Development of an automated roof bolting machine for underground coal mines

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This paper describes and discusses the steps taken towards the development of an automated roof bolter that performs the roof bolting operation in underground mining environments. Roof bolting operations in underground mining expose human operators to a number of risks. Successful completion of bolting tasks depends heavily on operator judgment, fatigue, and experience to perform these tasks. During bolt installation, the operators are exposed to a potentially unstable roof, cumbersome consumables, and heavy spinning masses that could lead to fatal or serious injuries. The accident record motivates the development of automated roof bolting machines that removes humans from this process. The primary function of the operator would be to supervise all the operational tasks and to control the automated roof bolting via a human-computer interface (HCI) and intercede where necessary. The automated roof bolter performs a sequential bolting operation which includes drilling, drill steels removal, resin placement, and bolt installation. A six-axis robotic arm was integrated into the system to replace tasks performed by humans during the bolting operation. The robotic arm mimics and improves human tasks which in turn enhances productivity. Some novel technologies were developed with respect to the components that form the automated roof bolter such as the plate feeder, the bolter feeder, and the wrench. Other components such as the robotic arm controller, the programmable logic controller (PLC), the HCI, the drill control unit (DCU), and the hydraulic roof bolter are integrated through the process of 'handshake'. Integration of all components and technologies enables the proper sequencing of roof bolter operations. The study shows that the robotic arm can successfully perform human activities during roof bolting operations. More importantly, the operator can supervise the bolting process via a remote control touchpad which allows the operator to stop the operation in the event of a malfunction.

INTRODUCTION

According to Sammarco *et al.,* (2016), mining has the second-highest fatality rate among U.S. employment sectors, with 15.1 fatalities per 100,000 full-time equivalent workers. Ruff *et al.,* (2011) stated that mining machinery related accidents accounted for 41% of all serious accidents between the years 2000 and 2007 in the US mining industry. Roof bolting is a universal ground support system used in underground coal mines to ensure the stability of a potentially unstable roof. Roof bolting equipment installs the roof bolts that bind and reinforce the discontinuous rook mass to prevent roof deformation and potential failure. Roof bolting is a labour-intensive task that includes the functions of drilling, resin placement, and bolt installation. During bolt installation, the operator drives several components such as the drilling machine (roof bolter), drill steels and bits, resin cartridges, the steel bolt, and the faceplate. The roof bolting operation follows the extraction task and aims to reinforce the roof to provide a safe working environment as mining progresses. Roof bolting remains the primary roof support system in the majority of underground operations and its objective is to minimise immediate roof movement (Mark, 2002).

Despite the large number of injuries associated with mining equipment, most underground mines are still using manually operated roof bolters which are human-driven operations. Roof bolter operators work in the proximity of potentially unstable roof, loose bolts, and a heavy spinning mass which are major contributors to operator's injuries in the underground mining space. Due to the multiple tasks performed by the operators, they are exposed to different levels of injuries depending on the phase of the roof bolting cycle. Kyslinger (2017) argued that in underground mining, roof bolting operations present many risks to the human equipment operators. Roof bolting accidents account for 39% of equipment-related accidents in US coal mines. Operator injuries were classified into different categories: drilling, installation of bolts, tramming, walking, traversing the walk-through area, setting the temporary roof support (TRS), material handling, and others (Mine Safety and Health Administration, 2014).

Apart from equipment-related accidents, the operators are also exposed to potential roof falls, inhalation of dust, and noise from drilling and bolting processes which can be traced to the several pumps from the roof bolter machinery. Continuous exposure to these risks would inevitably lead to fatal accidents and injuries. Therefore, there is a need to automate the roof bolter machine to enhance the safety of mine workers which would remove operators from hazardous work environments and allow the robot to perform human tasks.

Therefore, there is a need to distance (move) mineworkers away from hazardous conditions and allow automated machines to perform the roof bolting operations. Automation will not completely eliminate the presence of humans from the face area; it is envisaged that a supervisory role will be assigned to roof bolter operators that will improve their working environment in terms of health and safety and at the same time increase operational efficiency and productivity.

Study Objective

There is a concern that needs to be addressed when developing an automated rock bolting system for underground coal mining operations. These and many thoughts led to the following questions that are yet to be answered. This study will answer the following questions:

- Is it possible to remove humans from the bolting operations?
- Can humans still be relevant in the automated roof bolting process?
- Is it possible to develop a roof bolter that can be operated remotely?

This study presents the steps taken towards the development of an automated roof bolter system that performs most of the bolting cycle with the main goal of moving humans away from the face where bolting takes place. As a result, the operator is assigned the role of supervising one or more automated units and can exercise control via a human-computer interface (HCI). Apart from supervisory and control of the automated roof bolter, humans are also needed to perform maintenance on the automated equipment to ensure that all components are working effectively and efficiently.

Autonomous and Automated Technologies in Mining

According to Rogers *et al.*, (2019), the introduction of automated technologies in mining has changed the design of workflows. Frank *et al.*, (2018) predicted that the implementation of automated technology would disrupt labour demand. Similarly, Paredes and Fleming-Muñoz (2021) stated that the adoption of automated technologies could affect the labour market in the future as mining is regarded as a capital-intensive economic process. Tasks that were done manually by miners could be achieved by automation. On the other hand, Paredes and Fleming-Muñoz (2021) stated that the implementation of automation in mining operations does not remove humans from the operation but rather allocates them to new tasks that might require new skills. The study suggested that the deployment of automated systems would bring about an increase in high-skilled workers as the systems would require a workforce with a suitable background, such as computing and coding, to work on automated technologies.

In the last decades, various applications of automated equipment are in use in all the phases of mining operations. The current trends in mining show that automated technologies and digital solutions are deployed across the mining value chain from the exploration to the processing stage (Sager, 2021). Also, studies by Shinohara *et al.,* (2015); Wakita *et al.,* (2010); Blidberg *et al.,* (1991) discussed the development of autonomous underwater vehicles (AUVs) for marine mineral exploration. The current research of the National Aeronautics and Space Administration (NASA) and other space exploration programs are also focusing on the application of robotics and autonomous systems for space mineral exploration (Gao & Chien, 2017). Li and Zhan (2018) developed equipment with independent intellectual property rights for unmanned control technologies for rock-drilling jumbos, down-the-hole (DTH) drills, underground scrapers, underground mining trucks, and underground charging vehicles. Marshall *et al.*, (2016) introduced an automated way to load material using draglines and shovels. Similarly, Dunbabin and Corke (2006) proposed an automated approach to detect and avert dipper stall in an electric rope shovel.

The introduction of autonomous technologies in mining operations has significantly reduced mining accidents but zero harm has not been attained. The current trend in the mining process shows that the integration of automated systems has minimised mining equipment-related fatalities and injuries (Sammarco, *et al.*, 2016).

In the early 1970s, automated temporary roof support (ATRS) was first incorporated into the roof bolter machine to serve as roof support. This innovation was incorporated as a result of frequent injuries from roof falls which are attributed to an unstable and weak roof (Hammons, *et al.*, 2009). The primary aim of developing the ATRS mounted rocker pad deflector system is to prevent roof skin failure during roof bolting operations. This development of the deflector system has improved the safety of the operator during bolting operations although there are still dangers lurking overhead that can pose risks to the operator of the roof bolter. Also, Finfinger *et al.,* (2000) developed a monitoring and control system that identifies different rock properties during the roof bolting drilling operation; Kyslinger (2017) designed and manufactured a roof bolting machine that can drill and install six bolts simultaneously with a limited number of operators. To reduce the roof falls injuries on roof bolter operators, Robert and Prosser (2007) developed a system that can be used to collect data related to torque, thrust, and rotational speed during drilling operations. They used a real-time device of Fletcher Information Display to examine the roof condition during the roof bolting drilling operations to monitor the stability of the roof during the roof bolting operation.

Component Development and Integration

Automated systems typically operate a pre-defined set of actions within operational parameters. These are run by heuristic models that control the timing, order of operations, and what needs to be monitored. When operational parameters are exceeded or challenged, human intervention is needed; often human intervention is necessary for automated systems to work at all. For instance, lane-keeping systems available on current cars can sense road lines and keep the car centred in the lane by steering. However, these systems typically require the driver to keep their hands on the steering wheel and will only operate above certain speeds, that are controlled by the driver or the cruise control.

In comparison, autonomous systems are capable of making decisions toward a goal by learning and adapting to the environment that they sense. Like the automated systems, these systems have predefined sets of actions, but these actions are often smaller, simpler actions than an automated system. The autonomous systems then decide which actions should be undertaken to complete the goal, as opposed to the automated system that is told to perform a task which is a set of actions. An example is an autonomous vacuum robot, it has actions such as accelerate, turn, and reverse and is set with the goal to cover as much ground as possible. It may start out in a pre-defined pattern, such as a spiral that is a combination of accelerating and turning right. When it encounters an obstacle, it must decide how to avoid the obstacle and then decided how or if to resume the pattern.

For this discussion, a roof bolter is considered an automated system and not an autonomous system. Therefore, an automated roof bolter is expected to perform a complete roof bolting cycle without any operator involvement. The bolting cycle includes tasks such as the positioning of drill steel, drilling of the roof, pumpable resin insertion and bolt installation. The operators control the bolting process and interact with the bolting equipment via a remote control HCI touchpad.

A hydraulic roof bolter machine was acquired from a roof bolter manufacturer and transported to the Rock Mechanics Lab at the University of Kentucky. The lab is equipped with an overhead crane, high voltage outlets, compressed air outlets, and hydraulic pumps to drive the hydraulics of the roof bolter. Several systems and technologies were then developed and integrated so that they could transform a simple roof bolter into an automated roof bolter. These systems and technologies include a six-degree of freedom robotic arm with five revolute joints (Figure 1), a plate feeder (Figure 2), a bolter feeder (Fiure 3), and a robotic arm controller. In addition, other components such as the programmable logic controller (PLC), the HCI, the drill control unit (DCU), and the hydraulic roof bolter were integrated through the process of 'handshake' and allow the roof bolter unit to properly sequence its tasks.

Figure 1. An ABB robotic arm next to a roof bolter unit.

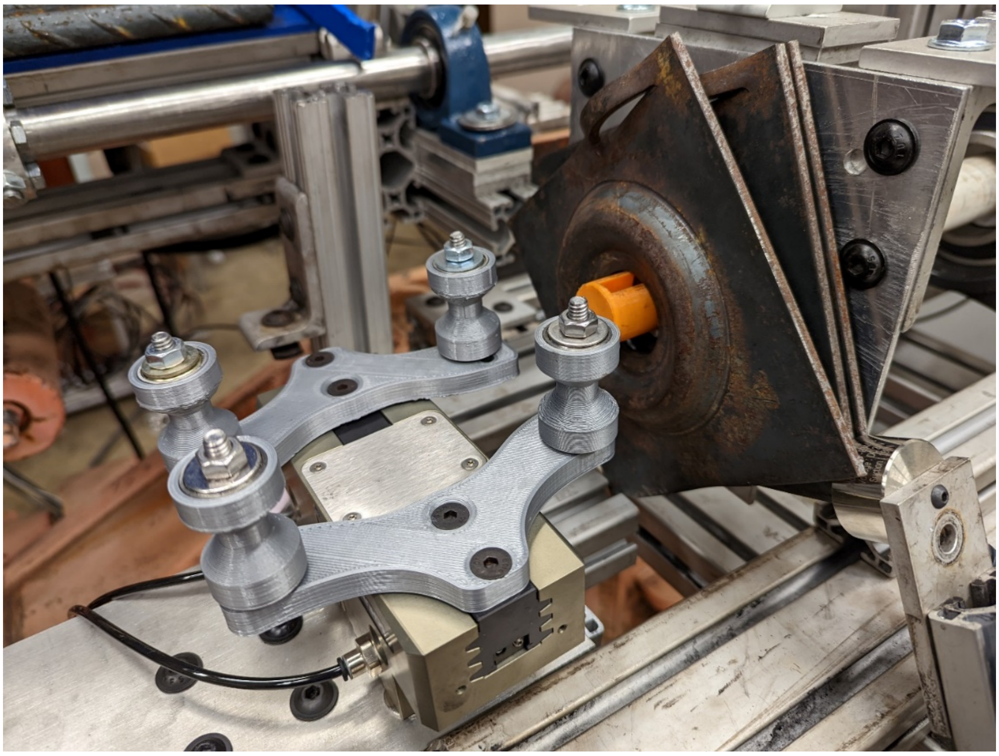

Figure 2. Automated plate feeder used by the robotic arm.

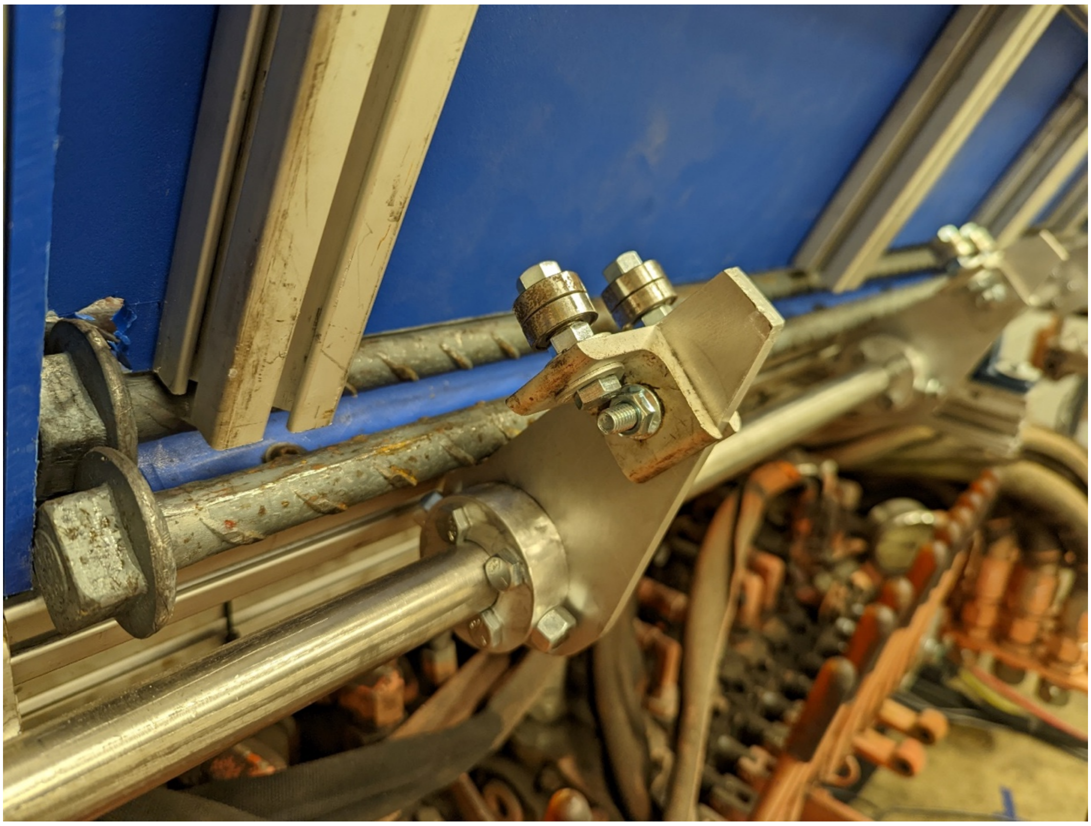

Figure 1. Automated bolter feeder used by the robotic arm.

The robotic arm was integrated into the automated roof bolter to imitate human tasks. The introduction of a robotic arm does not only imitate human tasks but also improves performance and productivity. One of the advantages of the robotic arm over humans in the bolting process is the ability to adapt and work under high ambient temperature which affects human performance. The HCI controls the robotic arm by approving all the tasks to be carried out by the arm and overrides the system in the event of unsafe actions. The robotic arm trajectories are created using the flex pendant and the paths are saved in the ABB programming software package called Robot Studio. The Robot Studio package provides an interface that controls and manipulates the robot's motion to perform certain tasks such as grasping, positioning, moving, and lifting objects through a programming language called RAPID. During roof bolting operations, the robotic arm performs functions similar to those performed by the operator such as the positioning of drill steels for drilling, grabbing the drill steels for removal, installing resin through a pumpable resin system, and positioning the bolts in the chuck for installation.

The automated roof bolter is controlled by a PLC. The PLC is connected to all the components to monitor all the bolting operations. The programmable hydraulic valves from the drill head are connected to the DCU to monitor the drilling operations. A communication path is created between the user and the PLC by sending a controller area network (CAN) message. When a CAN message is generated by the PLC, the message is sent to the Anybus communicator which translates and sends it to the robotic arm controller for the robotic arm to execute. The Anybus communicator in the PLC receives, translates, and sends a CAN message into a signal the robotic arm will understand. That is, the Anybus communicator controls the communication between the robotic arm and the hydraulic roof bolter through an Ethernet/IP interface. The CAN message allows the user to control the bolting process through Parker Hannifin's iQAN system.

The iQAN software provides an interface that allows programming outlook that sends messages to the PLC controller. Also, the software presents easy access to the communication protocol of CAN and enables the users to interact with both the robot and the hydraulic roof bolter. An example of the interaction is the application of timing on the roof bolter to perform a task. Other components such as the plate feeder, bolt feeder, wrench, and the robot controller are connected to the PLC. The HCI is connected to the PLC to control the robotic arm and the hydraulic roof bolter through the iQAN system. Also, other components are controlled by the HCI. When a button is pushed on the HCI, a CAN message is generated from the PLC and translated for immediate execution of the tasks. This is the principle of establishing a communication path between the components to perform the roof bolting process.

Discussion

As previously mentioned, roof bolters have evolved over the years to provide more protection to the operator(s) and also to provide tools and/or roof monitoring functions that could help the operator(s) avoid hazardous conditions at the face. These improvements have helped decrease accidents related to roof bolting operations, but have not actually removed the operator from the working area that presents most hazards.

Using a robotic arm to install roof bolts requires re-imagining the bolt installation procedure, which relies to a great extent on the skill of the human operator. Historically, locating the installation assembly relied on the operator. The basis of this project and its novelty is to use an automated system, in this case, a six-axis anthropomorphic robot, in place of a human (i.e. remove the human from the face) to handle the positioning and feeding of the drill steel on the bolting module (Figure 4 and Figure 5), feed the second drill steel if needed for longer holes, remove the drill steel(s), retrieve the bolt and plate from the bolt and plate feeding system, position the bolt and instruct the bolting module to complete the bolting process. Thus, the robotic assembly will run the entire roof bolting sequencing instead of the human operator.

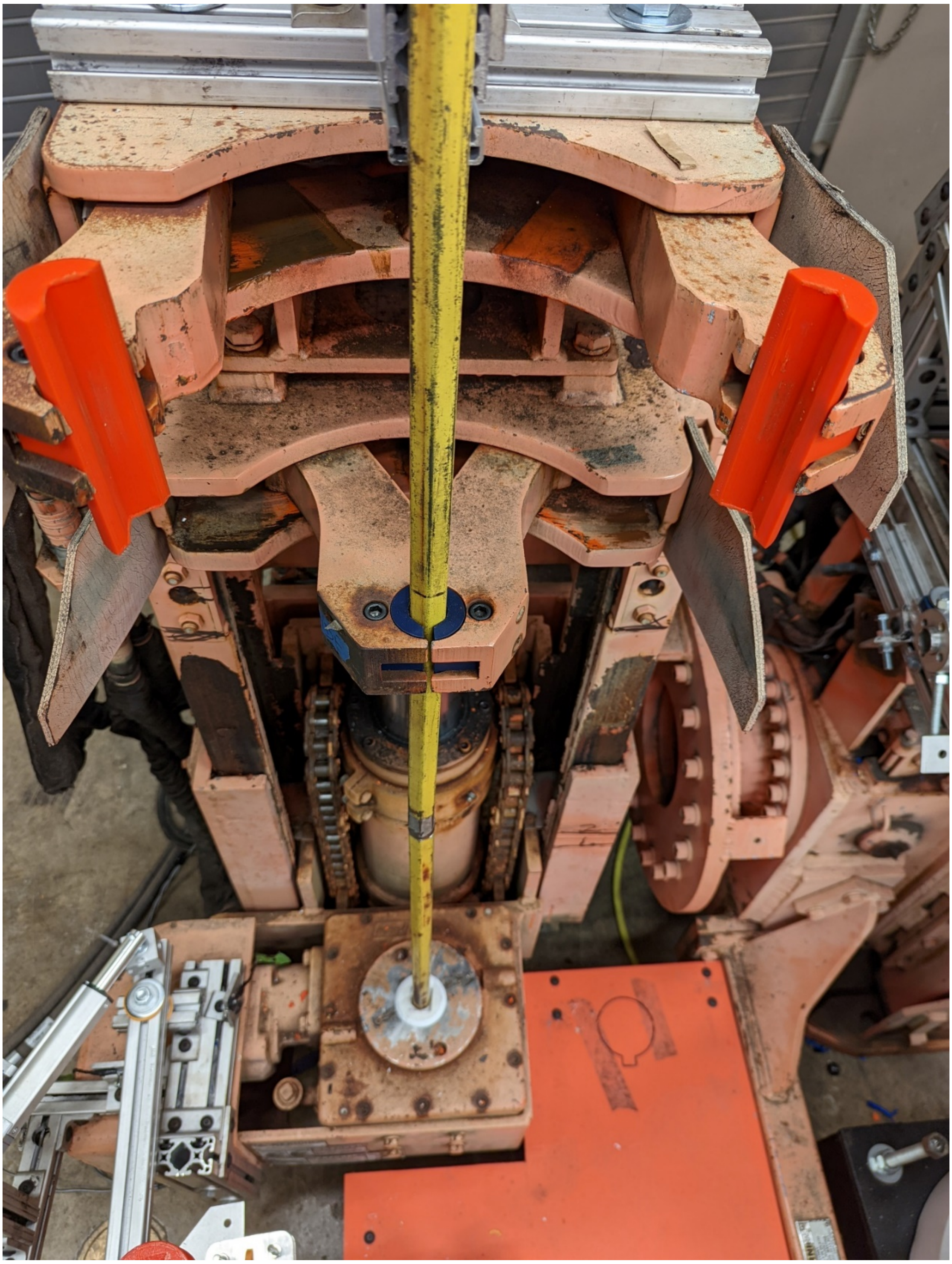

Figure 4. Modified bolting module to be compatible with the robotic arm functions.

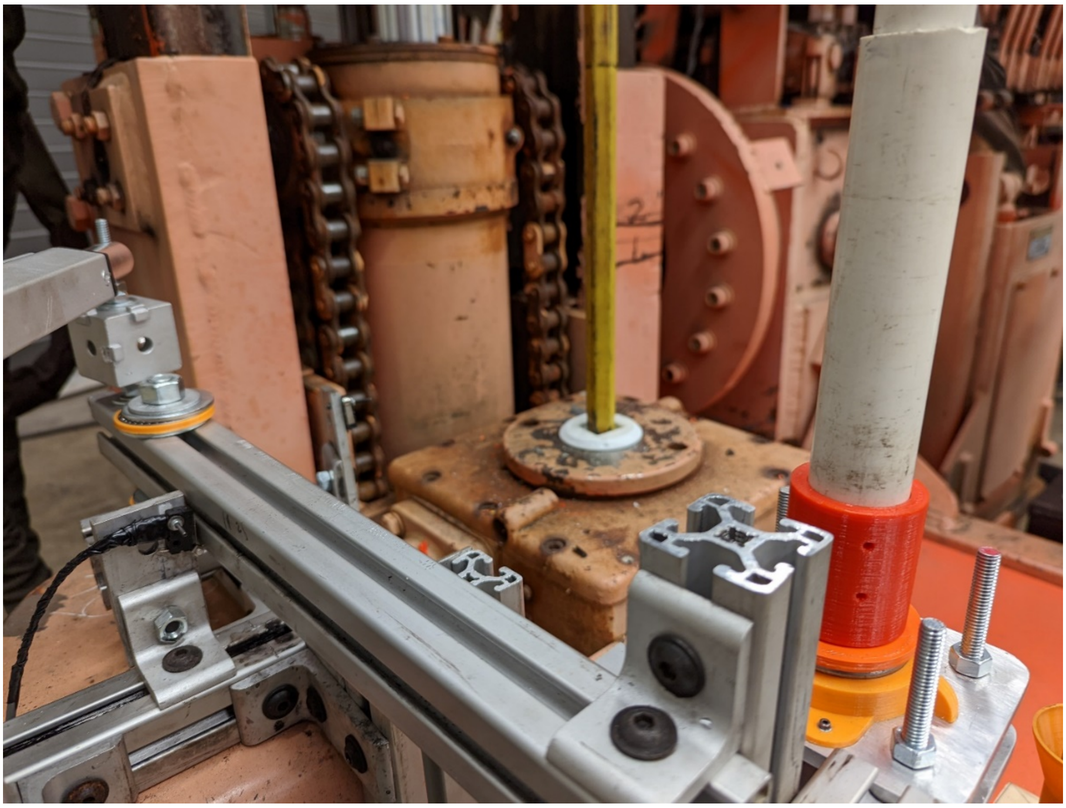

Figure 5. Base of the bolting module equipped with a tube that holds the drill steel when not used.

The hydraulic system will be synchronised with the operations carried out by the robotic arm. A human operator will be required to approve primary operations such as move the bolting head, or start a new drilling sequence, while also maintaining the ability to operate the robotic arm and the hydraulic system. The only human interaction with the automated roof bolter should be re-provisioning the onboard storage, maintenance, and supervisory control of the machine. Human interaction tasks for roof bolting operations were already identified in the 1990s as discussed by Jobes (1990).

One of the most challenging tasks of automating the operation of the roof bolter is that the manipulator arm should perform the specified functions while operating in limited space. The placement of the robotic arm with respect to the roof bolter machinery is critical as the arm should be able to have access to all consumables required for the bolting operation. In addition, arrangements should be made to provide the automated roof bolter so as not to impact or delay roof bolting operations.

As such systems evolve, autonomous functions may be programmed into the robotic assembly, such as positioning adjustments based on machine learning algorithms.

CONCLUSIONS

This study demonstrated the steps taken towards developing an automated roof bolting machine. The entire roof bolting process is automated and controlled from the touchpad HCI device, which allows operators to remotely supervise and control the bolting process. The automation of the process provides safe working conditions for workers, thereby minimising their exposure to endangering health and safety risks. The automation process is achieved by the integration of the six-axes robotic arm into the system to replace human tasks during the bolting operation. The robot imitates all human tasks and improves the performance of workers as it has the potential to adapt and work in harsh conditions such as underground mining environments. The roof bolter is controlled by the PLC which is connected to the touchpad that controls both the robotic arm and the hydraulic roof bolter. The manipulation of the hydraulic roof bolter was done in iQAN software. The software presents the user with easy access to communicate with the hydraulic bolter through CAN messages. The PLC generates CAN messages and the Anybus communicator inside the PLC translates the CAN message and sends it to the robot controller for the robot to execute.

In addition, some novel technologies were developed as components of the automated roof bolting machine. These technologies include the plate feeder, the bolt feeder and the wrench system. All these systems were built in the rock mechanics laboratory in the Mining Engineering Department at the University of Kentucky, USA. These components are linked to the PLC and controlled by the HCI touchpad. Other components of the roof bolting machine comprise the robot controller, the PLC, Anybus communicator, the DCU, the HCI, the robotic arm and the hydraulic roof bolter. The establishment of communication paths among all the components led to the automated roof bolting system. However, all the above-mentioned components are subroutine into two (start and stop) buttons on the HCI touchpad to carry out the bolting operation. The start and stop buttons are displayed on the HCI for the humans to supervise and control the bolting operations. Also, the HCI enables the operator to stop the operations in the event of an unpredicted activity. This paper shows that the robotic arm has the potential to mimic human activities during the roof bolting operation by performing bolt grasping, holding, lifting, placing and removal of drilling steels during roof bolting operations. As a result, human operators can be moved away from the hazardous areas to a safe distance and control the roof bolting operation via an HCI touchpad.

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