The creative process for the development of an autonomous bolting arm for underground mines

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ABSTRACT: Ground support installation is essential in the underground mining industry. However, it is one of the riskiest activities due to the operator's exposure to unsupported faces recently excavated. From this reality, this work was performed to develop autonomous drilling and bolting arm for underground support purposes. The primary considerations for machinery are the rock mass interaction, artificial intelligence for recognition and mechanical requirements. First, some of the latest technologies that can be related to this research of the autonomous underground mine will be discussed. Secondly, the insight from the miners obtained from interviews will be reported. Finally, the challenges, premises and steps taken will be discussed. This research cannot be compared to one standard automatization due to the extreme variability encountered in rock masses during excavations.

Keywords: Autonomation, machine learning, rock mechanics, ground support.

1 INTRODUCTION

Underground mines have risks inherent to their uncertainties related to the terrain heterogeneity, geological structures (e.g. faults, discontinuities, wedges formation), seismicity, human-related mistakes during operation. For this reason, the search for autonomation and remotely operated devices have been more latent, aiming to decrease human exposure to such risks.

Some recent advances in this aspect that can be mentioned are the AutoMine® Concept from Sandvik for haulage, loading and, more recently, fully autonomous surface drilling (Sandvick, 2022). The successful use of autonomous trucks at the Brucutu mine from Vale in Brazil, completing 100 million tons transported in five years with no human operation and no accidents (Vale, 2021).

Between the risks involving underground mining, threats applied to the ground support are the most present. In a risk assessment made by the ministry of labor in Ontario (Dey & Barclay 2018), four of the top five risks for underground operations were ground support related. Among the top ten risks in the underground mines made in 2014, the ones related to ground control were: rock bursts, loose rock at the face injuries related, exposure to hazardous substances, falls of ground while installing support, and the inexperience of workers.

This research is part of the MITACS acceleration program titled "Intelligent and autonomous mines" with the project management of MISA and partnership with diverse private companies and universities. This research aims explicitly for the conceptualization of autonomous drilling and bolting machinery.

The work was performed in two phases. The first aimed to define the optimum sequence of ground support installation (drilling and bolting) and specifications to design an autonomous mechanism. The instrument was intended to be prepared to proceed with a self-detection, position, drill, and bolt, following an engineering ground control project. Finally, to describe the technical input and output data needed to be determined based on the primary and secondary functions of the designed mechanism.

The second research aimed to propose a methodology to obtain geotechnical parameters taken into consideration in the system, to define the sensors to be potentially used, to define the possible accuracy methodologies from the drilling/bolting location, to create the programming sequence for the arm and finally to propose subproducts that could be developed in the meantime for data acquisition. Figure 1 summarizes the direction and product development acquired by this research.

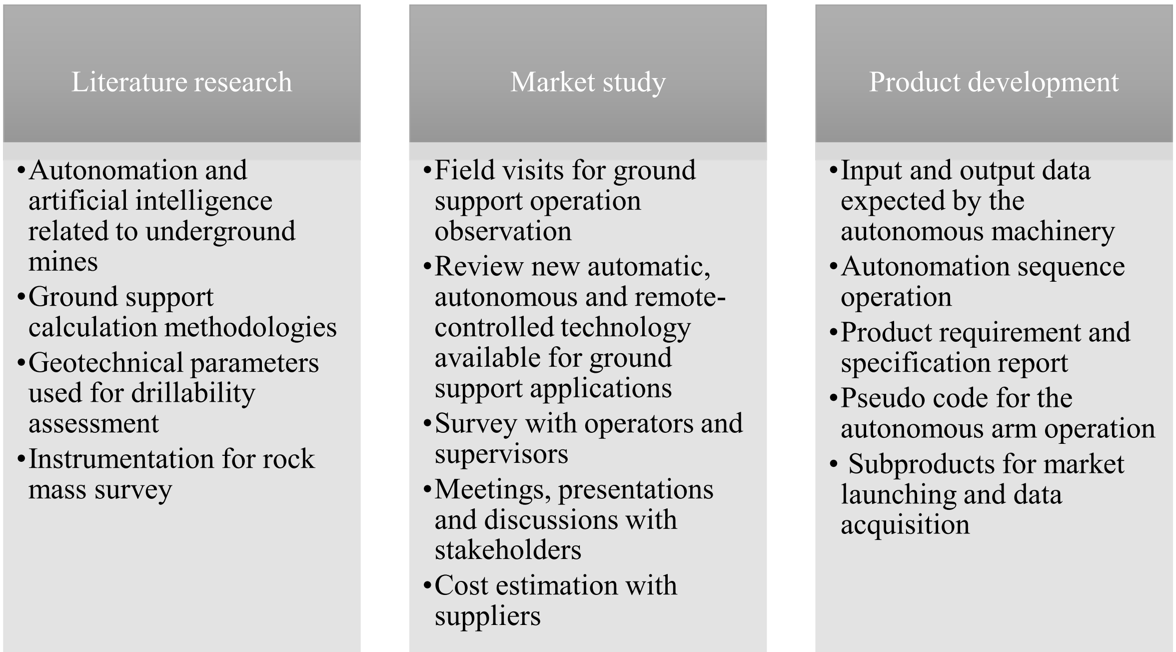

Figure 1. Research summary.

2 METHODOLOGY

Following is a summary of some considerations and studies performed in this research.

2.1 Existing machinery observed

Some of the machinery observed by field visit, videos observations and brochure study to understand the limitations and operability were: JackLeg and Stoper, DS-311 and DS-411 Sandvik bolter, Sandvik production drill automation, Sandvik DD422i/DD422iE Automation Upgrade, MacLean Series 900 Bolters, Multibolter 3045 and electro-hydraulic "E-bolter" from JOYGLOBAL, autonomation options for tunnel management series from ATLAS COPCO, Simultaneous

Localization and Mapping (SLAM) from GeoSLAM, Autonomous drones produced by ExynAero, FARO® Trek 3D Laser Scanning Integration.

2.2 Ground support calculation methodologies

Although the primary objective of autonomous machinery is to follow the engineering specification, it is essential to define the arm behaviour in cases where the ground and dimensions don't follow the plan, and the position needs to follow a direction aiming for a better safety factor. Some of the methodologies considered were: Load bearing capability for sliding blocks, Block sliding calculations, Lang (1961) method, Bieniawski (1989), System-Q, Barton et al. (1974, 1993), RMi: méthode Palmström (1995). Other significant design methodologies, such as the "Deformation-based support design" proposed by Kaiser and Moss (2022), have the potential for future implementation. However, it was not within the scope of this research to consider them at the present stage.

2.3 Geotechnical parameters used for drillability assessment

A study was performed to identify the importance of parameters for the drillability assessment (penetration rate), which later would mean the arm response to the terrain while drilling and bolting. Figure 2 shows the parameters influencing the drillability, according to the literature research examined. Even though over 30 parameters were listed, some can be found by correlations.

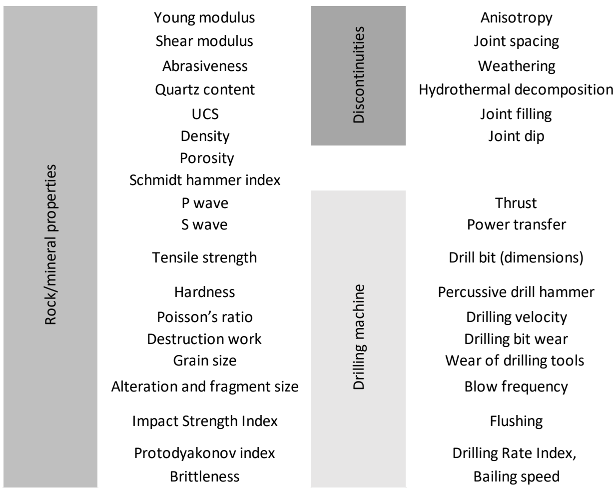

Figure 2. Parameters reported as affecting drillability in the literature research.

2.4 Instrumentation for rock mass identification and adaptation

Some of the technologies that were considered but not necessarily taken for the final design for the autonomous arm were: ground penetration radar (GPR), Schmidt hammer, measure while drilling (MWD) or logging while drilling (LWD), Lidar, simultaneous localization, and mapping (SLAM), 4K camera and built-in lighting, inertial motion sensors.

2.5 Survey with operators and supervisors

This research was performed by interviewing operators in four different mines in Canada located in British Colombia, Quebec, and Ontario. The professionals were observed during their work, and an equal questionnaire was made to understand the unique challenges of the operation with the ground control crews available at the moment of the visit and with the supervisors that had experience with ground support operations. The base questions aimed at understanding:

- Their comparison of machinery used currently and in their previous experience with the pros and cons related to each;
- What were the problems usually faced and the hazards involving the ground support operation from their perspective,
- their vision of the different bolts problematic,
- what were their criteria for choosing the spot to bolt, and what would they do according to different ground conditions,
- What are the possible challenges that they would expect with the automatization.

The following table classifies the mines and systems used.

Table 1. Characteristics of ground support operation in visited mines.

Mine	Province	Machinery	Bolt types	Shifts
A	Quebec	Jack leg and Stopers	Rebar, Splitset and Swellex	2 teams; 2 persons 11h/each; 7/7 days
B	Quebec	Mac Lean	Rebar, Splitset, Cable bolt	2 teams ; 1 person 11 h/each; 7/7 days
C	Ontario	Jack leg and Stopers	Rebar, Splitset, Par1	2 teams; 2 persons 11h/each;7/7days
D	British Colombia	DS 411, DHS(CMAC)	Rebar, Swellex	2 teams ; 1 person 11 h/each; 14/14 days

3 AUTONOMATION CHALLENGES

At this moment, some essential assessments from this research are reported.

3.1 *From the existing machinery available*

Different companies have presented important innovations that will lead for the automatization and, later on, autonomatization. Some critical advances that must be cited are:

- Teleremote control for electro-hydraulic jumbo,
- boom discretization for no collapse,
- machines operating by the drill plan without operators inside,
- adaptive drilling/measure while drilling systems,
- prevention of drill bending and water blockage,
- rotation from drilling to bolting function with the machine in the same position,
- secondary arm to position the mesh.

However, as important as the installation of the primary support type, a primordial necessity for the autonomous arm will be to recharge the bolts and plates and insert the secondary support type (e.g. mesh, shotcrete). A secondary device to place the mesh or shoot the shotcrete must be considered. The programming to use simultaneously with the autonomous bolting arm, avoiding possible collisions, is needed. The recharge system's logistics and operability must also be designed for minimum human exposure.

3.2 *Ground support calculation methodologies*

The autonomous ground support installation arm isn't meant to design the ground support system. However, due to the constant change in tunnel headings, it is interesting that the machine can make acceptable adaptations and send alert signals to the ground control group about specific ground alterations found during the process.

Since input parameters such as rock strength (by MWD), discontinuity spacing and orientation (GPR, MWD, image recognition) can be constantly recorded for parameters test and feedback, these parameters and others needed can be used to obtain the necessary information for methods such as

System-Q, RMR, calculations. Works using artificial intelligence for rock mass classification have already been done. Sheng et al. (2022), as an example, used deep learning to predict the rock mass rating (RMR).

Geological and geotechnical previous studies could obtain other critical parameters not offered by the sensors used; these can be input into the autonomous machine to assist the terrain prediction. It is crucial, however, to extensively train and validate the image recognition and other parameters prediction before using it to classify the rock faces.

3.3 From the operators' and supervisors' perspective

A crucial aspect of the survey was the main complaints about the machinery to understand the advantage of the autonomous process and somehow seek to avoid common mistakes (see Figure 3). Although the miners had experienced multiple types of machinery, the preference for a specific style or model wasn't unanimous. It would fluctuate between the ones presented here and others.

Jackleg with Stopper	DHS (CMAC) - When instaled in a Roadheader	MacLean bolter	DS 311, DS 411 (Sandivick)
• Rockfalls • heavy equipment and operation • vibration • handling the equipment • noise • Working at heights (when installed in a Scissor Deck like equipment) • noise	• Rockfalls • vibration • dust • working at heights • noise	• Rockfalls • working at heights	• Noise • More disruptions due to mechanical problems when compared to the previous

Figure 3. The main complaints about the types of machinery during the visits.

Other vital information was, given the ground support plan, the criteria the operator chose to choose the hole location. All the operators reported similar answers: "*The spot is chosen by an approximation between the expected distance from the ground plan and how space should be, based on the mesh spacing. The mesh is used as a decision-making point to avoid the steel and to obey the squares overlap*". In the case of DHS and Jackleg, the drill is used to flatten the surface if the place chosen is not ideal/flat. Lastly, the criteria to stop the operation and call the supervisor or ground control engineers were: extensive ground fall/bad ground/joints, seismicity, water and energy supply problems, fire, injuries, and machine issues.

3.4 From a geotechnical parameters and artificial intelligence perspective

Aiming for autonomous machinery means seeking ground recognition with a decision-making tree that can consider the different rock mass conditions. For that is important to recognize the exterior of the surface with measuring distance tools (e.g. Lidar, ultrasonic measurer) and/or camera vision technology. Simultaneously, the changes must be obtained inside the rock mass as well, with MWD, GPR technologies. Independent of the exact tools used for clearly comprehending the terrain, the autonomous behaviour success will depend directly on the training parameters and suitability to the ground of the mine. In this sense, a previous step with tele-remote operation is essential to obtain sufficient data for machine learning and to have a deeper understanding of the operational particularities of the process.

4 CONCLUSION

This work aimed to share some of the creative processes behind the idealization of an autonomous bolting machinery. Due to privacy agreements, some pieces of information related to product key features, subproducts, detailed product requirements, operational flowcharts, and other details on the site surveys cannot be disclosed. However, it is essential to mention the importance of the autonomous arm being capable of recognizing the terrain conditions and possible non-conformities that are normal in underground environments. It also is critical to reaffirm the importance of extensive training for the machine to identify the specific variabilities of the site, rock formation and geological structures present.

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