually configurable robots are usually task-specific. Regarding coupling, powering and number of degrees of freedom (DoF), there are several technologies available, like permanent magnets, electromagnetic, mechanical, and electromechanical. Regarding powering, it must be pointed out that most modular robots use a cable to power the system. Finally, regarding the degrees of freedom of the joints between modules, there is a clear tendency of using chain configurations with one or at most two DoF, although recent lattice modules show greater flexibility with a greater degree of connectivity and autonomy.

In terms of locomotion, micro-locomotion (i.e., individual modules' locomotion) has been introduced to increase the autonomy of the modules and is a trend observed in recent modular robots. As for controllers, in recent years the focus has been on developing highly distributed and scalable controllers. The controllers have always been highly dependent on intermodular communication for synchronization and coordination between modules. A recent trend in controllers also reflects biologically inspired control models.

While ground robots move on the solid ground and underwater robots in water, the mining environment has both properties, e.g. it is a multiphase environment consisting of mixed solids and liquids. Amphibious robots exist that can move either in water or on solid ground but not in the environment in between, thus this problem statement of the Robominers project is unique from a robotics point of view. Additionally, the harsh mine environment poses serious challenges as far as mechanical and electrical coupling of the modules.

Self-Assembly in an enlarged borehole section

Applying these considerations of modularity and self-assembly to the Robominers project can be envisaged in conjunction with the enlarged Open Hole Section as shown in Figure 8. When using an enlarged borehole section as the space for self-assembly, the sequence of lowering the robot modules through the borehole will be governed by the design of the self-assembly process. Figure 11 presents the design for the ROBOMINERS prototype robotic explorer/miner.The robot will comprise several modules, recognisable are so-called 'Archimedes screws' for propulsion and 'pods' in which the internal systems of the robot are installed.

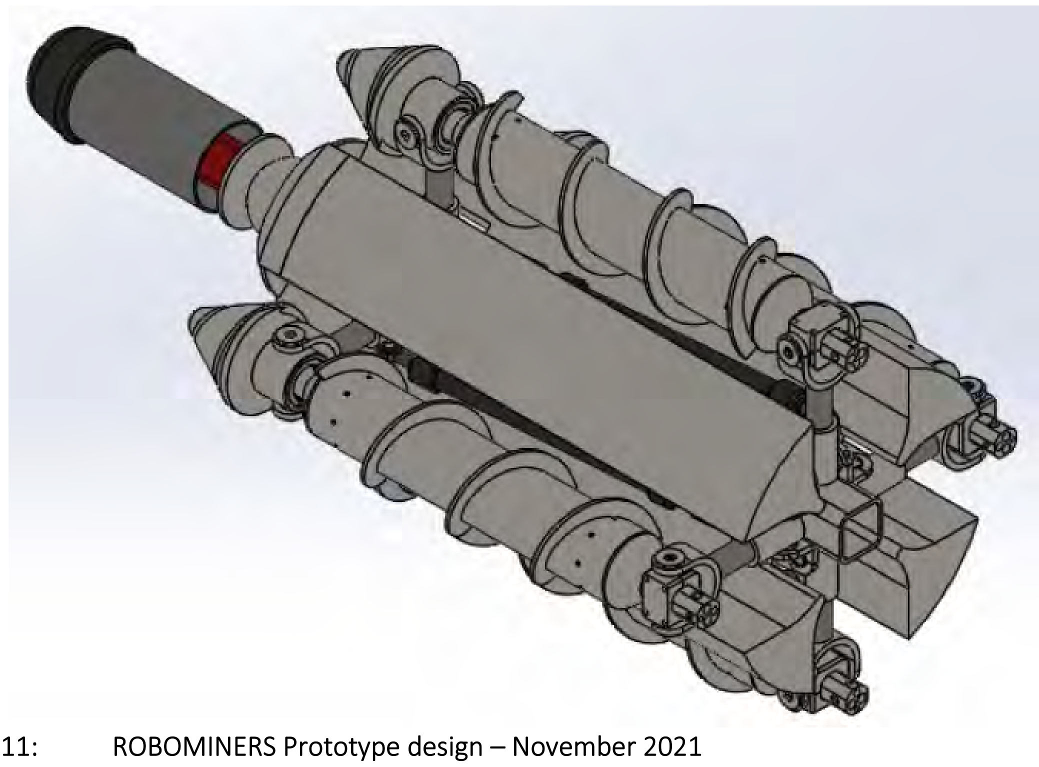


Figure 11: ROBOMINERS Prototype design – November 2021

This prototype design lends itself quite well for self-assembly in a underreamed borehole as illustrated in Figure 12. By using a type of active 'assembly jig' which can manipulate the lowered robot modules in the right place in the enlarged borehole, the robot can be assembled in this confined space. The assembly jig would 'load' the modular 'cartridges into a revolving assembly. This process resembles the loading of a revolver firearm well-known from 'Western' movies.

In a first step the 'spine' of the robot, recognisable in Figure 11, is lowered into the borehole and stabilized by, for example, manipulating assembly arms (temporarily) mounted to the spine. In the second step, shown in Figure 12, an assembly jig is lowered into the borehole in a retracted form to be expanded in the enlarged hole section.

The assembly jig can be envisaged as a set of manipulation arms, equipped with for instance assembly tools and/or claws, set in an expandable frame which can be stabilized in the enlarged borehole section. Once the assembly jig is ready, the separate robot modules can be lowered into the borehole. The assembly jig will receive the modules and manipulate them onto the robot spine below.

In Figure 12 the Archimedes screws are lowered and assembled in the third picture, followed by the pods in the fourth illustration. In the final picture, the assembled robot can be seen while the assembly jig is being removed from the borehole. After this step the robot can be connected to potential further modules, assembled in the same manner, and finally to an umbilical connected to the support systems on the ground surface. After connection of the umbilical, the robot can start exploration and/excavation of the ore body.

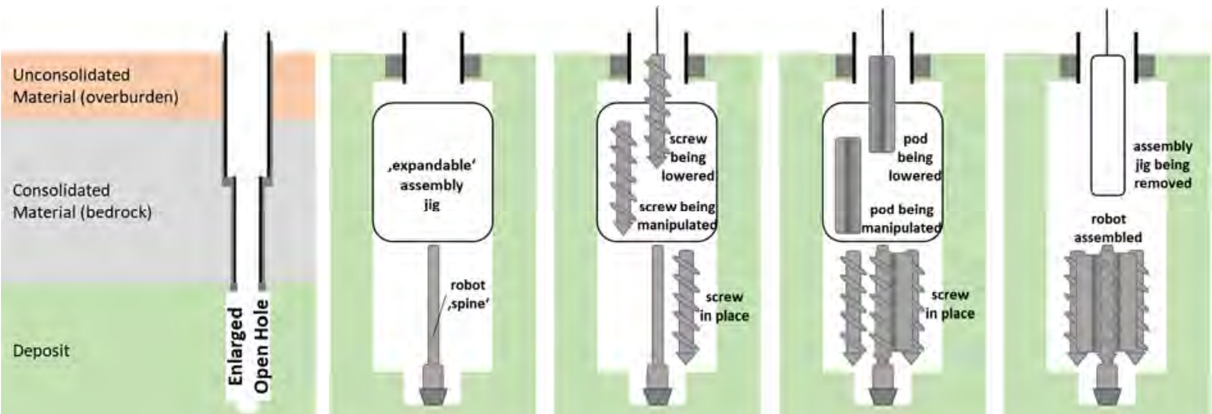


Figure 12: Self-assembly of ROBOMINERS prototype (Nov. 2021) in an enlarged borehole

The vertical assembly position shown in Figure 12 can suffice for the assembly of the robotic miner even for inclined or even horizontal orientation of the ore body. Provided the robot is able to excavate and navigate curves, the effective exploitation of, for example, thin-bedded or vein type mineral deposits can be achieved. To assist the robotic mining process, pilot exploration drilling could be used in an attempt to follow the ore zone. This necessitates the drilling of a non-vertical borehole track and potential side-tracks, which are discussed in Section 3.1.4.

In a robotic miner eco-system, directional drilling and side-tracking technologies, as discussed in section 3.1.4, can be very applicable within the 'keyhole' mining scenario described in the introduction of this chpater. A technology proposal by the Eavor Company[6] from Calgary, Canada called the Eavor-Loop™, see Figure 13, uses advanced drilling and well technologies from the oil & gas industry to construct a sub-surface 'radiator' for the harvesting of geothermal energy through a closed loop system.

[6] www.eavor.com/technology/

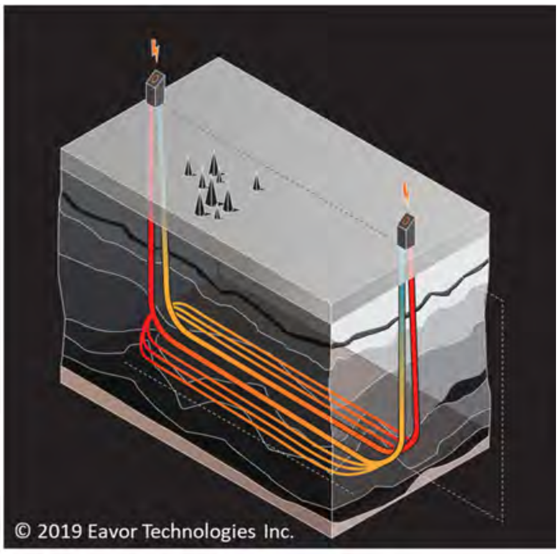


Figure 13: The Eaver-Loop™, a technology proposal for closed loop geothermal system (www.eavor.com/technology/)

This proposal, which has now been evolved into an operating pilot plant near Rocky Mountain House, Alberta, Canada, has inspired the ROBOMINERS team to envisage a keyhole mining operation with a layout similar to the Eavor-Loop™, i.e. the 'pilot-hole' layout for robotic exploitation of deep or otherwise hard-to-reach mineral deposits. By using two single borehole entry points at the ground surface and the directional and side-tracking technologies, a potential robotic mining layout such as illustrated in Figure 14, Figure 15 and Figure 16 can be achieved. These illustrations describe a potential mining sequence, using the robotic miner discussed in the previous paragraph, in which state-of-the-art technology is used to drill a series of 'pilot' holes for a robotic miner to follow. In step 1, Figure 14 (Figure 14), a series of pilot holes are drilled from two single well entries which 'meet in the middle'. In a second step, the robotic miner is self-assembled using the jig system described previously, and the exploitation phase can start. For a thin-bedded deposit, as shown in the picture on the far right in Figure 14, this could, when combined with a backfilling operation, lead to a near 100 % extraction rate through a 'doublet' of wells.

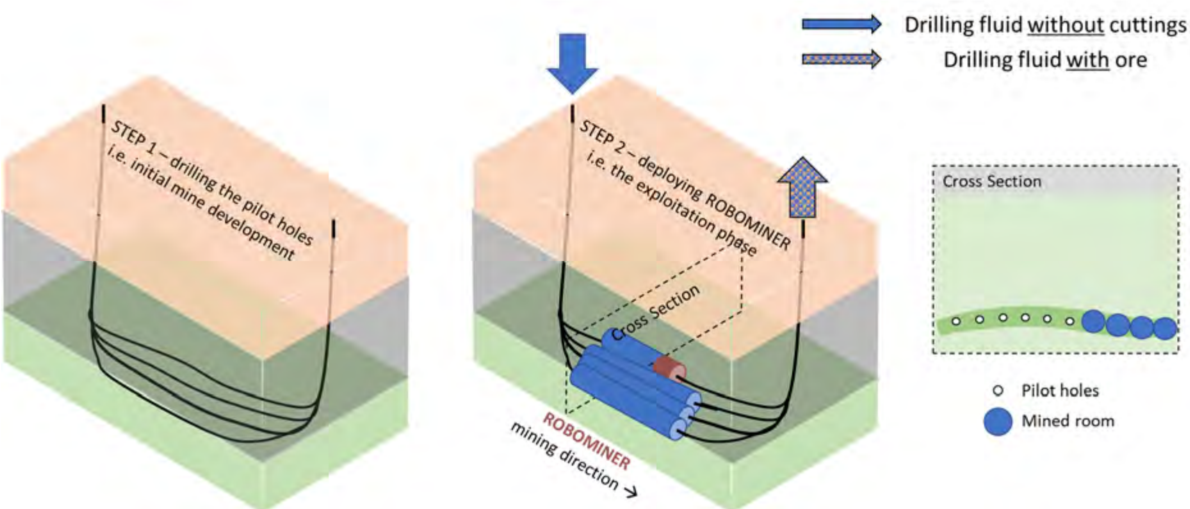


Figure 14: ROBOMINERS 'pilot' hole mining sequence for robotic exploitation of mineral deposits

In this system, a drilling fluid, clean of cuttings, is pumped underground through the first borehole and towards the robot miner. The robot miner uses electrical and/or hydraulic power to excavate the ore by, for example, a cutter head and the cuttings are pushed through the pilot hole towards the second borehole. Using this basic system, one or more robot miners can exploit a range of geometries as illustrated in Figure 15. By using logging while drilling (LWD) and measurement while drilling (MWD) technologies in combination with the directional drilling technology, a series of pilot holes can be drilled which follow an ore-rich stratum or vein. Multiple veins/strata and even massive ore bodies can be exploited using this potential method for the robotic miner application.

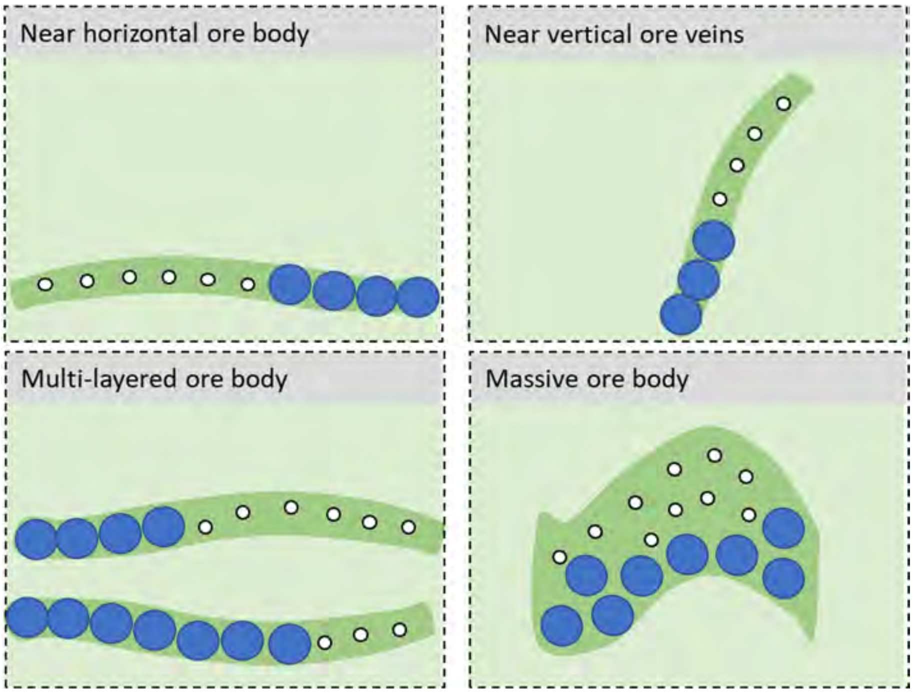


Figure 15: Potential mining layouts for the ROBOMINERS pilot hole mining system

Whereas the mining layouts in Figure 15 are all based on either a very stable ore body, needing minimal support, or a subsequent backfilling operation to avoid collapse of the underground openings, the following Figure 16 illustrates how the ROBOMINERS pilot hole system can also potentially be used in a type of overhand caving method for friable and/or highly fractured ore deposits. In this 'pilot-hole-caving' concept, the pilot holes are drilled at the bottom level of an ore body (or block thereof) and the robot miner is allowed to excavate a series of closely spaced underground openings. Selecting sufficient spacing of the openings in relation to the rock strength to hold up the opening while being excavated but allowing collapse soon after, the robot miner can create a block caving mining operation such as used often in diamond mining (see Figure 16).

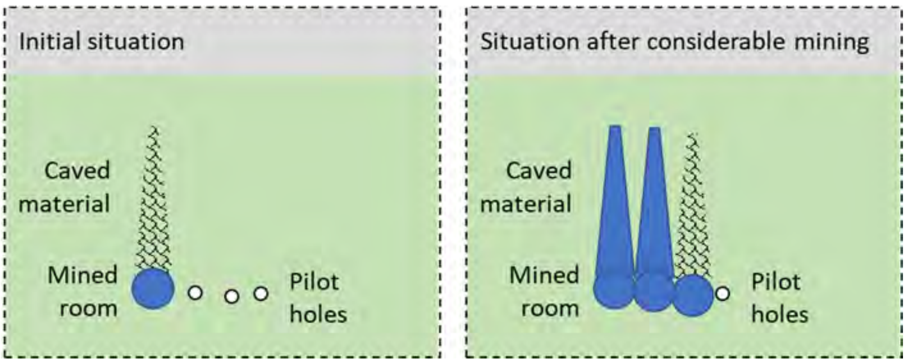


Figure 16: ROBOMINERS pilot-hole-block-caving concept

Once a block has been destabilized sufficiently by the undercutting, the broken ore can be removed from the initial tunnels repeatedly until all the caved ore is removed. The destabilisation can be aided by minimising the spacing between undercuts, thus enlarging the span of the excavated undercut with each tunnel. By positioning the initial tunnels at a gradient, the flow of ore towards central collection points can be promoted. Further assistance by some type of screw or conveyor system in the initial openings is also imaginable to this end.

This Section 3.1 has discussed which and how several state-of-the-art drilling technologies can potentially be used in a robotic explorer/miner eco-system. The assembly of the robot in an enlarged borehole and the potential mining layouts using drilling technology have been discussed. In the next sections, two other very traditional mining related technology fields, namely shaft sinking and tunnelling, are presented and discussed in relation to a robotic miner eco-system.

3.2 SHAFT SINKING AND RAISE BORING

3.2.1 Shaft sinking

The ROBOMINERS team envisages the application of robotic explorer/miner technology through a so-called 'key-hole' mining operation using boreholes as discussed in the previous section. However, when considering the roadmap for robotic explorer/miner technology deployment (Figure 2) it can be expected that shafts may be required to provide access to a mineral deposit for which robotic exploration/exploitation is planned. This requirement may either arise in the earliest stages of ROBOMINERS technology line development, when the key-hole mining using boreholes as described in the previous section is not yet possible, or the geology of mineral deposit is unfavourable for key-hole mining concept deployment and a shaft is required to allow access to the deposit by robotic explorers/miners.

Shaft sinking is the process of creating a vertical opening to access an ore body and is considered the costliest and most time-consuming part of mine development. Moreover, the shaft sinking process is intricate and arduous and often considered as one of the most risk prone jobs in mine development (Barr 2004). Donaldson et al. (1952) lists a number of very traditional methods for shaft sinking which can deal with unstable and water-bearing ground. Deep shafts have been sunk using these technologies for over 100 years, however more advanced methods have been developed in recent decades as well. These methods allow for a more continuous shaft sinking process in which excavation and lowering of the caissons, or lining the shaft in another manner, is done simultaneously. As such, these methods can be considered a valuable analogue for a robotic miner/explorer eco-system, albeit in lesser extent for the keyhole mining system envisaged by the Robominers project. As this report aims to inspire robotic mining in a wider sense than only the envisaged keyhole mining concept, the a few examples of advanced methods are provided by the following figures taken from the Herrenknecht AG website[7].

The first shaft sinking method to discuss is the Vertical Shaft Sinking Machine (VSM) shown in Figure 17. A VSM is suitable for both competent rock and soft, heterogenous (water-bearing) soils and excavates shafts from 4.5 to 18m in diameter. In a VSM the shaft liner is continuously lengthened from the top by adding prefabricated sections or casting in place. As the shaft is being excavated, the shaft liner is lowered into the shaft. By flooding the shaft with water, the VSM equipment can operate submerged, the ground water pressure on the outside of the shaft liner is compensated and dewatering is avoided. By avoiding dewatering, the VSM method limits or eliminates any subsidence of the shaft surrounding ground and is therefore of particular interest for shaft sinking operations in urbanized areas.

[7] https://www.herrenknecht.com/en/products/mining/

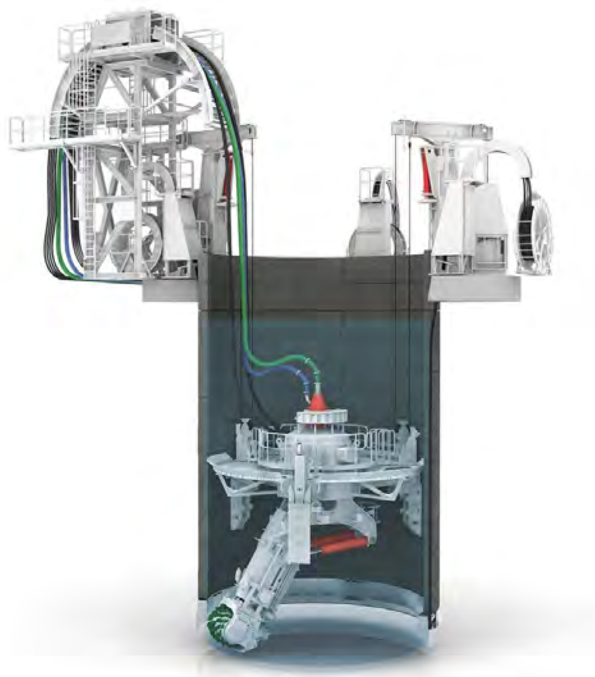


Figure 17: Herrenknecht AG Vertical Shaft Sinking Machine (VSM) (www.herrenknecht.com/en/products/mining/)

When more stable ground conditions are present at the shaft sinking site, for instance when there is no unconsolidated overburden to deal with, several other advanced shaft sinking methods can be considered. The Herrenknecht portfolio offers a wide range of equipment for continuous shaft sinking of deep shafts in rock of which a few examples are included in Figure 18.

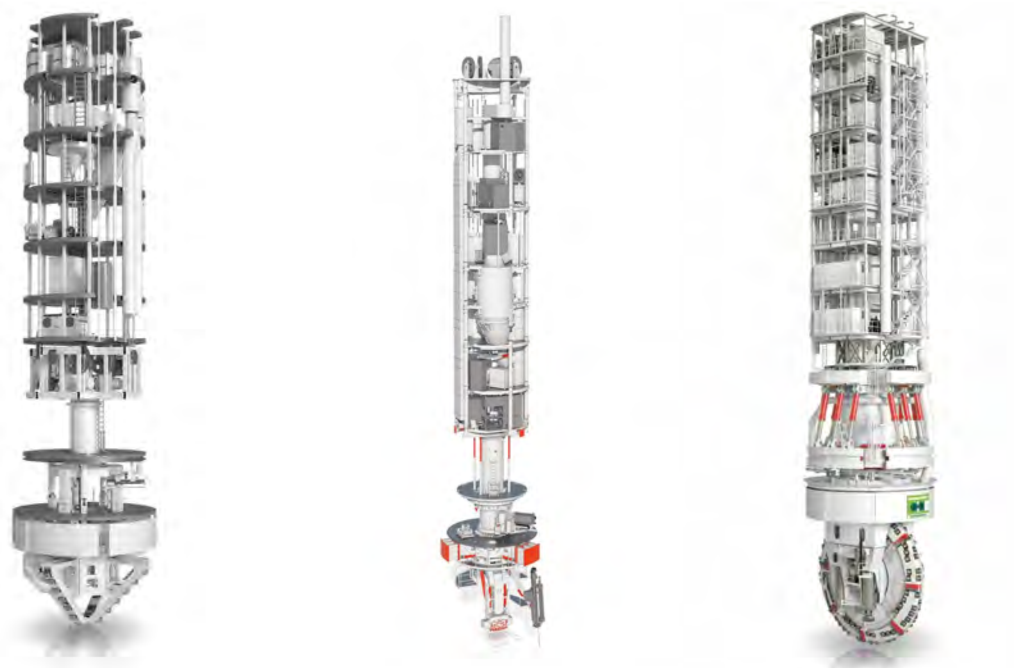


Figure 18: Herrenknecht AG equipment for continuous shaft sinking (f.l.t.r.): Shaft Boring Cutterhead (SBC, 8-9m diameter), Shaft Boring Roadheader (SBR, 7–12m diameter) and Shaft Boring Machine (SBM, 10–12m diameter) (www.herrenknecht.com/en/products/mining/)

The way this equipment is used to sink a shaft is determined by the local geology and site conditions for the shaft planned to be sunk. Submerged shaft sinking is possible using some of these methods, thereby balancing any groundwater pressure on the outside of the shaft liner. Several types of shaft liner can be applied using these machines as well, for instance concrete prefabricated, concrete poured in place and steel construction. Also, the handling of cuttings from the shaft excavation can be adapted to the site conditions. Pneumatic, hydraulic, and mechanical cutting transport are all possible, even in the direction of a location below the shaft sinking operation using a pilot-hole, and the basic layout of these systems can be adapted to suit the chosen cuttings handling method.

3.2.2 Raise boring

Raise boring is a process for shaft creation which uses a cutter head which is pulled up rather than sunk as in the shaft sinking methods discussed in the previous paragraph. As for the shaft sinking equipment, Herrenknecht AG is also one of the leading manufacturers for raise boring and examples of the equipment used have been taken from their website [8].

To raise bore a shaft (see Figure 19) first a pilot hole is drilled from the shaft starting point, at the ground surface or from an existing level within a mine, to the shaft landing point at a lower level in the mine. The pilot hole is drilled by the so-called Raise Boring Rig (RBR), for instance using a roller-cone drill bit as discussed in Section 3.1. Once the pilot hole has been drilled, the drill bit is removed and a cutter head such as shown in Figure 19 (bottom right) is attached to the RBR. The raise boring is then performed by the RBR by rotating the cutter head while keeping a pulling force on the cutter head. The cuttings will drop down into the heading where the raise was bored from and can be removed by underground mining equipment such as a Load-Haul-Dump truck (LHD) to be discharged at another location for instance as backfill material.

[8] https://www.herrenknecht.com/en/products/mining/

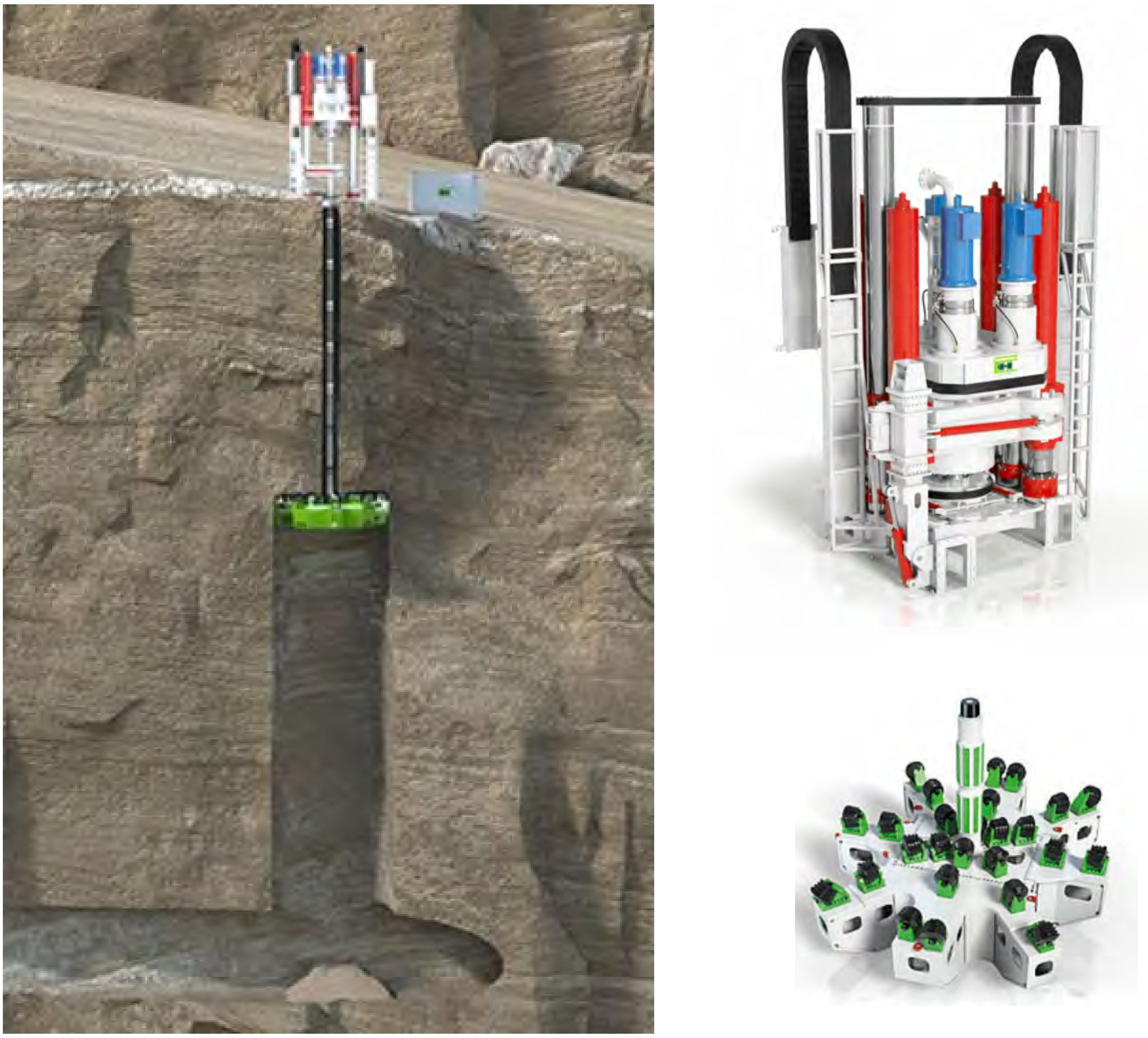


Figure 19: Herrenknecht AG Boring Rig (RBR) in action (left), detailed view of RBR (top right) and Raise Boring Cutter Head (bottom right) (www.herrenknecht.com/en/products/mining/)

3.2.3 Link to Robominers

The presented examples of shaft sinking technology as discussed in Section 3.2.1, can be projected onto the prototype design as presented in Figure 11. In this figure the prototype, located at the bottom of the enlarged borehole after deployment (see Figure 12) is shown while starting to excavate material.

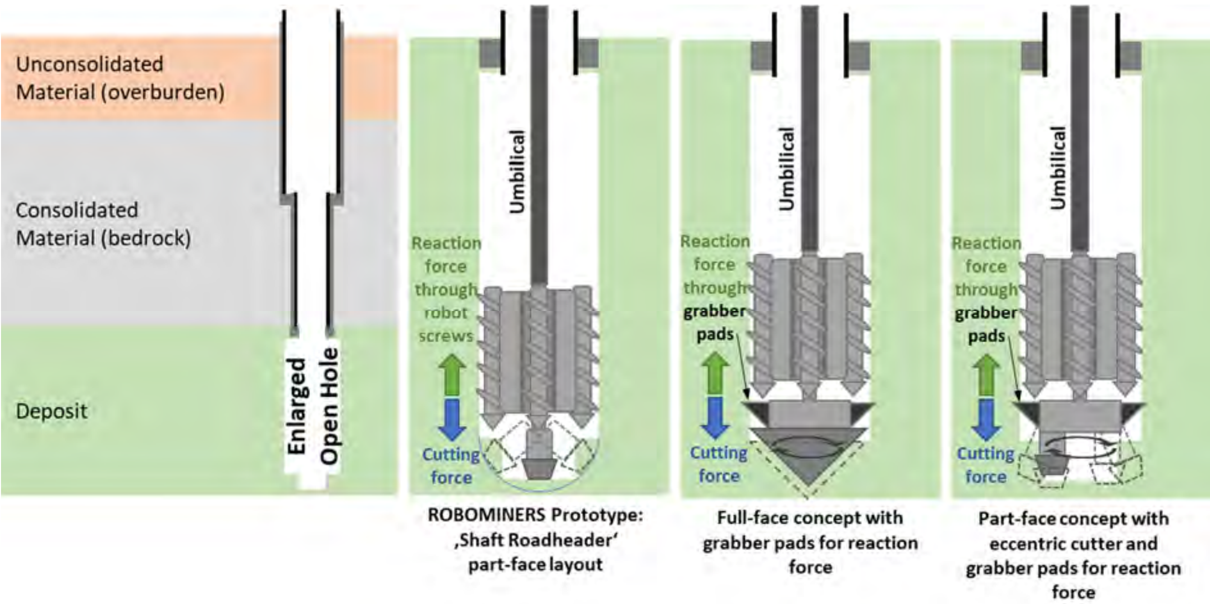


Figure 20: Conceptualisation of shaft sinking technology for a robotic miner eco-system

Figure 20 shows conceptual layouts for the ROBOMINERS prototype (left), using a centrally positioned roadheader-like excavation tool, a full-face cutting tool concept, using some form of grabber pads to take up the cutting forces (middle), and a rotating, eccentric positioned cutting tool again with grabber pads. These layouts can all be envisaged as allowing for a fair degree in flexibility in terms of steering ability if the cutting tool can be tilted to some extend as is shown in this figure.
The excavated material can be 'hoisted' by a drilling fluid as described in paragraph 3.1.2, either through a tubular in the umbilical or through the space created by the excavation, in which case the umbilical is used to provide the drilling fluid.

For the ROBOMINERS project, sole vertical excavation such as intended in shaft sinking will not likely be a subject which is directly linked to robot development, however, the vertical position in which the robotic miner is shown in Figure 20 can furthermore be envisaged as a starting position for non-vertical exploration/miner paths such as suggested in 3.1.5.

Although raise boring technology (Section 3.2.2), as the shaft sinking technology, is not considered to be directly linked to robotic miner development as envisaged by the Robominers project, there is a potential of automating the raise boring technology and incorporating it in a (submerged) robotic miner eco-system. In this case, the raise boring could be used as a production method rather than a method for creating a shaft using a suitable mining layout. This concept can be applied for ore seams, for instance stratabound, that are well well-explored and understood but cannot be reached using traditional mining methods, for instance due to depth.
The envisaged concept is illustrated in Figure 21 where a simplified sketch of how an automated raise boring rig can be used as a production tool in a robotic miner eco-system. The mining layout shown in this figure, i.e. the layout of the production rooms, is representing a style of honeycomb mining which is further discussed in Section 0. Using an automated raise boring rig to excavate ore enables a mucking robot to collect the cuttings from the raise boring from the lower level and transport it to a hoisting

system in the shaft. Backfilling the thus created production raises could enable a secondary mining phase in which the remaining pillars are extracted thus creating a very high extraction efficiency.

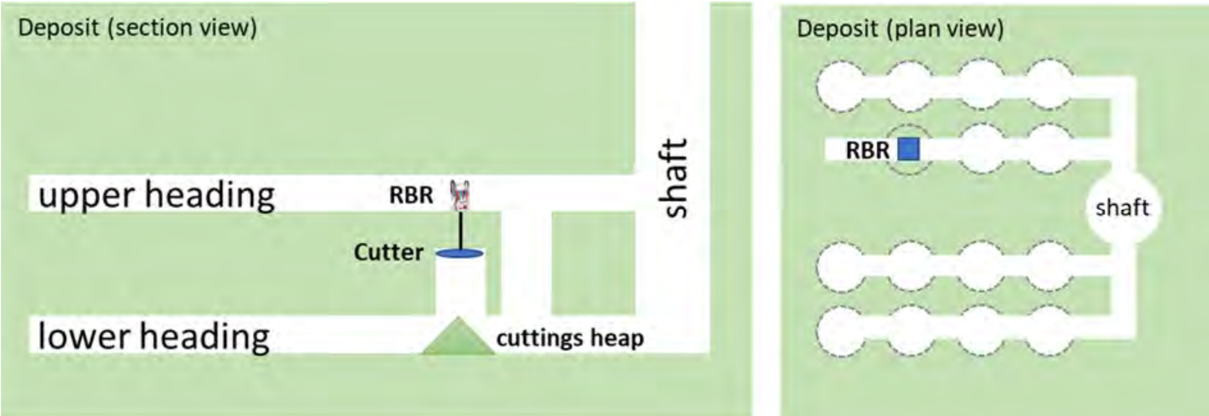


Figure 21: Using raise boring technology as a robotic mining method in a honeycomb layout

Whereas shaft sinking and raise boring create vertical headings, the development of a mine usually also involves the creation of (sub-)horizontal headings, or tunnels, to reach the limits of the mineral deposit. Equipment similar to the raise boring equipment discussed above and the underreaming equipment discussed in paragraph 3.1.3, can also be used in a horizontal direction, i.e. using a 'hole opener' as illustrated below in Figure 22.

Figure 22: Herrenknecht AG 48-inch Full Face Hole Opener with milled tooth cutters and 47-inch centering device behind (l), schematic operating principle explained (r) (www.herrenknecht.com/en/products/mining/, adapted)

Combining the presented shaft sinking and raise boring technologies with directional drilling technology and the 'pilot-hole' layout as discussed in paragraph 3.1.4, leads to a concept whereby a robotic explorer/miner can follow a deposit through self-steering or using a pre-drilled pilot hole. This envisaged concept is illustrated in the following two figures, Figure 23 and Figure 24.

The first illustration, Figure 23, envisaged a self-steering robot excavating a so-called blind tunnel (heading). In this case the robot will have all exploration equipment needed for navigating the ore body while in the second illustration, Figure 24, a pilot hole is used by the robot. In this pilot hole a pull rod or cable can provide additional reaction force for the cutting action of the excavation tool.

The pilot hole can be drilled in advance by a directional drilling operation using logging/measurement while drilling technologies to follow the deposit and determine the future mining path of the robot. The pilot hole can potentially also be drilled by the robot itself if a suitable drilling tool is incorporated. In this case, the pilot hole can both aid the exploration task and aid in providing reaction force by including a type of rock anchor at the end of the drill rod by which the drilling rod can double as a pull rod. This concept is purely theoretical and will not be investigated through the Robominers prototype.

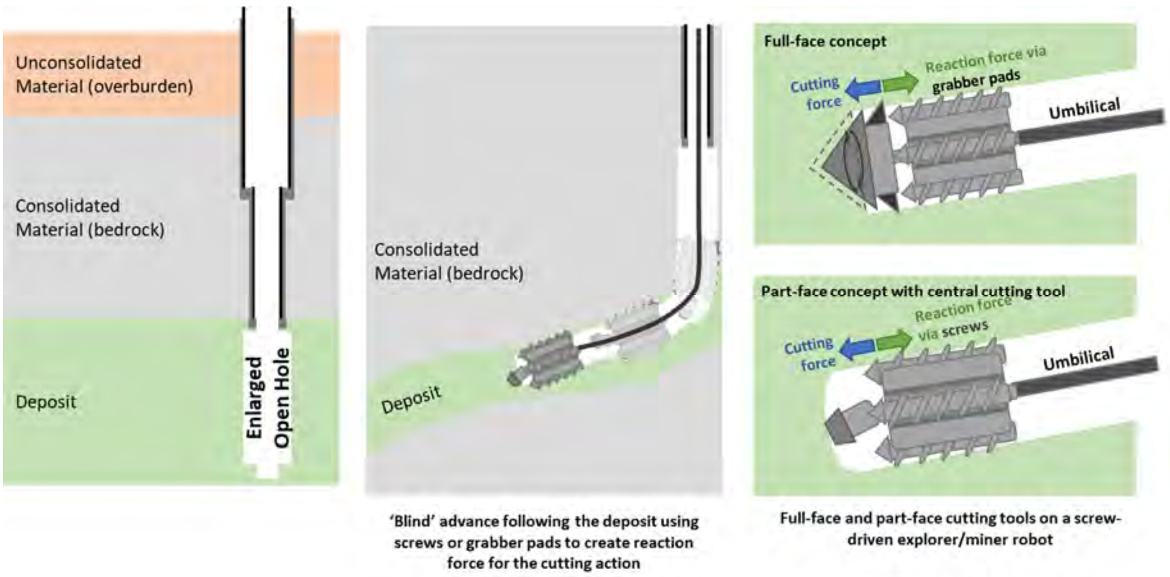


Figure 23: Blind advance of a robotic explorer/miner from an enlarged borehole

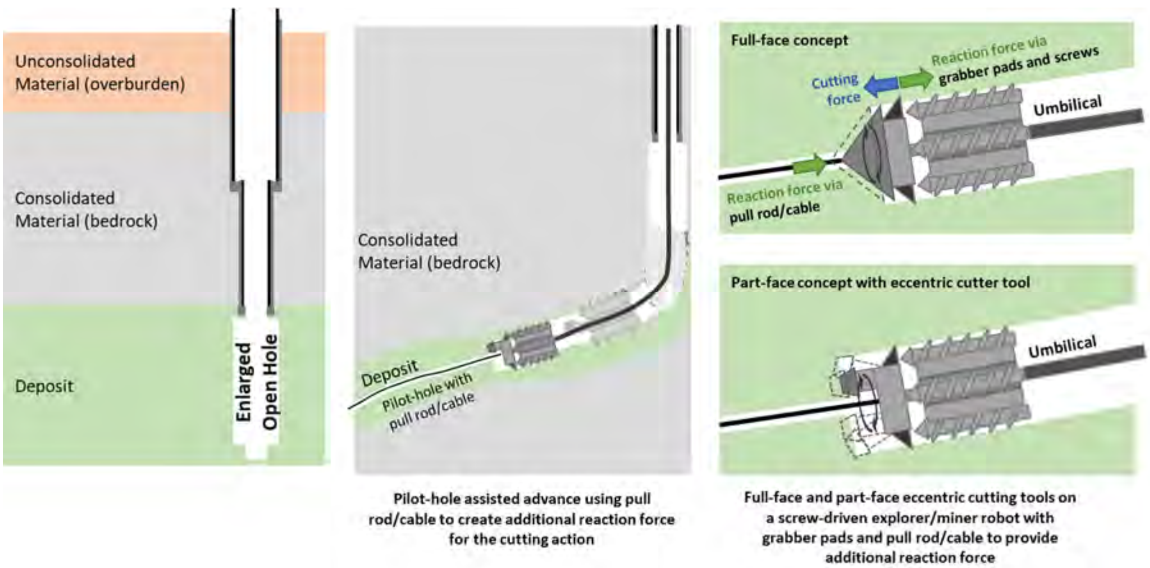


Figure 24: Pilot-hole assisted advance of a robotic explorer/miner from an enlarged borehole

3.3 TUNNELLING

Tunnelling, or 'road heading' which is a more common term used in the mining industry, is a process in which a (sub-) horizontal tunnel, or heading, is created using specialized excavation methods. The known history of tunnelling goes back 6 millennia and started in Mesopotamia where ancient humans transitioned to living in urbanised areas with high population densities. In these ancient cities the need for subterranean infrastructure arose in the form of water piping, drainage and sewers. A full history of tunnelling through the ages is not provided in this report, but the paper by Diamond et al. (2018) and the book "Introduction to Tunnel Construction – Second Edition" by Chapman et al. (2018) provide an excellent overview and are referred to for more information.

Since these highlights in early tunnelling methodology development, the tunnelling industry today can be considered able to, at least technically, construct any tunnel, anywhere, under any ground condition. With the ever-increasing world population and urbanisation, the importance of tunnelling technology to develop subterranean space cannot be underestimated (Chapman, 2018). However, tunnelling technology is only a limited analogue for the development of a robotic miner eco-system, because the stress state of rocks in an underground mine is much different than those in tunnels, because mines usually far exceed the depth of tunnels constructed as part of transportation infrastructure projects. Some of the latest developments in tunnelling technology, in particular micro-tunnelling, are still relevant for the ROBOMINERS project and, as such, will be further elaborated in the following sections.

3.3.1 Recent advances and trends in tunnelling technology

The two main tunnelling technologies trending today in infrastructure projects, such as rail tunnels, are the application of Tunnel Boring Machines (TBM) and the use of the Sequential Excavation Method (SEM), also called the New Austrian Tunnelling Method (NATM) or the Shotcrete method. The Sequential Excavation Method (SEM) excels in its ability to deal with difficult and, especially, varying ground conditions. (Clark et at., 2017) By allowing some deformation after initial excavation before stabilisation the amount of additional support material required is reduced. This is illustrated in Figure 25Figure 25 below.

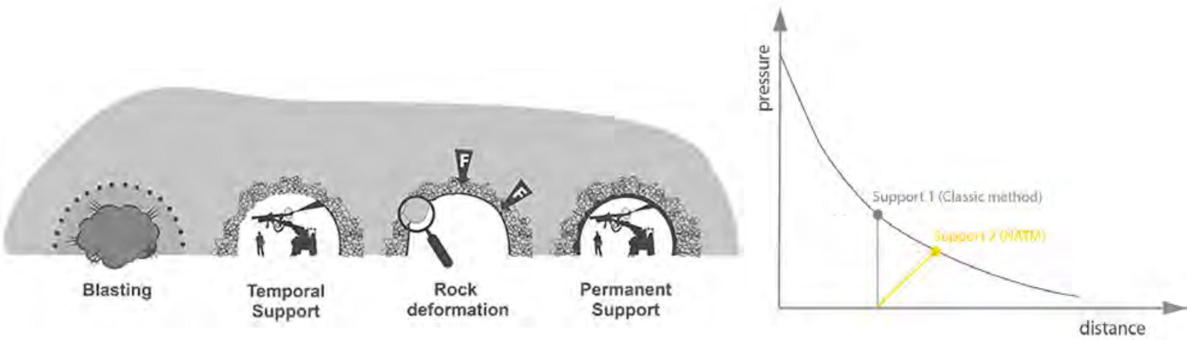


Figure 25: Sequential Excavation Method (SEM) illustrated, left the process steps in SEM (or NATM), right the deformation curve of the rockmass and a comparison of the classic method of direct installation of permanent support versus allowing some rock deformation before permanent support is installed. (Putzmeister, www.bestsupportunderground.com/natm-shotcrete)

By continuous monitoring of the surrounding and supported ground, this method can dynamically meet changing underground conditions and requirements. SEM is often referred to as a "design as you monitor" approach choosing from a wide array of available ground support methods to address any encountered ground condition (Clark et at., 2017).

A TBM is mostly used for large diameter tunnels of over a mile length. The initial investment for the TBM is considerable and increasing as TBMs are becoming more sophisticated. Extensive ground investigation maximising knowledge on local conditions is thus crucial for the specification of the TBM to be used for a specific project. TBMs today are increasingly capable of dealing with very adverse ground conditions and high groundwater pressures while minimising surface impact due to settlement. Tunnel boring technology has advanced such that tunnels can be constructed today which would not have thought possible a decade ago (Clark et at., 2017). An illustration of a typical TBM layout (in this case for a Double Shield TBM from TunnelPro S.r.l., Rome, Italy) is presented in Figure 26 below.Figure 26

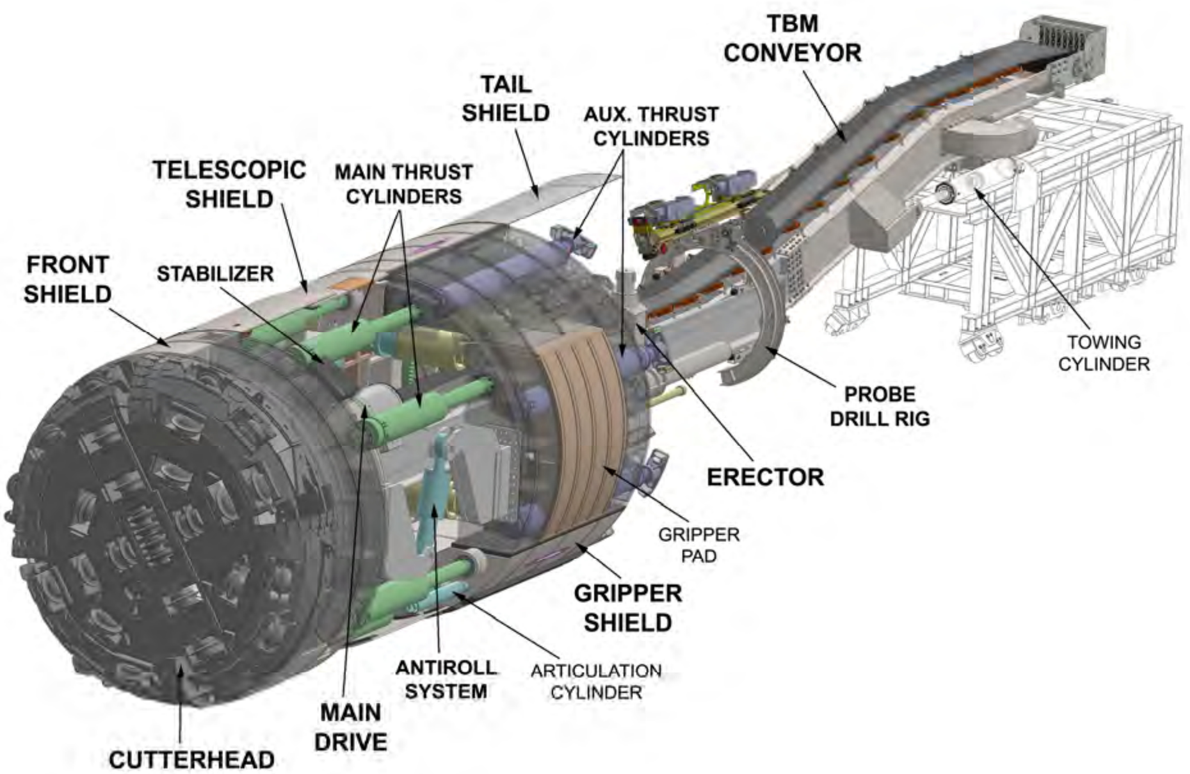


Figure 26: Double Shield Tunnel Boring Machine (TBM) with main components indicated (Tunnelpro, www.tunnelpro.it)

Figure 26 shows the main sections of a TBM which comprise:

- a cutter-head at the front which excavates the encountered ground and/or rock;
- a collection system for excavated material, this can be (relatively) dry (e.g. Earth Pressure Balance TBM) or wet (e.g. Slurry TBM). This removes the excavated material from the cutter-head;
- a shield of some sort to support the fresh tunnel walls directly after excavation and before any tunnel liner is installed (steel or concrete);
- a tunnel liner installation system (erector) which constructs the liner from concrete or steel liner segments which fit together much like a jig-saw puzzle, thus forming a watertight and pressure resistant shell around the tunnel space;
- a system to thrust the cutter-head forward using the installed liner as a support for the reaction forces, hydraulic jacks are often used for this purpose;
- a system to transport the excavated material out of the tunnel, this can be a conveyor for dry material, or a pipeline for slurry;
- a system to transport the liner segments to the erector.

The trends in TBM manufacturing are the ability to safely deal with increasing ground water pressures, increasing diameter of tunnels and so-called multi-mode TBMs. These multi-mode TBMs can operate in multiple operational modes (slurry support, earth pressure support and open face shield) to manage variable ground along the alignment of a tunnel. Where traditional TBMs designed for one of these modes would not be able to construct a tunnel with varying ground conditions, the multi-mode TBM can switch between modes and thus always operate in the optimal mode for the encountered ground conditions. (Weir, 2020)

There are several manufacturers of TBM active globally of which Herrenknecht AG (see also paragraph 3.2.1), Komatsu, The Robbins Company, Akkerman and CREG TBM Germany are well known. The informative website of CREG TBM Germany[9] provides an overview of the most common types of TBMs which are briefly described below:

- An Earth Pressure Balance (EPB) TBM uses the excavated material to support the tunnel face whilst it is plasticised (using additives) to make it transportable and impermeable. The excavated material is then transported away from the cutting action by a screw conveyor allowing control of the earth pressure on the face.
- A Slurry TBM uses pressurized slurry, comprising the excavated material and water, to support the excavated face and balance the ground water pressure acting on the face. The excavated material is removed using a slurry circulation system thus maintaining sufficient pressure at the tunnel face. The pressure on the face can be regulated by controlling the in- and outflow of the pressurized face compartment or by using an air buffer to apply pressure to the slurry acting at the face.
- A Multi-Mode TBM can switch between operating modes such as EPB (for soft ground) and Open Face (for soft and hard rock) or between EPB (for soft/mixed soils) and Slurry (for water rich soils). Multi-Mode TBMs are capable to navigate tunnel routes which encounter variable geology without having to switch equipment and/or excavation methods.
- A Hardrock TBM is aimed at excavating tunnels in (medium/hard) rock and comprises an integrated equipment set for tunnelling, rock support, excavated material discharge and material transport. As such they can be applied, under the right circumstances, in a fast, cost-effective and safe manner using a wide range of sensors and other online data acquisition equipment to control the tunnelling process.
- A Gripper TBM is a type of Hardrock TBM which uses a gripper to deliver the reaction force for the face cutting rather than (hydraulic) jacks pushing on the installed liner as with the previous TBM-types in this list. A Gripper TBM can be used in hard rock environments where a tunnel liner does not need to be installed and the tunnel stability can be ensured with rock bolting alone.
- A Double-Shield TBM combines the main functionality of a Gripper TBM and a shield TBM (such as EPB and Slurry TBMs) in a single machine for use in competent hard rock. By using a gripper shield and tunnel liner system in parallel, the excavation and tunnel lining processes can take place simultaneously. Compared to the previous described TBM types, the Double Shield TBM has a continuous and higher advance rate. This makes this type suited for long tunnels in competent rock. Intervals of incompetent or faulted rock can be navigated by switching to a discontinuous mode which does not use the gripper shield and thus avoids incompetent rock to be damaged by the gripper.

[9] www.creg-germany.com

Apart from these common types, a few less-common configurations are also available in the market:

- Cross Passage TBM: a special TBM used to excavate so-called cross passages between parallel tunnels. This parallel configuration is often used for rail or road tunnels and the cross passages are installed to allow for escape routes and for service purposes.
- Non-circular TBM: tunnel boring machines with a non-circular cross section such as:
  - Horse-shoe-shaped, i.e. circular top and flat bottom section of the tunnel cross section;
  - Rectangular, i.e. a rectangular tunnel cross section with rounded corners in either 'portrait' or 'landscape' orientation (see Figure 29);
  - U-shaped, in practice this relates to an egg-shape with a flattened bottom section.

The non-circular TBM use multiple cutter heads which, combined, cover the non-circular cross section of the TBM, an example of such cutter-head layout is shown in Figure 27. These types of TBM resemble to some extent the so-called continuous miners for the production of thick-seamed coal or salt for example. Continuous miners are further discussed in Section 4.3.

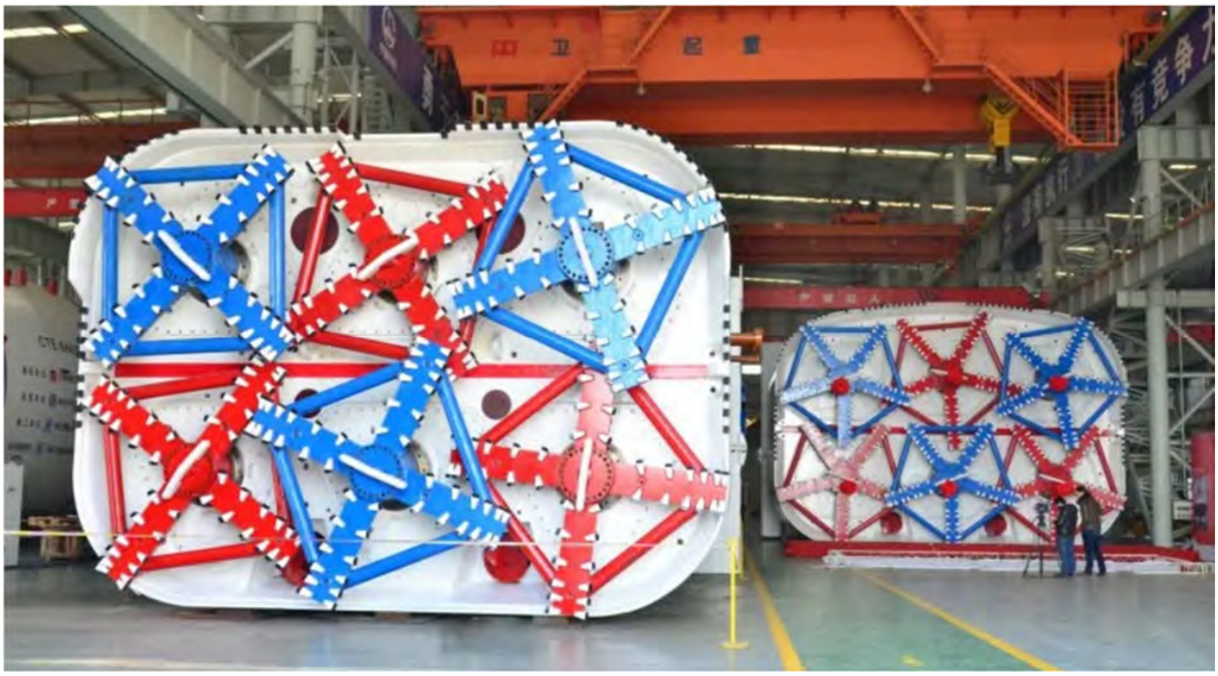


Figure 27: Non-circular TBM: rectangular-shaped with multiple cutter-heads (CREG TBM Germany, Düsseldorf, Germany, www.creg-germany.com)

As in many other industries today, the trend of "data is king" is also present in the tunnelling industry. Extensive ground investigations prior to, and continuous monitoring of a vast range of parameters during, the tunnelling process allow for increasing levels of automation of equipment. Increased data collection and analysis in combination with automation can improve the overall picture of the tunnelling process and evaluate and control a project. As tunnelling projects are increasingly sited in difficult geological conditions, at high groundwater pressures and often underneath highly urbanised areas, the ability to acquire and sustain a complete picture of the tunnelling process and the impact on its surrounding lowers the risk and thereby the initial & long-term costs for a project. (Weir, 2020)

A final trend in the tunnelling industry worth mentioning with regards to robotic mining is micro-tunnelling which is discussed in the next section.

3.3.2 Micro-tunnelling

In micro-tunnelling, the tunnel diameters are becoming smaller with time, and now range from 0,6 m to 2,4 m. Up until the 1970s almost all tunnels, even the smaller diameters (except for auger bores) required an operator at the face (Brierley, 2015). Today, micro-tunnelling is mostly performed unmanned to optimise the utilisation of the smaller diameter of the tunnelling equipment for material transport rather than space for humans to work in. For this and other features, current micro-tunnelling technology holds several interesting analogues for the ROBOMINERS project and is therefore discussed at this point, especially with regard to the methods used for excavating material, the reduction of the grain size of excavated material and the transport of material away from the cutting face.

Currently several companies around the world produce equipment for micro-tunnelling, for instance Iseki Microtunnelling from the United Kingdom, Akkerman from the United States and MTS Microtunnelling Systems from Germany. The last company has developed several product lines of micro-tunnelling equipment which can be considered as analogues for robotic mining. A micro-tunnelling machine could already be considered to some extent as being a robot, namely unmanned and controlled remotely. The material transport system of micro-tunnelling equipment is of interest for robotic mining as is illustrated by the following figure taken from the MTS Microtunnelling Systems GmbH (MTS) brochures (https://mts-tunneling.com/en/). The position of the drive for the cutter head, in this case covering the full face of the micro-tunnelling machine, can be positioned centrally (see left hand picture in Figure 28 below) or peripherally (see right hand picture in Figure 28 below).

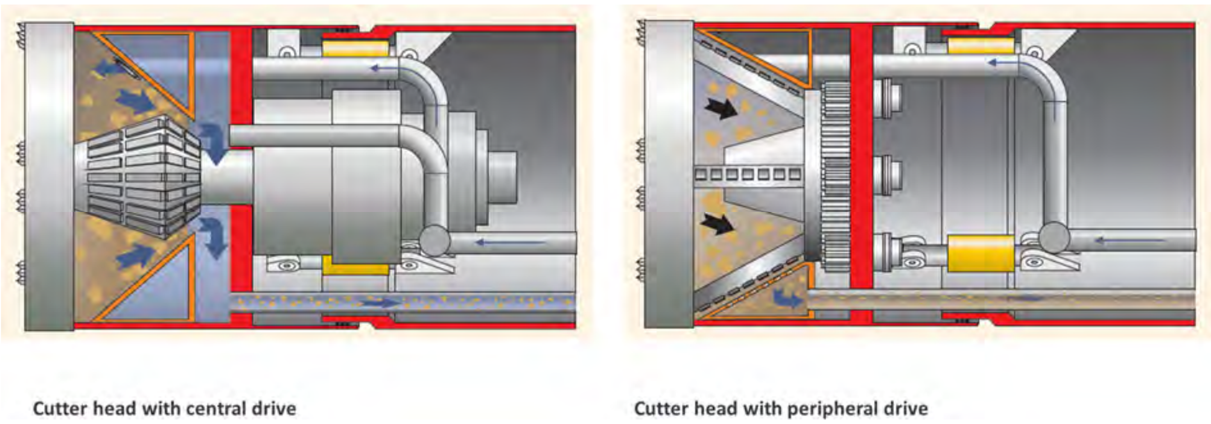


Figure 28: MTS Microtunnelling Systems GmbH – drive types (https://mts-tunneling.com/en/)

3.3.3 Link to Robominers

With reference to the three cutter head designs for a robotic miner as proposed in Figure 20, the peripheral drive system of microtunnelling equipment, see Section 3.3.2, is of particular interest for the full-face and eccentric cutter head layouts of a robotic miner concept. Using a peripheral drive, in combination with a ring gear, could allow for excavated material to pass centrally through the robot. In the layout of micro-tunnelling equipment, the material pass-through is near the bottom of the machine (Figure 28) however for a robot which should be capable to excavate in all directions, including upwards, such orientation of the material pass may not be suitable. A peripheral drive and ring gear combination as envisaged for a robotic miner concept are shown in Figure 29.

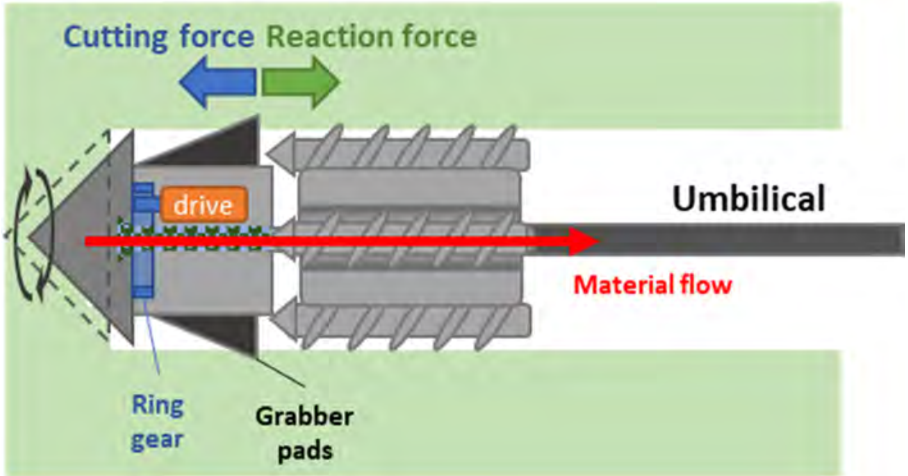


Figure 29: Robotic miner with full face cutter head, peripheral drive and central material pass

The MTS documentation, see Section 3.3.2, presents several operational modes similar to those used by TBMs (see Section 3.3.1). The mtsSlurryTec® system depicted in Figure 30 allows for operation of the equipment in variable ground conditions.

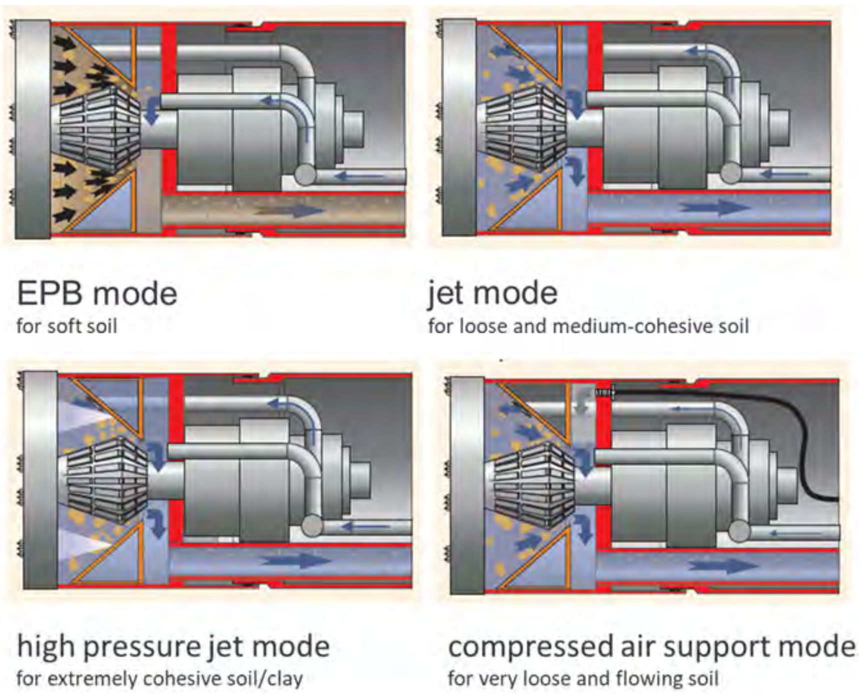


Figure 30: MTS Microtunnelling Systems GmbH – mtsSlurryTec® operational modes for variable ground conditions (www.mts-tunneling.com/en/)

As can be seen from the figure above, MTS microtunnelling equipment uses a full-face cutter head in combination with what is effectively a cone crusher as used in primary comminution of ore in mining processing. The shaft connecting the drive to the cutter head has been equipped with a cone shaped tail end acting as a rotating crusher which forms a gap to the static housing of the cutter head. This gap determines the grain size of the excavated material leaving the space directly behind the cutter head. MTS have also developed a solution for grain size control using the width of this gap as a parameter which can be considered a valuable analogue for robotic mining. This mtsCrushAdjust® system is shown in Figure 31.

Figure 31: MTS Microtunnelling Systems GmbH – mtsCrushAdjust® grain size control by adapting gap width for the "cone" crusher (www.mts-tunneling.com/en/)

The positioning of a cone crusher directly behind the excavation tool in a robotic miner can thus enable hydraulic transport of the excavated material by sufficiently decreasing the grain size. A series of these crushers, perhaps each with their own drive, could provide a primary comminution process within the robot. This is illustrated in Figure 32 where a robotic miner with a full-face cutter, peripheral drives for the cutting and crushing action and a two-stage cone crusher has been conceptualised. When sufficient suction can be created behind the cutter head through a pump, the ore is transported mechanically and hydraulically through the crushers and thus allowing the robot to excavate in any direction.

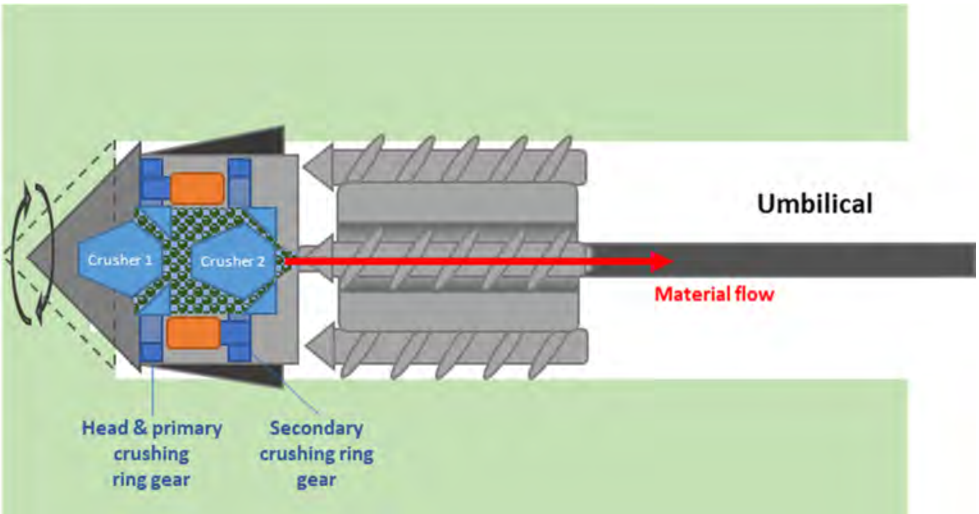


Figure 32: Robotic miner with full face cutter head, peripheral drives and two stage cone crusher

The idea of using a rotating cone in a stationary bowl/funnel as a primary crushing step for excavated ore in the above proposal, is directly based on the MTS micro-tunnelling equipment.

3.4 ROADHEADING

3.4.1 Tunnelling for mining

Creating a tunnel in a mine as part of mine development is called *road heading* and is performed by *road headers*. Full-face road headers used in mining are basically TBMs, as discussed in Section 3.3.1, but are adapted to the mining industry conditions. Road headers are primarily used to develop a mine, i.e. to drive the tunnels used for the mining infrastructure, e.g. conveyor belts, pipelines, cables. They are not commonly used as a means of ore production because infrastructure headings are very often in geological strata above, below or around the ore body (depending on its structure). Full-face ore production is performed by so-called continuous miners as discussed in Section 4.3. The State-of-the-Art roadheading technology, i.e. part-face excavation of tunnels in the mining industry is briefly presented in the following.

An example of a road header as manufactured by Sandvik AB from Sweden for use in hard rock conditions is shown in Figure 33 below. As can be seen, a road header uses a cutter head on a movable boom to excavate material. The boom can be attenuated in three directions allowing for a dome shape cutting envelope. Excavated material drops on the floor below the cutting tool and is collected by the material collection system visible on the lower front of the road header in this figure.

Figure 33: Sandvik AB - MH621 Roadheader for hardrock (www.rocktechnology.sandvik)

Material collection is helped by rotating arms scooping material onto a conveyor belt or chain conveyor running through the centre of the road header. The cutting force applied to the rock face is significant and is compensated for by the weight of the machine. For a part-face cutting machine, the reaction forces of a road header are smaller than for a full-face cutting machine with a similar cutting reach such as TBMs (Section 3.3.1) or continuous miners (Section 4.3). The lower reaction force required allows road headers to be lighter and hence more versatile and mobile. In the mining practice road headers are used in a multitude of applications as a work horse in mine development, maintenance, and process optimisation such as for removing loose rock, re-cutting headings which have converged, rounding corners, removing pillars, etc.

3.4.2 Link to Robominers

Within the Robominers concept for a keyhole robotic explorer/miner as discussed in previous sections, the road header is a strong analogue for the design of a flexible robotic miner/explorer as it is imaginable to miniaturise parts of the road header design. Especially the cutting tool, the boom and the material collection layout can be used as inspiration for robotic miners. This is reflected by the prototype design as illustrated in Figure 11. Considering the prototype design for the excavation tool as developed by the Robominers team (Status as at November 2021, see Figure 34), the idea proposed by Figure 32 can be further adapted as is shown in Figure 35.

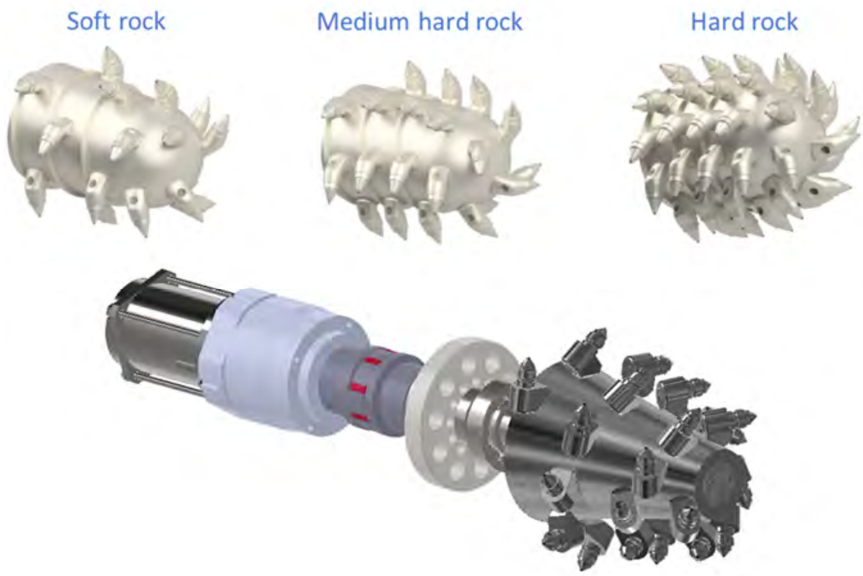


Figure 34: Robominers excavation tool prototype design (November 2021)

In this further conceptualisation, the prototype excavation tool shown above is encased in a mantle which doubles as the inside crushing face for the cone crusher. The outside face forms a funnel around the excavation tool and directs the coarse rock to the secondary crusher housed inside the front of the robot. The complete assembly of drive, crusher, mantle, and funnel thus function as a boom which, provided a suitable coupling can be designed, can move around a pivot. Movement can be accentuated by water hydraulic cylinders as the rest of the drives used in the envisaged Robominers prototype.

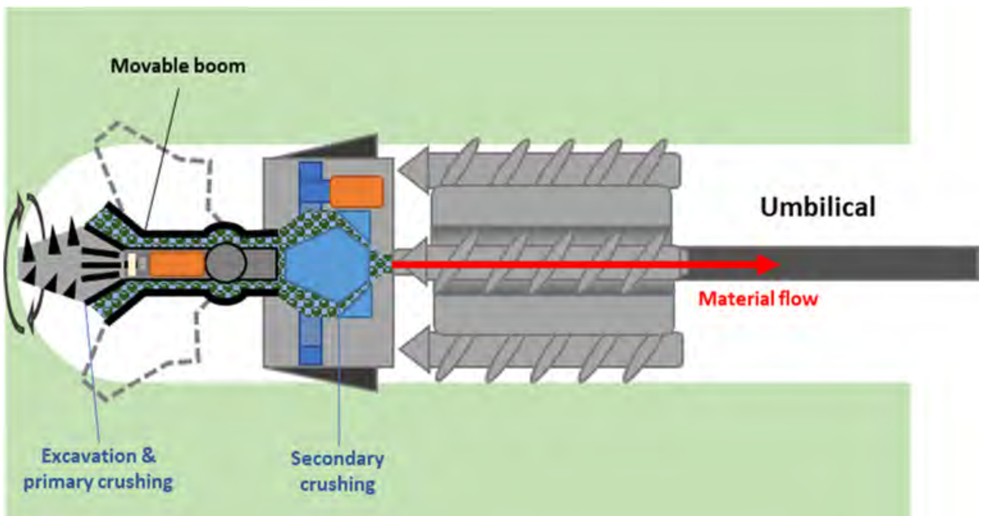


Figure 35: Robotic miner with part-face cutter head, centrally driven and with an integrated crusher, and a secondary crusher downstream.

A variation on the concept presented in Figure 35, which can be directly linked to the layout of a road header, is presented in Figure 36.

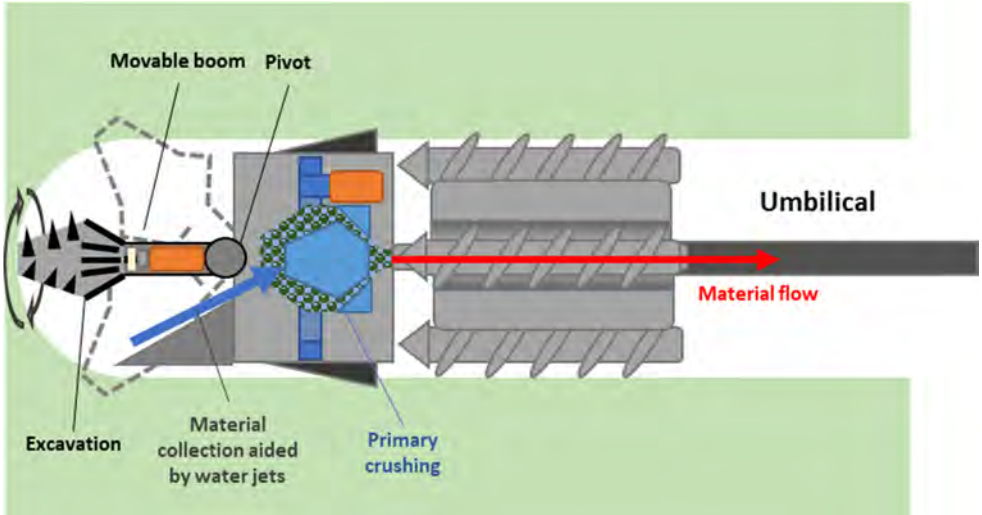


Figure 36: Robotic miner with part-face cutter head, centrally driven, a material collection system aided by water jets and with an integrated crusher downstream.

In Figure 36 the concept for a robotic miner with an integrated cone crusher as presented in Figure 35 is combined with the layout of a road header with regards to the material collection. To this purpose, the robot is equipped with a moveable arm based on the excavation tool prototype design presented in Figure 34 and a material collection system at the lower front of the robotic miner/explorer. The material excavated by the cutting tool drops to the floor and is collected as the robot travels forward by, for instance, rotating arms to be fed to a cone crusher inside the front module of the robot. Water jets can help the crusher feeding process and provide the transport medium for the hydraulic transport of the ore through the umbilical. This layout will only work in a limited range of near-horizontal heading gradients as gravity is used to feed the material collection system.

In addition to the excavation and primary crushing module shown in Figure 36, further robot modules could be added housing further ore processing steps. In this way a train of robotic modules (see Figure 37 below) can be specifically configured to address the geological conditions at hand. When geological conditions are variable in an ore deposit, modules can be replaced or reconfigured to address the changing conditions.

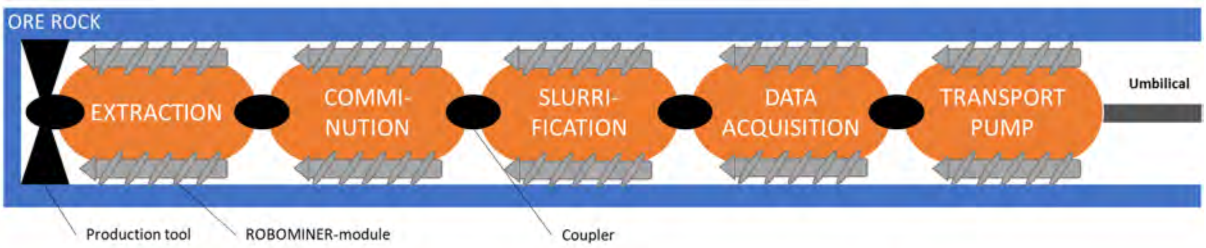


Figure 37: Robotic miner “train” with separate (re-)configurable modules for ore production, primary processing, slurrification of comminuted ore, data acquisition and transport.

3.5 MINING LAYOUTS SUITABLE FOR ROBOTIC MINING

The identified mining layouts suitable for robotic mining as envisaged by the Robominers team and discussed in the following sections, have been based on the roadmap for robotic explorer/miner technology deployment (Figure 2). The mine layout in an abandoned mine is, dependent upon the mining methods used and the deposit geometry, defined and probably follows one of the conventional designs such as those described in Section 4 of deliverable D2.2. However, extending mineral extraction into new areas by robotic mining allows some relative freedom in selecting the most appropriate mine layout for robotic mining.

A layout suitable for robotic mining will be different from a traditional layout as the envisaged robotic mining equipment is smaller than traditional mining equipment. The exploitation of small, thin-bedded or otherwise unfavourable geometries can be envisaged using such small robotic mining equipment. Second, the safety requirements for robotic mining can be adapted to the fact that human presence in the mined openings does not have to be considered. As the robots represent a considerable investment, the safety requirements will still need to be sufficient to avoid loss of capital due to, for example, roof collapse.

In a new mine developed for robotic extraction of a small mineral deposit the objective of mine planning is to choose the most efficient and most mechanically stable mine layout, subject, of course, to the robot capabilities, deposit geometry and other physical and chemical properties of the ore material. Conventional mine layouts include (not an exhaustive list):

- open stoping and shrinkage stoping (with or without backfill)
- cut-and-fill stoping
- caving (including block caving and sub-level caving)
- room-and-pillar mining
- longwall mining

Any of these layouts can be adapted for robotic mining operations in theory, though in methods such as shrinkage stoping (Figure 38) or cut-and-fill stoping (Figure 39), where mining equipment rests on either broken ore or backfill material, this material must be sufficiently solid to support the robot. For the case of shrinkage stoping this will significantly challenge the perception and locomotion capabilities for the robot as the terrain to manoeuvre is very rough and especially unpredictable.

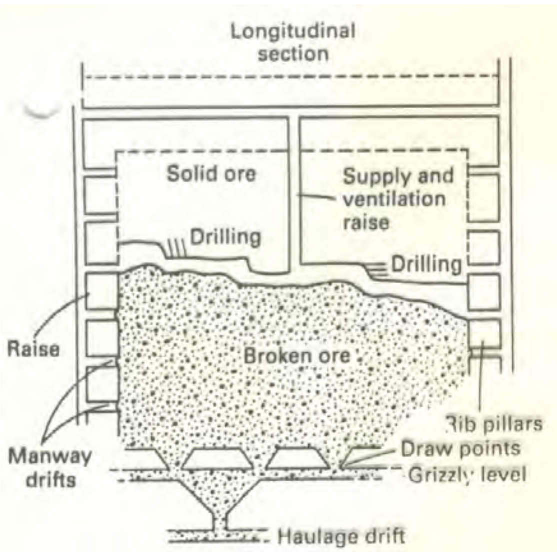


Figure 38: Shrinkage stoping (after Harraz, 2010)

For cut and fill stoping (Figure 39), which can be considered the most traditional mining method for selective vein mining, these challenges of perception and locomotion for a robotic miner are significantly smaller. The backfilled material can be engineered to providing sufficient bearing capacity for the robot and the backfilling method can be planned in a way that the surface of the backfill is largely flat and predictable.

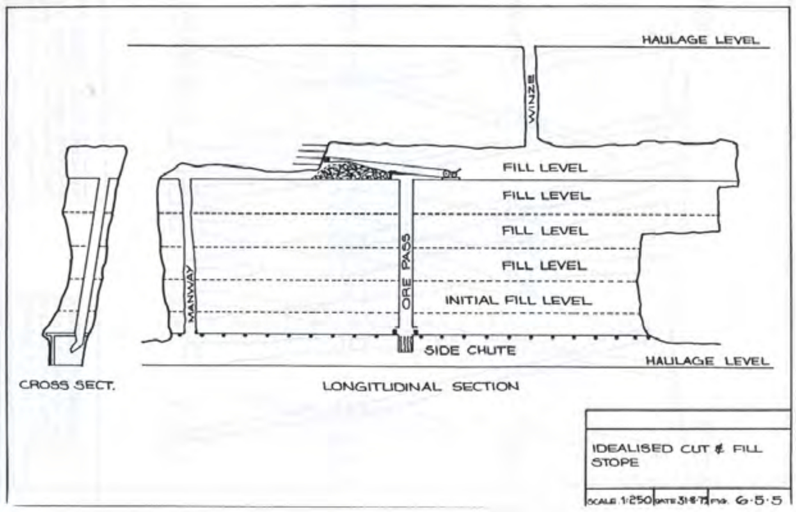


Figure 39: Cut and fill stoping (after Western Mining, 1979)

Considering new robotic solutions in mining, innovative and new mine layouts could also be envisaged, such as those that are bio-inspired (Section 6 of deliverable D2.2). Of the bio-inspired examples presented there, a mining layout inspired by the Dactyloidites (Figure 40) is particularly suiting the keyhole mining robotic miner concept proposed by the Robominers project. As can be seen in Figure 40, pictures B and C, the access to the extraction “panels” (Figure 40D) is a singular access tunnel. The extraction panel is thus a fan of short tunnels developed from a single access point, i.e. a keyhole.

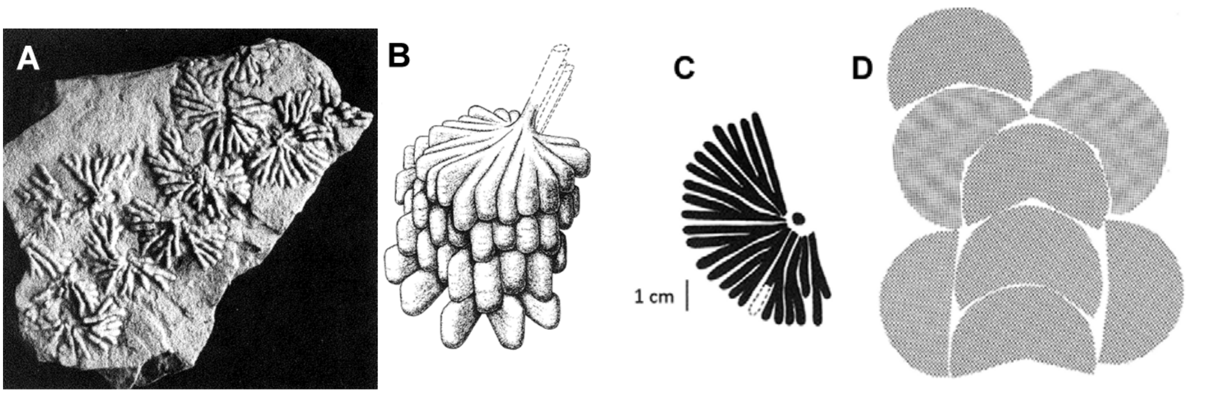


Figure 40: Dactyloidites trace fossil as a mining layout inspiration. A: Photograph of a *Dactyloidites* trace fossil with several rosettes. B: Perspective sketch of (A) a rosette of burrows. C: Sketch plan view of one rosette. D: How rosette mining layouts might fit together for mineral extraction.

This layout allows for the further development of concepts for robotic miners inspired by drilling and (micro-) tunnelling technology presented in Sections 3.1, 3.3 and 3.3.2 as is presented in Figure 41. Through a combination of directional drilling technology (Section 3.1.4) and a modular robotic miner which can be deployed in an enlarged borehole (Figure 12) the mining sequence illustrated in Figure 41 can be envisaged. During the directional drilling phase, the main access branches are created while mapping the deposit. The resulting small-diameter boreholes can be used as pilot holes for the robotic miner during the mining phase. The multi-tracking technology discussed in Section 3.1.4 allows for multiple branches off the main keyhole access borehole. These branches can be organised vertically, shown in the top left picture in Figure 41, and horizontally, as shown in the bottom picture. From the main branches, the fan-shaped production panels are developed.

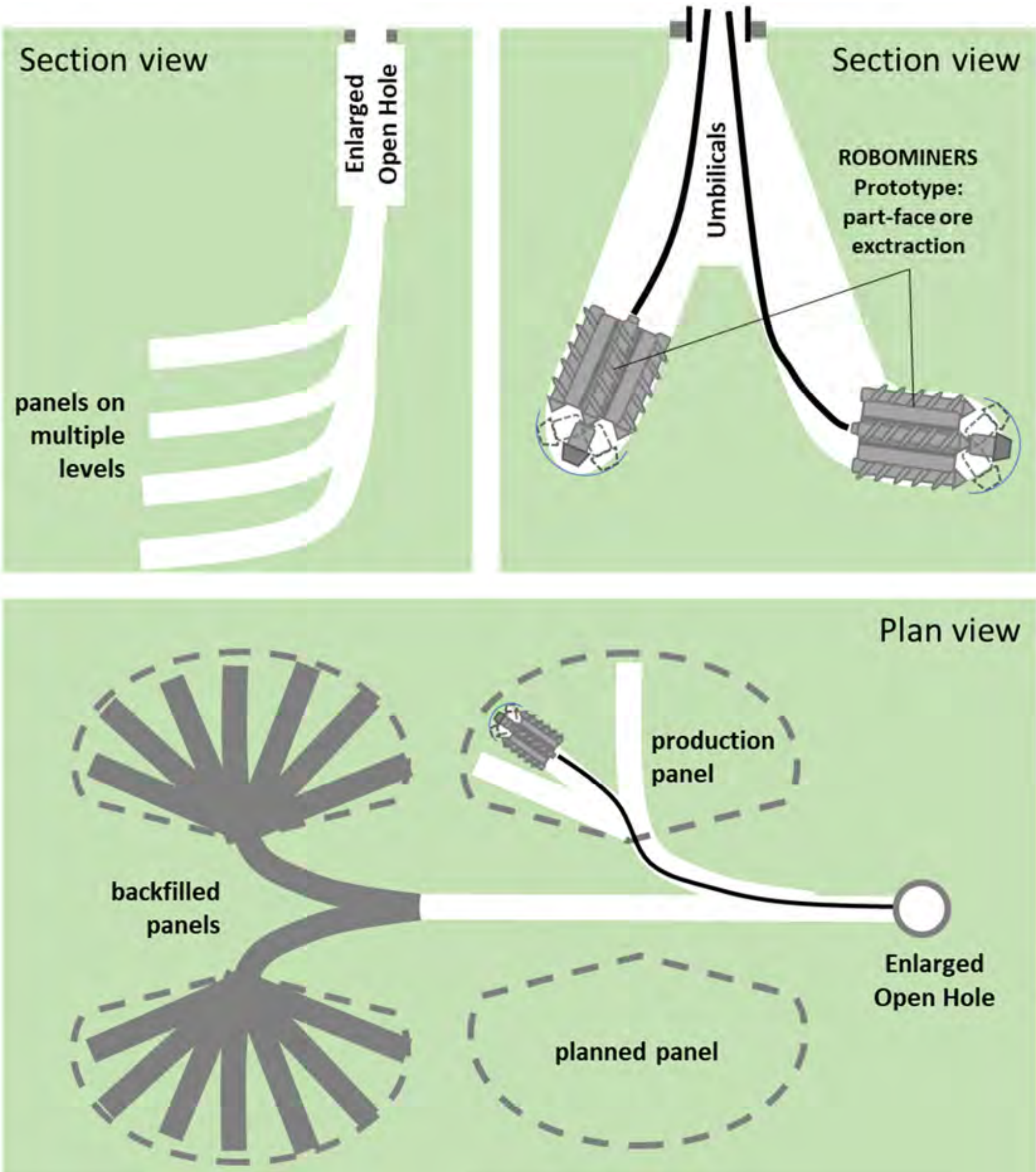


Figure 41: Bio-inspired mining layout based on Dactyloidites' rosettes using a part-face cutter head on a tethered robotic explorer/miner in a keyhole mining operation

As the extraction rooms in the fan are fairly short relative to the main branches, a robotic miner with two modules which can be pushed apart by a hydraulic ram can be further envisaged. The robotic miner would then excavate the main branches while the umbilical is continuously extended. The panel production does not require the length of the umbilical to change thereby easing the mining operation. This concept is further illustrated in Figure 42.

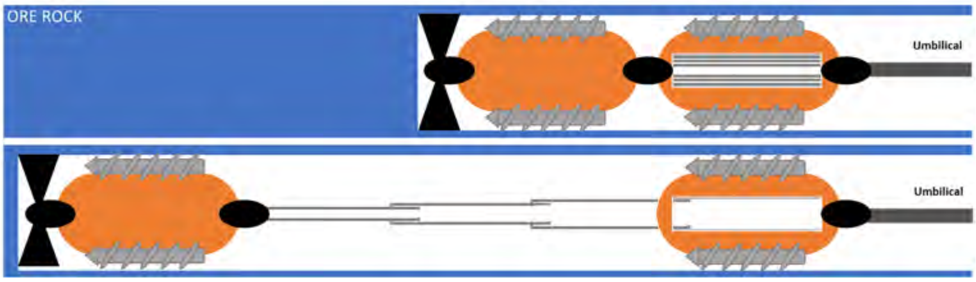


Figure 42: "Short stroke" robotic miner locomotion using a hydraulic ram between two modules

Another potentially innovative mining layout suitable for robotic mining would be the so-called "honeycomb" mining layout (Figure 43), with close-packed cylindrical extraction openings (raises) leaving support pillars between them. Shown in this figure is an analytical model of three-dimensional structure of pillars in convergent "nature-like" geotechnology with parallel arrangement of stopes: Z, X, Y—coordinate axes; σ_z, σ_x, σ_y—principal normal stresses; τ_{xy}, τ_{xz}, τ_{yz}—shear stresses (Eremenko et al, 2020).

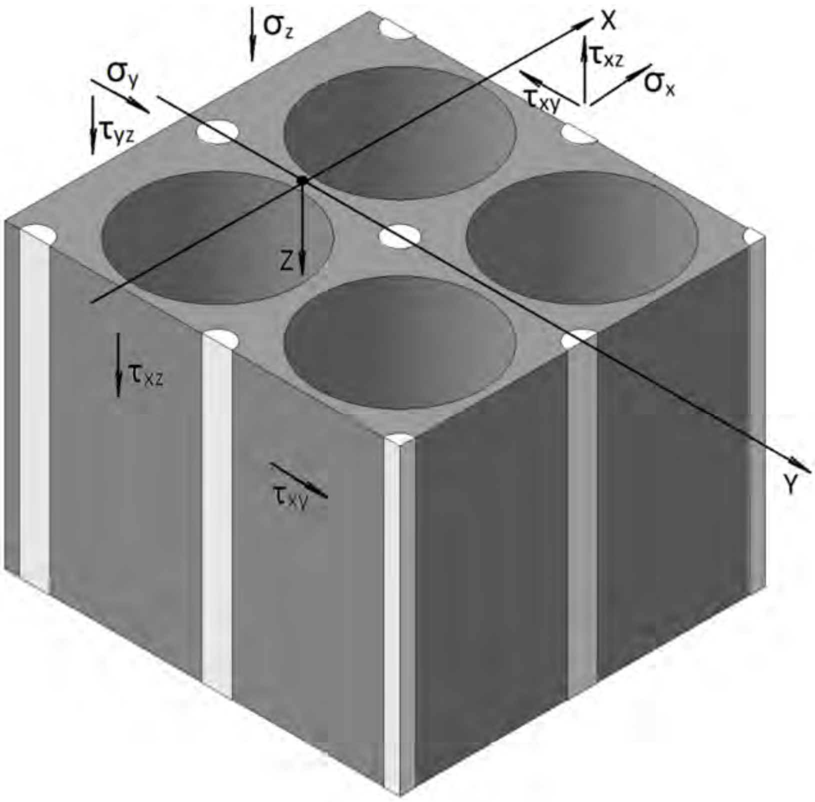


Figure 43: Honeycomb mining: cylindrical raises leaving pillar supports (after Eremenko et al, 2020)

The raises can be developed by robotic miners comprising separate modules for different functions such as ore extraction, primary processing, and data acquisition (Figure 37). General access to the raises can be provided from both the top and the bottom through larger sized tunnels, possibly extending from an existing mine. The access tunnels on the bottom side can be used for ore transport as gravity will then aid the transport of ore away from the robotic miner excavating upwards. The access on the top side of the honeycomb can be used to backfill the raises with the waste products of primary and/or secondary ore processing. When the primary processing is performed underground, either by the robotic miners themselves or by equipment positioned in the bottom access tunnels, the waste material from primary processing can be directly backfilled thus lowering the volume of material that needs to be hoisted the ground surface for secondary processing.

It is unlikely that secondary processing of ore, i.e. from a primary concentrate to a marketable product, will be performed underground for the foreseeable future due to the large size of ore processing plants and the perceived impracticalities of placing an elaborate plant underground. In a more futuristic vision however it may seem beneficial to also integrate secondary processing in the underground components of a robotic miner eco-system to save space on the ground surface. This would be of particular interest to mining operations in urbanised areas. In the case secondary processing is done at a processing plant on the surface, further waste material will need to be disposed. This material could be hydraulically transported back underground and used as a second source for backfill material for the vertical stopes. The carrier medium for the solid backfill material can either be drained through the bottom access or left in-situ if a binder is added to the backfill suspension which chemically binds up the liquid. The just described concept of using the honeycomb mining layout with robotic miners is presented in Figure 43.

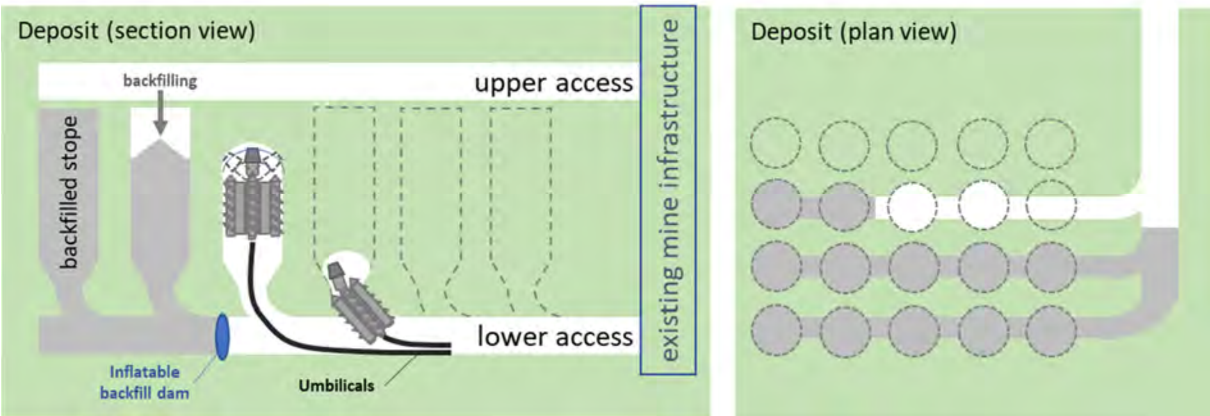


Figure 44: Honeycomb mining layout using a part-face cutter head on a tethered robotic explorer/miner as an extension of an existing mining operation

It needs to be noted that variations on and combinations of the concepts presented in Figure 41 and Figure 44 are also possible, depending on the local circumstances and final capabilities of the robotic mining equipment envisaged by the Robominers team (when available).

4 MINING ANALOGUES: MINERAL EXTRACTION

4.1 EXCAVATION METHODS COMMONLY USED IN MINING

Generally, excavation systems commonly used in the mining industry can be divided into drill and blast, mechanical excavation systems, alternative excavation systems and combined excavation systems, see the schematic in Figure 45 below.

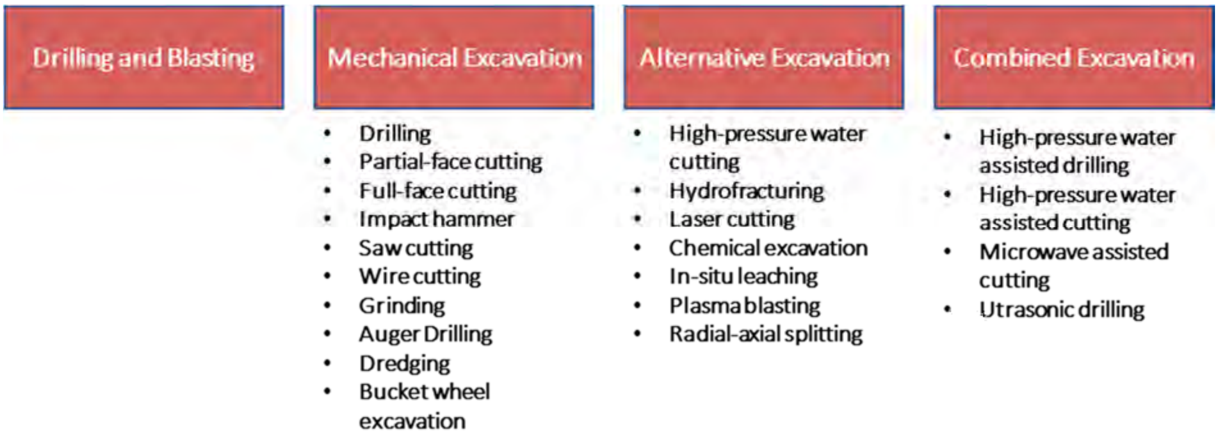


Figure 45: General classification of excavation methods

The drill and blast method is one of the most used excavation technologies due to the generic applicability in mining and tunnelling further to its high production rate. In addition, the ability to excavate very hard rock with considerably low capital costs makes it inevitable in the mining industry. Mechanical excavation systems are at least equally popular compared to drill and blast and exhibit some benefits, such as a safer operation, a better ability for selective mining and continuous material excavation. The majority of mechanical excavation systems are full-face and part-face cutting methods. Full-face cutting machines mainly consist of tunnel boring machines (TBMs), whereas road headers or continuous miners are considered part-face cutting machines - to mention some examples.

Alternative excavation systems cover non-conventional excavation methods (water cutting, hydrofracturing, laser cutting, saw cutting, etc). The main application areas are precision tasks, pre-weakening of the rock to be excavated (used in combined excavation systems) and tasks for which the ambient conditions do not allow conventional methods. Combined excavation systems unite the advantages of mechanical excavation systems with alternative, auxiliary methods. Auxiliary tools provide an additional energy input to pre-fracture the rock or to amplify the effect of the mechanical excavation system. The current state-of-the-art technologies are not profitable due to very high specific energy requirements (Bilgin et al. 2013, Sifferlinger et al. 2017).

Depending on the excavation and mining method being used, different infrastructure, material processing and conveying technologies are applied. Figure 46 Figure 46 shows a comparison between the operating cycles of drill and blast and mechanical cutting. The left picture of Figure 46 shows the typical tasks of a drill and blast cycle:

(1) Drilling of boreholes
(2) Loading the explosives
(3) Blasting
(4) Venting of the blast gasses
(5) Hauling and transportation of the muck
(6) Scaling (Removing of loose material)
(7) Installing roof support

The right picture shows the operating principles of mechanical cutting, basically consisting of:

(1) Excavating the rock accompanied by simultaneous loading and conveying
(2) Installing Roof support

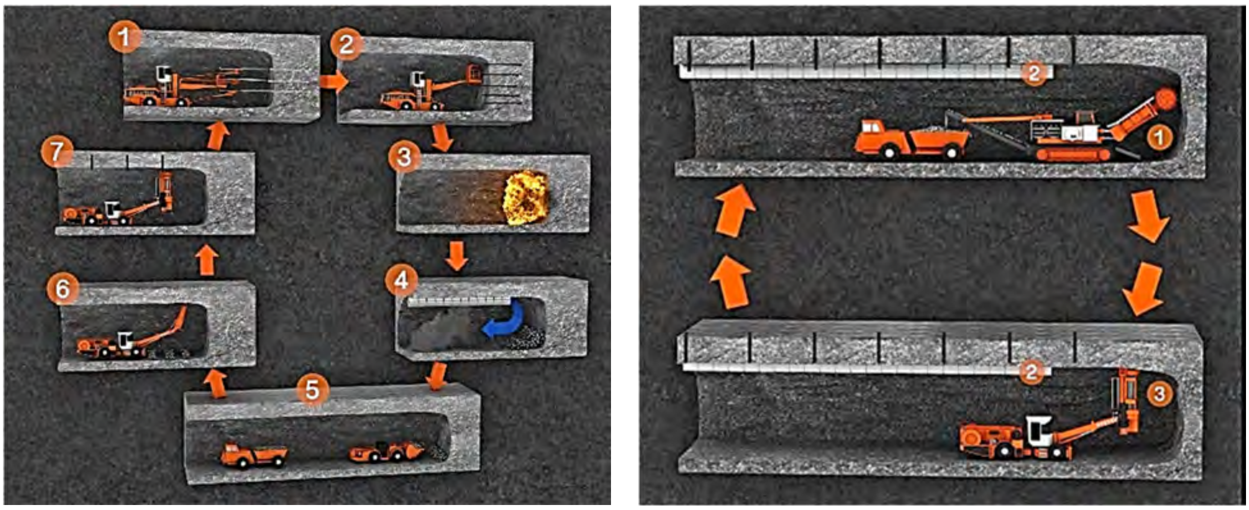


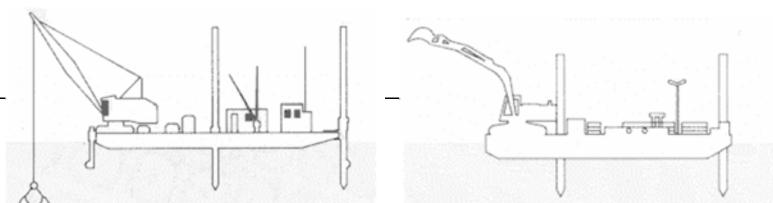
Figure 46: Comparison of excavation by drill & blast (left) and mechanical cutting (right)

As can be seen, drill and blast operations require more individual tasks than mechanical cutting. Future challenges in mining due to sustainability and ecological aspects require additional efforts in research and development. With the help of fully automated machines and/or autonomous robots, new deposits can be accessed, or abandoned mines can be re-opened and operated economically. Possible tasks for robots in mining are the maintenance of machinery, exploration (e.g. of abandoned mines) and excavation (especially in difficult to access areas). Depending on mine layout, mining method and numerous other parameters, the design of autonomous robots can be drastically different compared to the current machinery. Outdated paths may have to be left to create room for thinking outside the box and to develop innovative solutions which assist making future mining more sustainable and economical. The future scenarios require novel approaches and adaption of existing technologies. In particular, current excavation technologies must be assessed with new standards in order to fulfil the upcoming criteria (Hiltz 2020, Siciliano 2016).

4.2 MINERAL EXTRACTION ANALOGUES FROM DREDGING

Dredging is defined by the various dredging associations, (e.g. European Dredging Association (EuDA), Central Dredging Association (CEDA)), as the process of removing material from one part of a water (submerged) environment and relocating it to another. It is a very common and old civil engineering task used, for example, to create and maintain ports and waterways, recover valuable material or assist in infrastructure construction and land creation. Some of the modern State-of-the-Art dredging equipment is of particular interest to the ROBOMINERS project as it specialises in the excavation of material in a wet environment, which is the preferred environment for robotic mining as discussed in paragraph 1.2, and is able to excavate rock rather that loose soils.

Vlasblom (2002) distinguishes between mechanic and hydraulic excavation and, subsequently, mechanic and hydraulic transportation of the excavated material. Mechanical dredgers are, for example, equipped with a bucket ladder excavator, a backhoe excavator or a grab such as illustrated below.



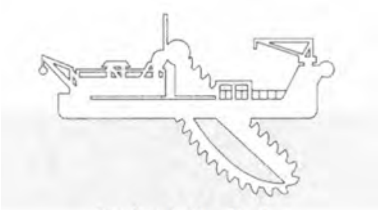


Figure 47: Mechanical dredger equipment (from: Vlasblom 2003)

Hydraulic dredging equipment is used for non-cohesive materials, e.g. loose sand and/or silt, and uses the force of water flow to loosen the material. Hydraulic dredgers are the plain suction dredge, cutter dredge and trailing suction hopper dredge as illustrated below.

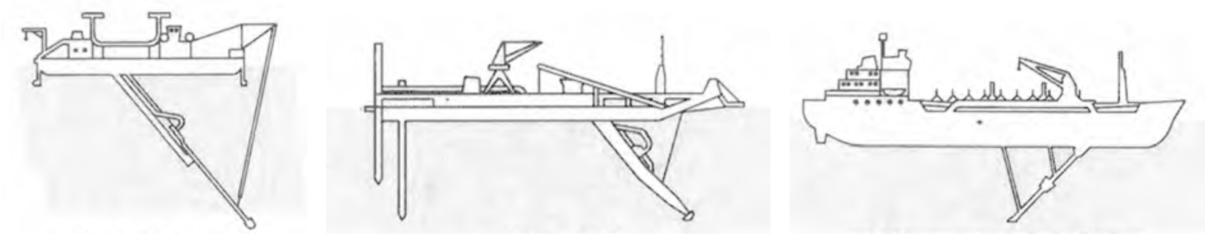


Figure 48: Hydraulic dredger equipment (from: Vlasblom 2003)

Except for the trailing suction hopper dredger, all shown dredger types, are operated from a stationary position aided by anchors and/or “spuds”/”spud poles” (the latter are shown as pointed vertical “poles” in Figure 47 and Figure 48) (Vlasblom 2003).

In particular, the cutter dredger used for excavating submerged rock material provides valuable insights in potential ways to excavate and slurrify rock for robotic miners. The design of a trailing suction hopper can also provide inspiration for a robotic excavation system, in particular regarding the collection system for excavated ore. More detailed views of a cutter head used in a cutter dredge and a so-called “draghead” used in a trailing suction hopper, both manufactured by Royal IHC from The Netherlands, are shown in Figure 49.

Figure 49: Cutter head for cutter dredger (l) and draghead (www.royalihc.com)

The cutter head and draghead shown in Figure 49 are connected hydraulic material handling system which is shown in detail in Figure 50 taken from the Royal IHC documentation (www.royalihc.com). In this figure, the several components of the material handling system are indicated with numbers. The most important of which are:

1. Cutter head, to excavate material
2. Onboard pump, to boost the material flow for long distance transport (via 7 and 8)
3. Submerged pump, to lift the excavated material from the cutter head to the onboard pump (2)
4. Onboard rubber hose, allowing one degree of freedom for the cutter head boom and connecting the onboard piping (5)
5. Onboard piping, connecting the components of the material handling system
7. Turning gland, allowing one degree of freedom for the vessel rotating around its piles
8. Floating rubber hoses, floating pipelines, floaters, ball joints, for long distance transport

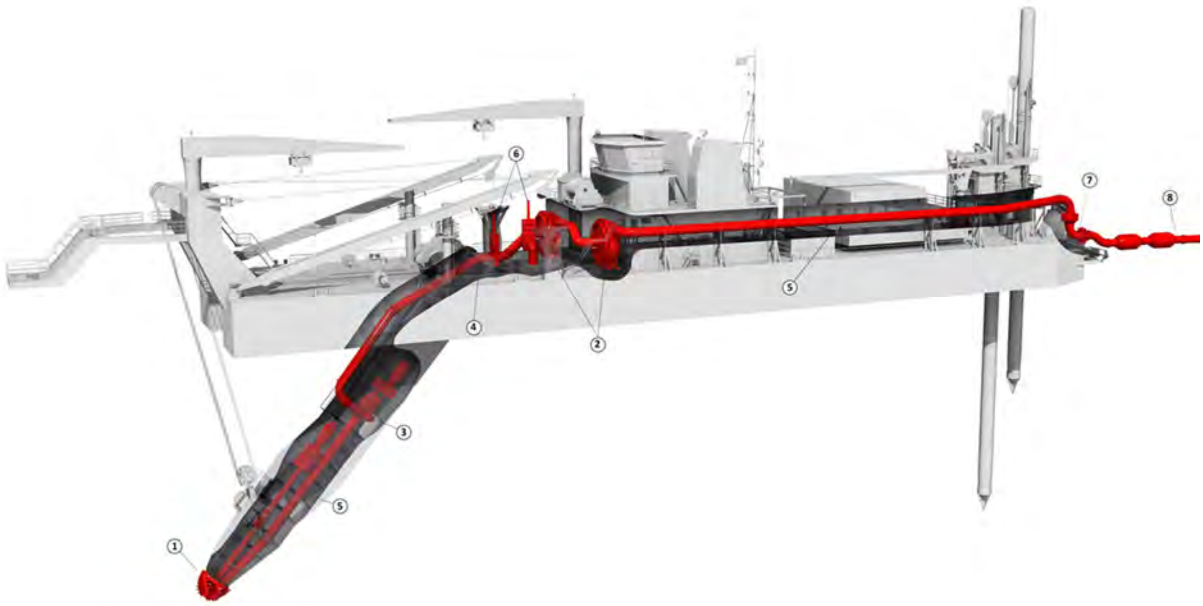


Figure 50: Hydraulic material handling system of a cutter suction dredger (www.royalihc.com)

The layout shown in Figure 50 of a hydraulic material transport system used in, for example, a cutter suction dredger can be considered as an analogue for a submerged robotic miner eco-system.

4.3 CONTINUOUS MINERS

Continuous miners are used in the mining industry to excavate massive, thick-bedded, usually flat-lying, ore deposits such as coal and (potash) salt. They can be equipped by part-face or full-face cutting heads. Using continuous miners, galleries can be excavated which are several meters high and wide. A few examples of continuous miners used in the mining industry are shown in Figure 51. Due to the massive reaction force required to cut over the full width or the full face of the excavation, continuous miners are some of the heaviest underground mining equipment in use for excavation. The sheer weight of the machine allows for the cutting forces to be compensated.

Figure 51: Examples of continuous miners: (left) XCEL 4-ROTOR CONTINUOUS BORING MINER from Prairie Machine & Parts Mfg (www.prairiemachine.com), (right) "Ural-20R" heading-and-winning machine from JSC «Kopeysk Machine-Building plant» (www.kopemash.ru/en), (bottom) 12CM12 continuous miner from Komatsu Mining Corp. (www. mining.komatsu)

Continuous miners can load the excavated material via an internal conveyor belt onto a shuttle car as shown in Figure 52. Several shuttle cars will cover the distance between the continuous miner and the nearest conveyor loading point.

Figure 52: Example of a shuttle car: TC790 Shuttle car from Sandvik AB (www. rocktechnology.sandvik)

Underground material transport methods are further discussed in Section 6, however the use of continuous miners as the basis for a robotic mining eco-system can be imagined and is therefore further elaborated in the next section as a potential analogue.

4.4 LINK TO ROBOMINERS

Several research and development projects are dealing with the development of robots for mining and exploration purposes. Examples of such research projects are UNEXMIN[10], UNEXUP[11] and PIPEBOTS[12] to name a few. Precision mining requires smaller robotic machines. However, their small weight and low available power comparing to classical mining machines are the most limiting factors and therefore require new approaches – in addition to adaptions to commercial off-the-shelf (COTS) products. The interaction between an excavation tool and rock creates reaction forces, which the machine needs to be capable of handling. Excavation methods can be separated into drill and blast, mechanical, alternative and combined excavation technologies. Whereas the first two listed are the most commonly applied in standard excavation engineering, the latter two are potentially interesting for a robotic miner eco-system. To ensure an efficient and economic application of robotic miners, the excavation tool needs to fulfil a multitude of requirements such as reasonable advance and excavation rates as well as flexible and mobile handling to adapt to the in-situ conditions, especially considering the scenario of small-scale deposits as discussed in paragraph 1.1.3.

Dredging

With reference to the mineral extraction analogue from the dredging industry presented in Figure 50 and using the prototype of the Robominers robotic explorer/miner as a basis, see Figure 11, a hydraulic material collection and transport system for this prototype can be envisaged as illustrated in Figure 53. In this figure, the robotic miner uses an excavation tool similar to the cutter head shown in Figure 49. The cutter head is connected to an arm which has three degrees of freedom and can thus create a dome-shaped production face. The drive for the cutter head is integrated into the arm, which in turn can be actuated using hydraulic muscles or rams.

As shown in Figure 53 there are two concepts proposed for the collection of excavated material:

- Cutter aided collection whereby, analogous to a Cutter Suction Dredger, the excavated material is pulled into the space behind the cutter head by the cutting action and subsequently sucked into hoses by a suction pump in the robot, analogue to the submerged pump ((3) in Figure 50).
- Floor collection whereby, analogous to a Trailing Suction Dredger, the excavated material is picked up from the floor of the excavation by a purpose-designed suction head. The suction is again provided by a suction pump in the robot.

The design of the Robominers prototype for a robotic explorer/miner has four compartments available between the Archimedes' screws, it thus can be imagined that a type of eccentric screw pump, for example one described on the following URL: https://www.wagner-group.com/en/guide/our-technologies/screw-pumps/, can be used as a suction pump due to its elongated shape. It is unlikely that the suction pump(s) alone will deliver sufficient pressure to transport the excavated material to the earth surface without further boosting like the onboard pumps ((2) in Figure 50). Further eccentric screw pumps in the robot itself and/or booster pumps at the end of the tether could enable a continuous hydraulic material system from the robotic miner up to the surface.

[10] www.unexmin.eu
[11] www.unexmin.eu/unexup/
[12] pipebots.ac.uk

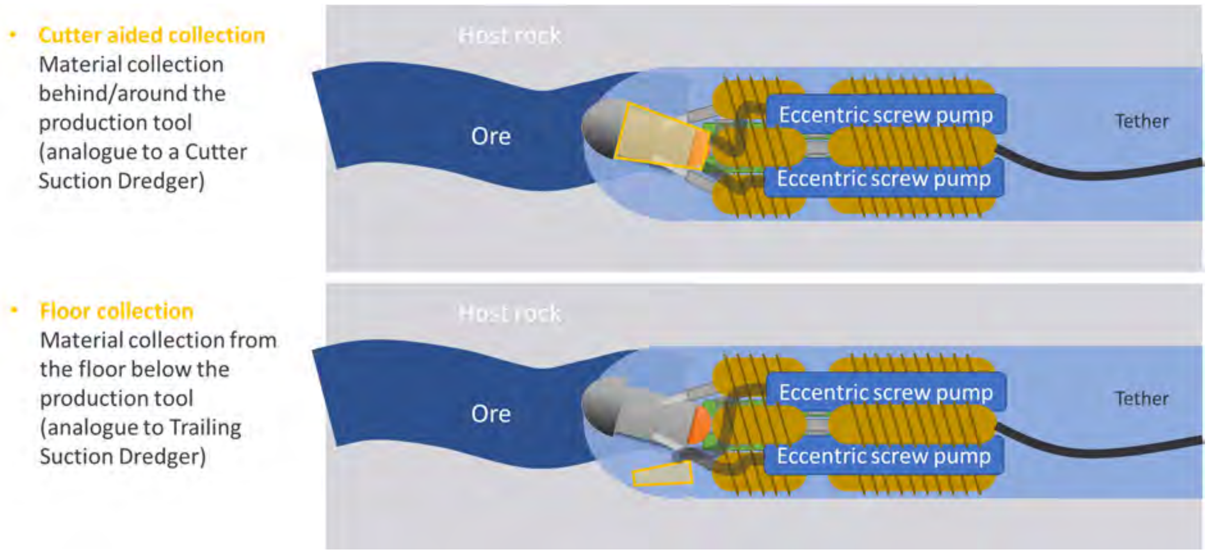


Figure 53: Analogues from dredging technology for material collection by a robotic miner

A hydraulic transport system as shown in Figure 53 is only possible if the suction capacity of the pumps and flow diameters of pipes and hoses are in perfect alignment with the cutting action. For example, when the material is cut too coarse the pumps may not be able to produce sufficient suction to pick up the material or to pump the material slurry to the booster pump. When the material is cut too fine, or fines are excessively produced by the cutting action, the viscosity of the slurry may become too high for the pumps to handle. It is thus paramount for the development of the robotic miner equipment to either have a very good understanding of the ore and host rock properties, or to have a modular design with interchangeable parts, especially cutter heads, to accommodate for variable rock conditions. This consideration is further elaborated in Section 6.1 on continuous material transport methods.

Continuous Miners

With reference to continuous miners as a mineral extraction analogue (Section 4.3), shuttle cars are usually used for the purpose of tramming material from the continuous miner, which is always advancing and thus moving, to the static conveyor belt loading point. The layout of the galleries and the mining sequence is designed to accommodate the intricate movements of the continuous miner(s), shuttle cars, support installation equipment and any other service equipment needed for such an operation. As such the continuous miner is not an obvious analogue for the robotic miner/explorer concepts proposed in previous section as a continuous miner cannot easily be deployed in a keyhole mining situation as proposed by the Robominers project (Section 3.1. Referring to the robotic explorer/miner development and deployment roadmap provided by Figure 2 in the Introduction of this report, the use of fully automated, remote controlled continuous miners can be imagined for industrial deployment in the 20+ year time frame.

Although automation of a continuous miner equipment can be imagined, the overall automated operation with independent shuttle cars is complex from a control and maintenance point of view. Furthermore, although large scale automated mining equipment may operate largely without direct human interaction, it can be hardly imagined that maintenance can also be automated for the foreseeable future. Nonetheless, operating continuous miners without human interaction for the majority of a 24h day and allowing for short maintenance intervals can minimize human exposure to adverse underground conditions and should thus be discussed in this report on potential analogues for robotic mining.

Automation and later autonomous operation of a robotic eco-system based on continuous miners is further aided by a direct (conveyor) link between the continuous miner and the (semi) static main conveyor infrastructure. Such a highly flexible and continuous transport system is available in the market today from Prairie Machine & Parts Mfg, Canada. Their Flexiveyor system comprises an "endless" series of linked, mobile conveyor belts that can manoeuvre much like a snake. The Flexiveyor product is shown in Figure 54 below.

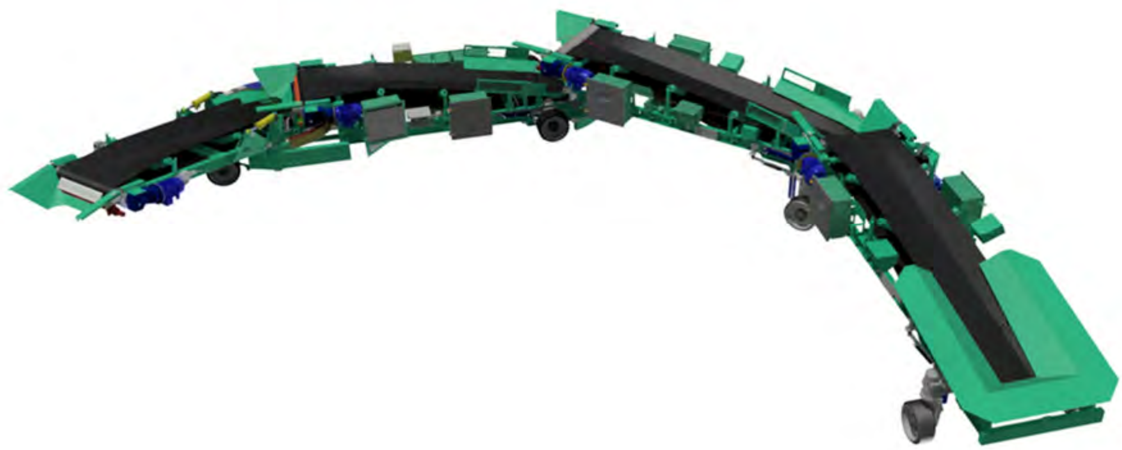


Figure 54: Prairie Machine & Parts Mfg – Flexiveyor – a highly flexible linked, mobile conveyor

The Flexiveyor picks up material from the advancing continuous miner while keeping pace with it. Material is conveyed over the linked conveyor cars until it reaches the discharge car at the other end. Driving the discharge car parallel along a main conveyor belt allows for discharge at any point along the main conveyor and thereby compensating for the advance of the continuous miner.

The excavation and material handling technologies just discussed can, possibly, be made self-driving and be equipped with geophysical exploration equipment as discussed in Section 2 thus allowing for a high degree of autonomous ore following. Robotic continuous miners and "Flexiveyors" could allow for the excavation of massive, thick bedded ore deposits, such as potash, which are strongly variable/undulating and therefore unpredictable. Also, the depth at which robotic continuous miners can likely operate will greatly exceed the depth at which humans can work for a full shift. Robotising continuous miners and their related infrastructure could therefore potentially unlock previously unattainable unpredictable and/or ultradeep resources (see also Section 1.1) especially as an extension or optimisation of an existing mining operation. The additional use of backfill could furthermore allow for a secondary mining phase in which the initial pillars left between galleries are also mined. For example, potash fertiliser production produces a large quantity of sodium chloride as a (nonsaleable) by-product, illustrated by large heaps of sodium chloride salt near to potash mining operations such as K+S AG in the Werra region in Germany or UralKali in the Perm region in Russia. This by-product can be used as a raw material for backfill thus enabling a near 100% extraction ratio as illustrated in the concept proposed by K-UTEC AG Salt Technologies at several occasions to improve productivity and mitigate environmental impact for potash mining (Figure 55).

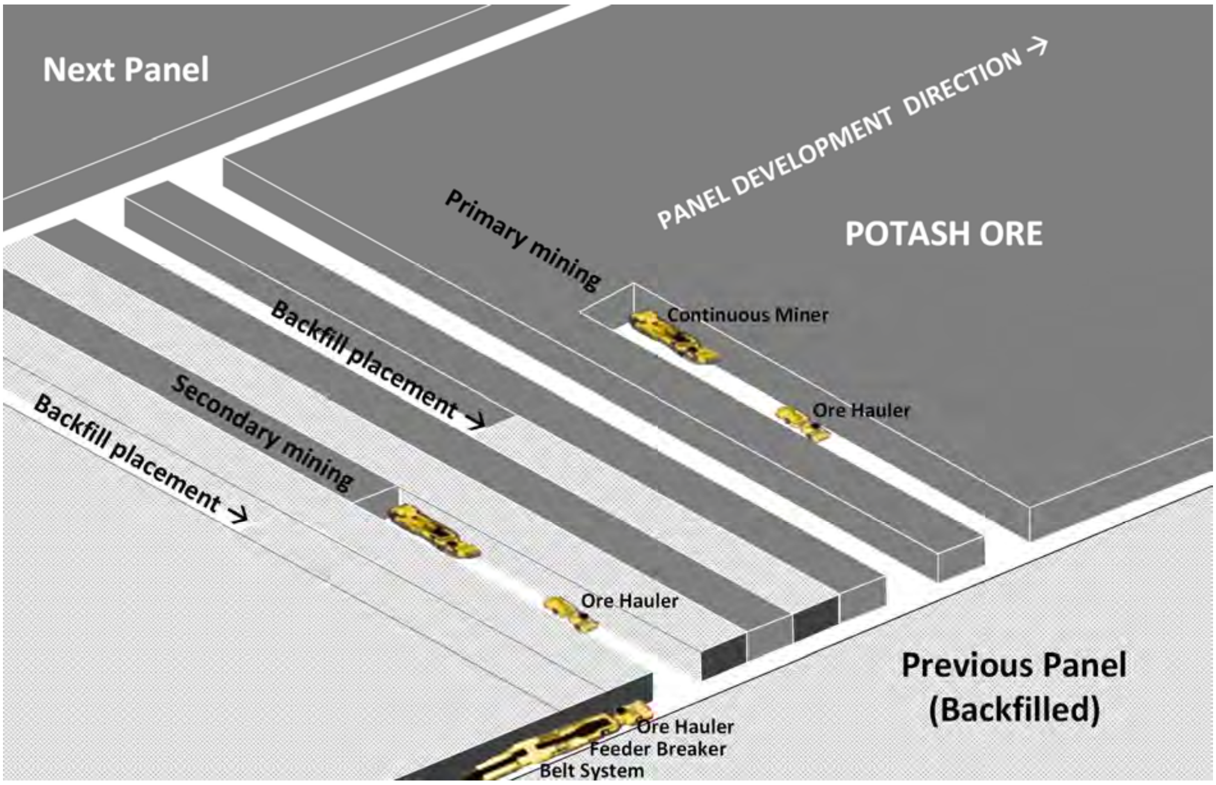


Figure 55: Concept for near 100% extraction of potash using continuous miners and competent backfill based on by-products from fertiliser production by K-UTEC AG Salt Technologies (www.k-utec.de)

The conclusion of this section is that continuous miners, as described in this section, currently do not suit the Robominers concept and is therefore not further explored in this report. Nonetheless it is considered a feasible idea which is recommended to be pursued in a separate research and development program, either academic or in partnership with industry.

5 MINING ANALOGUES: UNDERGROUND OPENING SUPPORT

Underground opening support is required in underground excavations when there is a danger of loose rock failing from its in-situ environment and presenting mining logistic challenges. The support inhibits rock mass failure. It also prevents long term deterioration.

One reason for rock mass failures is that the rock is not confined by surrounding rock. Loose rock could work free due to joints in the rock mass. Also, direct stresses could be imposed on the rock due to mining in the vicinity. These direct stresses could be caused by different mining actions such as cutting, blasting or collision with mining equipment. Stresses are often imposed on rock mass openings if there are other openings in the vicinity. Also, the in-situ siting of rock mass could be weakened due to weathering caused by water or air.

Rock mass failing may strike and damage or destroy a Robominers miner/explorer. The loose rock in the host rock surrounding the ore body may dilute the ore being recovered. Finally, the failure of loose rock would reduce the binding stresses surrounding other rock and thus be a precursor for a succession of underground failures in the area. This could make underground areas inaccessible. Using rock support could stabilise the opening, ensure loose rock does not fall into the opening or both.

The capital and operating cost of mining operations increases due to the installation of underground support to stabilise excavated tunnels, headings, and galleries. The capital cost increases because the means of reinforcement must be purchased along with the equipment configured to install it. The operating costs increase because the reinforcement means must be installed, and the equipment maintained.

Underground support of tunnels, headings or galleries can be divided into providing active or passive support. Active support refers to support that imposes a predetermined load to the rock surface while being installed. A load is not applied when passive support means are installed. Loads on the support measures are first imposed while the rock mass deforms.

Three means of supporting underground openings will be discussed: rock reinforcement, external support, and membranes. Rock reinforcement refers to providing structural support within the rock mass. External support refers to providing support on the outside of the rock mass. Finally, membrane support refers to providing external support on the outside of the rock mass which interacts with the rock mass itself and prevents weathering.

5.1 ROCK REINFORCEMENT

Rock reinforcement is established by linking the dynamic strength of the rock with the support. This then makes the rock self-supporting. There are three means that the load is transferred. Examples of these three means are depicted in Figure 56.

- *Continuously Mechanically Coupled Elements* (CMC)
A securing agent fills the annulus between a reinforcing element and the borehole wall. The securing agent is often grout. This securing agent provides a mechanism for load transfer between the rock and the reinforcing element which will resist deformation.
- *Continuously Frictionally Coupled Elements* (CFC)
The reinforcing element is in direct contact with the rock. The radial pre-stress set up at installation influences the amount of resistance that can be transferred from the reinforcing element to the rock surrounding the borehole.
- *Discrete Mechanically and Frictionally Coupled Elements* (DMFC)
Reinforcing elements are attached to an expanding anchor. This anchor expands outward against the borehole wall as the element tenses. The anchorage strength may be limited by the strength of the host rock.

The types of reinforcement outlined are rock bolts, rein anchored rebar bolts, frictional support, spiling, static reinforcement elements – cable bolt support, and dynamic reinforcement elements. The means that the load is transferred is noted after the title of every type of rock bolt with CMC, CFC or DMFC.

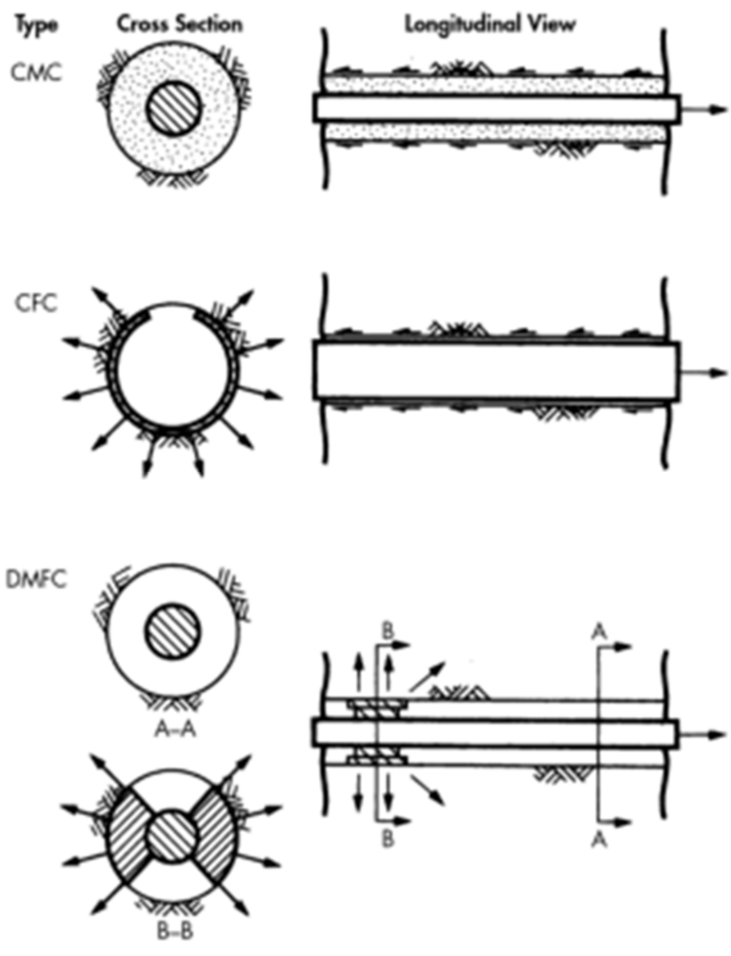


Figure 56: Categories of element load transfer Invalid source specified.

A number of rock bolt types are available on the market following one of the three load transfer methods shown in Figure 56 and comprising either steel bars or cables to take tension. For a robotic mining eco-system cable bolts are or particular interest. These bolts are generally several steel wires wound into a strand. They are either installed in tension or grouted into a borehole. Glass fibre cable bolts are also an effective means of rock reinforcement in mining.

Cable bolts can be installed during preparation to mine in an area to promote stability. If they are actively tensioned during installation, they would provide active support – DMFC. If they were left un-tensioned, they would provide passive support – CMC. Cable bolts are particularly interesting for robotic mining as they are flexible and can be coiled on drums, so the diameter of transportation is approximately one metre. From these drums, support can be provided many metres in advance from where mining is taking place which is usually about 20 metres. These coils can be placed in areas with limited headroom during installation or loaded into a robotic bolting unit to allow for prolonged autonomous operation.

5.2 EXTERNAL SUPPORT

External support provides support when forces are exerted on the means used for external support. External support is thus mostly considered passive support unless the supports can be actively extended to counteract the force of the rock deformation. The size of the support means is directly related to the size of the excavation. They also approach the size of the excavation.

If robotic mining is envisaged in abandoned mines, the size of old workings would not have been designed for the (small) robotic miner. Therefore, the means of installation outlined would be fairly cumbersome. New workings excavated by the robot would require smaller means of external support and traditional external support methods will need to be adapted or new methods need to be developed for the robotic miner eco-system. External support may however be appropriate for Robominers because although support units would have to be installed, little or no drilling, such as required for the installation of rock bolts (Section 5.1) will be required. Traditional external support methods or units used in mining are:

- Concrete liner: poured, sprayed or installed in segments, a passive method also used in tunnelling (Section 3.3).
- Timber, steel, concrete support: as single “sticks” or stacked to form “cribs” to support the roof or walls of a mined opening, a passive method shown in Figure 57.
- Steel sets: steel “arches” spanning the mined opening, a passive method shown in Figure 58
- Hydraulic props: single hydraulic cylinders that actively support the roof of the mined opening
- Membrane support: e.g., a “mesh of steel wire or chain held in place by rock bolts and plates (Figure 59) and/or sprayed concrete (shotcrete) shown in Figure 60.

Figure 57: Strata Worldwide secondary roof support: (from left to right) Timber standing prop support; (active) steel props; timber crib support using stacked interlocking blocks; concrete crib support using fibre reinforced blocks (www.strataworldwide.com/mining/strata-geotech-mining/roof-support-mining)

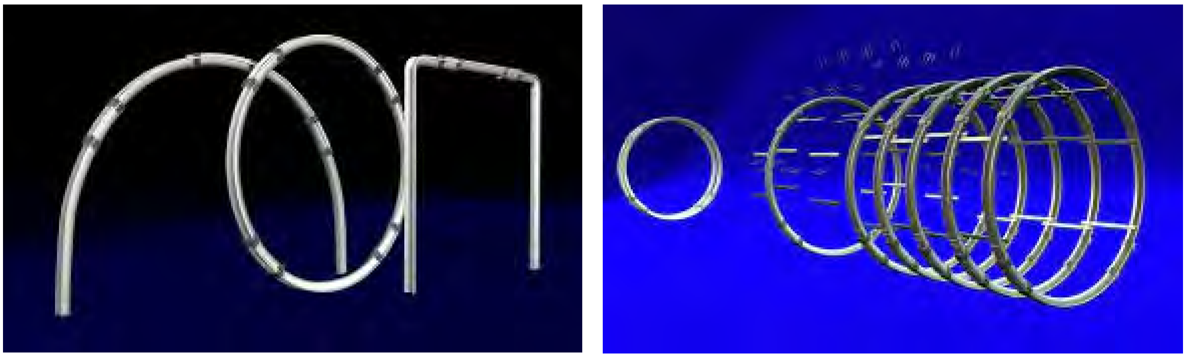


Figure 58: Becker Mining Systems AG - Steel arch support: (left) available shapes, (right) installation example (www.becker-mining.com)

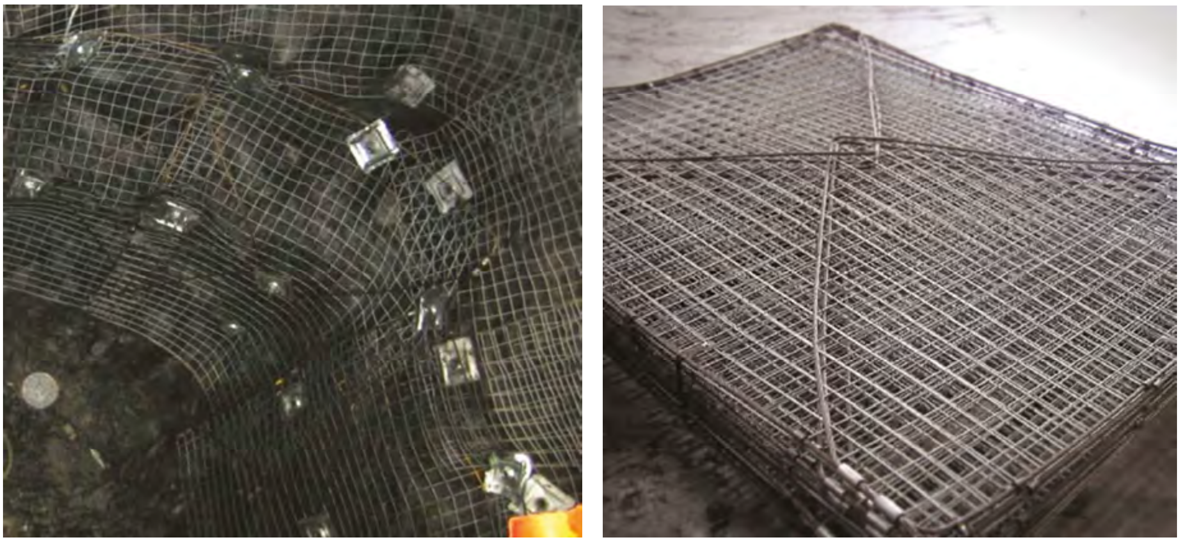


Figure 59: High Energy absorption (HEA) mesh for underground mining (www.dsiunderground.ca/products/mining/dynamic-bolts-products/hea-mesh)

Figure 60: Sprayed concrete (shotcrete) installation in an underground mine (www.sika.com/en/solutions-for-projects/mining.html)

5.3 BACKFILL

Backfill is extraneous material added to an underground void. The backfill provides support to the walls surrounding the void so that the rock immediately above, below or the adjacent to the opening can be mined. If the backfill is introduced into a large void, it will minimize the amount of space into which broken rock can displace or a mined opening can converge. As such, it would eventually interrupt progressive failure because there would be no room for failed rock or rock mass to go. Introducing backfill to mined openings (voids) will also allow for the disposal of mine/mill waste material from surface. Backfill can be consolidated into a coherent and stable material that has material properties that do not fail into open stopes. It would therefore improve ground stability conditions in that workers could work beside non-friable ground. It is difficult to achieve a 100% filling efficiency of mined openings in most cases as an air gap above the backfill may develop over time due to consolidation of the backfill material. As such, backfill does not always provide direct support to the roof of a mined opening. Nonetheless, filling a mined opening with backfill will support the load-bearing pillars between mined openings and thus provide underground opening support.

The State-of-the-Art means of backfilling mined openings based on processing wastes are (after Hambley, 2011):

- Dry sand & rock fill: dry processing wastes, and/or other natural rock material, is used to backfill mined openings with mechanical means (conveyors, trucks, Load-Haul-Dump trucks, etc.)
- Uncemented hydraulic fill: partially dewatered processing wastes are hydraulically transported to mined openings using a carrier medium and the solids are left to settle in the mined openings thus forming backfill. No cement or binder is added, and the carrier liquid needs to (partly) drain from the backfill material.
- Cemented hydraulic fill: processing wastes are mixed with a binder and a liquid to form a slurry fit for hydraulic transport underground. Cement is added to aid the hydraulic transport as a lubricant and decrease the amount of carrier liquid drained from the placed backfill material.
- Cemented rock fill: dry rock fill already placed in a mined opening (see first item in this list) is cemented using a cement mortar which can flow into the pores between the rock particles.
- Paste fill: (very) fine processing wastes are mixed with cement or binder to form a consistent homogenous slurry which can be hydraulically transported to mined openings as backfill. Due to the high cement content, paste backfill requires little drainage compared to cemented hydraulic fill. The backfill mixture composition design is usually aimed at minimising drainage (or bleeding) to avoid the need for a collection system for the drained liquid.
- Pneumatic fill: dry processing waste which is pneumatically transported to mined openings and deposited there to act as backfill.
- Flowable fill: a low-strength, free-flowing dry backfill material such as fly-ash

5.4 LINK TO ROBOMINERS

Rock reinforcement

For a robotic mining eco-system, the operation of a bolting rig such as that shown in Figure 62 should be fully automated and be able to operate continuously. Although it can be envisaged that the mechanics of this process can be extensively miniaturised and robotised, the supply of bolts is deemed challenging in a robotic mining eco-system. Individual steel bolts will be near impossible to handle however cable bolts, as mentioned previously, could mitigate this. By feeding cable to the robotic miner continuously through the umbilical, a rock bolting module can install cable bolts continuously, cutting the cable to length as it installs the rock reinforcement. Driving this idea one step further, the robot could also be fed by a continuous single strand of, for example, carbon-fibre, which is spun into a cable as it is installed into the prepared borehole to be followed by some type of grout or resin which can also be continuously fed through the umbilical. This “onboard winding” of a cable bolt would free up space in the umbilical as only a very small diameter conduit is necessary. To transport the single strand, compressed air can be used in a manner similar to the way optic fibre is installed in preconstructed conduits, for example, for communal internet distribution, see Figure 61. Even without incorporating a cable winder in the robot, the cable blowing system shown in this figure can be considered a valuable analogue to the continuous transport of, for instance, a carbon-fibre cable for rock reinforcement.

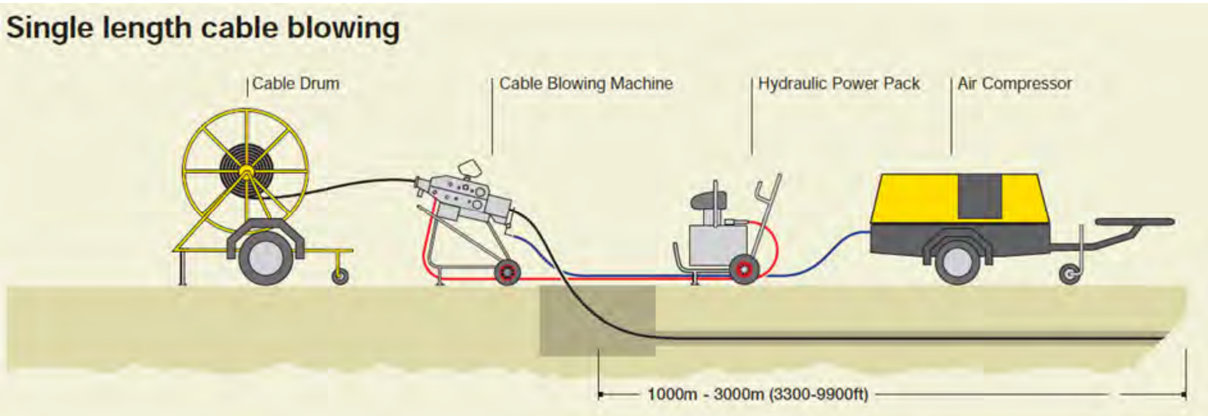


Figure 61: Fibre optic cable blowing (Thorne and Derick UK, www.cablejoints.co.uk)

Rock reinforcement in a robotic miner eco-system can be envisaged as an operation which is performed by a robot module within a train of modules as shown in Figure 37 as part of the primary excavation operation. Alternatively, the installation of rock reinforcement, i.e. “rock bolting”, is performed by a dedicated robot operating separately from the excavation robot, but in sequence to timely secure freshly excavated headings or galleries.

For the robot “train” case, the manner in which TBMs (Section 3.3) install rock bolts can be considered a valuable analogue to potential robotic installation of rock reinforcement. This is illustrated in Figure 62 in which a rock bolt drilling rig as part of the Herrenknecht AG Gripper TBM[13] is shown. This specific rig has two drilling units which can rotate around the central axis of the TBM “spine” to enable a flexible bolt pattern as shown in the right-hand picture of Figure 62. To minimise the risk of roof caving before bolts are installed, rock bolting is performed through the “fingers” visible on the rear edge of the TBM’s top shield. Once the bolts are installed and are able to take tension, the shield can be moved forward to support roof freshly exposed by the excavation action. The shield on this type of TBM can be retracted to some extent to allow for the rock mass to expand and tension the bolts.

[13] www.herrenknecht.com/en/products/productdetail/gripper-tbm/

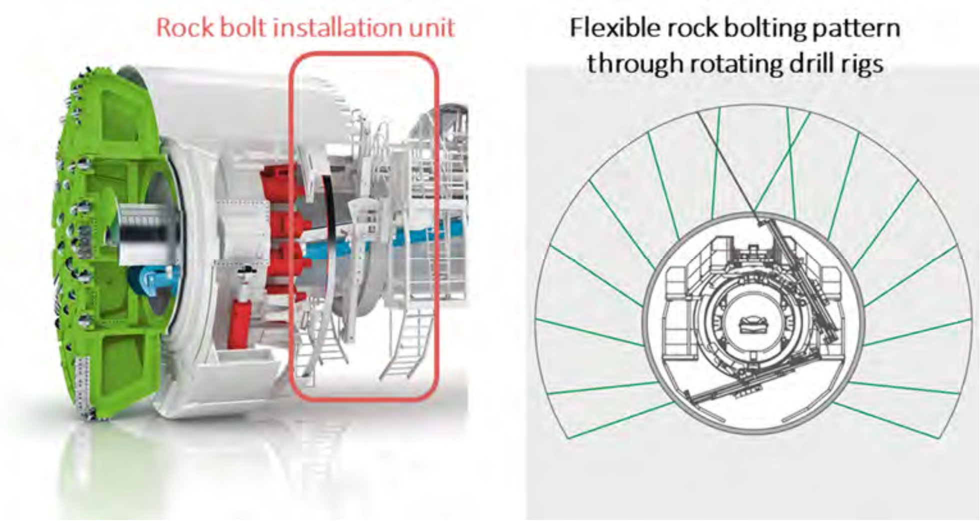


Figure 62: Herrenknecht AG Rock bolt installation rig as part of a Gripper TBM (www.herrenknecht.com/en/products/productdetail/gripper-tbm/)

Where geological conditions allow for a longer delay between excavation and installation of rock support, the use of a separate robotic rock reinforcement machine may be considered. Such an autonomous robotic bolter is of lesser interest to the keyhole mining concept discussed in this report, however some recent technology developments in the mining industry do offer some valuable analogues. The first example is a research project performed at the University of Kentucky which investigated the application of industrial robotics as a means of automating rock bolting (Xenaki, 2021). The research test used by the team in Kentucky is shown in Figure 63. This test rig combines a normally manually operated bolting rig with an industrial robot which manipulates the drill rods and bolts.

Figure 63: Actual roof-bolter located at the University of Kentucky, Rock Mechanics lab (Xenaki, 2021)

The work done by Xenaki (2021) and the resulting test rig shown in Figure 63 demonstrate ways of using human operated equipment as the basis for a robotic bolter. Whereas this will be a valuable development for "full-scale" mining, it will be less relevant to the type of keyhole mining envisaged by the Robominers project and is thus not further considered.

Another industrial research and development effort by Minova[14] in South Africa has developed a semi-automated remote controlled rock bolter as shown in Figure 64.

Figure 64: 2014 (left) and 2019 (right) versions of the Minova semi-automated bolter rig (Conner et al. 2020)

This rock bolter is a system developed for use in hard-rock mines with a mining height of between 0.9 m and 1.2 m. The rock bolter is part of a rock bolting system which, in addition to the bolter, also required development of novel rock bolts and a pumpable, fast-acting resin grout to secure the bolts. The rockbolter is one component of an equipment suite enabling full mechanization of rock-breaking by blasting, clearing of the broken rock and rock support. Development started in 2012 and the bolter has been operating on a platinum mine since 2017 (Conner et al. 2020). As a stand-alone robotic bolter solution, the Minova semi-automated bolter rig is a valuable analogue. For the keyhole mining concept envisaged in this report, the basic elements of this rig, especially the bolter unit on the front, are worth considering in future iterations of designs.

External support

The application of external support in a robotic mining eco-system may resemble the installation of prefabricated concrete liner elements as is performed by a TBM (Section 3.3). The continuous transport of the prefabricated concrete elements to the robot can, however, hardly be envisaged in the keyhole mining concept considered in the Robominers project. The use of a mesh and shotcrete can potentially be applied in a robotic mining environment as the resources for mesh (cable) and shotcrete (mortar) can be delivered continuously to the robot through an umbilical. In the state-of-the-art shotcreting process, there are often three to four steps in which the support is installed which are shown in Figure 65. The process starts with cleaning of the freshly excavated services to promote adherence of the shotcrete material. If overbreak, i.e. rock failure beyond the design contour of the tunnel, has taken place this can first be filled with sprayed concrete to smooth the contour. The first layer of sprayed concrete is applied next to stabilise the excavation. After curing of the first layer, and the possible installation of steel reinforcements (such as steel cable mesh), a second layer is applied to create the final external support for the tunnel.

[14] www.minovaglobal.com

Figure 65: Steps in shotcrete practice: (from left to right) 1. Cleaning using high pressure water; 2. Filling of overbreak; 3. 1st shotcrete layer (excavation stabilisation and adhesive bridge for second layer); 2nd shotcrete layer (excavation stabilisation) usually together with steel reinforcement (e.g. mesh) (Lindlar et al. 2020)

In the envisaged concept for the installation of external support by a robotic miner these steps could be mimicked by a robotic external support installation module as part of a robotic miner train (Figure 37). This module can be envisaged to perform the process steps shown in Figure 65 sequentially as the robot advances. The first process step, high pressure cleaning, is performed by a spray nozzle directly behind the production module of the robotic miner train. The first layer of sprayed concrete is applied directly after by a second nozzle spraying a quick-setting mortar. This is followed by the installation of a mesh as reinforcement. The mesh is envisaged to be weaved directly onto the excavation wall from a steel or carbon fibre cable that is fed continuously to the robot through the umbilical. This cable is manipulated by an arm on the robot module which attaches the cable along the perimeter of the excavation by for example rock nails or by pressing the cable into the part-cured 1st layer of sprayed concrete. After the mesh has been installed, a third nozzle installed near the rear of the module covers the woven mesh with a final layer of shotcrete. This final layer can also be of a quick-setting mortar corresponding to the advance speed of the robot.

It is not envisaged that all the excavated tunnels should be lined with such a system. The production galleries from which the bulk of ore production takes place only needs to be stable as long as the robotic miner is operating within. After completion of a gallery, the mined opening may be allowed to converge or collapse. Securing the gallery while the robotic miner is still active may be done by rock bolts alone (Section 5.1) depending on the local conditions. For the mine development tunnels, i.e. the main infrastructure, the stability of the excavation should be secured for a longer period. The application of external support, using a robotic module as just envisaged, may be necessary to avoid damages and/or capital loss.

Backfill

For the keyhole mining concept envisaged by the Robominers project paste backfill is considered the most relevant as it can be prepared at an above ground facility and hydraulically transported underground. In this case, processing wastes are mixed with cement, or an alternative binder (e.g. fly-ash), and a suitable liquid (water/brine) according to a pre-determined and strict composition. The produced “paste” is subsequently pumped through a pipeline system to the mined openings. The paste has a high viscosity and a high-pressure pump and corresponding pipeline infrastructure are required to overcome the significant dynamic pressure loss during transport. The clear advantage of using a paste backfill system in a robotic mining eco-system is that the backfill can be transported continuously to the mined openings and a drainage system is not required. As such a paste backfill system requires very little complex equipment underground, just a pipeline and a discharge nozzle. The placed backfill will cure (harden) due to the added cement or binder thus stabilising mined openings. When the orientation of mined openings is (sub-)vertical, a very high filling efficiency is possible when filled “bottom-up”, such as in the Honeycomb mining layout (Figure 44).

6 MINING ANALOGUES : UNDERGROUND MATERIAL TRANSPORT

A classification and an overview of the State-of-the-Art underground material transport methods used in the mining industry has been provided in Deliverable D2.2 "CONCEPTUAL MINING STRATEGIES AND REPORT ON STUDIES OF BOTTLENECKS AND OTHER LIMITING FACTORS" of the Robominers project. With reference to Figure 1, a robotic mining eco-system will need to include systems for both horizontal ore transport (haulage) and vertical ore transport (hoisting) as the ore processing plant will most likely be located on the ground surface. In relation to Figure 5.4 in Deliverable 2.2, a keyhole mining operation such as envisaged by the Robominers project will most likely use continuous/semi-continuous ore transportation methods for horizontal transport (haulage) as the robotic miner itself will most likely use a continuous excavation method. The use of a continuous transport method for the vertical transport can also be considered. Alternatively, the continuous haulage system can be connected to a batch hoisting method such as a traditional shaft skip transport system. When a transition between a continuous and a semi-continuous/batch transport method is considered, sufficient buffering capacity must be included in the overall process design for the transportation system.

The traditional haulage methods presented in D2.2, such as transport of material by trucks or conveyor belts, are considered of lesser relevance to the keyhole mining concept aimed at by the Robominers project (Table 5.1 in D2.2). As such these traditional methods are not further considered in this report. The use of a hydraulic haulage system seems to be the most appropriate for at least the distance between the robotic miner and a centrally located support installation coupled to one or more of the robotic miners. Further haulage and hoisting beyond this support installation can be hydraulic or use more traditional systems such as a conveyor belt and shaft skip transport. As the traditional methods are not further elaborated this section focusses solely on hydraulic transport methods for horizontal and vertical material transport.

6.1 HYDRAULIC MATERIAL HAULAGE AND HOISTING

In order to hydraulically transport excavated ore away from a robotic miner, a slurry comprising the excavated ore and a liquid carrier medium must be produced. A slurry is generally speaking a (homogeneous) mixture of solid(s) and liquid(s). In a practical sense, slurries can either be settling or non-settling under static conditions depending on the material parameters of the slurry components and the rheological parameters of the carrier liquid/slurry.

When the grain size of the solids is very small, following Stoke's Law on the terminal velocity of a sphere falling in a fluid, the solids in a slurry may fall very slowly thus creating a "quasi-stable" non-settling slurry considering a time frame of hours to days. Nonetheless, the solids in any slurry, comprising solids in a carrier liquid, will settle over time when not agitated. In the case of a robotic miner, the grain size of excavated ore will most likely be very coarse and some form of primary crushing and/or grinding will be necessary (as introduced in Figure 32) to sufficiently reduce the grain size to enable hydraulic transport in the first place.

Under dynamic conditions, e.g. during slurry transport in a pipeline, the settlement behaviour must be accounted for in the design. Depending on the Reynolds number, solids in a slurry can be kept in suspension by agitation, thus preventing their settlement. The Reynolds number helps to predict flow patterns in fluid flow situations and a general equation is shown below.

Reynolds number (general form): $Re = \frac{\rho u L}{\mu} = \frac{uL}{\nu}$ (Sommerfeld, 1908)

with ρ is the density of the fluid (kg/m^3), u is the flow speed (m/s), L is a characteristic linear dimension (m), μ is the dynamic viscosity of the fluid (Pa·s or N·s/m^2 or kg/(m·s)), and ν is the kinematic viscosity of the fluid (m^2/s).

In principle, the flow of fluids is dominated by laminar flow at low Reynolds numbers and by turbulent flow at higher Reynolds numbers. Furthermore, in a slurry, the Reynolds number required to keep solids in suspension in dynamic situations, is usually lower for fine-grained solids and higher for coarse grained materials. In relation to a hydraulic transportation system for keyhole robotic mining, this means that sufficient energy input is required to keep the solid particles in suspension while the slurry is transported. In practice, a sufficiently high Reynolds number must be achieved during slurry production directly after excavation and during the transport of the slurry through hoses and pipelines to avoid accumulation of solids.

Turbulent flow conditions are preferred for the slurry production process to ensure fast achievement of a homogeneous slurry. Laminar flow conditions are preferred for pipeline transport to minimise abrasive wear on the pipe inner surface and energy cost for pumping. However, when ore particles are relatively coarse, turbulent flow conditions may be required to prevent settlement of solids in pipelines and especially in any intermediate retention vessels such as buffer tanks.

In the case of hydraulic material transport of processing wastes from the (above ground) processing plant back to the underground mined opening as a basis for backfill material or for disposal, the expected grain size is very fine. As with the case for hydraulic transport of ore described above, particle settling of processing wastes should also be prevented in both the surface facilities and the hydraulic piping underground. However, in the case of underground waste disposal, settling of particles from or within the slurry is needed in most cases as the slurry is injected in a mined opening to effectively separate or segregate solid particles from the carrier liquid and achieve a high backfill efficiency in terms of the solids content in the mined opening after backfilling. The carrier liquid is thus drained from the waste material and should be collected and brought back to the surface facilities for re-use in this case.

For backfill operations which are aimed at providing underground support (Section 5.3) a backfill slurry can be designed to harden within its original slurry volume by addition of a binder. Such a hardening slurry can be applied in cases where the final strength of the backfill material after hardening will be crucial for the success of backfill operations, i.e. where processing wastes are used to geotechnically stabilize mined openings. In this case, a secondary mining phase, extracting pillars left after the initial mining, can potentially be incorporated into the overall mining operation. Pillar extraction is crucial to achieve a high utilisation of the mineral occurrence. For the high-grade, small-scale mineral occurrences aimed at by the Robominers keyhole mining concept, pillar extraction is thus very likely to be necessary for economic reasons. The application of hydraulically transported paste backfill is, therefore, also envisaged for a robotic mining eco-system.

Hydraulic material hoisting means the (sub-)vertical transport of mined ore through a pipeline from the underground mine to the surface processing plant. In the case of the envisaged keyhole mining concept, hydraulic hoisting would suit the hydraulic haulage system proposed in Section 6.1 and is therefore further elaborated. A clear analogue for hydraulic hoisting is the drilling of wells in the oil & gas industry (Section 3.1) where a drilling fluid is pumped down a drill string and the excavated material is hydraulically hoisted to the surface by the drilling fluid (Figure 10). This analogue is further discussed in the next section on the potential link to Robominers.

6.2 LINK TO ROBOMINERS

Translating hydraulic haulage and hoisting to the robotic mining concept of the Robominers project can be envisaged by two possible systems:

1. Driven by pumps in the robotic miner (Figure 37) and "boosted" by additional pumps in a support station and/or at the bottom of a shaft leading to the surface.
2. Driven by overpressure on (part of) the robotic mining eco-system.

These two envisaged systems are illustrated in Figure 66 and Figure 67 respectively and are elaborations on the proposed concept for honeycomb mining using a tethered robotic miner (Figure 44).

In the first conceptualisation (Figure 66), a series of pumps is used to draw the excavated material, after passing a crusher/grinder system incorporated in the production tool (Figure 32), away from the production area. The first pump will be incorporated into the robotic miner to keep sufficient suction on the production face and thus ensure a constant removal of mined materials from the crusher/grinder system. This pump also takes care of the first haulage leg to, for example, the start of the access tunnel. At that location a support system to which the umbilical is connected can include a booster pump to allow further transport towards the mine access, i.e. the keyhole. At the bottom of the keyhole, being a shaft or an enlarged borehole (Figure 12), a second booster (hoisting) pump can provide the pressure to hoist the ore slurry to the ground surface.

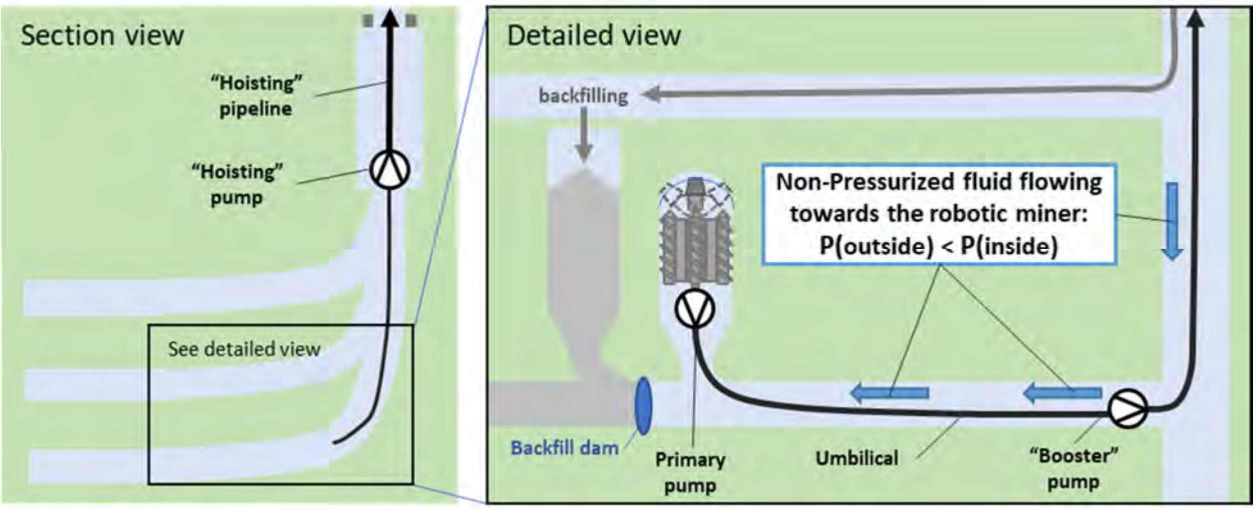


Figure 66: Robotic keyhole mining concept using hydraulic hoisting driven by pumps

In the second conceptualisation, (Figure 67) the hoisting energy is not provided by pumps within the transport system but by pressurising the complete miner eco-system to create a positive pressure gradient from the outside of the robot towards the inside of the umbilical. The pressure difference should be larger than the density difference between carrier fluid and ore plus an allowance for dynamic pressure losses due to friction.

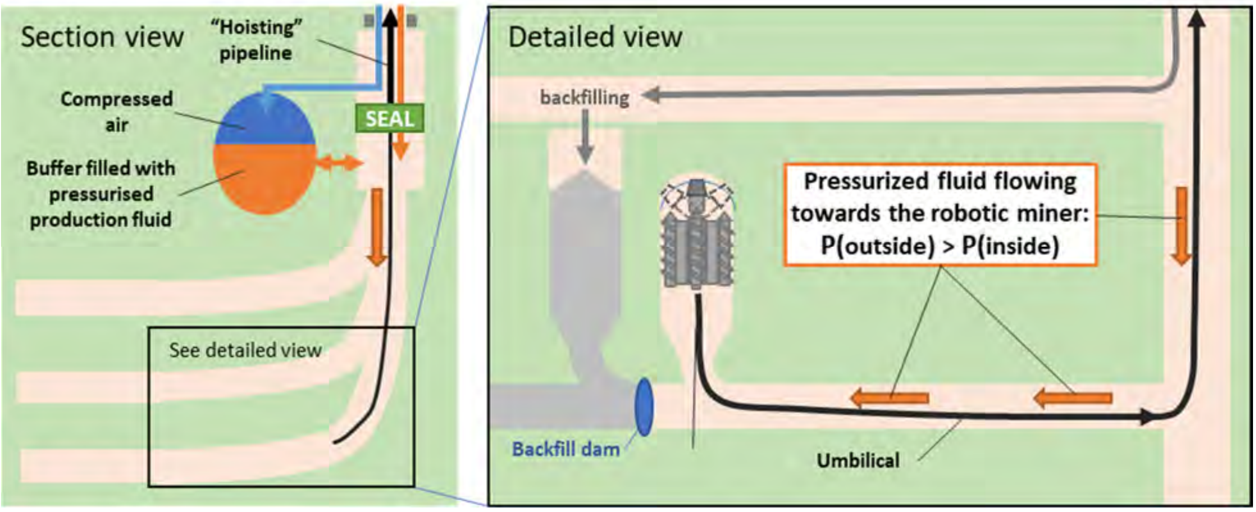


Figure 67: Robotic keyhole mining concept using hydraulic hoisting driven by pressurised fluid

To pressurise the miner eco-system a seal must be installed at the keyhole access which can withstand the required pressure difference. The mineral occurrence in which the eco-system is developed must also be able to withstand the overpressure to minimise fluid losses. Pressurising the eco-system is achieved by pressurising the production fluid within the mined openings. The fluid is pressurised primarily by a high-pressure pump pushing the fluid through a non-return valve. In addition to the high-pressure pump, a pressure buffer can be installed near the bottom of the keyhole access to balance the pressure in the eco-system during continuous in- and outflow of production fluid and ore-loaded slurry and, consequently, frequent pressure pulses and variations. The buffer is pressurised using compressed air and connected to an air compressor to maintain the required pressure on the buffer.

Where the geological/geotechnical circumstances are suitable for a pressurised system as proposed in Figure 67, the use of a such system is preferred over the system using pumps. The significant reduction of moving parts in this system (i.e. pumps) is considered a clear advantage.

7 CONCLUSION

Considering the possible scenarios and the varied tasks that the ROBOMINERS platform should perform, a large list of possible analogues from the mining industry was considered. The State-of-the-Art technologies and methods for the main activities in a mining eco-system have been studied to select relevant analogues for underground robotic mining. The concept of keyhole mining aimed at by the Robominers project has governed the selection of suitable State-of-the Art analogue from the mining industry. Consequently, potential analogues which are less suitable to act as inspiration for keyhole mining have not been included in this report. Relevant analogues have subsequently been used as a baseline or starting point for several “futuristic” conceptualisations for keyhole mining by robotic mining equipment.

The proposed concepts are all elaborations on or derivatives of the Robominers prototype in combination with technologies from the mining industry currently in use. The prototype will be designed and constructed during the project in accordance with the Grant Agreement. However, the concepts presented in this report are not intended to be further engineered and/or tested as part of the Robominers project but can be used by any follow-up study or industrial uptake project latching onto the finding from the Robominers project.

The presented concepts are not considered technically feasible at this time, even if the robotic miner prototype is fully functional and operational, able to cut through hard rocks. Technological advances will be required for the implementation of concepts, presented in this document, not only for the robotic miner equipment itself. The development of a robotic miner able to perform keyhole mining, for which the Robominers project is laying a foundation, will need to be accompanied by the development of a complete eco-system comprising the robotic miner(s), support systems, transport systems, data communication, deploy and extract systems for equipment, etc. It is thus highly recommended to continue further research and development projects related to robotic keyhole mining to include at least all sub-systems discussed in this report, rather than focussing solely on a robotic mining platform.

8 REFERENCES

Bar-Cohen and Zacny (eds.) (2009): Drilling in Extreme Environments: Penetration and Sampling on Earth and other Planets, *Wiley-VCH Verlag GmbH & Co. KGaA, https://onlinelibrary.wiley.com/doi/book/10.1002/9783527626625*

Barr, W. (2004): Mining in Manitoba – Intro to Mine Engineering – Unit 16 Mine Development, *R.D.Parker Collegiate, Thomson, Manitoba, Canda, https://miningandblasting.files.wordpress.com/2009/09/intro_to_mining.pdf*

Bawden, W. F. (2011). Ground Control Using Cable and Rock Bolting. In *SME Mining Engineering Handbook* (pp. 611-625). Society for Mining, Metallurgy, and Exploration.

Bilgin, N., Copur H., Balci, C. (2013): Mechanical Excavation in Mining and Civil Industries. Hoboken: Taylor and Francis, ISBN 9781466584747

Hiltz, R. (2020): Taking a step into the robotic future, Mining Magazine Online,

Brierley, G.S. (2015) Small-Diameter Tunneling: A Historical Perspective, *Tunnel Business Magazine, tunnelingonline.com, May 27, 2015, Benjamin Media Ltd., Brecksville, Ohio, USA*

Burlet, Ch., Stasi, G., Berner, M., Hartai, É., Németh, N., Henley, S., McLoughlin, M., Pinkse, T., Ristolainen, A. (2020): Miner perception report. *Robominers Deliverable D6.1, 51p.*

Chapman, D.; Metje, N.; Stärk, A (2018): Introduction to Tunnel Construction (Second Edition), *CRC Press, Taylor & Francis Group, Boca Raton, Florida, USA*

Clark, G.; Ramsey, M. (2017): Advanced Technologies Help to Overcome Tunneling Challenges, Save Time and Money, *Tunnel Business Magazine, tunnelingonline.com, October 18, 2017, Benjamin Media Ltd., Brecksville, Ohio, USA*

Conner, D.M., Sertic, T. (2020): Development of a remote-controlled rockbolting system for narrow-seam hard-rock mines, The Journal of the Southern African Institute of Mining and Metallurgy, 120, http://dx.doi.org/10.17159/2411-9717/851/2020

Devold, H. (2013): Oil and gas production handbook. An introduction to oil and gas production, transport, refining and petrochemical industry. Edition 3.0, *ABB Oil & Gas, Oslo*

Diamond, R.S.; Kassel, B.G. (2018) A History of the Urban Underground Tunnel (4000 B.C.E . – 1900 C.E.). Journal of Transportation Technologies, 8, 11-43. *https://doi.org/10.4236/jtts.2018.81002*

Donaldson, F.; Jarrett, E.; Chambers, R (1952): Shaft-sinking in unstable and waterbearing ground, *Mining Engineers' Handbook (editor Robert Peele), Third Edition, Sixth Printing, p8-01 – 8-24*

Eremenko, V.A., Galchenko, Y.P. & Kosyreva, M.A. (2020) Effect of Mining Geometry on Natural Stress Field in Underground Ore Mining with Conventional and Nature-Like Technologies. J Min Sci 56, 416–425. https://doi.org/10.1134/S1062739120036702

Frei, W. (2015): Seismische Kartierung der Gipsauslaugungsphänomene rund um den Dolineneinsturz auf dem Mühlfeld bei Reutte i.T., *17. Geoforum Umhausen Tirol, Tagungsband*

Frei, W. (2020): Hochauflösende seismische Vorerkundung – eine wirksame Maßnahme zur Minderung des finanziellen Risikos bei Geothermieprojekten., *Swiss Bulletin für angewandte Geologie*

Finger, J; Blankenship, D (2010): Handbook of Best Practices of Geothermal Drilling, *Sandia Report SAND2010-6048, Sandia National Laboratories*

Hambley, D. F. (2011). Backfill Mining. In *SME Mining Engineering Handbook* (pp. 1375-1384). Society for Mining, Metallurgy, and Exploration.

Harraz, H. Z., (2010), Underground mining Methods, DOI : 10.13140 / RG.2.1.2881.1124

Hartai, É., Németh, N., Földessy, J., Henley, S., Žibret, G., Galos, K. (2020): Review Document Giving Scope and Examples of Deposit Types of Interest. *Robominers Deliverable D5.1, 77p.*

Henley, S., Hartai, É., Németh, N., Pinkse, T., Ristolainen, A., Berner, M., Stasi, G., McLoughlin, M., Rhodes, T., van Moerkerk, H., Morrish, C., Howson, M. (2021): Conceptual mining strategies and report on studies of bottlenecks and other limiting factors. *Robominers Deliverable D2.2, 82p.*

Hiltmann, W., Stribrny, B. (1998): Handbuch zur Erkundung des Untergrundes von Deponien und Altlasten – Band 5: Tonmineralogie und Bodenphysik, *Bundesanstalt für Geowissenschaften und Rohstoffe (BGR), Springer Verlag Berlin Heidelberg*

Hiltz, R. (2020): Taking a step into the robotic future, Mining Magazine Online, https://www.miningmagazine.com/innovation/news/1387411/taking-step-into-the-robotic-future

ICOTA (2005): An Introduction to Coiled Tubing – History, Applications and Benefits, *International Coiled Tubing Association, www.icota.com*

Jones, M.; Barton, D; Hall, C (2009) Underreamer mechanics, *ESGI68, University of Southampton*

Knott, L (2018): Laparoscopy and Laparoscopic Surgery, *https://patient.info/treatment-medication/laparoscopy-and-laparoscopic-surgery*

Kuhn, O. (2004): Ancient Chinese Drilling, *Recorder, Vol. 29, No. 06*

Lindlar, B., Jahn, M., Schlumpf, J. (2020): Sika Sprayed Concrete Handbook, Sika Services AG, Corporate Marketing Services (available through: www.sika.com/en/solutions-for-projects/mining.html)

Lüth, S., Giese, R., Otto, P., Krüger, K., Mielitz, S., Borm, G. (2004): Seismische Vorauserkundung im Tunnelbau mit konvertierten Oberflächenwellen., *Zweijahresbericht 2004/2005, GeoForschungsZentrum Potsdam*

Mantle, K. (2014) The Defining Series: Directional Drilling Practices, *Schlumberger, Oilfield Review Winter 2013/2014: 25, no. 4.*

Martin, C., Bischof, N., Eiblmaier, M. (Editors) (2000): Bohrlochseismik, *Lexikon der Geowissenschaften, Spektrum Akademischer Verlag, Heidelberg, www.spektrum.de/lexikon/geowissenschaften/bohrlochseismik/2201*

Prinz, H., Strauß, R. (2018): Ingenieursgeologie, 6. Auflage. *Springer-Verlag GmbH.* ISBN 978-3-662-54709-0

ROBOMINERS (2019): Stage 2 Proposal for Resilient Bio-Inspired Modular Robotic Miners / ROBOMINERS, *Robominers Stage 2 Proposal for SC5-09-2018-2019*

Sasaoka, T., Karian, T., Hamanaka, A., Shimada, H., Matsui, K., & Ichinose, M. (2016). Effect of mine water on the stability of underground coal mine roadways. *Geotechnical and Geological Engineering*, *34*(2), 671-678.

SCHLUMBERGER (2021): Drilling-Type Underreamer -Retractable, retrievable underreamer with application-specific cutting structures, *https://www.slb.com/drilling/bottomhole-assemblies/reamers-and-stabilizers/underreamers/drilling-type-underreamer#related-information*

Siciliano, B., Khatib, O. (2016): Springer Handbook of Robotics, Cham: Springer International Publishing, 2016. ISBN 9783319325521

Sidorenko, O., Sairinen, R., Moore, K. (2020): Rethinking the concept of small-scale mining for technologically advanced raw materials production. *Resources Policy* 68, 101712, https://doi.org/10.1016/j.resourpol.2020.101712

Sifferlinger, N.A., Hartlieb, P., Moser, P. (2017): The Importance of Research on Alternative and Hybrid Rock Extraction Methods, BHM Berg- und Hüttenmännische Monatshefte, 2017, 162(2), 58-66. ISSN 0005-8912. doi:10.1007/s00501-017-0574-y

Sommerfeld, A. (1908): Ein Beitrag zur hydrodynamischen Erkläerung der turbulenten Flüssigkeitsbewegüngen (A Contribution to Hydrodynamic Explanation of Turbulent Fluid Motions).- International Congress of Mathematicians, 3, pp. 116–124.

Stolzenberger-Ramirez, A. (Editor) (2010): Flözwellenseismik, *GeoDZ.com – Das Lexikon der Erde, www.geodz.com*

Vlasblom, W. (2003): Introduction to Dredging Equipment, Central Dredging Asssociation (CEDA), www.dredging.org

Weir, K. (2020): Tunnelling: Breakthrough technology, *Construction Europe, www.construction-europe.com 21 January 2020, KHL Group, Wadhurst, United Kingdom*

Western Mining Corporation Ltd, (1979). Gold : a review of the technology of exploration and mining. Volume II Mining and Metallurgy. Melbourne, Australia

Xenaki, A. (2010): A methodology for autonomous roof bolt installation using industrial robotics, Theses and Dissertations--Mining Engineering. 67 (https://uknowledge.uky.edu/mng_etds/67)

9 APPENDIX 1

Z	Symbol	Name	Density (kg/L)	Abundance and total mass in Earth's crust (mg/kg)	USD/kg	Year	Source	Notes
3	Li	Lithium	0,534	20 (5.54×10^{17} kg)	81.4–85.6	2020	SMM	Min. 99% pure.
4	Be	Beryllium	1,85	2.8 (7.756×10^{16} kg)	857	2020	ISE 2020	Min. 99% pure.
5	B	Boron	2,34	10 (2.77×10^{17} kg)	3,68	2019	CEIC Data	In the form of boric acid, price per boron contained. Min. 99% pure.
6	C	Carbon	2,267	200 (5.54×1018 kg)	0,122	2018	EIA Coal	In the form of anthracite, price per carbon contained, assuming 90% carbon content. There is a wide variation of price of carbon depending on its form. Lower ranks of coal can be less expensive, for example sub-bituminous coal can cost around 0.038 USD/kg carbon. Graphite flakes can cost around 0.9 USD/kg carbon.Price of synthetic industrial diamond for grinding and polishing can range from 1200 to 13300 USD/kg, while cost per weight of large synthetic diamonds for industrial applications can be on the order of million dollars per kilogram.
9	F	Fluorine	0,0017	585 (1.62×10^{19} kg)	1.84–2.16	2017	Echemi	In the form of anhydrous hydrofluoric acid, price per fluorine contained. Range of prices on Chinese market, week of 1–7 December 2017.
11	Na	Sodium	0,971	23600 (6.537×10^{20} kg)	2.57–3.43	2020	SMM	Min 99.7% pure industrial grade sodium.
12	Mg	Magnesium	1,738	23300 (6.454×10^{20} kg)	2,32	2019	Preismonitor	Min 99.9% pure.
13	Al	Aluminium	2,698	82300 (2.28×10^{21} kg)	1,79	2019	Preismonitor	High-grade primary aluminium, at London Metal Exchange warehouse.
14	Si	Silicon	2,3296	282000 (7.811×10^{21} kg)	1,7	2019	Preismonitor	Min. 99.1% pure, max. 0.4% iron, 0.4% aluminium, 0.1% calcium. 10–100 mm.
15	P	Phosphorus	1,82	1050 (2.909×10^{19} kg)	2,69	2019	CEIC Data	Min. 99.9% pure yellow phosphorus.
16	S	Sulfur	2,067	350 (9.695×10^{18} kg)	0,0926	2019	CEIC Data	
19	K	Potassium	0,862	20900 (5.789×10^{20} kg)	12.1–13.6	2020	SMM	Min 98.5% pure industrial grade potassium.
20	Ca	Calcium	1,54	41500 (1.15×10^{21} kg)	2.21–2.35	2020	SMM	Blocks of 98.5% pure calcium obtained by reduction process.
21	Sc	Scandium	2,989	22 (6.094×10^{17} kg)	3460	2020	ISE 2020	Min. 99.99% pure.
22	Ti	Titanium	4,54	5650 (1.565×10^{20} kg)	11.1–11.7	2020	SMM	Min. 99.6% pure titanium sponge.
23	V	Vanadium	6,11	120 (3.324×10^{18} kg)	357–385	2020	SMM	Min. 99.5% pure.
24	Cr	Chromium	7,15	102 (2.825×10^{18} kg)	9,4	2019	Preismonitor	Min. 99.2% pure.
25	Mn	Manganese	7,44	950 (2.632×10^{19} kg)	1,82	2019	Preismonitor	Electrolytic manganese, min. 99.7% pure.

Z	Symbol	Name	Density (kg/L)	Abundance and total mass in Earth's crust (mg/kg)	USD/kg	Year	Source	Notes
26	Fe	Iron	7,874	56300 (1.565×10^{21} kg)	0,424	2020	SMM	L8-10 pig iron. At Tangshan, China.
27	Co	Cobalt	8,86	25 (6.925×10^{17} kg)	32,8	2019	Preismonitor	Spot price. Min. 99.8% pure. At London Metal Exchange warehouse.
28	Ni	Nickel	8,912	84 (2.327×10^{18} kg)	13,9	2019	Preismonitor	Primary nickel. Spot price. Min. 99.8% pure. At London Metal Exchange warehouse.
29	Cu	Copper	8,96	60 (1.662×10^{18} kg)	6	2019	Preismonitor	Spot price. Grade A. At London Metal Exchange warehouse.
30	Zn	Zinc	7,134	70 (1.939×10^{18} kg)	2,55	2019	Preismonitor	Min. 99.995% pure special high grade zinc metal. Spot price. At London Metal Exchange warehouse.
31	Ga	Gallium	5,907	19 (5.263×10^{17} kg)	148	2019	Preismonitor	Min. 99.99% pure. Free on Board China.
32	Ge	Germanium	5,323	1.5 (4.155×10^{16} kg)	914–1010	2020	SMM	Ingot. 50 Ω/cm.
33	As	Arsenic	5,776	1.8 (4.986×10^{16} kg)	0.999–1.31	2020	SMM	Min. 99.5% pure.
34	Se	Selenium	4,809	0.05 (1.385×10^{15} kg)	21,4	2019	Preismonitor	Selenium powder, min. 99.9% pure.
35	Br	Bromine	3,122	2.4 (6.648×10^{16} kg)	4,39	2019	CEIC Data	
37	Rb	Rubidium	1,532	90 (2.493×10^{18} kg)	15500	2018	USGS MCS	100 g ampoules of 99.75% pure rubidium metal.
38	Sr	Strontium	2,64	370 (1.025×10^{19} kg)	6.53–6.68	2019	ISE 2019	Min. 99% pure, Ex Works China.
39	Y	Yttrium	4,469	33 (9.141×10^{17} kg)	31	2019	Preismonitor	Min. 99% pure, Free on Board China.
40	Zr	Zirconium	6,506	165 (4.571×10^{18} kg)	35.7–37.1	2020	SMM	Zirconium sponge, min. 99% pure.
41	Nb	Niobium	8,57	20 (5.54×10^{17} kg)	61.4–85.6	2020	SMM	Min. 99.9% pure.
42	Mo	Molybdenum	10,22	1.2 (3.324×10^{16} kg)	40,1	2019	Preismonitor	Min. 99.95% pure.
44	Ru	Ruthenium	12,37	0.001 (2.77×10^{13} kg)	10400 – 10600	2020	SMM	99.95% pure.
45	Rh	Rhodium	12,41	0.001 (2.77×10^{13} kg)	147000	2019	Preismonitor	99.95% pure.
46	Pd	Palladium	12,02	0.015 (4.155×10^{14} kg)	49500	2019	Preismonitor	99.95% pure. London bullion market afternoon fix. In warehouse.
47	Ag	Silver	10,501	0.075 (2.0775×10^{15} kg)	521	2019	Preismonitor	99.5% pure. Spot price. At London Metal Exchange warehouse.
48	Cd	Cadmium	8,69	0.159 (4.4043×10^{15} kg)	2,73	2019	Preismonitor	Ingot, min. 99.99% pure.
49	In	Indium	7,31	0.25 (6.925×10^{15} kg)	167	2019	Preismonitor	Min. 99.99% pure.
50	Sn	Tin	7,287	2.3 (6.371×10^{16} kg)	18,7	2019	Preismonitor	Min. 99.85% pure. Spot price. At London Metal Exchange warehouse.
51	Sb	Antimony	6,685	0.2 (5.54×10^{15} kg)	5,79	2019	Preismonitor	Ingot, min. 99.65% pure.
52	Te	Tellurium	6,232	0.001 (2.77×10^{13} kg)	63,5	2019	Preismonitor	Min. 99.99% pure. Europe.
53	I	Iodine	4,93	0.45 (1.2465×10^{16} kg)	35	2019	Industrial Minerals	Min 99.5% pure. Spot market price on 2 August 2019.
55	Cs	Caesium	1,873	3 (8.31×10^{16} kg)	61800	2018	USGS MCS	1 g ampoules of 99.8% pure caesium.
56	Ba	Barium	3,594	425 (1.177×10^{19} kg)	0.246–0.275	2016	USGS MYB 2016	In the form of chemical-grade barite (barium sulfate) exported from China to United States. Price per barium contained, includes cost, insurance, and freight. Barium sulfate is the

Z	Symbol	Name	Density (kg/L)	Abundance and total mass in Earth's crust (mg/kg)	USD/kg	Year	Source	Notes
								primary feedstock for production of barium chemicals.
57	La	Lanthanum	6,145	39 ($1.08×10^{18}$ kg)	4.78–4.92	2020	SMM	Min. 99% pure.
58	Ce	Cerium	6,77	66.5 ($1.84205×10^{18}$ kg)	4.57–4.71	2020	SMM	Min. 99% pure.
59	Pr	Praseodymium	6,773	9.2 ($2.5484×10^{17}$ kg)	103	2019	Preismonitor	Min. 99% pure, Free on Board China.
60	Nd	Neodymium	7,007	41.5 ($1.14955×10^{18}$ kg)	57,5	2019	Preismonitor	Min. 99% pure, Free on Board China.
62	Sm	Samarium	7,52	7.05 ($1.95285×10^{17}$ kg)	13,9	2019	Preismonitor	Min. 99% pure, Free on Board China.
63	Eu	Europium	5,243	2 ($5.54×10^{16}$ kg)	31,4	2020	ISE 2020	Min. 99.999% pure.
64	Gd	Gadolinium	7,895	6.2 ($1.7174×10^{17}$ kg)	28,6	2020	ISE 2020	Min. 99.5% pure.
65	Tb	Terbium	8,229	1.2 ($3.324×10^{16}$ kg)	658	2019	Preismonitor	Min. 99% pure, Free on Board China.
66	Dy	Dysprosium	8,55	5.2 ($1.4404×10^{17}$ kg)	307	2019	Preismonitor	Min. 99% pure, Free on Board China.
67	Ho	Holmium	8,795	1.3 ($3.601×10^{16}$ kg)	57,1	2020	ISE 2020	Min. 99.5% pure.
68	Er	Erbium	9,066	3.5 ($9.695×10^{16}$ kg)	26,4	2020	ISE 2020	Min. 99.5% pure.
69	Tm	Thulium	9,321	0.52 ($1.4404×10^{16}$ kg)	3000	2003	IMAR	Price quotes from canadian producer, for 1 kg order. 99.5–99.99% purity, Free on Board Vancouver, Canada.
70	Yb	Ytterbium	6,965	3.2 ($8.864×10^{16}$ kg)	17,1	2020	ISE 2020	Min. 99.99% pure.
71	Lu	Lutetium	9,84	0.8 ($2.216×10^{16}$ kg)	643	2020	ISE 2020	Min. 99.99% pure.
72	Hf	Hafnium	13,31	3 ($8.31×10^{16}$ kg)	900	2017	USGS MCS	Unwrought hafnium.
73	Ta	Tantalum	16,654	2 ($5.54×10^{16}$ kg)	298–312	2019	ISE 2019	Min. 99.95% pure. Ex Works China.
74	W	Tungsten	19,25	1.3 ($3.601×10^{16}$ kg)	35,3	2019	Preismonitor	Powder, particle size 2–10 µm, 99.7% pure. Free on Board China.
75	Re	Rhenium	21,02	$7×10^{-4}$ ($1.939×10^{13}$ kg)	3010–4150	2020	SMM	99.99% pure.
76	Os	Osmium	22,61	0.002 ($5.54×10^{13}$ kg)	12000	2016	Fastmarkets	
77	Ir	Iridium	22,56	0.001 ($2.77×10^{13}$ kg)	55500 – 56200	2020	SMM	99.95% pure.
78	Pt	Platinum	21,46	0.005 ($1.385×10^{14}$ kg)	27800	2019	Preismonitor	99.95% pure. London bullion market morning fix. In warehouse.
79	Au	Gold	19,282	0.004 ($1.108×10^{14}$ kg)	44800	2019	Preismonitor	99.9% pure. Morning London gold fix.
80	Hg	Mercury	13,5336	0.085 ($2.3545×10^{15}$ kg)	30,2	2017	USGS MCS	Average European Union price of 99.99% pure mercury.
81	Tl	Thallium	11,85	0.85 ($2.3545×10^{16}$ kg)	4200	2017	USGS MCS	
82	Pb	Lead	11,342	14 ($3.878×10^{17}$ kg)	2	2019	Preismonitor	Min. 99.97% pure. Spot price. At London Metal Exchange warehouse.
83	Bi	Bismuth	9,807	0.009 ($2.493×10^{14}$ kg)	6,36	2019	Preismonitor	Refined bismuth, min. 99.99% pure.
90	Th	Thorium	11,72	9.6 ($2.6592×10^{17}$ kg)	287	2010	USGS MYB 2012	As 99.9% pure thorium oxide, price per thorium contained. Free on Board port of entry, duty paid.

Z	Symbol	Name	Density (kg/L)	Abundance and total mass in Earth's crust (mg/kg)	USD/kg	Year	Source	Notes
92	U	Uranium	18,95	2.7 (7.479×10^{16} kg)	101	2018	EIA Uranium Marketing	Mainly as triuranium octoxide, price per uranium contained.

Table addapted from Wikipedia article: https://en.wikipedia.org/wiki/Prices_of_chemical_elements
SMM = Shanghai Metals Market
ISE = https://en.institut-seltene-erden.de/
CEIC = China Petroleum & Chemical Industry Association
EIA = U.S. Energy Information Administration
Echemi = echemi.com
Ullmann = Ullmann's Encyclopedia of Industrial Chemistry
Preismonitor = Federal Institute for Geosciences and Natural Resources - Price Monitor newsletter
USGS = United States Geological Survey
Fastmarkets = legacy.fastmarkets.com
IMAR = Industrial Minerals & Rocks: Commodities, Markets, and Uses (7th ed.)