Analysis of Excavation Methods for a Small-scale Mining Robot

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Abstract -

The following paper is discussing the potential excavation systems and development of the production tool system of a small-scale mining robot. The limitations of power and weight increase the complexity of the design of the production tools immensely. Each excavation method's efficiency is depending on the material to be excavated, the available power and the machine's capability of handling the reaction forces. In this paper, different, individual excavation methods will be compared and analysed for their applicability. This includes conventional, alternative and combined excavation tools. The individual technologies are assessed in terms of their efficiency and feasibility by surveying existing technologies and analytical studies. The contribution of this paper is a summary of viable excavation methods for small-scale robotic miners.

Keywords -

Excavation; Production Tools; Robotics; Small-scale Mining

1 Introduction

Upcoming challenges in mining due to sustainability and ecological aspects require additional efforts in research and development. The trend towards zero personnel in underground mining demands full mechanization and automation of the mining process up to the use of fully autonomously operating robots. To reduce the residue risk to a minimum for workers in harsh conditions, it is indispensable to develop automated mining machines, which can take over the hazardous parts of the mining operation. Some of the work is already done entirely by independently working machines, but there is still personnel needed for many different tasks (e.g. maintenance). Possible tasks for robots in mining are the maintenance of machinery, exploration (e.g. abandoned mines) and selective mining (especially in difficult to access areas). [1, 2]

Today we see early research and development in robot technology [2], which are expected to replace the human workforce in underground mining within the next 30 years, see figure 1.

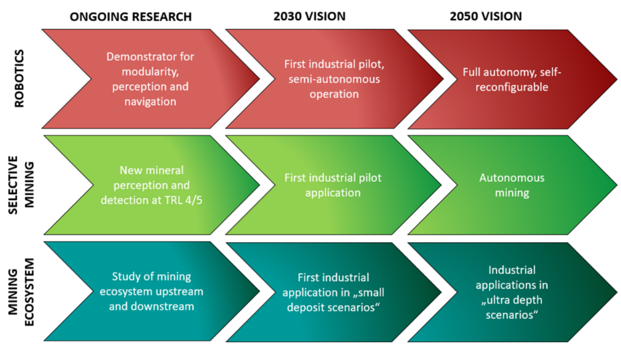

Figure 1. Robotics in mining - Prospect

The progress during this timeline can be divided in 3 parts, which will all develop consequently. Ongoing researches focus on the development of new mining and perception systems and also on sustainable mining ecosystems. The goal of the next 10 years is to create first industrial pilots, which can operate semi-autonomously in "small deposit scenarios". Eventually, the vision for 2050 is to have completely autonomous systems, which are able to work in ultra-depth scenarios.

In this paper, excavation methods are assessed in terms of their applicability for a small-scale mining robot.

Scope of this robot are exploration and selective mining underground, under water and in slurries. One of the key components of this robot is the production tool system, capable of mining hard and abrasive rock. Considerably low weight and power are challenges to be overcome in this project.

2 Excavation methods

In mining, the excavation of material can be performed by many different methods. For the subsequent analysis, the excavation methods are classified in four main categories: drilling and blasting, mechanical excavation, alternative excavation and combined excavation (figure 2).

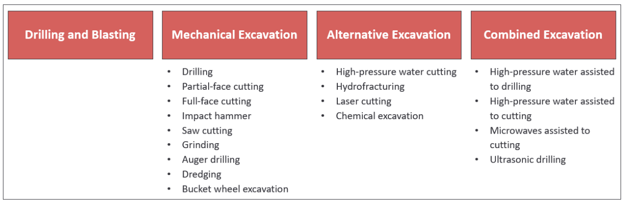

Figure 2. Classification - Excavation methods

2.1 Drilling and blasting

The drilling and blasting method is one of the most used excavation methods for extracting large amounts of hard rock [3]. Drilling the boreholes is usually done by automated drill rigs, equipped with specifically selected drills. Standardized drilling methods are electro-hydraulically, rotary or rotary-percussive drilling (explained in section 2.2.1). Applications of drilling and blasting can be found in rock excavation and tunneling. [3, 4, 5]

Drilling and blasting is known for its generic applicability, the high production rate and the high grade of fragmentation. Especially when mechanical excavation reaches its limits, drilling and blasting proves its effectiveness. On the other side, drilling and blasting requires a series of individual tools, the blasting process is accompanied by some side effects (noise, vibration and toxic fumes) and represents generally a discontinuous excavation process. [3]

The low reaction forces of the drilling process and the capability of excavating very hard material are beneficial f or t he r ealization o f t he m ining r obot and therefore, the applicability to a robotic-miner will be assessed in more detail in section 3

2.2 Mechanical excavation

Mechanical excavation is next to drilling and blasting the second main excavation technique in mining [3, 5]. Compared to drilling and blasting, mechanical excavation has some benefits [3]:

- Safer operation
- Potential for selective mining
- Continuous excavation

In this section conventional mechanical excavation methods are described and analysed in terms of their applicability to a robotic miner.

2.2.1 Drilling

Drilling is mainly used as one link in the chain of an excavation process (e.g. drilling and blasting) or as an auxiliary tool, but not as a standalone excavation method due to the low production rate. Further applications are drilling well holes and material collection by sample drilling [6].

Drilling is a comparatively easy technology and is able to excavate small amounts of both soft and hard rock with the suitable technology. State-of-the-art drilling methods used, are:

- Tophammer drilling
- Down-the-hole-hammer drilling
- Rotary drilling
- Core drilling

In section 3 drilling will be analysed in more detail in connection with the applicability assessment of drilling and blasting.

2.2.2 Partial-face cutting

Partial-face cutting machines are excavating only a part of the rock face at a time and are known for their mobility and flexibility. The cutting head is a rotating drum, equipped with picks and mounted on a boom. During the cutting process, only a number of the entire amount of picks is in contact with the rock to be excavated. [3]

With a partial-face cutting head, large volumes of soft to medium hard rock can be excavated, curves be cut and tunnels be created. [3, 7]

In the mining industry, partial-face cutting machines (e.g. roadheaders) are mining machines with usually high mass and weight to be able to penetrate the rock. The machine needs to withstand the high reaction forces resulting from the cutting process.

Small-scale cutting heads exist [8, 9], but are very limited in terms of rock strength. A robotic-miner equipped with a cutting head would possess very restricted capabilities, although the advantages of the system could be beneficial for certain scenarios.
Hence, partial-face cutting systems are considered in more detail in section 3.

2.2.3 Full-face cutting

The fellow of the partial-face cutting machine is the full-face cutting machine. As the name indicates, a full-face cutting machines' cutting head is constantly in contact with the rock face. The cutting head is a rotating part, equipped with pick or disc cutting tools and pushed against the rock face to excavate the material. [3, 10]
In reality, full-face cutting machines, e.g tunnel boring machines (TBM) [11, 12, 13], pipe-jacking machines (PJM) or boxhole boring machines (BBM) [14], are available in various designs from rather small to large diameters and mainly taken for boring tunnels, pipelines or shafts.

The cutting technology of full-face machines makes them capable of excavating very hard and abrasive rock. This requires, compared to the other methods, very high performance for the generation of the cutting and reaction forces. The demanded amount of power and traction lead to comparatively long and heavy machines, which make them much less flexible and mobile. [3, 7, 10]

Due to the existence of micro-tunneling machines or pipe-jacking machines with diameters below 1 m, it is worth checking the feasibility of the implementation in a mining robot (section 3).

2.2.4 Impact hammer

Impact hammers are rock excavation tools, especially used for breaking or scaling operations. A piston produces high frequent impulses and transmits it to the impact tool on the front end. [3]

The method is simple and an impact hammer can be mounted on different types of machines. Typical applications are breaking oversized boulders, quarrying or scaling operations. Impact hammers are mainly taken as an auxiliary tool to the main excavation machine. [3]
Excavation of soft rock or soil is not feasible. Further on, the reaction forces of an impact hammer are considerably high and the production rate is low. Hence, this technology is not further investigated.

2.2.5 Saw cutting

Rock cutting chainsaws are characteristically used in quarrying operations for extraction of dimensional blocks. The capabilities are limited to cutting of soft to medium hard rock. Rock cutting saws are not considered as a production tool for a robotic miner. [3]

2.2.6 Grinding

Characteristically for a grinding process are the high frequency and low amplitude of the process. Due to the fact, that grinding is not used for excavation and tools tend to wear off easily, it will not be analysed any further in this paper.

2.2.7 Auger drilling

Auger drilling combines both excavation and conveying in one method. Often used in coal seam operations, drill rigs with a rotating auger and a drill head on the front tool end require high thrust forces and torque. Continuous excavation of rock and tunneling are not viable with this certain method. [3, 15]

2.2.8 Dredging

Transshipping or excavation of very soft material can be managed by dredging. Excavation of greater amounts of hard rock and tunnels are not viable with a dredging technology.

2.2.9 Bucket wheel excavation

Bucket wheel excavators are employed for soft coal mining in open pit scenarios. The buckets dig into a layer of material and drop it onto a conveyor belt. [16] presents a mining robot with a bucket wheel excavation technology for lunar soil. This excavation method is not feasible for an underground, hard rock mining scenario. [17]

2.3 Alternative excavation systems

Alternative excavation systems cover non-conventional excavation methods apart from mechanical excavation and drilling and blasting.

2.3.1 High-pressure water cutting

Water jet cutting technology is a method for shattering and cutting material from very close distance. [18] The pressure of the water jet is increased by a high-pressure pump, pushed through a nozzle pointing towards the material to be cut. Often employed for precise cuts, high-pressure water jets have their reason for being utilized in the mining industry. Various forms of water jets can be applied for individual operations. [18, 19]

[18] defines following appearances of high-pressure water jets:

- Continuous plain water jets
- Pulsating and modulated water jets
- Abrasive water jets

Cutting rock reasonably well requires a minimum water pressure around 100 MPa. A comparatively high specific energy leads to a prerequisite of large volumes of water and decreases the potential as a production tool in a robotic miner. A combination of high-pressure water jets with conventional mining methods seems to be more practical and will be discussed in section 2.4.1 and 2.4.2.

2.3.2 Hydrofracturing

Hydrofracturing, or hydraulic fracturing, is the employment of pressurized liquid (mostly mixed with additives) into a borehole to fracture rock formations. If the present pressure exceeds the rock's tensile strength, crack formations are induced. [20] Mainly used in oil and gas production, hydrofracturing is currently not used for rock excavation and is considered to be not important for detailed investigations.

2.3.3 Laser cutting

Laser cutting technology exhibits high specific energy levels and is typically used for precise cuts of blocks with rather small thickness. [21] Excavation of big volumes is not feasible, therefore not considered for further analyses.

2.3.4 Chemical excavation

Chemical excavation is a very restricted technology, only used in very special scenarios and therefore not discussed in detail. [22]

2.4 Combined excavation systems

Combined excavation systems combine the advantages of mechanical excavation systems with alternative, auxiliary methods.

2.4.1 High-pressure water assisted to drilling

As pointed out in section 2.2, mechanical excavation has some benefits over drilling and blasting. Though, the operating field of mechanical excavation is limited by geotechnical conditions. Many activities involve overcoming those limitations by improving the conventional technologies or developing new excavation systems.
A number of researches and studies [18, 19, 23, 24] investigate the improvement of the overall drilling time and efficiency of rotary-percussive drills.
Assisting water jets enter the cracks in the crushed zone and, due to the water wedge effect, increase the crushing effect.[24]

If the water pressure exceeds the critical stress of the rock, cracks will be induced and result is a reduction of the required drilling performance. In order to decrease drilling time and increase lifetime of the drill bit, high-pressure water jet assisted to drilling seem to be a practical solution. [24] In this specific case, only drilling will be used, if for the excavation method of the mining robot drilling and blasting is chosen. A trade-off between complexity respectively costs and efficiency has to be made.

2.4.2 High-pressure water assisted to cutting

Besides from drilling, cutting can also be assisted by high-pressure water jets. The purpose of assisting water jets are the reduction of the cutting force and decrease of the tool wear. [23]
The greatest disadvantage of currently used, mobile and flexible excavators (e.g. roadheaders) is the limitation of cutting rock with UCS above 150 MPa [7]. Joy Mining [25] has introduced a new disc cutting technology with assisted water jets, the Dynacut™. Aim of this research project is combining mechanical excavation technology for hard rock cutting with high-pressure water jets. Until now, no test results could be found. [7, 25]

The importance of assisting high-pressure water jets arises, when conventional cutting method reach their limits. Scope of the robotic miner is the excavation of hard rocks. An implementation of a common cutting drum with pick tools will not even be capable of excavating medium hard rock, and therefore, cutting technology with assisting high-pressure water jets will not be discussed further in this paper.

2.4.3 Microwaves assisted to cutting

The basic idea of using microwaves is the same as of using high-pressure water jets: Implementation as an auxiliary tool to a main excavation process for decreasing the rock quality. [26]
One method is the use of microwave irradiation to reduce the rock strength by inducing cracks. Cracks pre-weaken the rock and lower the cutting resistance. Researches show, that the net cutting force can be reduced by approximately 10 %. [26]

The operating fields of the mining robot are wet or submerged underground scenarios. Microwaves are absorbed by water and as a consequence, the applicability of microwaves is not given.

2.4.4 Ultrasonic drilling

As mentioned in section 2.2.1, drilling is i.e. used for exploration, shaft drilling and extracting samples. Shortcoming of common rotary-percussive drills, while drilling hard and abrasive rock, is maintenance due to tool wear. Purpose of ultrasound drilling is the reduction of operating costs by increasing the penetration rate. A piezoelectric transducer converts the electric energy to mechanical vibration. This oscillation is superposed with the rotation of the drill and provides the penetration. [27]

Compared to conventional drilling, ultrasonic drilling is an elaborate technology and no applications in wet or completely submerged conditions have been found. A comparatively minimal increase of the penetration rate is not the most important point, hence, ultrasonic drilling is not investigated further in this paper.

3 Analysis

In this chapter, the most promising excavation methods, assessed in the previous section, are analyzed in more detail. The applicability of the production tool system is depending on some properties:

- Production rate
- Penetration rate (Advance rate)
- Specific energy
- Limitations

Following parameters are assumed for the calculations in this chapter:

- Input power: 40 kW
- Tunnel cross sectional area: 1 m^2

3.1 Drilling and blasting

The advantages of drilling and blasting already have been discussed in the previous section. The most important feature, for this study, is the capability of excavating larger amounts of very hard rock with one blast. Furthermore, a complete mechanization is state-of the art, however, a full automation of the loading process is a complex challenge to be mastered.

Drilling is the most time consuming step in drilling and blasting. To keep the blasting cycle to a minimum, the penetration rate of the drill to be used is crucial. The penetration rate reflects the drilled length per hour. In this case, a rotary-percussive drill is chosen with a bit diameter of 60 mm. The penetration rate is calculated after [28] (figure 3).

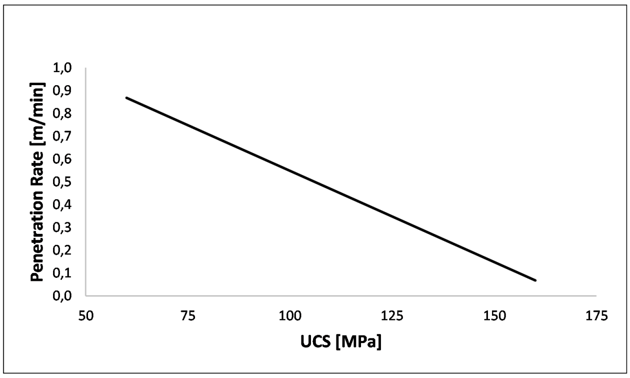

Figure 3. Rotary-percussive drilling - Penetration rate

The formula used for estimating the penetration rate results of a linear regression model of measurement data. The penetration rate is decreasing linearly with the rock strength. [28]

If a bore hole with 300 mm depth is assumed, the time for drilling varies between 20 seconds and 4.5 minutes. Depending on the employed explosives, excavating a tunnel with the assumed cross sectional area requires between 5 and 10 blast holes. Following from this, the total time for one blast (including loading the boreholes with explosives) is estimated between 1-2 hours. For simplicity, the time between drilling the individual holes, for crushing and for conveying is neglected. The precise analysis of the blasting cycle will be done in future investigations.

The specific energy is the amount of energy to excavate one unit volume of rock [3]. A drilling process exhibits, compared to other mechanical excavation systems, a high specific energy (calculated after [3]), see figure 4. However, this peculiarity is extensively decreased by the subsequent blasting operation.

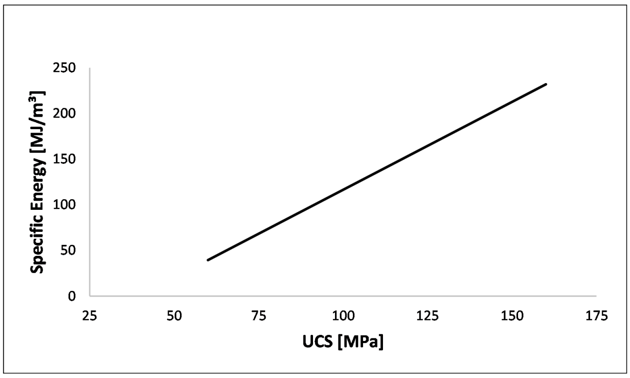

Figure 4. Rotary-percussive drilling - Specific energy

The specific energy of the drilling process is approximated by a linear regression model of [28]. This model provides satisfactory results according to the measurements.

3.2 Partial-face cutting

Partial-face cutting machines distinguish their self by their flexibility and mobility. Excavation of tunnels, cutting curves or limited selective mining are characteristic capabilities. Shortcomings are the severe restrictions by the rock properties. Standard partial-face cutting machines' cutting abilities fatigue at rocks with UCS around 150 MPa [3, 7]. In this paper, a cutting head with a considerably less lower amount of power is investigated, which will limit the mining robot's abilities to excavating soft rocks only. The instantaneous breaking rate, the rock volume excavated per hour, is calculated after [3] (figure 5) and is provided by a prediction model, which is based on full-scale linear cutting tests.

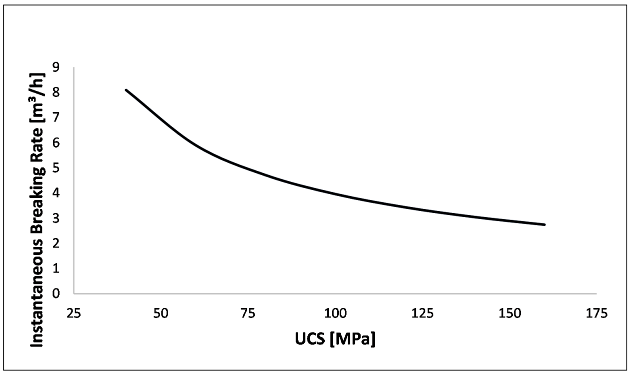

Figure 5. Partial face cutting - Instantaneous breaking rate

In practice, the mining machine would not be able to withstand the reaction forces, resulting from cutting, due to the little weight and traction. In this order of magnitude, the ability of cutting rock above 60 MPa is believed to be very unlikely.

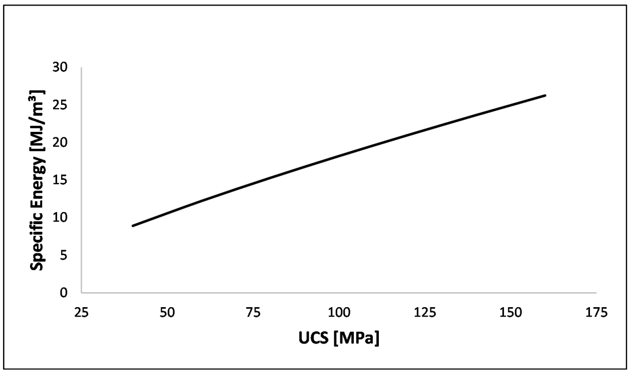

Figure 6. Partial face cutting - Specific energy

After [3], specific energies above 20 MJ/m^3 are not economical and lead to damage of the cutting tools. The estimated specific energy can be derived from the instantaneous breaking rate and the provided input power. [3]
However, for the chosen scope of application, the specific energy levels are bearable (figure 6).

The advance rate is the excavated length of the tunnel (with the determined cross sectional area) per hour. Again, for the advance rate, only the region below 60 MPa is important (figure 7). The estimation of the advance rate presupposes an ideal and continuous cutting operation and is calculated for the fictitious cross sectional area of 1 m^2.

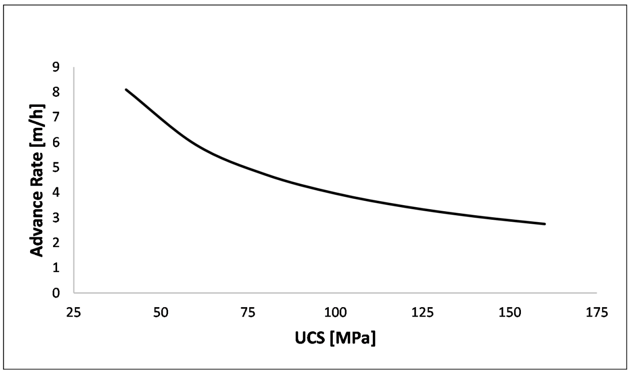

Figure 7. Partial face cutting - Advance rate

3.3 Full-face cutting

In practice, a number of reputable companies have developed small-scale full-face cutting machines. [11, 12, 13, 14] Exemplary machines are: Micro-tunneling machine (MTBM), pipejacking machine and boxhole boring machine.

Those machines already exist with diameters within the range of 1 m. Biggest advantage over the partial-face cutting machines is the ability of excavating hard rock. Despite the size, such machines are capable of excavating rock up to 180 MPa [11, 12, 13, 14].

The net production rate shows the volume of rock excavated per hour (figure 8), calculated after [3] and again based on full-scale laboratory cutting experiments.

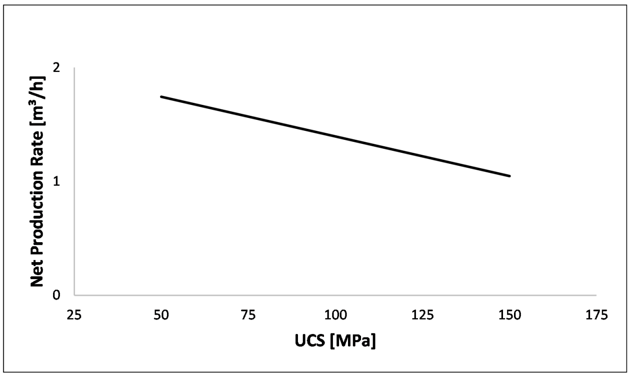

Figure 8. Full face cutting - Net production rate

Theoretically, an average net production rate of 1.5 m^3 per hour is feasible.

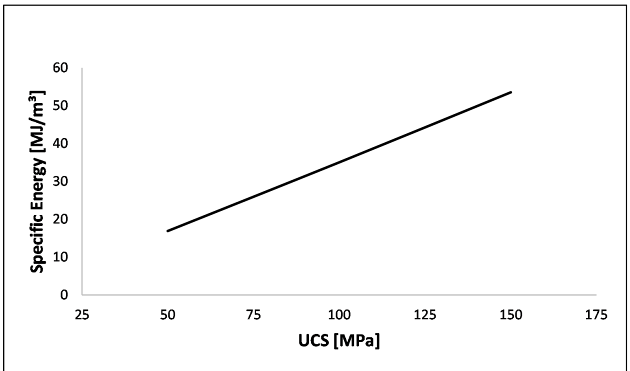

Figure 9. Full face cutting - Specific energy

Compared to the partial-face cutting machines, full-face cutting machines have relatively high specific energies, see figure 9 . D ue t he h igher p ower, f ull-face cutting machines are operating more efficiently in "high specific energy-regions". Specific energy levels are calculated by estimation formula of [3], obtained from full-scale cutting experiments.

The advance rate for the determined tunnel size is shown in figure 10. Ideal and continuous cutting operation is assumed and the fictitious cross sectional area of 1 m^2 is chosen for estimating the advance rate. In contrast to the partial-face cutting machines, the full-face cutting machines' advance generally slower, but does not slow down that much with increasing UCS.

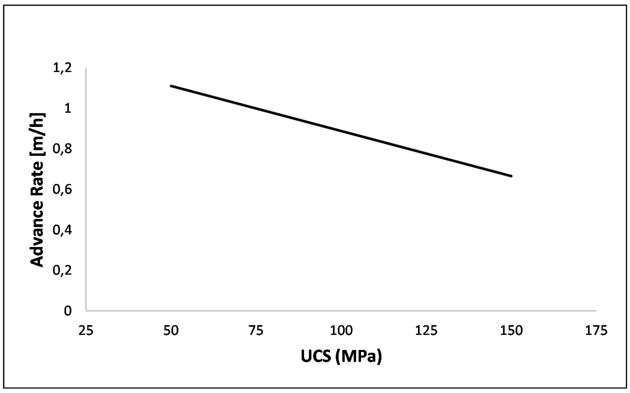

Figure 10. Full face cutting - Advance rate

Eventually, the cutting rate of full-face cutting machines is a crucial parameter to be investigated. The tendencially high cutting forces represent an omnipresent problem of mechanical excavators [3, 7]. [29] has introduced regression models for estimating disc cutting forces. In this certain case, the extraordinarily high cutting forces (calculated after [29]), seen in figure 11, can not be withstood by the robotic miner.

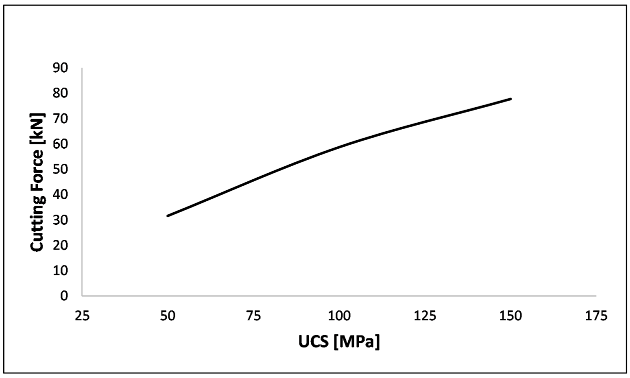

Figure 11. Full face cutting - Cutting force

4 Discussion

From the literature survey and analytical studies following conclusions can be made:

- Advantages of the partial-face cutting systems are the continuous material excavation, the high production rate, the flexibility and the possibility of selective mining. But they are limited by the rock's strength (UCS) and abrasivity (CAI). The excavation process requires very high cutting forces and frequent maintenance of the cutting tool. The cutting forces for excavation hard rock cannot be provided by the given power and weight. Partial-face cutting is only a viable option for small amounts of soft rock. For these special cases, a partial-face cutting robot seems to be a practical solution.

- The capabilities of full-face cutting machines (MTBMs or BBMs) theoretically exceed those of the partial-face cutting machines, but the cutting forces are generally even higher. Furthermore, the less flexibility and higher specific weight are additional limitations and counteract the applicability.

- Drilling and blasting is a very complex process. Multiple, individual tools and working steps increase the efforts of rock excavation and need to be adjusted precisely. Advantages are the comparatively low reaction forces acting on the robot and the excavation of hard rock. To excavate justifiable amounts of hard rock with the given boundary conditions, it is worth to focus on further investigations of drilling and blasting.

In the following chapter, a concept for the implementation of drilling and blasting process is introduced.

5 Conclusion

As explained previously, drilling and blasting requires a minimum of three individual steps:

1. Drilling: Drilling of the borehole
2. Loading: Charging of the boreholes with explosives
3. Hauling/Transporting: Transportation of the fragmented rock

The tool set which is required for excavation process only, consists of a drill, a tool for clearing the blastholes from the drilling debris and an arm for charging the blastholes with the explosives. In figure 12, the implementation of the main operations of the excavation process is visualized. The autonomous work of the mining robot demands a fully mechanized and automated production tool system,

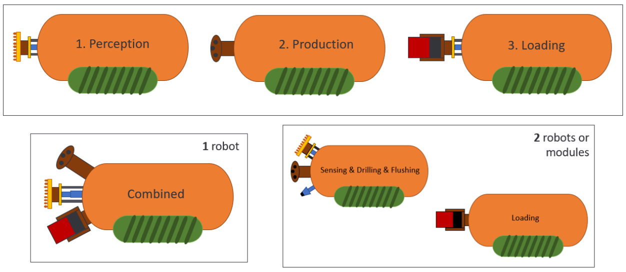

Figure 12. Implementation of drilling and blasting

including drilling, removing residues (debris or small rock grains), loading the blast holes and blasting.

Following the boundary conditions (limited size, weight and power) impede the development of an universally operating robot. Therefore, it is beneficial splitting up the tools into a reasonable number of robots. At least, one drilling and one blasting robot. Due to safety reasons and potential shortage of space inside the robot, the loading setup is completely isolated from the other equipment. In return, other instruments (e.g. perception and navigation instruments) can be installed in the drilling robot.

Aim is to develop a fully mechanized and automated robotic miner, which is capable of detecting the ore, excavating the material and transporting. For a better understanding of the complexity of the drilling and blasting method, a few important points need to be discussed: In addition to the excavation tools, a number of other instruments and equipment are necessary. Navigation and perception shall be executed completely autonomously and demand corresponding technology. If the robot has detected a potential ore vein, a decision of further proceeding has to be made. Samples of the material decide if it is worth mining. A sample can be extracted with the drill and then be assessed in terms of quality by chemical analysis. The fragmented rock is rarely evenly distributed in terms of grain size. Therefore, an on-board crusher is mandatory. After crushing the rock, the material has to be conveyed to a desired area. A feasible, mobile way of transporting material in an underground mining scenario is the slurrification of the excavated rock. Eventually, a couple of side tasks accompany the main excavation process. The mined tunnel possibly requires stabilization and mechanical parts typically tend to wear out. General utility and maintenance are tasks not to be underestimated.

The above mentioned tasks describe an entire mining ecosystem. To turn this ecosystem into a fully autonomously operating operation, it is not avoidable to define a robotic family with complete division of labor. A universal robot body creates the base for the individual robots. The tasks to be executed define the instruments and tools implemented in every single robot. In this specific case at least six individual modules need to be built. A combination of specific modules can reduce the amount of robots. In figure 13 it is visualized, if every main task is done by an individual robotic vehicle.

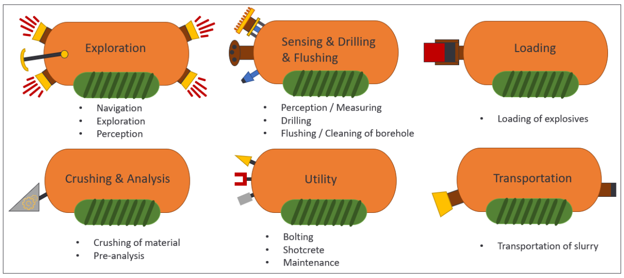

Figure 13. Robot family

The figure shows an exemplary robot family with the following tools implemented:

1. Exploration: Navigation, exploration and perception
2. Sensing, drilling and flushing: Perception / measuring, drilling and clearing of blastholes
3. Loading: Charging of the blastholes with explosives
4. Crushing and analysis: Crushing the fragmented material to evenly distributed size and analyse the excavated material
5. Utility: Stabilization of structures and maintenance
6. Transportation: Transportation of the crushed ore/slurry

Funding

This project has received funding from the European Union's Horizon2020 research and innovation programme under grant agreement No. 820971.

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