# Alpha Foundation for the Improvement of Mine Safety and Health

Final Technical Report

AFC820-68 - Roof Bolting Module Automation for Enhancing Miner Safety

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# 1 Executive Summary

Roof bolting is a universal ground support system used in underground coal mines to ensure the stability of a potentially unstable roof. The installed roof bolts bind and reinforce discontinuous rock masses to prevent roof deformation and potential failure. The bolt installation involves moving quickly and manipulating awkward and heavy tools while being vigilant about the safety of the area. Successful completion of bolting tasks depends heavily on operator judgment, fatigue, and experience to perform these tasks. Due to working conditions, roof bolter operators are exposed to hazardous conditions due to their proximity to the unsupported roof, loose bolts, and heavy spinning mass. Prolonged exposure to these risks inevitably leads to accidents and injuries.

The purpose of this project was to develop an automated roof bolting machine that performs the entire sequence of roof bolting operations in underground coal mining environments. This report presents the steps taken towards developing an automated roof bolter module that performs most of the bolting cycle with the primary goal of moving humans away from the face where bolting takes place. The automated bolting machine can perform roof bolting operations of drilling, drill steel removal, resin placement, and bolt installation without human intervention. As a result, the operator is assigned a new role of supervising one or more automated components and also controlling the whole automation process via the human-machine interface (HMI).

A six-axis robotic arm was integrated into the system to mimic human tasks during the roof bolting operation to enhance operator safety and improve productivity. During the automation process, the robot performed tasks such as grasping, moving, lifting, and positioning of drill steels, insertion of simulated resin membrane, and bolt installation. The integration of the robotic arm has eliminated the presence of humans from the face area and assigned the operator to supervise and monitor the roof bolting process through the HMI. A reliable communication system was established between the robot arm and other components. The EtherNet/IP protocol is used to pass messages between components of the automated roof bolter machine through a CAN bus device which is installed to enable communication using CAN protocols. Establishing a robust communication network between the components prevents collision and manages the movement of the robotic arm and other automated units during the bolting process.

In addition, some novel technologies were developed as components that form the automated roof bolter, such as the plate feeder, the bolt feeder, and the wrench. These systems were built to support automation and minimize human intervention during roof bolting operations. These components were linked to the PLC and controlled by the HMI touchpad. Setting up communication paths among all the components led to the automated roof bolting machine. Also, an HMI was developed for the operator to control and monitor the automated process away from the active face. The HMI controls the bolting process with start and stop buttons from the subroutine of all the components to perform the roof bolting operation. These buttons enable the operator to stop the operation in the event of unsafe acts.

In conclusion, the researchers have conducted laboratory tests to evaluate the performance of the newly developed automated roof bolting machine. The tests showed 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 drill steels during the roof bolting operations. As a result, humans can be moved away from hazardous areas to a safe location and control the roof bolting operation through an HMI touchpad. It is also essential to state that human operators remain a relevant and integral part of the automation process of the roof bolting machine.

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# 2 Problem Statement and Objective

This project is a health and safety intervention by machine design. The intervention entails the developing an automated roof bolting module for enhancing miner safety.

Underground coal mining involves repetitive processes in confined and hostile environments. Equipment operators, and especially roof bolter operators, are prone to exposure 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. After hand tools, the roof bolter machine is responsible for the second highest number of nonfatal lost-time injuries, where the average injury incurred several months away from work. Physically demanding work over long periods of time in unfavorable environments also increases the probability of unsafe actions leading to accidents or near misses. Research has shown that roof bolting accident account for 39% of equipment-related accidents in US coal mines. 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. Considering these raised concerns about the safety of personnel working close to roof bolter machines, these are long-standing problems that can pose a serious threat to the mining industry's sustainability. For this reason, these hazards need to be controlled. Therefore, there is a need to automate the roof bolter machine to enhance the safety of mine workers, which would distance (move) operators from hazardous work environments and allow the robot to perform human tasks.

## 2.1 Specific Aims

Roof bolting is one of the most dangerous processes in underground mining that exposes miners to multiple hazards. Over the years, there have been improvements and attempts to automate the roof bolter machine, to reduce accidents and injuries at the mines, but up to now, injuries and fatalities still happen when working with machines. Although accidents and injuries have significantly reduced due to technological advancement and improvements made to the equipment since its introduction to underground coal mines. Despite these tremendous improvements to the conventional roof bolter machines, a completely automated roof bolter has yet to be developed.

The overarching goal of this research project is to make roof bolting operations safer and prevent underground mining personnel exposure to unhealthy conditions and bodily injuries. This can be accomplished by moving operators from the hazardous working environment under a freshly exposed roof. Instead, an automated robotic arm capable of mimicking human movements would be deployed to carry out all the unit operations with roof bolting. These robots are programmable, thus ensuring that they can be utilized under a wide variety of mining conditions and with a provision for the operators to override its functionalities if needed rather than humans operating the equipment directly. However, the study introduced a robot to imitate human

activities during the roof bolting operation. The robot mimics human activity during the drilling task, drill steel removal, simulated pumpable resin insertion and the bolt placement on the chuck for installation.

## 2.2 Research Objectives

The research project included the following research objectives and tasks:

***Objective 1 - Evaluate existing technologies and identify the mission list of the robotic assembly.***

***Task 1.1 Perform background research.***

The researchers conducted a detailed literature review of automated and autonomous mining equipment, including operator-independent haul trucks and trains. Their data gathering mechanism and interaction process with the environment were used to select a suitable robot for the project. In addition, the capabilities of existing related robotic arm mechanisms were studied in detail. Based on existing systems and laboratory capabilities, mission statements and tasks to accomplish those missions were defined.

Equipment operating in a repetitive manner is typically easier to automate compared to equipment that continuously needs human input. However, due to the dynamic and hostile nature of the underground mining environment, automating any mining process brings numerous challenges. The researchers reviewed the literature on the automation of mining machinery in general and robotic arms in particular. Driverless haul trucks and trains were investigated for their sensor technology and data gathering system that keeps them aware of the surroundings. Built-in safety mechanisms were also reviewed. The application of similar mechanisms outside the mining industry and the feasibility of technology transfer were studied. This step is crucial to ensure the robot behaves safely and predictably when deployed in an underground mine. The researchers also conducted extensive studies on various electrical and mechanical components used to develop several units of the test system. More importantly, attention was paid to the PLC operating voltage, current, and consumables such as lubricants for their permissibility and environmental implications in a mine environment. The background research is presented in Appendix D.

***Task 1.2: Define the Mission List***

The overall objective of automating roof bolting operations is to deploy a robotic arm that can mimic human tasks during the roof bolting cycle. That is, a complete cycle of drill steel positioning, drilling, bolt orientation and placement, resin placement, and bolt securing were studied in detail. The robotic arm was used to perform each process that makes up the roof bolting cycle.

***Objective 2 – Build and test the robot assembly.***

The robot and other components of the roof bolting operation were tested for motion under different constraints. The automation process of the roof bolter machine implemented the ABB

IRB 1600 robotic arm, which can perform roof bolting with minimal human intervention. In addition, human-machine interface (HMI) was built to enable the interaction of the operators with the machine. Also, the HMI allows operators to control all actions of the automated roof bolter machine and to overrule any actions that might be deemed unsafe.

### *Task 2.1 Build an Analog of Bolt Module*

The automated roof bolter was built and tested in the Rock Mechanics Laboratory at the Mining Engineering Department, University of Kentucky. The laboratory is equipped with electrical power, compressed air, vacuum, heavy lifting equipment, three-dimensional (3D) printers and other relevant facilities to undertake research projects, including building a prototype of the bolter module. This prototype was able to make the motions of a production bolt module without the heavy-duty work like actual drilling of rock. The purpose is to demonstrate the automation, not the cutting and affixing. A cylindrical pipe was used as a roof simulator. During the roof bolting process, the bolt module runs drill steels into the simulated roof, places the simulated injectable resin (not real setting resin) and runs bolts into the hole. The specific details of mechanical systems of the roof bolter that require modification were worked on to suit the automation process. Thanks to the advances in 3D printing technology, modifications of several parts of the machine were reproduced and made the automation process seamless. For instance, the chuck, clamps and guides were redesigned and printed in the 3D printer, which allowed the researcher to produce the machine. Also, the 3D printer was used to print the grabbing finger attached to the robot end effector for the automated roof bolter system.

### *Task 2.2 Develop and Test Motion Patterns*

Individual components of the robot model were tested. This was followed by testing the robot model with all the components assembled. The assigned laboratory space, where the bolt module was built, was also used for testing multiple trajectories of the robotic assembly under confined conditions. Multiple obstructions of different sizes, shapes, and reflective properties were added to space and customized trajectories using waypoints were defined. These trajectories were programmed into appropriate computer simulation software (e.g., ABB Robot Studio). A high-level programming language called RAPID was used to control the robotic arm. Suitable corrections using optimization techniques were built into the algorithm to account for deviations encountered in real life mining conditions. A detailed study of human motion was carried out using RAPID code, a section in the robot studio computer software that comes with the robot for controlling the robotic arm. Different motion patterns were developed and tested for the roof-bolting tasks. This is done by setting important waypoints as targets for the robot. Consequently, the robot follows the waypoints automatically. Once the motion patterns are set, the robot accurately and repeatedly executes the tasks. The roof bolting process was divided into tasks and the above approach was used for planning of each task.

### *Task 2.3 Develop an HMI for the Machine Operator*

The researchers developed a system that enables human operators to interact with the machine. Developing a user-friendly HMI for the roof bolter operator is one of the primary goals of this project. The progress bar was created to show the operator the level of work done and the

remaining tasks to be completed. The HMI was designed in a way that the operator needs to approve every task before being executed by the robot. Provisions were made to let the operator override the computer programs in case of emergency or unexpected actions. The operator can stop the roof bolting process if any abnormalities or unplanned events arise when compared to the expected position and orientation of the robot. The HMI provides the operator with options to rectify the errors and reset the machine. Also, these computer programs allow the operator to edit the operational parameters on the fly without having the system go out of operation.

### *Task 2.4 Integrate Individual Actions, Bolt Module, and HMI*

Integration of computer software and hardware was carried out in this stage. The iQAN software developed by Parker Hannifin controlled the motion of individual components and integrated them with the robot actions which can be updated accordingly. Suitable buffer times were built into the computer software for a smooth transition between the motions of individual components. Time studies of the individual components were carried out, followed by time studies of a complete cycle of roof-bolting. The researchers examined the mechanism iteratively to minimize the time required for safe operation towards reducing the overall cycle time of the operations. The iQAN program allows modification and control of individual components to achieve the desired motion path. The researchers examined the mechanism iteratively to minimize the time required for safe operation, and to reduce the overall cycle time of the operations by assigning suitable buffer time for each task.

## *Objective 3 – Redefine the mission list objective and demonstrate automated operation.*

The ultimate mission list includes the steps enabling safe maneuvering among obstacles and being able to drill and insert roof bolts. The machine was able to carry out all these steps with human supervision and approval.

### *Task 3.1 Redefine Mission List and Individual Actions*

A detailed study of human tasks during the roof bolting process was carried out in the robot studio software. The study is based on the operator's movement relative to the motion of a roof-bolting machine boom arm. At this stage, some immediate goals were redesigned to accomplish all tasks leading to safe and efficient roof bolting. For instance, the design of the tool interchanger (wrench system), the chuck, the robot end effector and the resin simulator have been revisited during construction to minimize human intervention. The design modifications allow the automated roof bolter to perform tasks based on an appropriate architecture that enables the technology to make sound decisions similar to those made by human operators during the bolting operations. After several modifications, the automated roof bolter can successfully perform the roof bolting functions such as drill steel positioning, drilling, bolt orientation, and placement, resin placement, and bolt securing without human intervention.

### *Task 3.2 Demonstrate Automated Bolt Module*

The automated bolt module was tested in the laboratory. The robot's performance during the drilling and bolting cycle was evaluated under different configurations of the roof and the floor.

The mechanism and drivers of other components of the automated roof bolter machine, such as the wrench system, the plate feeder, and the bolt feeder, were evaluated. In some cases, the drivers of the component were replaced to improve the speed and performance of the system, which in turn influence the cycle time and operational efficiency. Operational efficiency is the ratio of active drilling to the machine availability time and was an important parameter that defined the machine utilization and is directly related to the productivity of the mining operations. For instance, the linear actuator on the wrench system was changed to a step motor to improve the speed of the wrench system. Modifications of several components were worked on until a reliable and repeatable performance of the system is obtained.

### *Task 3.3 Define Pathway to Certification*

The coal mining industry has stringent regulations to ensure that safe practices are followed. This is also significant since many unit operations in mining are carried out in a challenging environment. Thus, implementing any new technology in underground coal mines requires rigorous testing and certification before it can be deployed underground. Underground coal mining conditions were considered when selecting and constructing components for the automation process. The researchers ensure that the electrical units of the robot and other components of the automated roof bolter machine have the potential to withstand and operate in the underground mine environment, often under elevated levels of temperature and humidity. This evaluation is important to prevent system failure and downtime in mining operations. Suitable power cables for underground coal mining environments were used to power the robot for resilience/damage against roof falls. The robot is mounted on a movable platform that can be moved from the active mining face during operation and maintenance, which allows operators to perform roof bolting operations. This will prevent downtime in operation during the operation and maintenance of the robot. These and many more factors were considered during the design to satisfy the certification criteria.

## *Objective 4: Reporting and dissemination*

The researchers have been submitting progress reports and findings to the Alpha Foundation periodically. These reports contain the engineering progress and expenditure incurred for that period. The outcome of the project was presented at various conferences and seminars. Also, there are plans to submit and present discoveries and results of the project at international conferences and peer reviews journal papers.

### *Task 4.1 Reporting*

Finding and milestones achieved in the course of developing the automated roof bolting machines were submitted to the Alpha Foundation periodically. These reports include the technical progress achieved and the update on the expenditure figures.

***Task 4.2 Dissemination***

Outcomes of the project were presented at the following conferences and seminars;

- The Society of Mining, Metallurgy and Exploration (SME) Annual Meeting 2022, Salt Lake City, Utah, USA;
- The Society of Mining, Metallurgy and Exploration (SME) Annual Meeting 2023, Denver, USA;
- 5th International Future Mining Conference, 2021 Sydney Australia (virtual presentation);
- The Society of Mining Professors (SOMP) Conference 2022, Windhoek, Namibia;
- National University of Singapore, University of Washington CSE Robotics Colloquium;
- University of California Los Angeles (UCLA) ECE Department Seminar Series;
- University of Texas at Austin Forum for AI;
- Carnegie Mellon University (CMU) Robotics Institute Seminar Series;
- Harvard EconCS;
- University of Pennsylvania GRASP Robotics Talk Series;
- Stanford University Robotics Seminar, Massachusetts Institute of Technology (MIT) Robotics Seminar;
- Cornell University Robotics Seminar;
- Apple AI and Machine Learning Research; and
- Autodesk Research

The researchers published a section of this project in peer-reviewed conference (SOMP) while there are other manuscripts are currently undergoing review.

# 3 Research Approach

This project proffers a reliable engineering solution to prolong the problem of roof bolting operations by providing an alternate solution for the roof bolting process in an underground coal mine. This solution addresses the issue of debilitating injuries to roof bolter operators and prevents its occurrence as well as minimizes the exposure of operators to falling rock and rotating machinery. The research identified human motion parameters and adopted them to an automated robot. The robot was able to perform human duties on the roof bolting operation, such as securing the drill steel, maneuvering and positioning it, drilling into the roof, inserting the simulated injectable resin and installing the bolt. . For the injectable resin, a metal rod with a plastic base was used to simulate the resin cartridge.

## 3.1 Roof Bolter Machine Laboratory Set Up

The Rock Mechanics Laboratory in the Department of Mining Engineering was identified as a suitable space for the construction of the automated roof bolter machine. The laboratory space is equipped with electrical power, compressed air, vacuum, heavy lifting equipment, 3D printers, and other relevant facilities to aid in research projects, including a prototype of the bolter module acquired from a roof bolter manufacturer (J.H Fletcher & Co). The bolt module runs drill steel into these holes, places resin cartridges (not real setting resin), and runs bolts into these holes. The specific details of the mechanical systems of the roof-bolter, which could be modified to suit the automation needs are studied.

Before the roof bolter machine assemblage, the first task was to identify the best place to position the prototype of the roof bolter module; a laser scanning of the laboratory was conducted to produce the digital roof bolter module in space. Also, the resulting point cloud data from the digitalized roof bolter module provides access to 3D modeling of the machine. The machine was scanned on a medium-high detail density, and the point cloud was stitched and simplified, as shown in Figure 1, before being delivered back to the research team from Carlson Software.

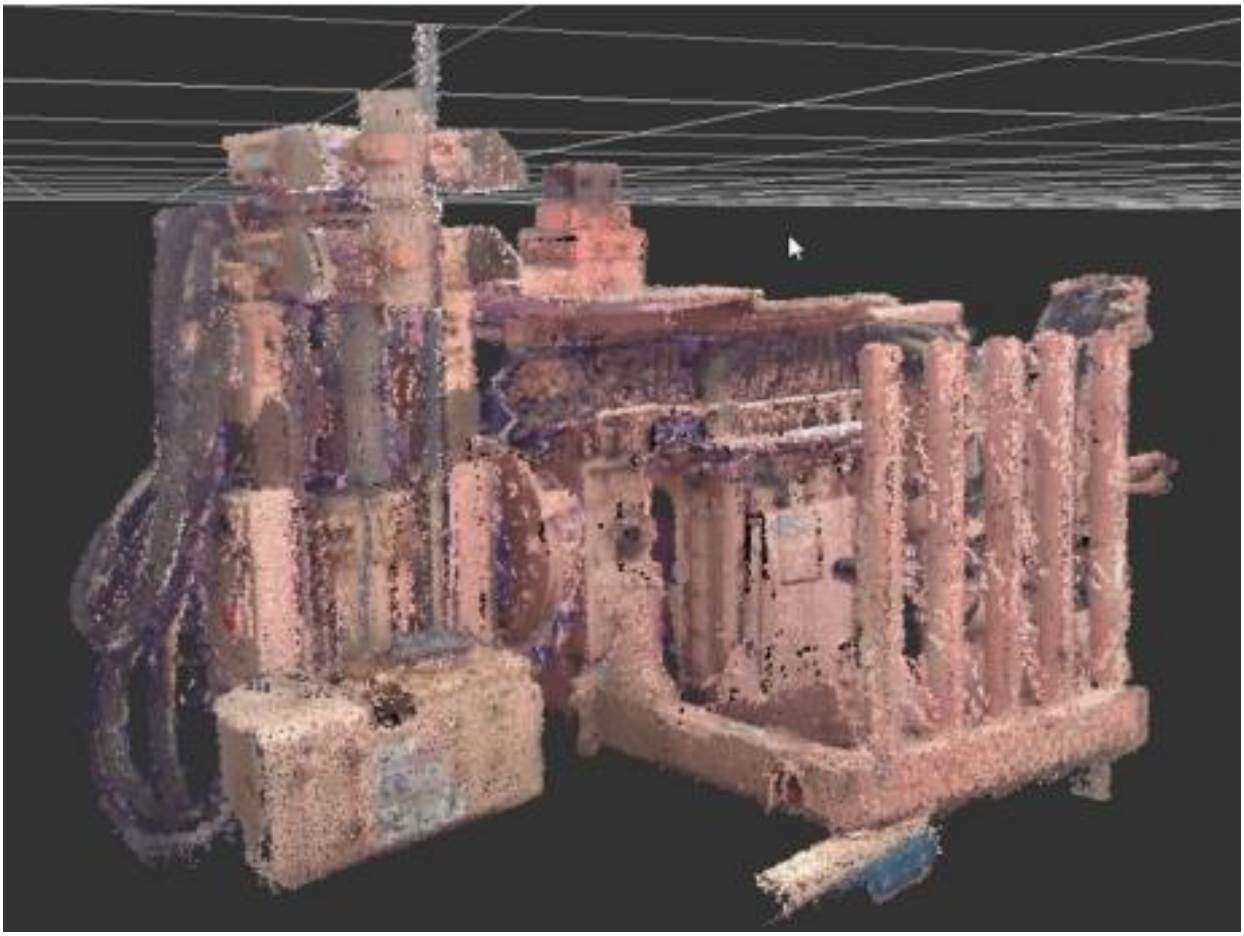

Figure 1:The 3D point cloud data of the roof bolter machine module.

## 3.2 Development of Control Module System

From the 3D point cloud data evaluation, the researchers identified a suitable location in the laboratory to position the roof bolter module. Thereafter, a Programmable Logic Controller (PLC) was developed to monitor and control the roof bolting operations. A Drill Control Unit (DCU) was also set up to automate the drilling and bolting cycle. Figure 2 and Figure 3 show the connection of the PLC to the modular control unit and for controlling the roof-bolter's hydraulic system.

Figure 2: Setting up of modular control system.

Figure 3: Connection of the modular control system to the PLC

The programmable holes connected the hydraulic roof bolter to the PLC to control the machine from the iQAN logic program. A control unit was set up to convert the mechanical energy from the hydraulic holes to electrical energy on the PLC. The modular control system is responsible for overseeing various processes of controlling the hydraulic roof bolter, such as closing and opening of the clamp and guide, the up and down movement of the pod, and rotation of the chuck in clockwise and counterclockwise directions. The iQAN logic was built to perform these functions from the I/O devices and generate control signals that allow the machine to be automated. Figure 4 shows the connection of the hydraulic valves from the bolter and the programmable cable from the PLC.

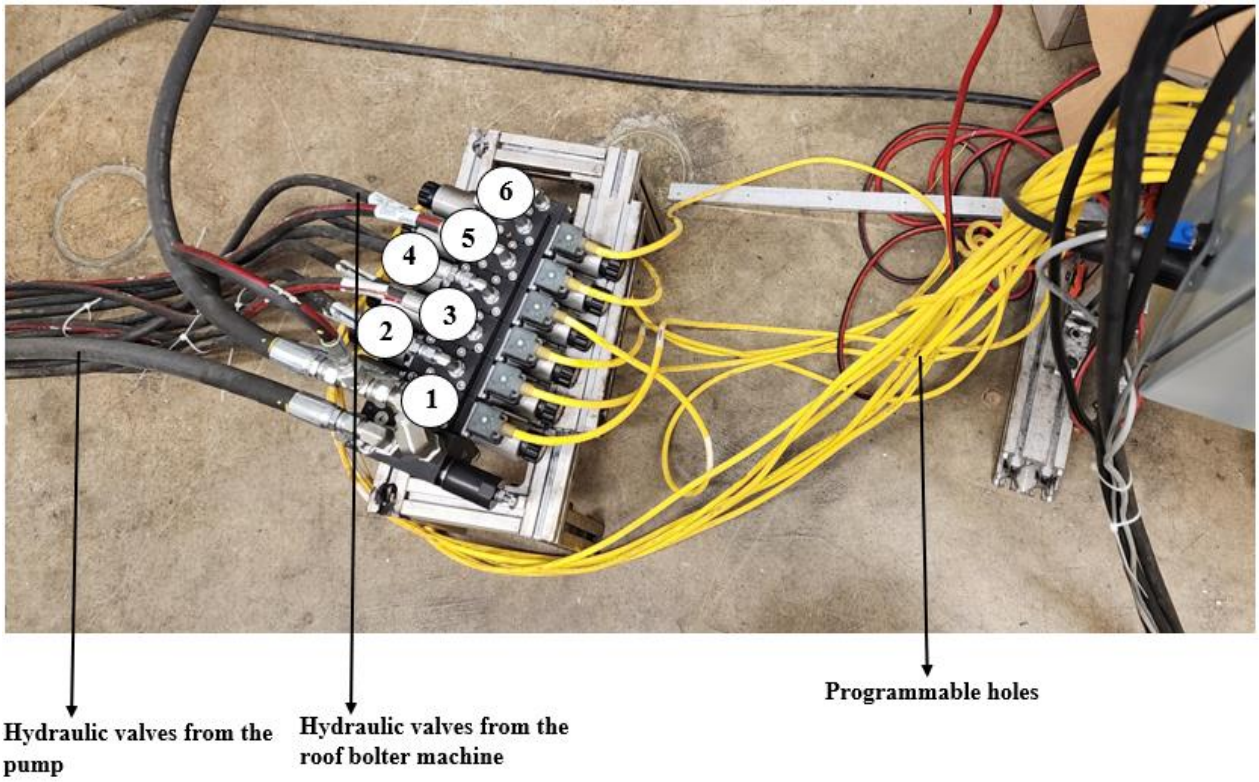


Figure 4: Architecture of hydraulic modular control system

The hydraulic valves are connected to the electric pump and the roof bolter to control the flow and pressure of fluids from the pump. These valves control the fluid flow by adjusting the opening size through which the fluid can pass to actuate components of the roof bolter, such as the closing and opening clamps and guides. Each valve connected to the modular control system represents a particular task. For instance, section one from the hydraulic valve controls the rotational movement of the chuck; section two powers the up and down movement of the pod; while section three controls the guide; section four manages the closing and opening of clamps, and the fifth section monitors the activity of the inner mast. These are the components of the roof bolter machines that move during the roof bolting operations. Currently, section six of the control unit needs to be connected, as only five sections are required to control the machine.

## 3.3 Integration of ABB IRB 1600 Robotic Arm

The robotic arm was integrated into the automated roof bolter to imitate human tasks. Introducing 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 temperatures, which affects human performance. A robotic arm can also perform continuously precise motions over long timescales without decrease in performance because of fatigue.The automation of a roof bolter machine comprises of a complete cycle of drill steel positioning, drilling, bolt orientation and placement, resin placement, and bolt securing was done using an anthropomorphic robotic arm. The robotic arm is envisaged to perform human operator tasks on the roof bolting process. That is, the robotic arm will mimic the functions performed by humans during the roof bolter operation, which would remove operators from hazardous work environments and assign them a new role to monitor the roof bolting process from a safe location.

For this project, an ABB IRB 1600 robot was deployed in the automation process of the roof bolter machine. This robot comprises of two main parts, the manipulator and the controller, shown in Figure 5. The body of the robotic arm consists of links, joints, and other structures with a net weight of 250 kg (551.156 lbs). The IRB robot can lift a load of 10 kg (22.05 lbs) and can grasp an object at a distance of 1.45 m (4.67 ft) as shown in Figure 6. In this project, the manipulator is regarded as the robotic arm. The robotic arm is a mechanical linkage that can be compared to the human arm with six degrees of freedom (axis) and five revolute joints. The robot arm can imitate human intelligence during bolting operations by performing the operator's tasks, such as grabbing drill steels for drilling, removing drill steels after drilling, pumpable resin installation, and bolt placement for installation.

The robotic arm installation project requires reimagining the bolt installation procedure on the dexterity of the human operator. The robotic arm was positioned in the operator space during the roof bolting operation. The ability of the 6-axis anthropomorphic cobot technology to replicate human arm movement during roof bolting operations supports the process of imitating operator tasks to handle the drill steels, bolts, and other consumables. During the laboratory testing, the robotic arm was able to perform the entirety of the roof bolting. The iQAN program was able to manage the sequencing of the movement between the hydraulic roof bolter machine, the robotic arm movement, and other components which led to the automation process. Meanwhile, human operators still control the system by approving tasks to be executed by the automated systems.

In addition, the controller manages the robot's wrist and prevents interference within the robot's vicinity. The robot arm and the controller are usually paired together by the robot manufacturer to be able to function. That is, the controller was designed to control the robot and to ensure that the robot performs optimally. The ABB IRB 1600 robot is a 6R robot (also called an articulated robot, revolute robot, or anthropomorphic robot) with six revolute joints arranged, as shown in Figure 6.

Figure 5: ABB Robotic Arm next to a roof bolter unit

The aim of integrating the ABB IRB 1600 robot in the automation of the roof bolter is to move humans from the roof bolting operations by allowing the robot to perform the bolting tasks while the operator supervises the robot performing the tasks. The robot performed human functions such as grasping, moving, lifting, positioning of drill steels, inserting simulated pumpable resin, and bolt installation. Establishing a reliable communication system between the robot and other components is crucial as it prevents collision and manages the bolting process. The project uses iQAN software developed by Parker Hannifin to control the hydraulic roof bolter machine. The software provides an easy access communication protocol using a controller area network (CAN). The CAN allows the robot to communicate with the operator by sending a signal immediately after task execution. The robot configurations and the mode of integration into the automated bolter are discussed in the subsections.

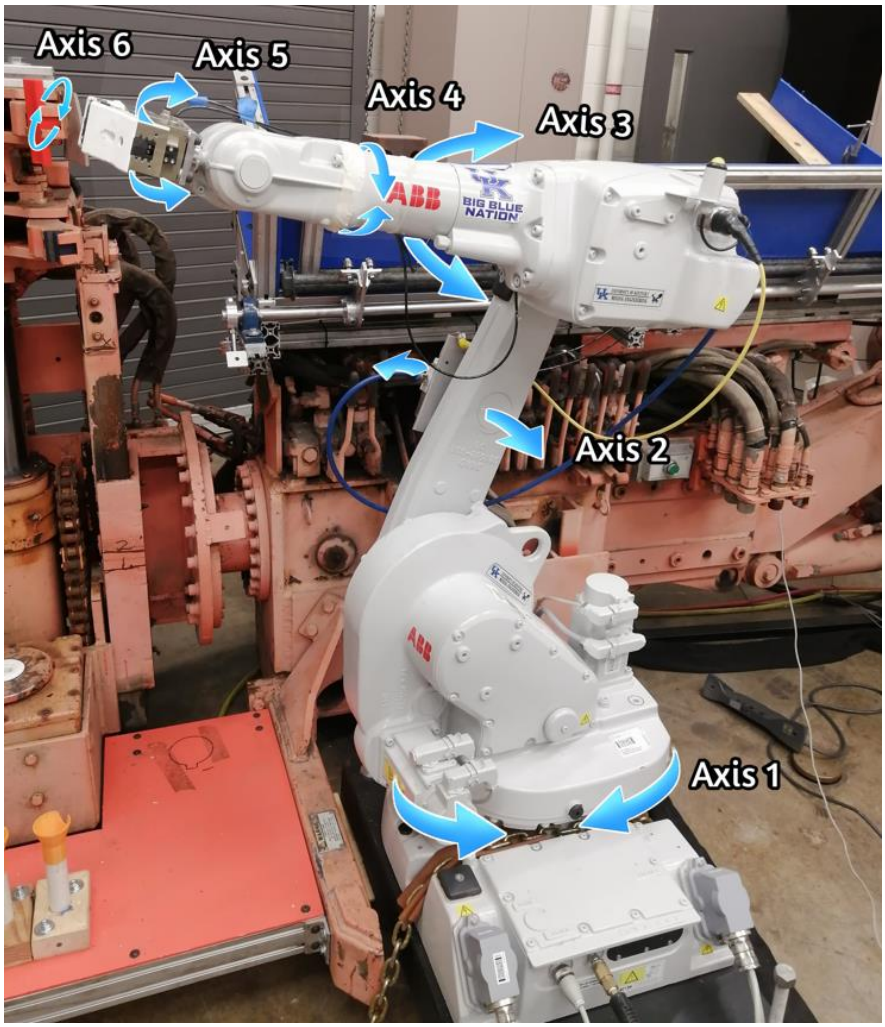

Figure 6: Geometric description of ABB IRB 1600 Robotic Arm

## 3.4 Development of Components of the Automated Roof Bolter Machine

Some novel technologies were developed for the automation process of the roof bolter machine. These technologies were built by our team to minimize or have no human intervention during the roof bolting operations. The researchers ensure minimal usage of sensors in the automation process of the roof bolter to prevent challenges of equipment failure which are regarded as one of the critical considerations in underground coal mines. The technologies include the plate feeder, the bolt feeder, and the wrench system.

### 3.4.1 The Plate Feeder

The plate feeder is designed to perform the primary function of feeding the plate for the bolt to wear. In roof bolting operation, operators use their hands to fix the square plate on the bolt. This is an integral step toward the roof bolting procedure. Fixing the square plate on the bolt during the bolting operation has been one of the most challenging steps for the operator during the roof bolting process as shown in Figure 7. Like the bolt feeder, the plate feeder contains a linear

actuator that initiates the movement by pushing the square plate to 1.25 inch PVC shaft to drop the plate on an inch shaft.

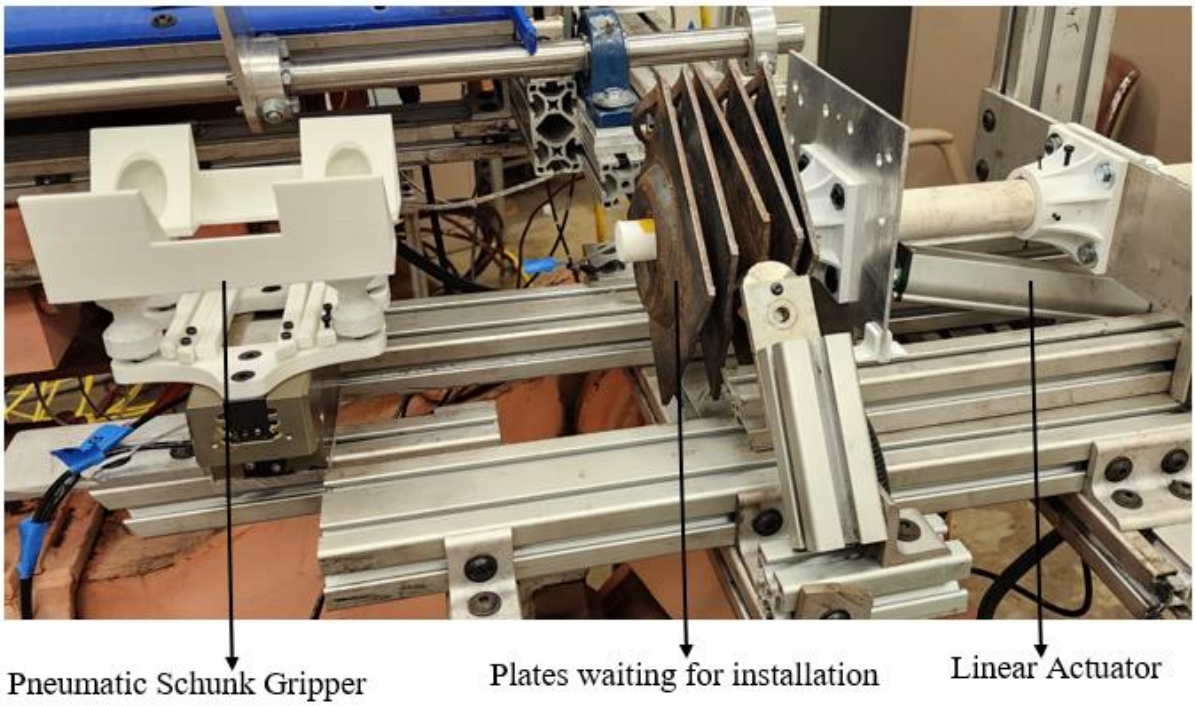


Figure 7: The plate feeder system

The pneumatic schunk gripper was introduced to align the bolt with an inch of PVC pipe. During the roof bolting process, the robot places the bolt in between the gripper to enable the bolt to be aligned with the plate feeder PVC pipe for a smooth fixing of the bolt's plate. The pneumatic controller, connected to the PLC, powers the gripper to close and open. This makes it possible for the system to be controlled from the iQAN touchpad. The main function of the actuator on the plate feeder is to push the plates until one of the plates drops on the sensor installed on the one- inch pipe; the sensor will, in turn, energize the 180N solenoid magnet and produce a magnetic that holds the remaining plates on the 1.25-inch pipe.

### 3.4.2 The Bolt Feeder

Despite the improvement in mining equipment over the years, the current roof bolting machine in the mining market has yet to develop a machine prototype that can store bolts. This project developed a bolt feeder, which is strategically placed at a position where the robotic arm can grab for installation, as shown in Figure 8. The current prototype of the bolt feeder is designed to allow the bolt to slide without frictional force. The main function of the bolt feeder is to house multiple bolts and position the bolt for grabbing. The bolt feeder was constructed so that a bolt can only be allowed to slide when the actuator produces a motion that pushes the shaft through the feeder for the robot to grasp at a time. Figure 9 shows the position of the actuator that drives the shaft for the bolt to slide for grasping by the robot. During the design evaluation, researchers

ensure that the position of the bolt feeder is close to the robot for easy grasping and maneuvering of the bolt for installation.

Arranging bolts at a close radius of the robot arm is considered good practice. The construction of the bolt feeder makes it easier to create an easy route for the robot arm to grasp the bolt and can precisely and repeatedly grab the bolt at a position over a period of time if there is no change in the robot's position or the feeder. This concept of placing the bolt in a position where the robot can grasp it would improve cycle time and the autonomous process. The bolt feeder was designed in a way that it will only allow a bolt to slide for grasping. The rib serves as a discharger which eases the movement of the bolt to the shaft area for the robot to grasp. The housing of the bolt feeder is constructed with high-density polyethylene (HDPE) plastic materials with strong surface durability that can withstand heavy weight. The manufacturer specifications of the linear actuator installed on the bolt feeder are summarized in Table 1. The performance of the actuator was observed during the laboratory test later in the project, and some changes were made to improve its performance in terms of speed and efficiency.

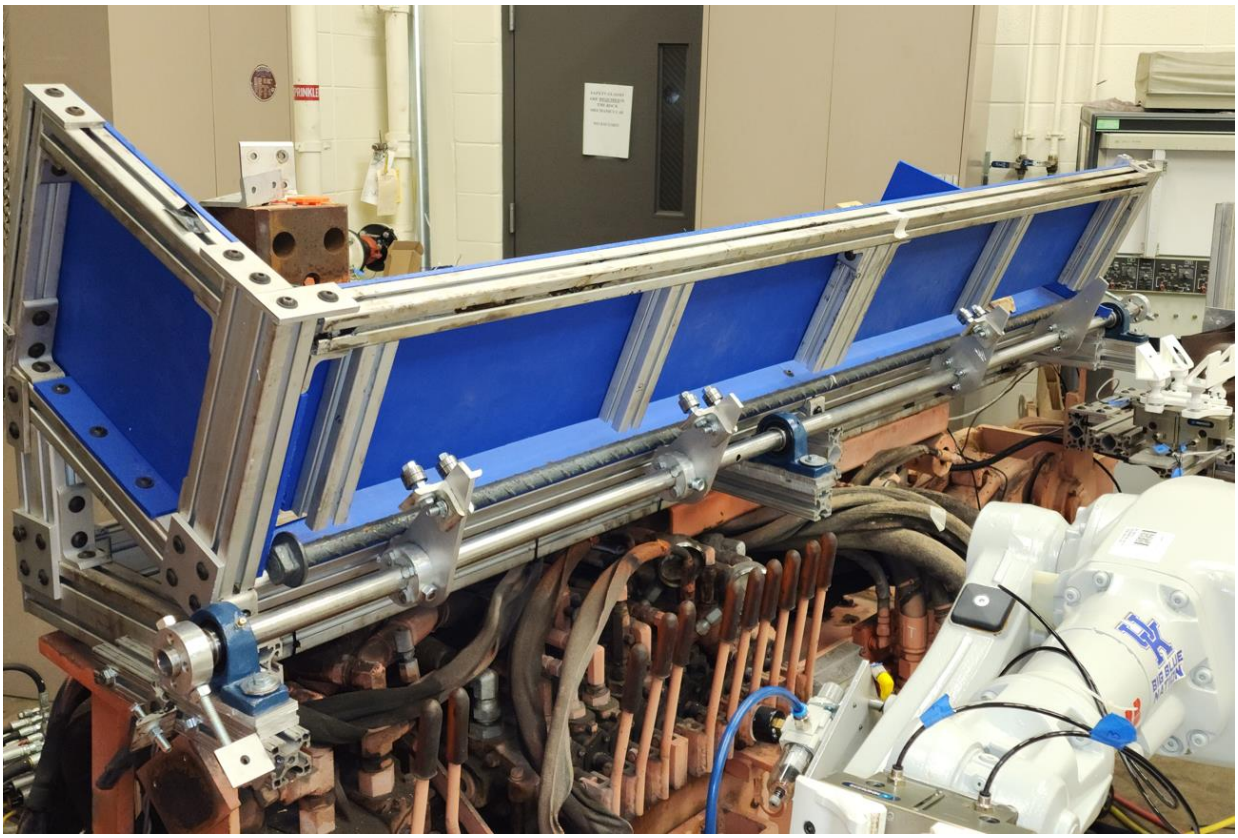

Figure 8: The bolt feeder

Table 1: Summary of prototype linear actuator specification on the bolt feeder

| | |
|---|---|
| Manufacturer and Model | Glide force LACT4P |
| Motor type | Brushless dc |
| Input Voltage | 12VDC, 24VDC |
| Maximum Current | 3. Amps @ 12VDC |
| Speed | No load: 0.28 in/sec [7 mm/sec] - to - 1.73 in/sec [43.9 mm/sec]<br>Full load: 0.22 in/sec [5.5 mm/sec] - to- 1.44 in/sec [36.5 mm/sec] |
| Nominal Stroke Length | 2” [50mm], 4” [100mm], 6” [150mm], 8” [200mm], 10” [250mm], 12” [300mm] |
| Maximum Static Load | 562 lbs. [2,500 Newtons] |
| Gear ratio | 20:1 |

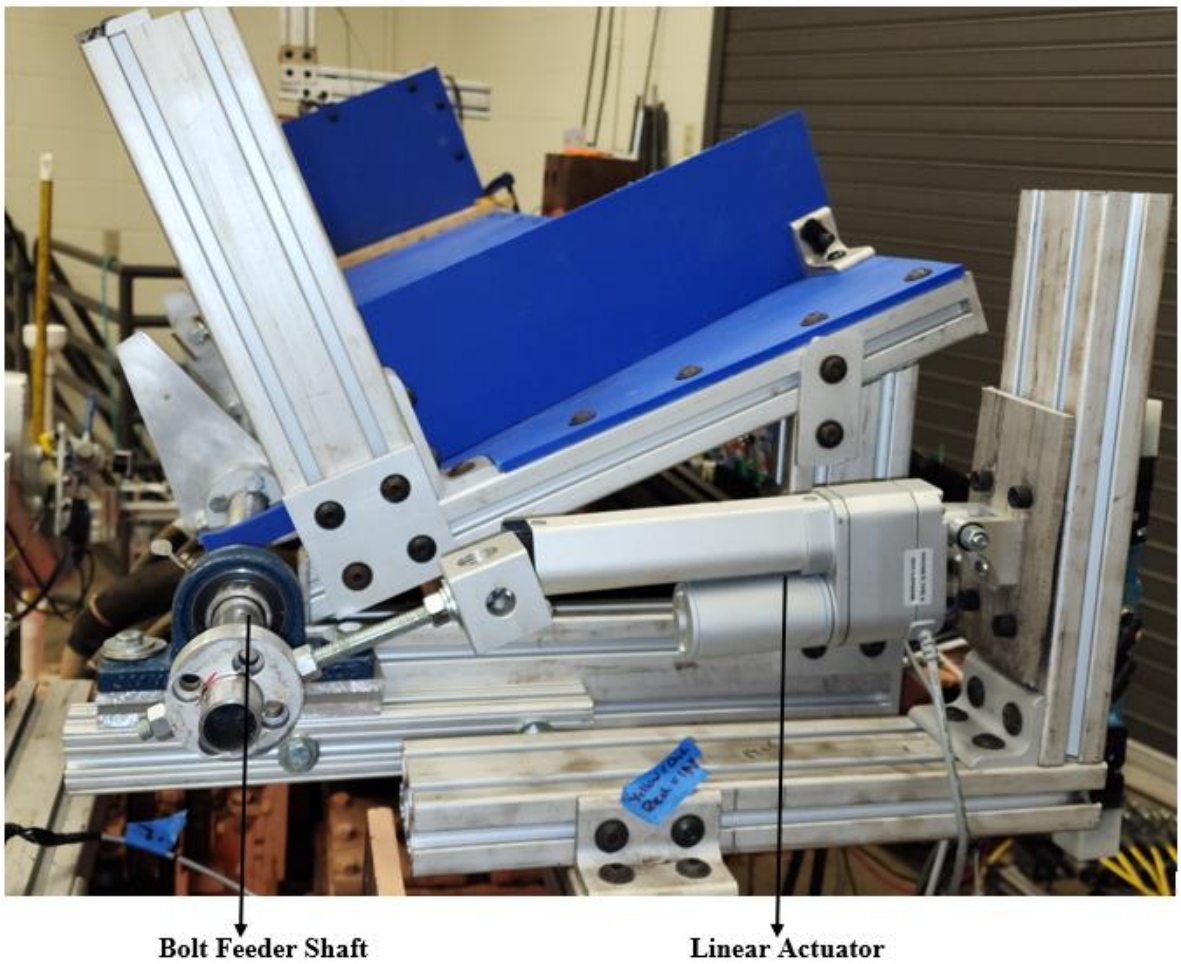


Figure 9: Location of the linear actuator connected to the PLC.

### 3.4.3 The Wrench System (Tool Interchanger)

To prevent human intervention during the automated roof bolting operation, there is a need for a tool interchanger to perform the duty of human support. In this project, the tool interchanger system is referred to as the wrench system. The wrench system was designed to quickly and efficiently change tools, while the roof bolting process was in operation. The wrench is positioned beside the drill head roof bolter to stabilize the drill steels and the bolt during drilling and bolt installation, as shown in Figure 10.

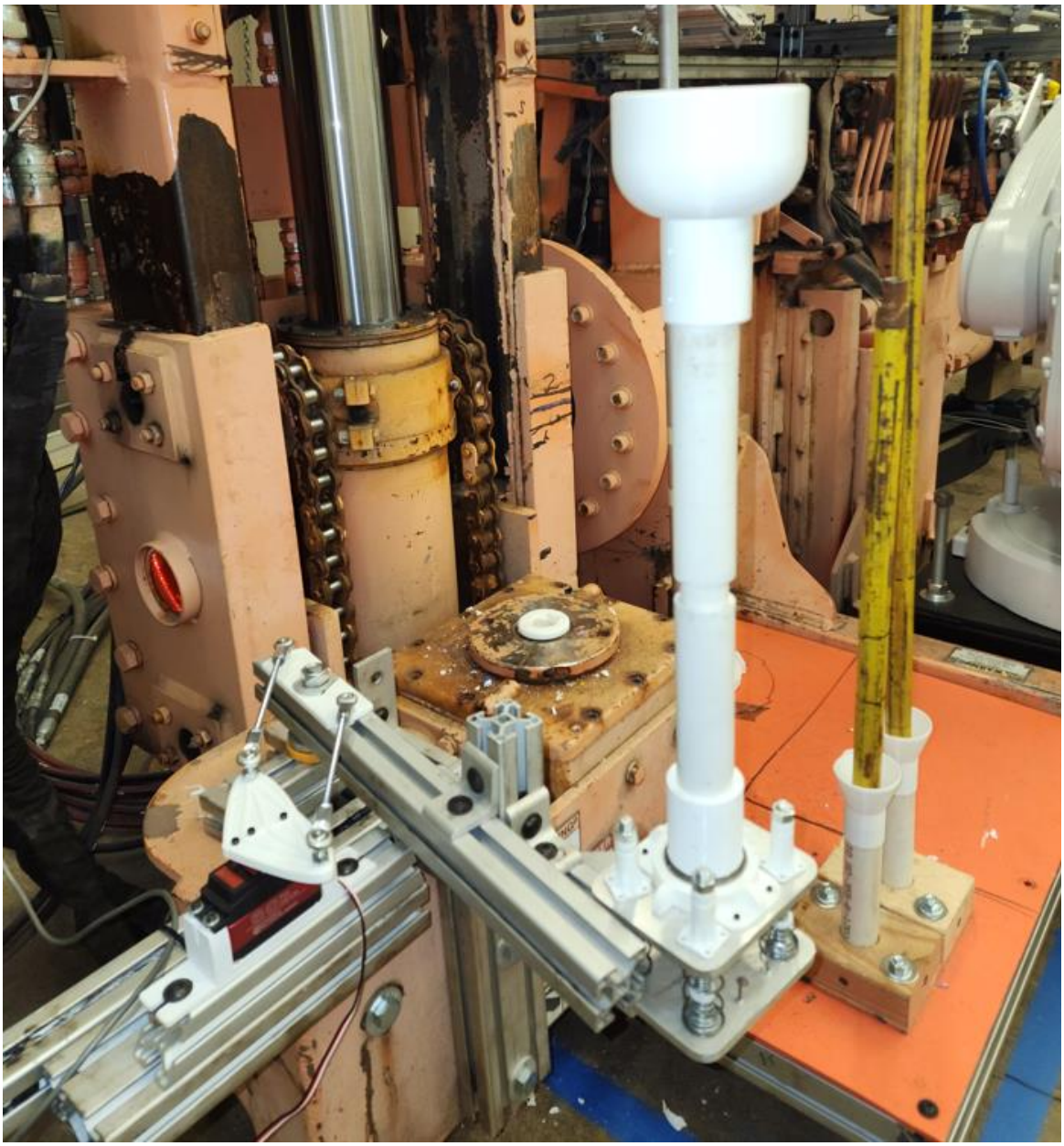

**Figure 10: The wrench system**

The wrench allows the drill steels and the bolt to be positioned appropriately and prevents possible disengagement of drill steels during drill steel coupling and bolt installation. More importantly, it serves as the connector between the drill head and drilling tools to be able to achieve maximum drilling and bolting height. The automated wrench comprises a step motor connected to a mini controller, which sends high and low signals to the PLC for task execution. The step motor that drives the movement of the wrench via the touchpad and iQAN program is shown in Figure 11. When the communication path is established between the mini wrench controller and the PLC, the wrench system can be controlled from the IQAN system via the touchpad.

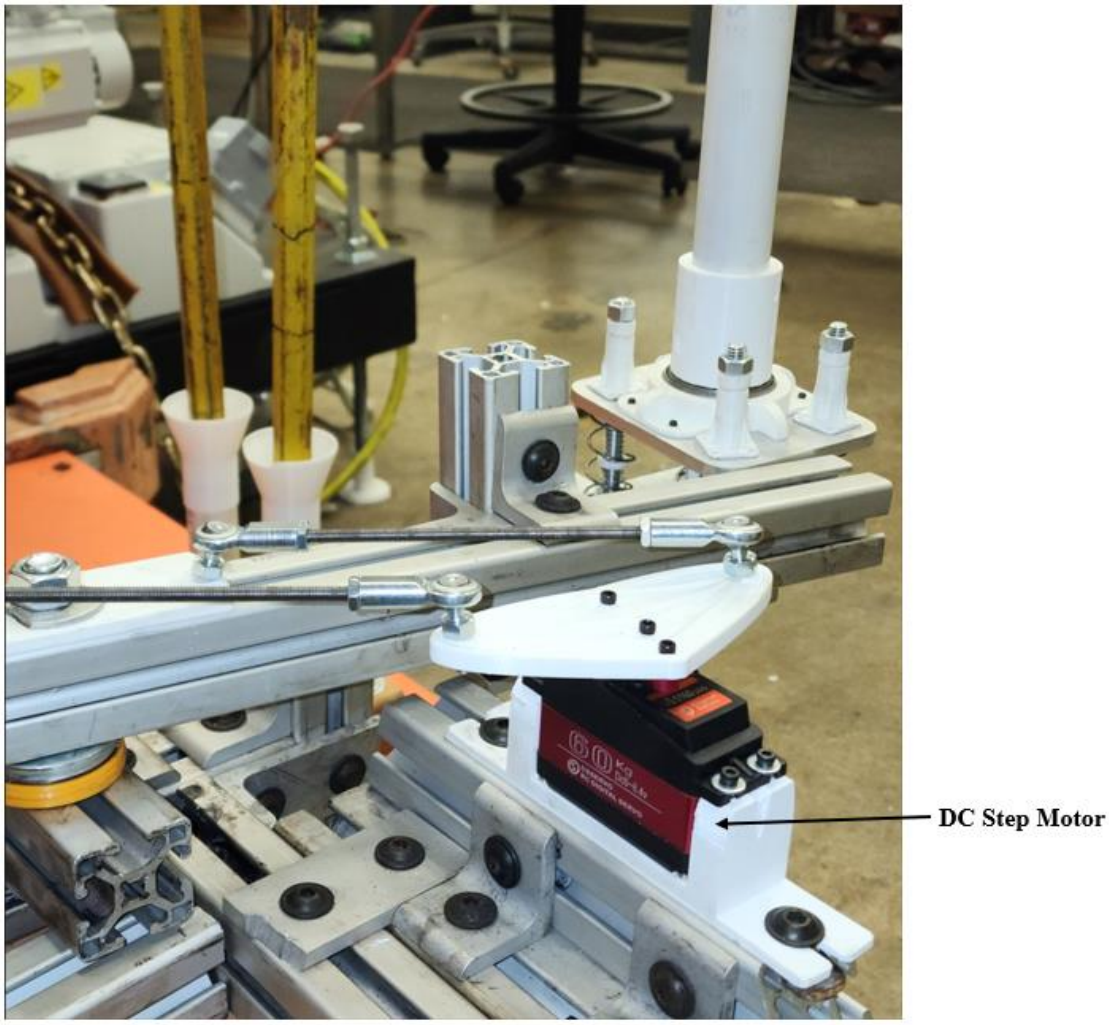


Figure 11: DC Step Motor

The communication between the wrench mini controller and the PLC controls the directional movement of the wrench in and out. Also, the ability of the wrench mini controller to communicate with the PLC opens up possibilities for integration on IQAN and for all other components of the roof bolter for the automation process.

## 3.5 The Development of the HMI for Human Operator

The development of an operator friendly-human-computer interface device is one of the objectives of this project. For more intuitive and operator -friendly human-robot interaction, an HMI was designed and developed, through which the user can send commands to the robot and monitor the robot's status in real-time. The design of the HMI is targeted to provide an easy-to-use interface for the operators to command the robot, the hydraulic roof bolter machine and other components from desktop computers, smartphones, or tablets. For instance, the interaction mechanism between the robot and the human is presented in Figure 12. The video streaming serves is a program that can efficiently decode and transmit images. It communicates with the operator interface through the Websocket protocol while the server is connected to the Robot Studio API module. The Robot Studio API module is connected directly to the robot, and it listens continuously for connection with an operator interface through a static IP. In this project, the researchers did not use video streaming; instead, the photographs of each action of the robot and other components were added in the IQAN program, and the operator interface displays them as automation progresses.

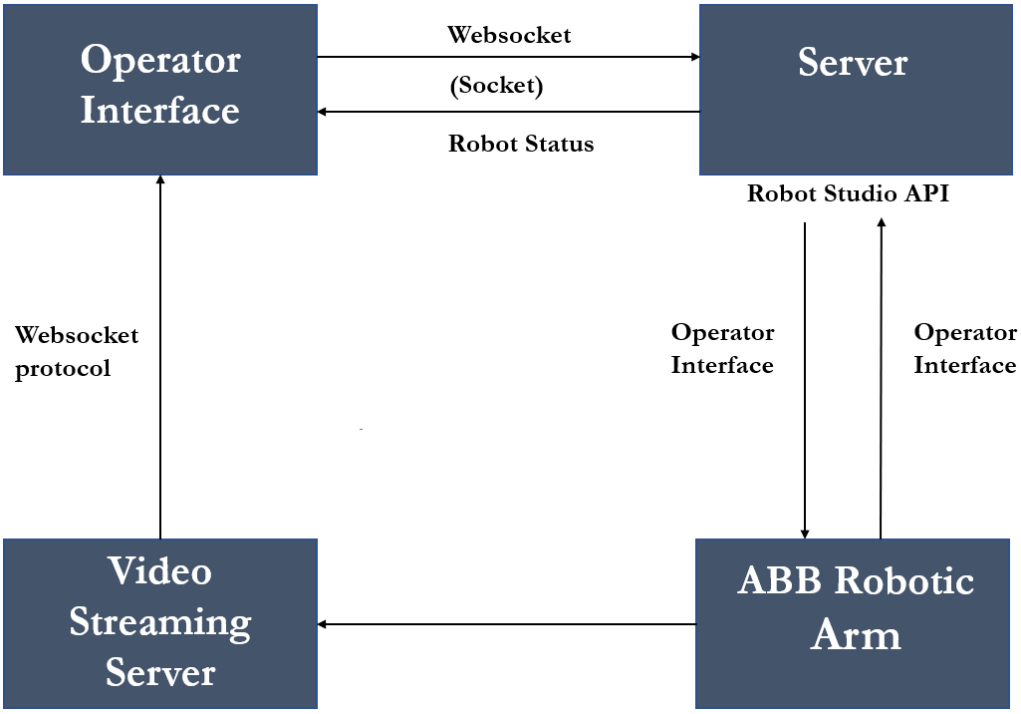


Figure 12: Human-robot interface for computer environments

The Flex Pendant is designed to control the robotic arm by approving all the tasks to be performed by the robotic arm, and it is equipped with an emergency stop button that overrides the systems in the event of unsafe acts. The Flex Pendant is a handheld operator device that performs many of the tasks involved when operating a robot system. In this project, the Flex Pendant is used when the human operator works closely with the robotic arm in various roof-bolting activities or during task and motion planning. The human-robot interface for the Flex-Pendant is developed using the ABB Screen Maker software. The interface consists of different

buttons corresponding to other motion modules. At the end of the project, the research team successfully moved all the buttons in the Flex pendant to the HMI touchpad, which allows the operator to focus and control the system from the HMI.

The HMI system allows the operator to control and monitor the automated roof bolter machine operations away from an active mining face. The HMI is an interface that requires the operator to approve every task before being executed by the robot or the hydraulic roof bolter machine. Additionally, in the design of the HMI, provisions are made to let the operator override the action of the hydraulic rood bolter and the robot in case of emergency or unexpected events. Figure 13 shows the home interface details that control the automatic operation, manual operations, hydraulic bolter functions, and robot functions.

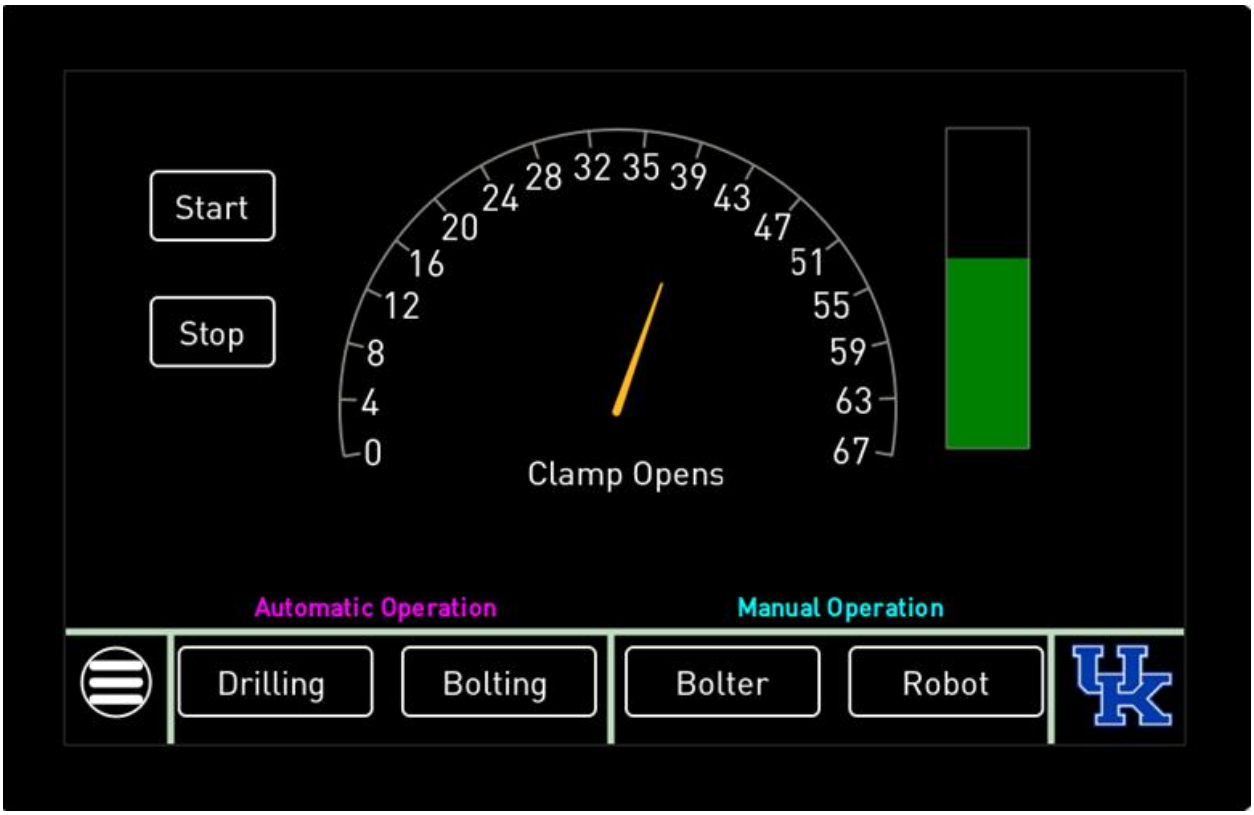


Figure 13: Main window for controlling the roof bolting operation.

The interface details are shown in Figure 14. The HMI has two sections: automatic operation and manual operation. Automatic operation pertains to settings that allow for automated roof bolting operations to be performed, which consist of the drilling and bolting sections. The operator only initiates the roof bolting operation by pressing the start button, and the automated operation commences. During the roof bolting cycle, if the operator notices unplanned actions, the operator could stop the process via the reset button. The green bar and the gauge counter on the HMI show the operator the progression of the task. On the other hand, the manual operation consists of buttons and actions from the robot and the hydraulic roof bolter machine. In a scenario where the operator is required to perform some hydraulic bolter functions, the manual operation can be used. The main features of manual operation section are presented in Figure 14.

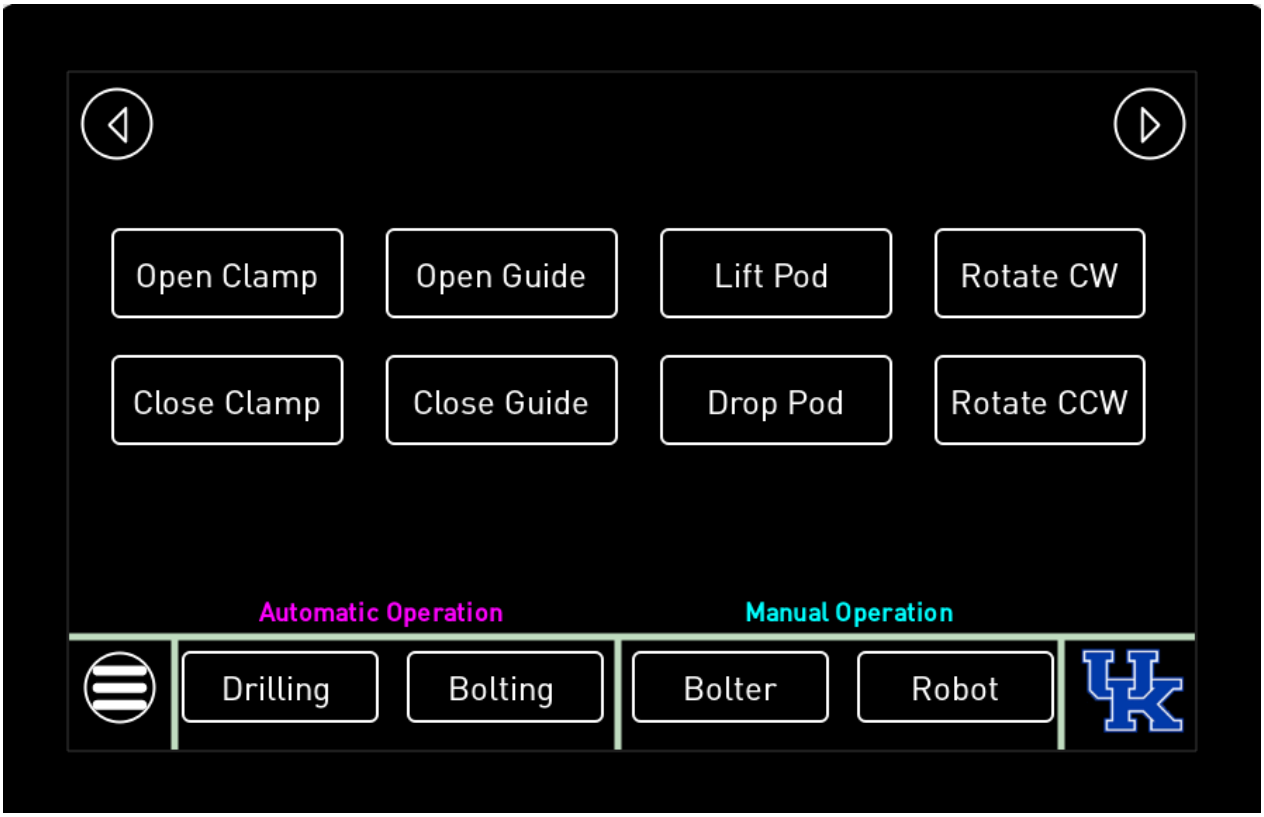


Figure 14: Hydraulic roof bolter button interface of the HMI

Similarly, the interface of the robotic arm function is shown in Figure 15. The robotic interface presents the basic tasks that are performed by the robot when it is not operating in automatic mode. These buttons control the robot to perform specific tasks. The HMI interface for the robot actions allows the operator to override the robot actions if any unplanned actions are noticed. This is a crucial feature for controlling the system in the case of accidental or unexpected actions that can pose risks to the safety of the personnel working near the equipment.

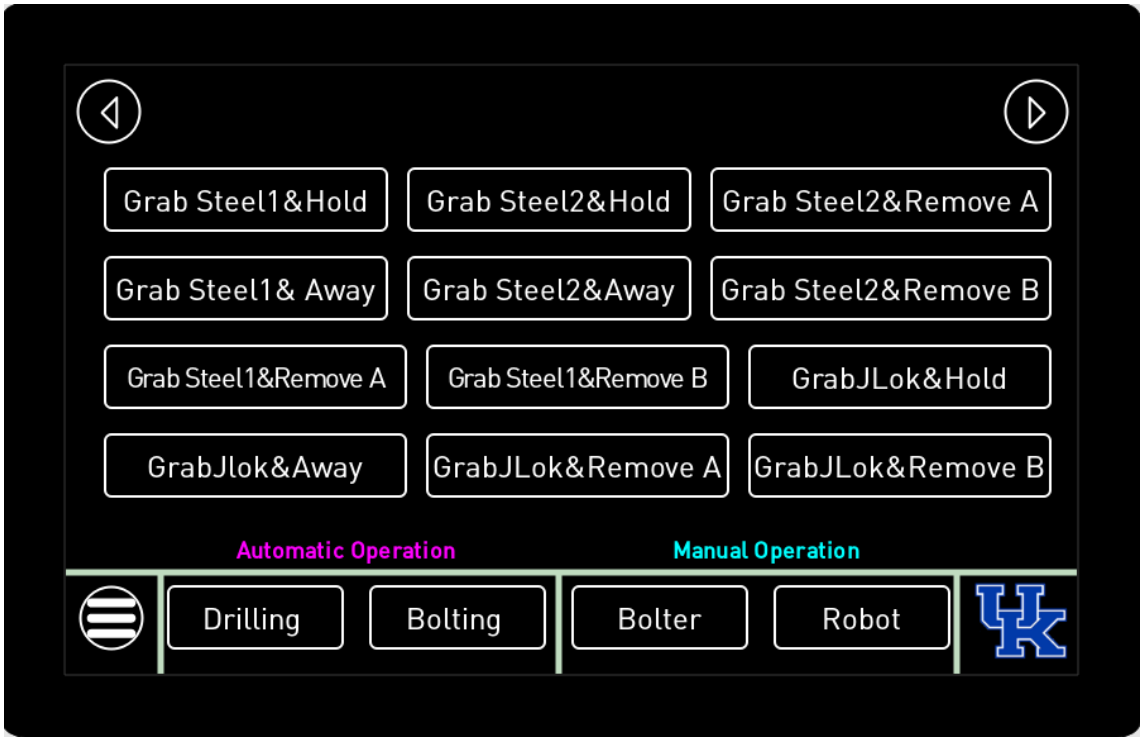

Figure 15: Robotic arm buttons interface of the HMI

The HMI controls the automated roof bolter machine by sending CAN messages to the PLC for the execution of tasks. The HMI is connected to the XA2 module in the PLC. The integration of the IQAN system and ABB robot controller allows the operator to send commands to both the robotic arm and the hydraulic roof bolter machine. The iQAN program enables the users to make changes or set up pages on the touchpad. The program allows users to see module information and logs, set preference, measure system Input and Output (I/O), or adjust parameters. The iQAN program has many icons or features that enable users to explore various designs option depending on user requirements and tasks. The goal is to design a user-friendly interface that presents to the user the progress of the roof bolting process and at the same time provide the user with options to override the process.  After designing the HMI on the computer, the project file is uploaded to the modules on the PLC via USB cable to CAN device cable. The MC42 also has pins to wire in an Ethernet communication port. The Ethernet port is used for uploading/downloading applications and diagnostics and is designated for computer communication.

## 3.6 The Anybus Communicator

The Anybus device is installed in the PLC cabinet. This device allows the robotic arm to be incorporated successfully with the iQAN systems. The primary function of Anybus systems is to translate the command from the iQAN touchpad to the language the robot controller understands, and the robot will execute the function. It serves as a protocol converter, allowing the robot to communicate with the hydraulic bolter using another protocol. The iQAN interface communicates to the programming panel and the ABB and PLC through the Anybus CAN to Ethernet/IP interface, as shown in Figure 16. The RS232 connector from the CAN Bus is

connected to the Anybus device to exchange data between the robot and the iQAN system. The scripts can bypass the Anybus interface, allowing the testing and development to move forward before the final map between the two interfaces is developed. It supports data buffering and data transfer prioritization during the automation process.

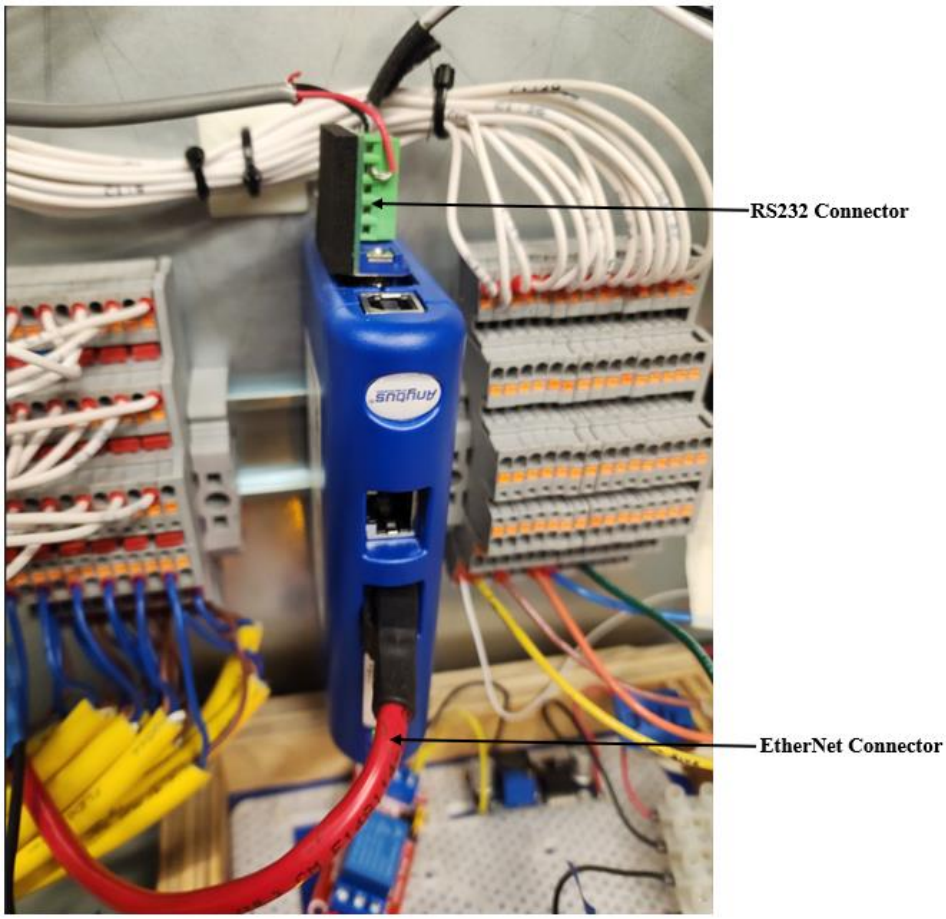


Figure 16: AB7317 Anybus Device

## 3.7 Robotic Arm Task and Motion Planning

The researchers developed an algorithm that can generate task-and-motion plans for the ABB robot to manipulate drill steels, bolts, and other tools like digging bars, and shovels autonomously. The goal is to allow the ABB robot and the roof bolter to collaborate seamlessly to automate the majority of the roof bolting tasks. During the planning phase, the researchers manually created robot paths to pick up the drill steel and bolts and install them into the roof bolter. However, this is unrealistic since the manually created paths will be infeasible when the robot works in different environments, such as underground mines. Moreover, the researchers consider the situations where the ABB robot will not only have to manipulate objects like drill steels and roof bolts, but it will also have to manipulate objects, like digging bars and shovels, to clear space for manipulating the drill steels and bolts.

For the ABB robot to manipulate these objects autonomously, executable task plans and motion paths should be generated. The problem of developing the executable task plans and motion

paths is called task-and-motion planning (TAMP), where the project combines task and motion planning techniques to perform functions such as installing drill steels into a series of robot-executable motion paths. Task planning generates a sequence of discrete actions, such as picking up a drill steel and installing it into the roof bolter, while motion planning is used to compute the actual paths the robot should execute. Manipulating the drill steels and bolts is an important subclass problem of TAMP, namely, geometric task-and-motion planning (GTAMP). GTAMP is a problem where the robot has to move several objects to specified regions in the presence of other movable objects. Previously, GTAMP has been addressed efficiently in single-robot domains.

In this project, the researchers view the roof bolter and the ABB robot as a multi-robot system; thus, the researchers defined the problem as a multi-robot geometric task-and-motion planning problem, where the robot collaborates to move several objects to regions in the presence of movable obstacles. In the simulations, the roof bolter was treated as a simple robot with only one degree of freedom such that the drill base could move up and down to install the drill steel, bolt and resin. . The robot places the objects in the designated locations, following which the hydraulic roof bolter executes installation procedures. Thus, collaboration between the roof bolter and the manipulator is required. The planner generated collaborative plans so that the manipulator can pick up the required objects and hand them over to the roof bolter. In the course of the laboratory testing, the robot is programmed to identify and remove any objects from the roof bolter.

The concept of planning an algorithm is to generate robot executable motion paths to install the drill steel into the roof. To achieve this goal, the researchers developed an algorithm that identifies and moves away obstacles that may be found in the working environment. In the environment shown in Figure 17, two digging bars must be moved out before we can pick up the bolt.

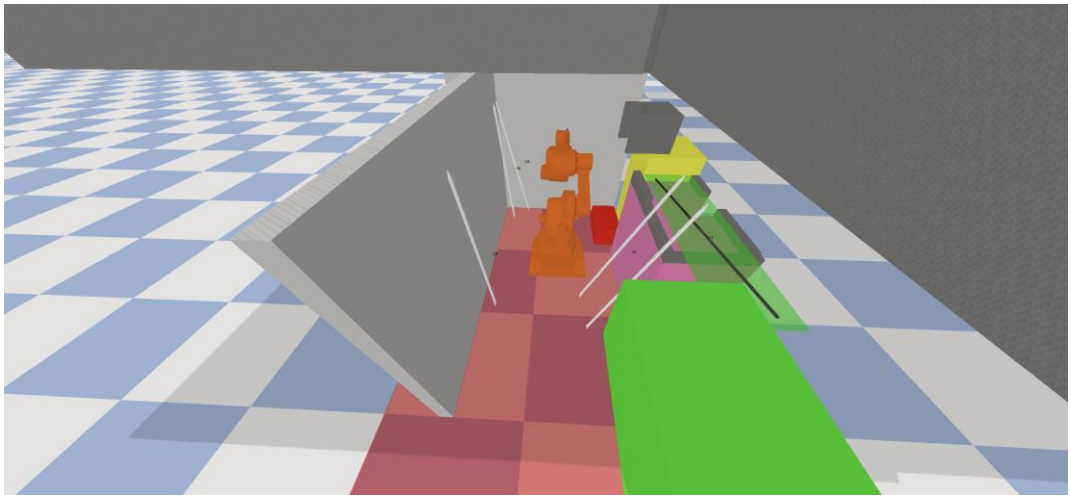

Figure 17: Simulation roof bolting task environment

### 3.7.1 Creation of task and motion approach

The project applied a two-phase planning algorithm in this section. In the first phase, the system computes the collaborative manipulation information, i.e., the occlusion and reachability information for the ABB robot. At the same time, the second phase entails searching for task-and-motion plans. The search process depends on a key component that generates promising task plans and a key component that finds feasible object placements and motion trajectories for the task plans to construct executable task-and-motion plans.

This project used the recently developed mixed-integer linear program (MIP) solvers that generate promising task plans by solving the formulated MIPs. A task plan specifies the direction in which the robotic arm should move using a series of MIPs to generate task plans. An MIP is a problem with the linear objective function, linear constraints, and restrictions on some variables to have integer values. In the MIP formulation, the researchers encode the precedence of manipulating different objects as formal constraints. For instance, the developed algorithm enables the robot to move blocking objects away from the robot path before it picks up the drill steel, such that we can generate promising task plans to be successfully converted to executable robot motions. Also, the researchers encode the number of moved objects in the task plan as the optimizing target, such that they can generate task plans that move only a few objects to achieve the goal i.e., to install the drill steel and the bolt.

### 3.7.2 Plan motion trajectories and find object placements for the task plans

Once a set of promising task plans were generated, then a plan motion trajectories and object placements to were executed. The project applied a reverse search algorithm that could efficiently find feasible object placements. The researchers started by executing the task plans from the last time step. That is, to plan motion trajectories to place the bolt on the hydraulic roof bolter for installation. Given the planned motion path, if the robot determines that there are objects obstructing the planned paths, it moves them out of the way and places them in new locations. The new locations should not induce blockage between the moved objects with the bolt. During the simulation, the researchers tested the robotic arm’s potential to keep moving the encountered obstacles until we do not have any blocking objects.

### 3.7.3 Experiments in simulation and real world

To generate task-and-motion plans in the real world, the researcher first constructed a simulated environment based on a physics engine named PyBullet to assume that we have the position information of the objects, the ABB robot, and the roof bolter. Subsequently, the researcher runs the algorithm to generate a task-and-motion plan in the simulation. The project also tested the generated plans in the real world and the results show that our generated plan can be transferred from simulation to the real world.

In the laboratory experiments, the researchers tested two scenarios that are common in the roof bolting process: (1) a scenario was tested where the ABB robot has to move obstacle objects like

extensions and retrieve simulated resin to install the bolt; (2) a scenario was tested, where the ABB robot and the hydraulic roof bolter machine have to first uninstall the drill steel and then install the bolt. The plan execution of the first scenario is shown in Figure 17. In the plan shown in Figure 18, the ABB robot moves away a bolt, an extension, and the simulated resin before it can hand a bolt over to the roof bolter to finish the installation.

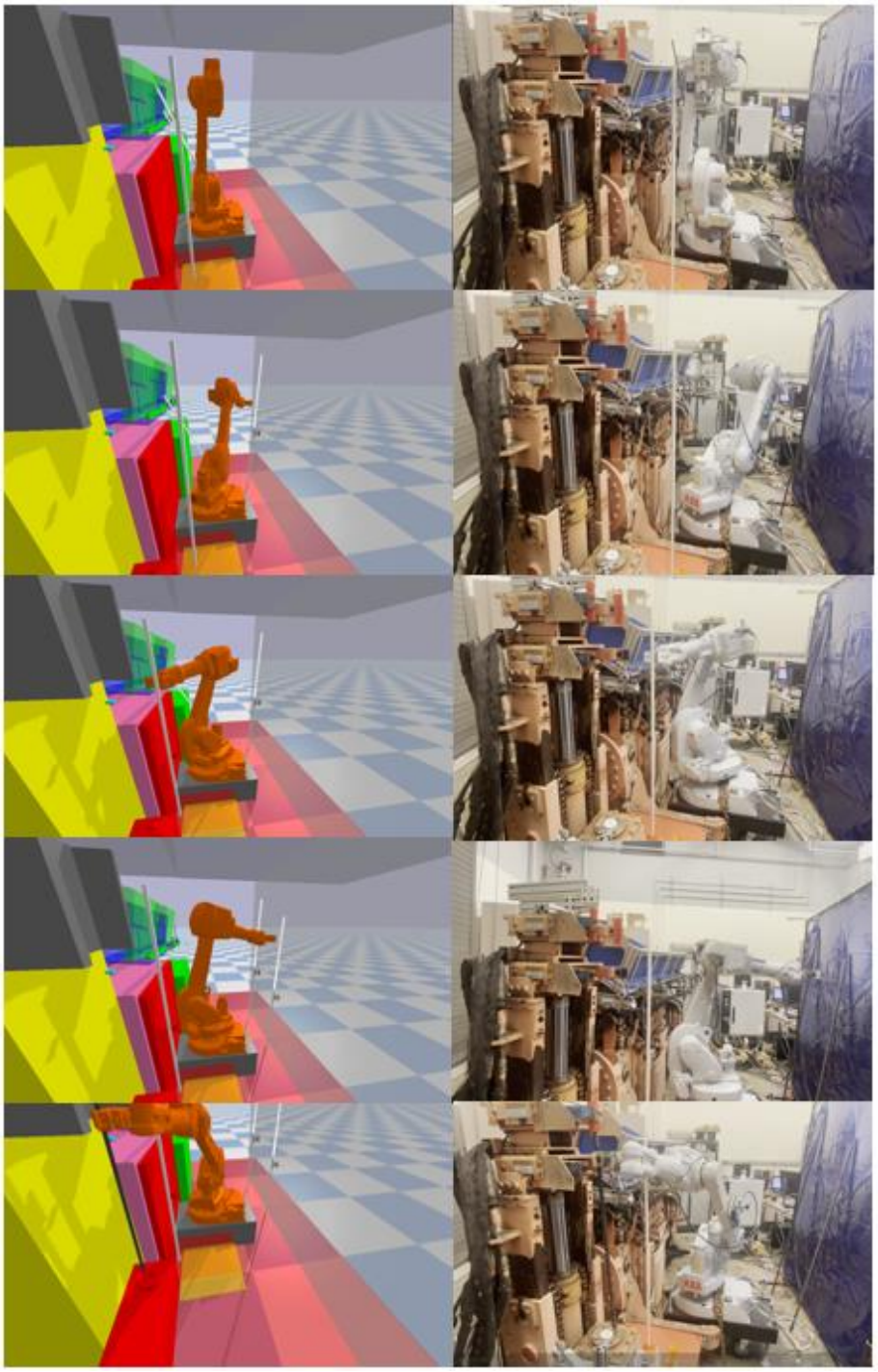

Figure 18: An example plan execution

## 3.8 Integration of Hydraulic Roof Bolter and Other Components

This project entails the integration of several technologies, and the communication between the devices is critical to the success of the automated roof bolter machines. The integration of all components of the roof bolter machine is the most important phase of the project, as individual component needs to execute assigned tasks without collision. The integration was done in the iQAN program. The program provides a platform to control and monitor the behavior of machines such as hydraulic systems, which makes it suitable for this project. The iQAN program allows users to monitor different iQAN-units connected through a CAN-network. One of the main reasons for using the iQAN program for this project is the easy access communication protocol of the CAN network.

The ABB IRB 1600 robot imitates human intelligence in automating the roof bolting process. The robot makes use of the EtherNet Industrial Protocol (EtherNet/IP) to create communication with other components of the bolting process. This process is industrial EtherNet/IP based, with the ability to communicate between the robot and the control system in real time. Establishing a reliable communication path between the robot and the PLC is vital in the automation process. The communication path was set up by sending CAN messages from the touchpad to the Anybus communicator, which translates the message to a signal that the robot understands for immediate task execution. The robot only listens to the Anybus communication for commands and sends the signal back to the user after completing the task. The communication architecture illustrates that the Anybus communicator controls the communication in the form of consume protocol (sending CAN messages to the Anybus system via EtherNet/IP connection) while the robot feedbacks the operator after executing a task in the form of produce protocol (sending a signal from the Anybus system to the touchpad) as shown in Figure 19.

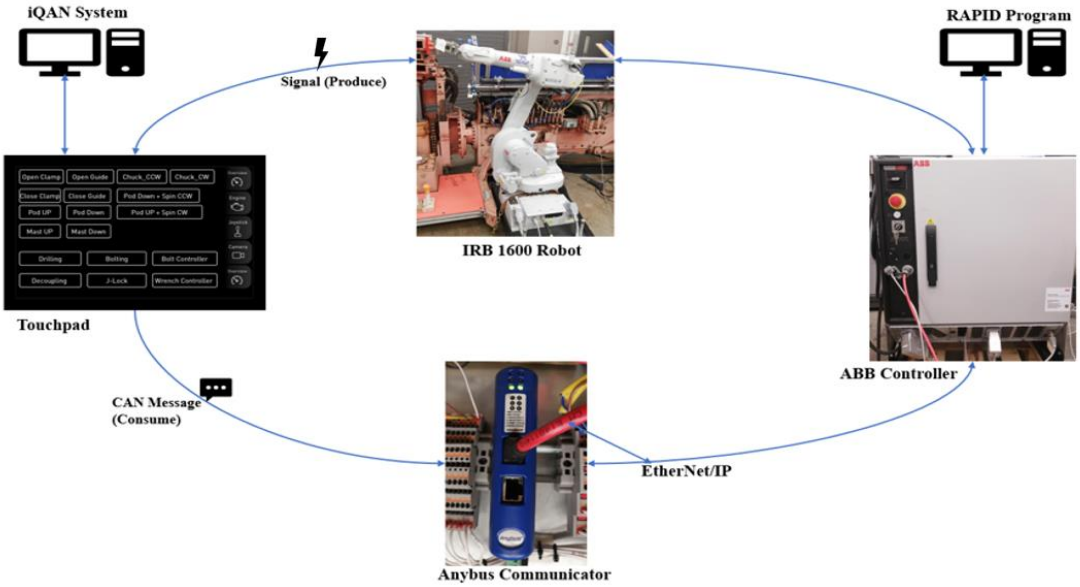


Figure 19:Automated roof bolter machine communication and system integration

The Anybus Communicator is an EtherNet/IP-based system that serves as a gateway between the ABB IRB robot and the PLC system that controls the hydraulic system. This device works based on data exchange between a serial subnetwork and EtherNet/IP network. The technology allows sensors and other digital systems to communicate based on trigger events presented by the control system in the higher-level network. The technology is designed that a CAN message cannot be sent to the robot unless the value sensor is mapped on the Anybus device. This process involves several virtual communications between the robot and the PLC, known as “handshake” communication. The main function of the handshake is to integrate two systems. When the touchpad generates via PLC, the Anybus translates it into a signal and sends it to the robot for execution. The subroutine in the robot controller performs the function of translating the signal from the robot and converting it back to the original state.

## 3.9 Communication Architecture

A reliable communication link was established between components to control the roof bolter module without human intervention. EtherNet/IP protocol is used in passing messages between components of the automated roof bolter machine. A CAN bus device is installed to enable communication using the CAN protocol. A CAN Bus system interface is integrated directly into the valve section to connect to the master control unit and control the roof bolter's hydraulic system shown in Figure 20. Using the CAN bus as the primary communication interface makes the communication network more accessible to sensors and other devices. This project used CAN protocol, designed to be robust and reliable, even in harsh environments. Also, the network supports applications where high-speed communication and real-time response are required.

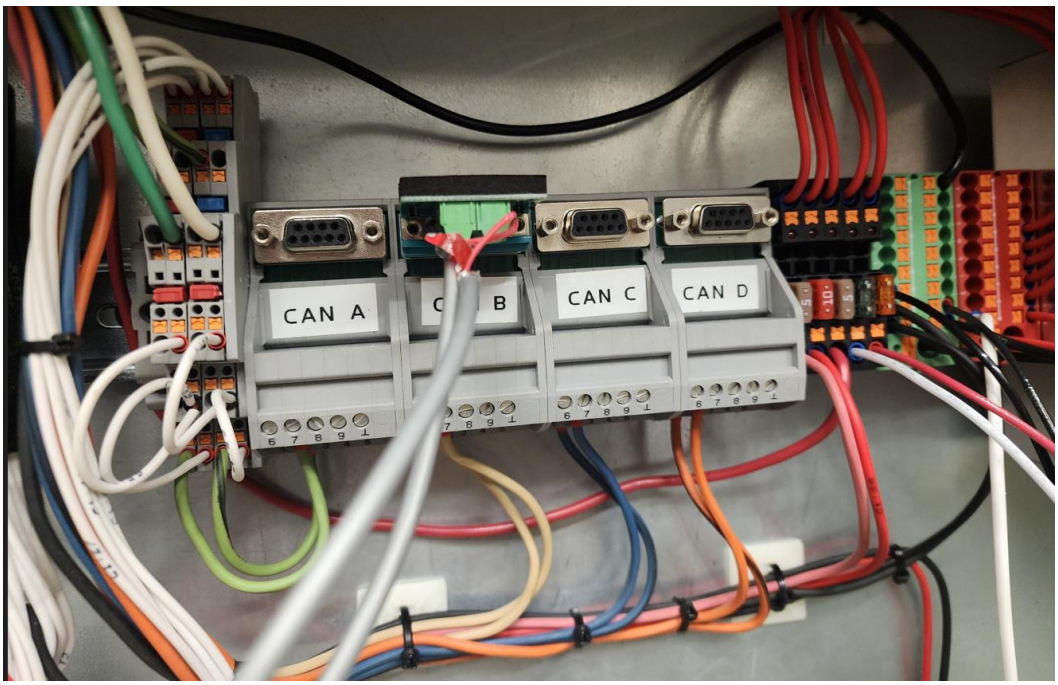


Figure 20: CAN Bus connection point from Anybus device and iQAN system

The CAN from Parker Hannifin’s iQAN system is a message-based protocol that allows messages to be sent in the form of a packet of data known as a CAN frame. In the CAN

communication protocol, messages are sent from one device to another using the CAN bus. When the iQAN device sends a message to the CAN bus, each message contains a unique identifier and control bits. The message contains the actual data to be transmitted, and the control bits include parameters such as the data length, which states the number of bytes in the data.

The CAN frame can send a maximum of 8 bits of data and each frame can carry up to 8 bytes of data which is 64 individual signals for the entire frame. The data field consists of 0-8 bytes (0-64 bits) of data that are inserted in the actual data message sent. For a communication path to be established between the Anybus system and the iQAN program, the CAN frame must have the same CAN identifier. For instance, the first task in the roof bolting automation process is drilling and has a CAN identifier of 183 on the Anybus system. The CAN identifier on the iQAN system must have the same value of 183 for the system to establish a communication path. The configuration of the Anybus communicator is made using X-gateway software which is installed on the PC and connected to the Anybus device configuration port of the X-gateway with a USB cable. This allows the user to define the input and output (consume and produce) data on each network side and data mapping between the cyclic input and output data where applicable. Setting up a proper device configuration guarantees a robust connection and reduces faults since a single data line is used to manage all communications.

The iQAN program also controls other components, such as the hydraulic roof bolter, the wrench, the plate feeder and the bolt feeder, by sending messages to the PLC controller through graphical programming. The program has multiple CAN buses that can be used for communication and diagnostics. A CAN communication adapter was installed on the computer to configure and manage all the systems that are connected to the iQAN systems. In this project, the signals are communicated based on the CAN protocols that are assigned to service ports A and B (CAN Bus) as shown in Figure 21. The master controller of the system is a Parker MD4 with an X7 expansion module running the iQAN interface, which includes a touchscreen and joystick. The iQAN interface communicates to the programming panel and the ABB and PLC controller through the Anybus CAN to Ethernet/IP interface.

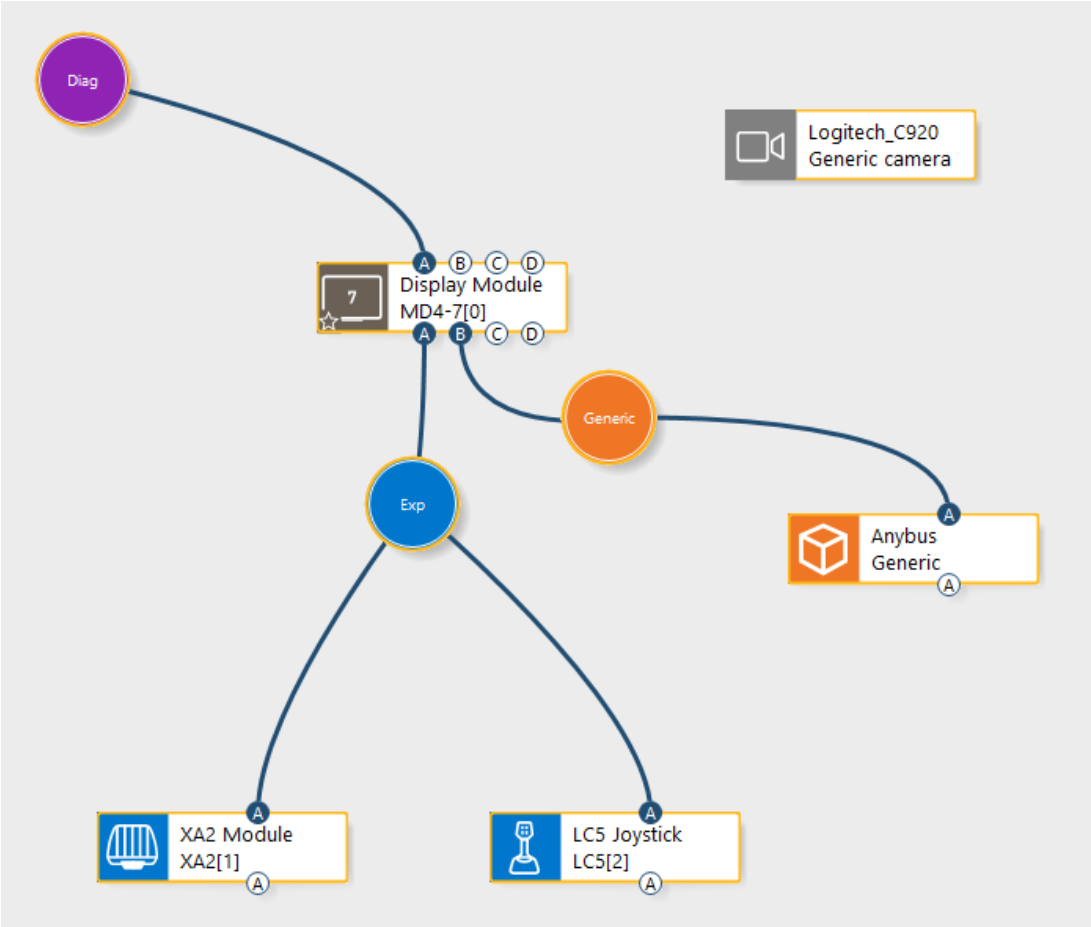


Figure 21: Communication interface diagram

One of the advantages of using the CAN bus is minimizing the wiring connection and providing communication between different electronic control units (ECUs) through CAN-based displays. The system provides easy access to interfere with the CAN communication protocol between the robot and other components. The iQAN system provides an interface that can be used for uploading, downloading the application, or checking errors in the system. The touchpad is connected to the PLC via the iQAN-XA2 module, which is extended to the master control unit that controls the roof bolter hydraulic system. In addition, the display and control can be activated through the touchpad. The iQAN interface is connected to a computer where all the systems manipulations are done. Also, the conventional joystick is linked to the XA2 module that controls the hydraulic roof bolter system. The iQAN-XA2 works with a 24 VDC power supply. A rectifier was installed in the PLC controller to convert the power from 240VAC to 24VDC.

In addition, the iQAN program controls the movement of all the components of the automated roof bolter, such as the wrench, the bolt feeder, the plate feeder, and the programmable hydraulic valves from the drill head, which are connected to the drill control unit, the joystick and the HMI touchpad. The movement of various components is achieved with the programmable time sequence in the iQAN program. The application of the time base logic program prevents collision between the hydraulic roof bolter, the robotic arm, and other components of the

automated roof bolter machines by properly sequencing their tasks. However, the time-based logic does not only permit cycle time estimation but also optimizes the bolting operation, which in turn influences the performance of the bolting operation. Whenever a change is made to the iQAN program, the program is uploaded to the PLC for the update.

## 3.10 Modifications of Hydraulic Roof Bolter Parts

Modifications were made to the hydraulic roof bolter machine fit for laboratory scale testing. The research team decided to change the drill size to one inch, which the machine designed for a 1 ½ inch drill.

For effective and efficient drilling and bolting operations, researchers also redesigned the clamp and guide on the hydraulic roof bolter shown in Figure 22. The initial clamp and guide could not perform their function effectively for the laboratory scale testing. The newly designed clamp was able to effectively mimic the human hand in holding consumables during the roof bolting process. Likewise, the chuck was reconstructed to properly engage the drill steel while spinning during drilling and during the removal of drill steels. The robot placed the drill steel in the clamp and the chuck must engage the steel. The angle of the opening on this wrench works very well for engaging the steel; however, this part is currently being redesigned. However, the design also works perfectly for resin injection and bolt installations.

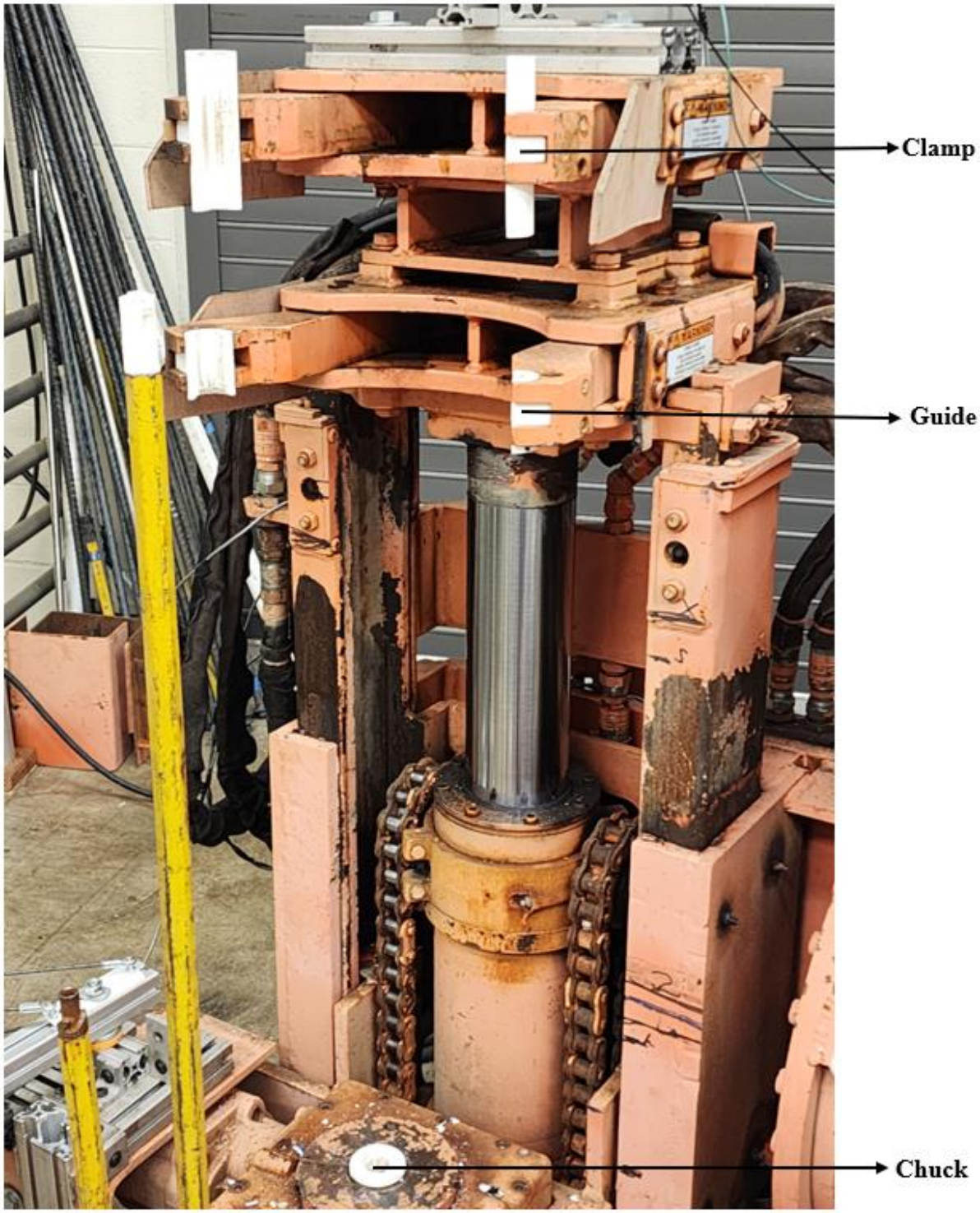


Figure 22: Modifications made on the hydraulic roof bolter machine

# 4 Research Findings and Accomplishments

The main goal of this project was to develop an automated roof bolter machine that can perform a complete roof bolting operation with no human intervention. The researchers were able to build some components of the automated roof bolter, establish a robust communication link within systems and develop a program in the iQAN programming environment that allows integration of all the components, which form the automated roof bolter machine. Likewise, a user-friendly HMI was developed for the operators to control the roof bolting process at a safer distance from the active mining face. This has completely eliminated the presence of humans from the face area and assigned the operator a supervisory role to monitor the roof bolting process. Implementation of the automated roof bolting machine in mining operation will enhance operators' health and safety and at the same time, increases operational efficiency and productivity.

In the process of testing the automated process in the laboratory, the researchers classified the whole process into two categories. These include the drilling and bolting operations. The drilling operation in the roof bolting process entails penetrating the roof and removal of consumables such as the drill steels and drill bit. On the other hand, the bolting operation involves inserting the resin tube which consists of a simulated injection tube and a base. The final process of the bolting operation is bolt installation.

## 4.1 Automated Drilling Process

The robotic arm was integrated into the automated roof bolter to imitate human tasks. The automated drilling task is conducted by allowing the robotic arm to perform human tasks in roof drilling. The robotic arm's action does not only imitate human tasks but also improves performance and productivity. The operators control the bolting process and interact with bolting equipment via a remote-control HMI touchpad. The operators only start the process by pressing the start button on the automatic section of the HMI and watching the robotic arm perform the whole drilling operation. The operator monitors the drilling process in a safer location from the active mining face and can control the process from the HMI. The HMI 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 as discussed in section 2.6, are created using the flex pendant, and the path are saved in the Robot Studio software. The Robot Studio provides an interface that controls and manipulates the robot's motion to perform certain tasks during the drilling operation. These tasks include the robotic arm placement of drill steels on the hydraulic roof bolter machine and retracting back to its initial position after achieving the task, as shown in Figure 23. After completing the drilling with the first drill steel, the robot moves to grab the second drill steel and positions it to couple the first drill steel to achieve the desired drilling depth.

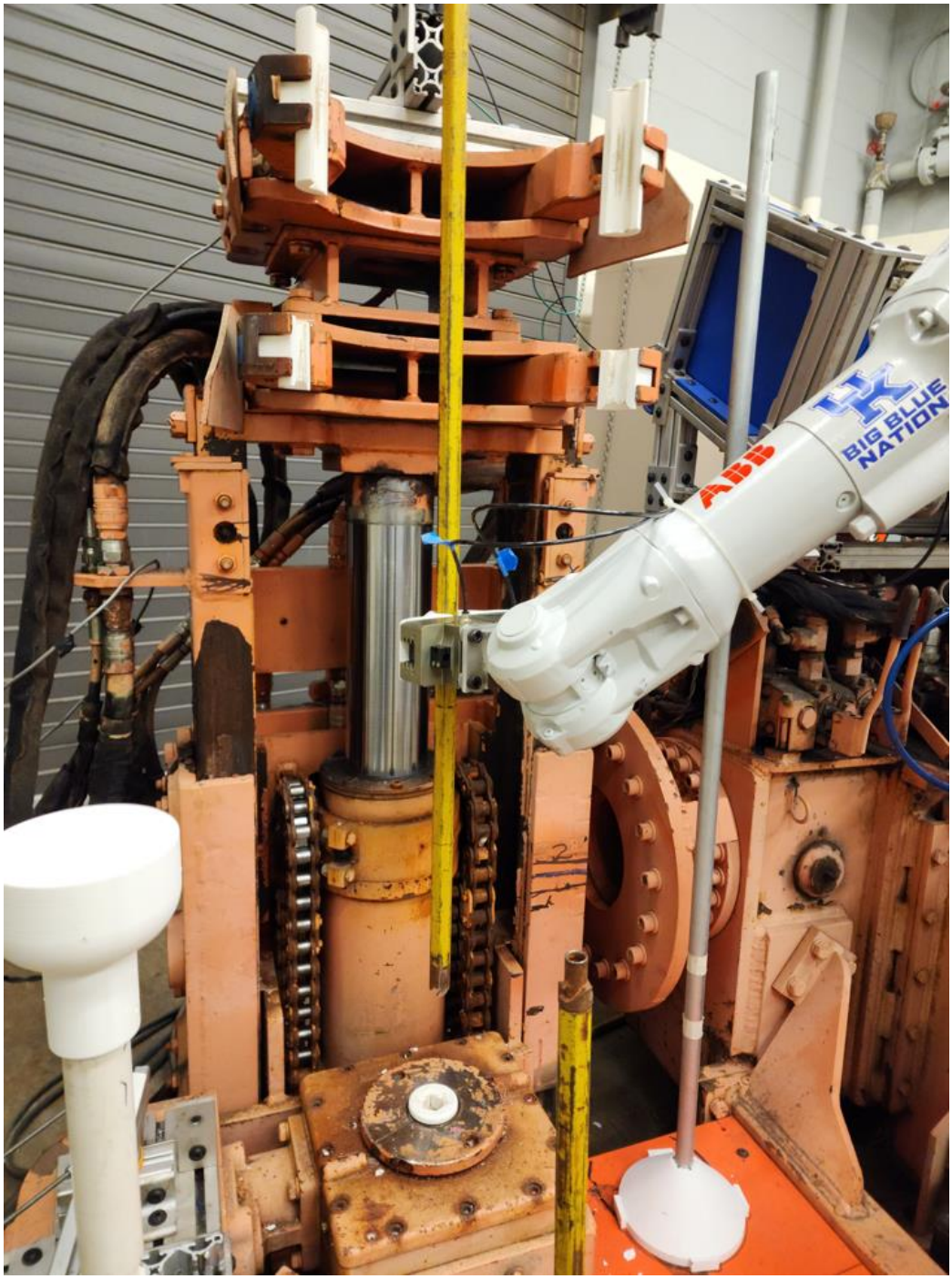

Figure 23: Robotic arm placing the first drill steel for drilling operation.

It is important to note that before the robotic arm can perform an automated operation, the RAPID program in the Robot Studio has to be carefully planned, programmed and tested to ensure the safety of operators and equipment. Before the automated operation, the researchers ensure that the robot space is clear of any obstruction along the robot's path that could interfere with the robot's movements. Once the robot's path is free from obstacles, the robot is set in RAPID mode and the researchers monitor the automated operations. During the operation, if the

researchers notice any irregularity in the movement of the robotic arm, the hydraulic system and other components, it may be necessary to stop the operation and adjust the IQAN program parameters or make modifications in the code to ensure optimal performance for the automated process.

The iQAN program provides the 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 operators to interact with both the robot and the hydraulic roof bolter. The major task performed by the robotic arm in the drilling process of the automated roof bolting operation includes the placement of drill steels and the drill bit on the roof bolter machine and also during the removal of the drill steels after the completion of the drilling tasks. The robotic arm reduces the need for human intervention for the automated process, which improves the speed and accuracy of roof bolting operations. The robotic arm performs and improves the automation process and quality of the results for precise work.

## 4.2 Automated Bolt Installation

Installing bolts in underground coal mines traditionally relied on operator experience and judgment. However, this project introduced a robotic arm to install bolts in roof bolting operations. Operators fix the plate on the bolt and use one hand to place it on the hydraulic roof bolter for installation while the other is used to operate the machine. The developed novel technologies, such as the bolt feeder and plate, were linked to the PLC to provide support for the automation of the roof bolter machine.

During the laboratory testing of the automated roof bolting operation, the bolt installation is classified into two main processes, resin insertion and bolt installation. In this project, resin insertion is done with a pumpable resin that comprises two components, a resin and a hardener, which are mixed during installation, creating a strong reinforcing material between the rock and bolt installed. After curing, the reinforcing material forms a solid mechanical interlock that helps to hold the rock and the bolt together. The mechanical interlock created during the curing process ensures that the bolt remains securely in the rock even under heavy load and vibration. The resin serves as a bonding agent between the bolt and the surrounding rock. Pumpable resin systems are designed so that little to no reaction takes place until the bolt is inserted and rotated through the cartridge, mixing the components and initiating the curing action. In manually operated roof bolting operation, human operator uses the hand to insert the resin into the already drilled hole before installing the bolt, and it then hardens to form a secure anchorage system. The resin helps evenly distribute loads across the bolt and surrounding rock, reducing the risk of bolt failure. The material handling issues associated with the resin cartridge is too challenging for a single robot grip for the cartridge and the other items the robot must handle. These shortcomings prompted the researchers to engage with the manufacturers and concluded that a pumpable resin, similar to the Jennmar J-Lok system, would be better suited for autonomous laboratory testing of the roof bolter machine. Due to the soft nature of the resin, the researchers developed a surrogate to simulate pumpable resin using steel with a plastic base shown in Figure 24. The simulated resin rod is about 4.3ft (131cm) long.

Figure 24: Simulated pumpable resin injector for automated roof bolting operation

The plastic base is designed and printer from the 3D printer to stabilize the simulated resins. The selected rod allows the robotic arm to grab the simulated resin for positioning. It is also suitable for the hydraulic roof bolter to perform the installation, as shown in Figure 25. After the task is completed, the robot places the simulated resin on the hydraulic roof bolter machine and removes it from the machine. From the laboratory test, the robot was able to imitate human functions during the insertion of the resin by inserting the resin into the hole.

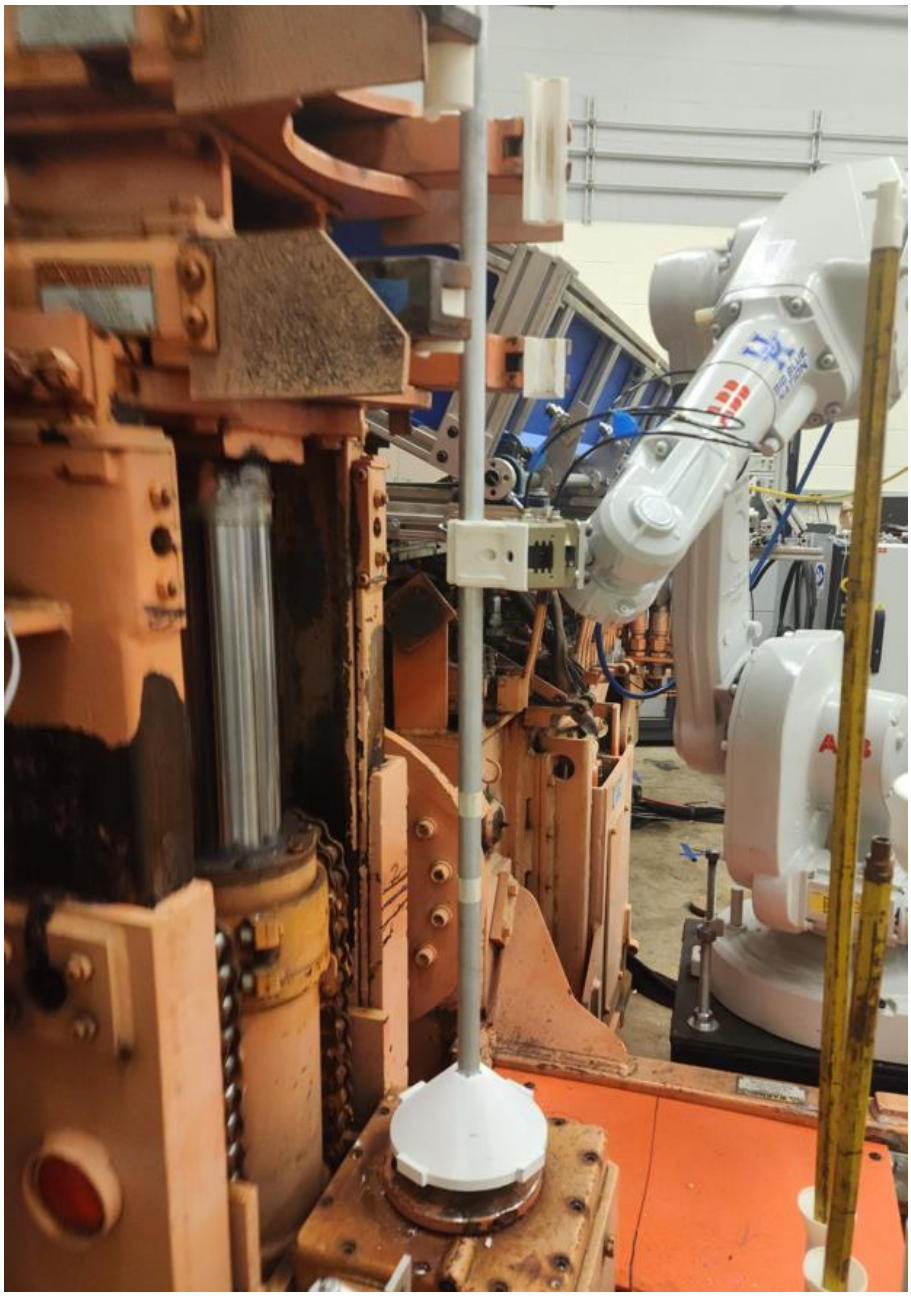

Figure 25: Robotic arm placing the simulated pumpable resin injector on the hydraulic roof bolter machine.

After the resin installation, the bolt feeder opens to drop the bolt at a position where the robot can grasp the bolt and fix the plate on the bolt, as shown in Figure 26. The operator initiates the bolt installation process from the HMI touchpad and allows the robotic arm to perform human tasks on the roof bolting operation. The robot positioned the bolt with the plate on the hydraulic bolter and the bolting module completed the bolting process by lifting the pod to insert the bolt. Thus, the robotic performed the entire roof bolting sequence instead of the human operator.

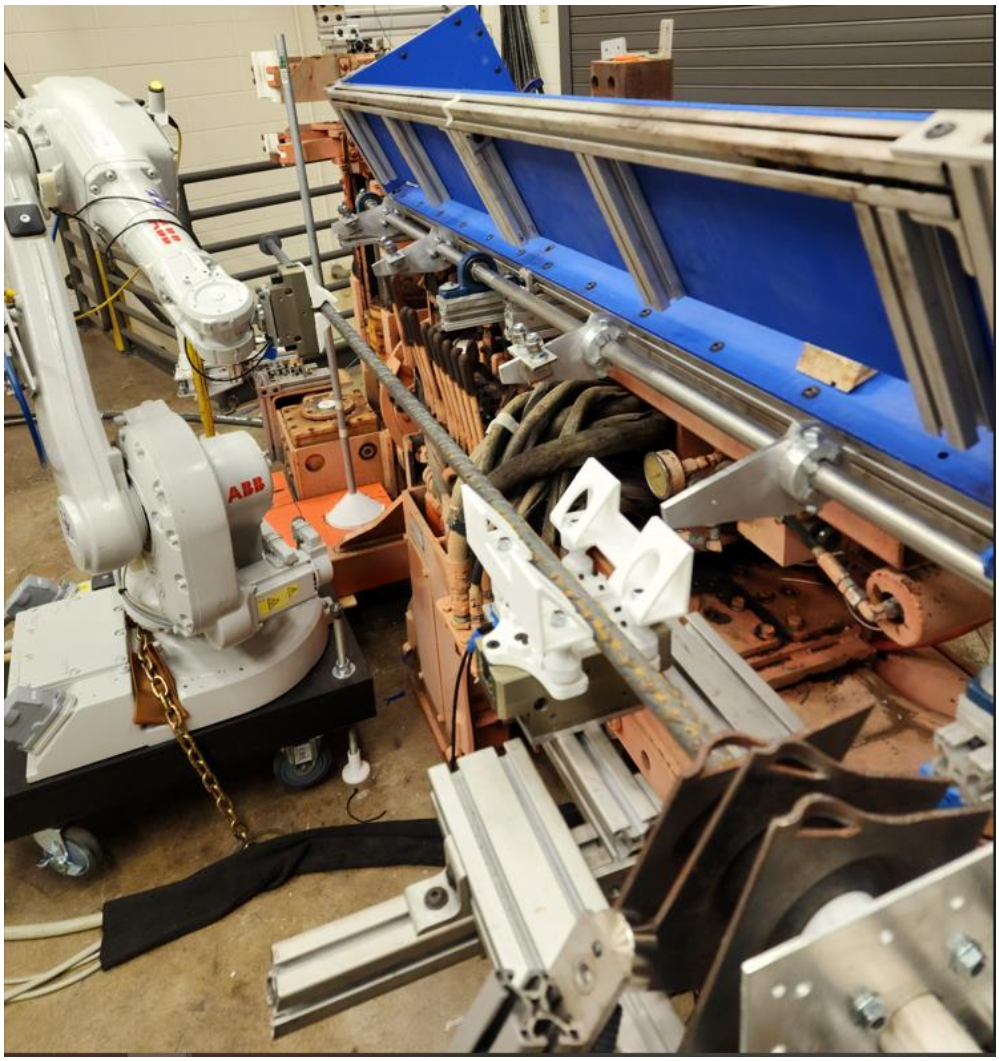

Figure 26: Robotic arm grabbing the bolt to fix the plate on the bolt.

## 4.3 Summary of the project

The final deliverable of this project is an automated roof bolting machine. The entire roof bolting process is automated and controlled by the touchpad HMI device, which allows the operator to supervise and control the bolting process remotely. Based on the outcome of this project, the operator is assigned the role of supervising one or more automated units and exercising control via the HMI. It is important to state that humans are still important in the automation process of the roof bolter machine. The integration of the robotic arm to mimic human tasks on the roof bolting process does not entirely remove humans from the process but assigns operators a new role. Apart from the 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.

The automated roof bolter machine comprises the movement of various actions. Each of the actions of the automated bolter module is inspired by an observation of the strategies adopted by

the roof bolter operators. The robotic arm involvement in the automated bolting process is presented in Table 2.

Table 2: The robotic arm intervention during the automated roof bolting process.

| Robotic arm movement | Description of movement |
|---|---|
| Robot grasping and placing drill steel one | The first step in the automated roof bolter machine is placing the first drill on the bolter module. Once the drill steel is placed on the bolter, the robot retracts to its initial position. |
| Robot grasping and placing drill steel two | The robot and grasps and places drill steel two for the hydraulic to couple it with drill steel one to complete the drilling task. |
| Drilling completed | |
| Robot removes drill steel two | The robot moves to take away drill steel two after completing the drilling tasks. The hydraulic bolter lowered drill steel two to a designated position that has been programmed in the iQAN system for the robot to grasp and drop the steel into the holder. |
| Robot removes drill steel one | The robot moves to take away the drill steel one from the drill area. The trajectory movement of the robot was planned in the Robot Studio, which defines the movement of the robot to grab and place the drill steel in the holder. |
| Drill roof is completed, and drill steels removed | |
| Robot grabs and places the simulated resin for installation | After drilling the hole, the next step is to install the resin. The robot grabs the simulated resin and places it for installation. |
| Robot moves to retrieve the simulated resin cartridge after installation | The robot travels to retrieve the simulated resin cartridge after installing the resin in the hole. The simulated is retrieved and positioned in its initial position. |
| Resin installation completed | |
| Robot grabs bolt to fix the plate on it | The robot travels to grasp the bolt after sliding from the bolt feeder. The plate feeder fixes the plate on the bolt when the robot pushes the square plate to the shaft, which systematically drops the plate on the bolt |
| Robot moves the bolt with the plate for insertion | After fixing the plate on the bolt, the robot places the bolt with the plate on the hydraulic roof bolter machine for insertion. |

Similarly, the roof bolter module was also programmed from the iQAN software for the system to perform in an automated mode. The automation of the roof bolter module uses a time-based approach from the iQAN software to control the components of the automated roof bolter

machine. Suitable buffer times were built into the iQAN logic program for a smooth transition between the motions of individual components. Before integrating all components, time studies of the individual mechanisms were carried out, followed by time studies of a complete cycle of roof-bolting. The research team examined the mechanism iteratively to minimize the time required for safe operation towards reducing the overall operation cycle time. For instance, in the underpowered laboratory setup the time taken to close the clamp is 3500 milliseconds, while the time to close the guide is 3850 milliseconds. The variation in time of these tasks can be attributed to the difference in the actuator of each component and the time taken to supply hydraulic fluid to the actuator. The four basic functions performed by the roof bolter module during the automation process are tabulated in Table 3. All the functions in the table use specified timeframe to perform their tasks in the iQAN logic program.

Table 3: Roof bolter module intervention during roof bolting automation process

| Roof bolter module movement | Description of movements |
|---|---|
| Closing and opening of the clamp | The clamp is the upper clamp. The closing and opening of the clamp replicate the operator's hand in gripping consumables for the roof bolting operations. When the clamp is closed, there would not be movement or rotation of the consumable. The clamp will completely grip the consumable to prevent movement and rotation. |
| Closing and opening of the guide | The guide is the lowered clamp. It performs a similar function to the clamp, but consumables can move and rotate while closing. The main function is to align consumables with the drilled hole. |
| Up and down movement of the pod | The up and down movement of the pod is used to insert and remove consumables during drilling, drill steel removal, resin insertion, and bolt installation. |
| Rotation of the chuck | The chuck rotation is useful during drilling to perforate the roof and also during the coupling and decoupling of drill steel one and drill steel two. The chuck can either move in a clockwise (CW) or a counterclockwise (CCW) direction. |

## 4.4 Pathway to Implementation and Certification

The coal mining industry has stringent regulations to ensure the safety of the workers. Any new technology introduced in underground coal mines is required to undergo rigorous testing and certification before it can be deployed in active operations.

Implementing the automated roof bolting machine in an underground coal mine requires a deep understanding of the roof bolting system, the regulatory environment, as well as the safety concerns all of which are available in the original equipment manufacturer. During the design phase, the research team paid attention to the power needs of the equipment and always designed them for possible permissibility alternatives. The laboratory setup includes the integration of various machine parts such as electrical components, sensors, a DC servo motor, linear actuators

and other specialized equipment. These were included in the demonstration and are not intended to be part of a commercial version of this style automated roof bolter.

To successfully convert the laboratory prototype of the automated roof bolt scale to industrial equipment for underground coal mining operations, most of the components need to be replaced. Most of the electrical components of the automated machine can be replaced with hydraulic systems. The hydraulic system uses pressurized fluids from pumps or motors and transmits the energy from one point to another. Hydraulic systems produce mechanical force and motion to perform various industrial applications such as lifting heavy objects and controlling the speed of the equipment. The hydraulic system on these machines is already approved for use in permissible areas and a modification for the machine can reasonably be sought.

Some of the developed technologies such as the bolt feeder, plate feeder and wrench system, can be replaced with hydraulic systems for better efficiency, reliability and responsiveness. Especially in underground coal mines, where there are harsh and hazardous working conditions, the hydraulic systems are designed and built with several features that enhance their durability and reliability.

This consideration was critical as the researchers designed and installed components. For the researchers in the laboratory, electronic components enabled flexibility of design and speed of development. These laboratory mechanisms would be extremely difficult to certify for permissible environments. The following sections detail changes that are suggested so that the automated roof bolter may be able to operate in underground coal mines.

### 4.4.1 The bolter feeder

A linear actuator moves the shaft that feeds the individual bolt from the hopper. The linear actuator device offers precise and repeatable extending and retracting movement that allows accurate bolt positioning of the bolt. For industrial applications such as in underground coal mines, replacing the linear actuator on the bolt feeder with a hydraulic cylinder system is necessary. The hydraulic cylinder device is a cylindrical tube that uses hydraulic pressure to initiate linear movement. An example is the double-acting hydraulic cylinder shown in Figure 27. The double-acting hydraulic cylindrical system is designed to produce greater speed and positive control for an application that requires an extra measure of strength, reliability, and safety.

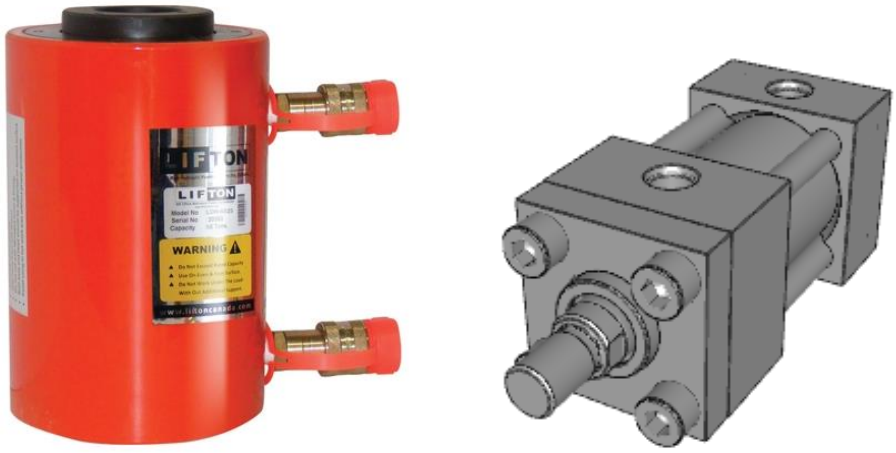


Figure 27: A sample of hydraulic cylindrical device

The double-acting hydraulic cylindrical device is incorporated into the bolt feeder for extending and retrieving (pushing and pulling) movement of the bolt feeder shaft. This type of hydraulic cylinder uses hydraulic pressure to move the piston back and forth with the cylindrical barrel. The system comprises a cylindrical barrel with a connector where the bolt feeder shaft is linked to produce linear motion during operations. The hydraulic cylinder is fixed at one end and the other is connected to the bolt feeder shaft that enables the bolt to slide. The device pumps hydraulic fluid into the cylinder via the control valve which directs the fluid flow to either side of the piston. As soon as the fluid increases, it pushes the piston to one direction, and the direction of the fluid flow is reserved; the piston goes back to the opposite direction. This causes the back-and-forth movement of the piston that produces the force necessary to move and perform the extended and retracted tasks.

The selection of the hydraulic system to replace the linear actuator depends on several factors, such as the size of the bolt feeder and the number of bolts to be stored in the bolt feeder. These factors dictate the specifications of the hydraulic cylindrical to be installed on the plate feeder. More importantly, the hydraulic cylinder must meet certain environmental conditions of underground coal mines to prevent equipment downtime due to failing components. Apart from being able to adapt to the toxic underground coal mine environment, the hydraulic cylinder must meet performance requirements, such as high pressure, high temperature and anti-wear properties. The above-listed features must be considered when selecting an appropriate hydraulic cylinder for the bolt feeder.

## 4.5 The wrench system

Figure 28 shows the original wrench deployment system. In this system, a linear actuator is used to rotate the wrench from the storage location to the chuck. This is a much more robust mechanism than the final mechanism, but it is extremely slow. The slow speed of the linear actuator is slowed further by the distance the wrench must travel and the lever arm distance. The

slow speed of this mechanism caused timing problems for the researchers, which is why it was replaced with the significantly faster servo motor system.

Similar to the linear actuator used on the bolt feeder, this mechanism would be both significantly faster and easier to deploy in coal mines by using a hydraulic cylinder.

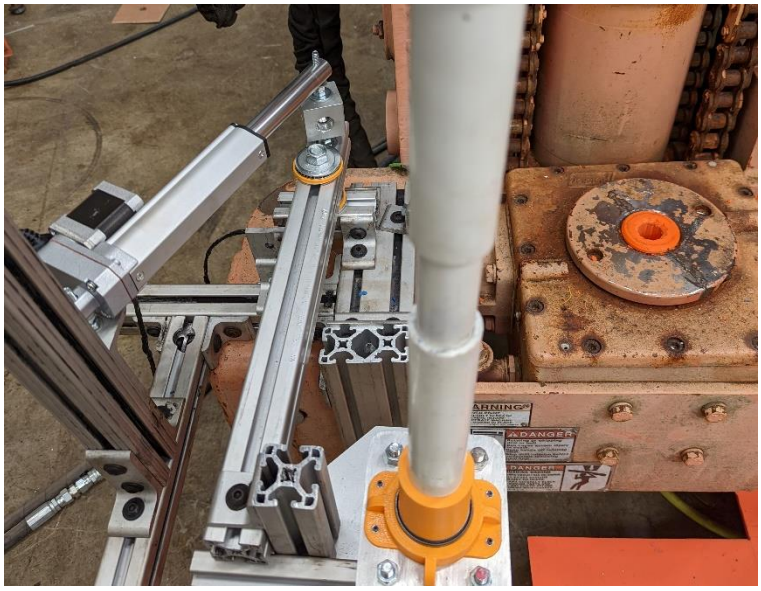

Figure 28: Previous Wrench Deployment System

## 4.6 Hydraulic throw-out bearing on the wrench system

The current wrench system uses springs to disengage from the chuck after drill steels or bolts are removed. Introducing hydraulic throw-out bearings will improve the mechanical transmission and linkage of the wrench system. The hydraulic throw-out bearing is inside the bellhousing attached to the tool interchanger holder. The spring system does not reliably engage and disengage from the chuck, while a powered system would. Additionally, it is uncommon to find unprotected springs in underground coal mine machines. Although they are intrinsically safe, they are prone to clogging, rust, and breakage. Figure 29 shows a hydraulic throw-out bearing.

These bearings allow a shaft to rotate internally while moving in and out. These are commonly found in transmissions and clutches. The bearing should be extended in the de-energized state and moves down in the engaged state. This will force the wrench into the chuck as well as out of the chuck, which is the primary purpose of this plate.

Figure 29: Hydraulic throw-out bearing

## 4.7 The plate feeder

The linear actuator does the extension and retraction of the bolt feeder by pushing the plate for loading. Like the bolt feeder, for proper industrial applications such as underground coal mining operations, the linear actuator should be replaced with a hydraulic cylinder shown in Figure 27. The double-acting hydraulic consist of cylindrical barrel, plunge, seals and port for fluid movement. The double-acting hydraulic system can push the shaft that drives the plate effectively at high speed, improving the speed of the plate feeder. This should be replaced with a slow acting cylinder so that when the proximity detection switch is tripped the plates will be stopped.

Several alternatives to the proximity switch were explored by the researchers. All alternative switches available on the market utilize springs or mechanisms that will not reasonably tolerate the difficult conditions. These switches are available in a variety of voltages and currents and can reasonably be expected to be found permissible. There is a spring in this mechanism behind the plunger. This spring is completely sealed and is reasonably protected for use.

## 4.8 Alternatives to the IRB 1600

The ABB IRB 1600 is an electrically powered robotic arm that imitates human activities in the roof bolting process. Although a protected version of the IRB 1600 is available from ABB, it is unreasonable to expect that a servo motor controlled robotic arm could be permissible. A hydraulic robotic arm has the potential to adapt to hazardous underground conditions. An example of a hydraulic robotic arm is ABB IRB 4400 robotic arm. The IRB 4400 is a six-axis industrial robotic arm with a payload capacity of up to 132 lbs (60 kg) and can reach up to 2.4 meters, as shown in Figure 30. The robotic arm is designed for high-performance operations with a cycle time of 0.34 seconds for full motion. ABB IRB 4400 offers a range of optional features and accessories such as force sensors, vision system, collision detection, and emergency stop, just as the IRB 1600 has available. The design and ease of integration make it suitable for

various industrial applications. It is a six-axis robot that can move in six different ways because it has six degrees of freedom.

Figure 30: Hydraulic ABB IRB 4400 robotic arm

The robotic arm is equipped with an IRC5 robot controller, same as the IRB 1600, that provides control of the robot's motion, such as speed, acceleration and deceleration. The controller is critical in ensuring the robot's accuracy, safety and efficiency. This controller and its connections to the rest of the machine will be the most significant impediment to the use of a robotic arm on a permissible machine.  It is a crucial component that manages the robot's input and output signal, allowing it to interact with other devices connected to the robot.

### 4.8.1 The pneumatic clamps

The gripper attached to the robotic arm is powered by compressed air. Compressed air is readily available in the laboratory setup but is not available on a typical roof bolter. The pneumatic schunk clamping device on the demonstration robot and the plate feeder would need to be replaced with a hydraulically actuated two-jaw clamping device developed with high clamping force. The technology uses a hydraulic actuator to expand the tool holder, allowing materials to be held and secured. Figure 31 shows the KSH3 hydraulic schunk system, which can be actuated to grip and hold the workpiece with a two-jaw power vice. It has an operating pressure of about 10 to 120 bar, and the clamping force at maximum operating pressure is 1011.6 lbf (4.5 kN).

Figure 31: KSH3-LH 64-Z Hydraulic Schunk system

The two-jaw clamping system is a versatile, reliable solution for gripping and clamping workpieces. For the underground coal mining environment, it is necessary to consider the environmental conditions that may affect system's performance. The device requires a clean and free from contamination hydraulic fluid and debris that can damage the system. Vulnerability to dust is inevitable in underground coal mining operations, which can cause problems leading to failure over a period of time.

# 5 Publication Record and Dissemination Efforts

## 5.1 Publication Record

Outcomes and significant milestones of this project that are relevant to the industry were (or are in the process of being) published in international peer-reviewed journals and conferences. In addition, the team has presented their findings in multiple conferences.

### 5.1.1 Peer – Reviewed Journal Publications

- Zhang, H.**,** Chan, S-H., Li, J., Kolapo, P., Koenig, S.; Agioutantis, Z., Schafrik, S., & Nikolaidis, S. (2023). "A MIP-Based Approach for Multi-Robot Geometric Task and Motion Planning**".** *Robotics and Automation* [Under review].
- Kolapo, P.**,** Zhang, H., Schafrik, S., & Nikolaidis, S., (2023). "Application of Cobot Technology in Roof Bolter Machine Automation**".** *Mining, Metallurgy & Exploration Journal* [Pending submission].
- Kolapo, P., Schafrik, S., & Agioutantis, Z., (2023). "Design and Development of a Sensorless Automated Roof Bolting Machine for Underground Coal Mines: A System Thinking Approach**".** *MDPI Sensors* [Pending submission].

### 5.1.2 Peer – Reviewed Conference Publications

- Schafrik, S., Kolapo, P., Agioutantis, Z. (2022), Development of an Automated Roof Bolting Machine for Underground Coal Mines, Proceedings, 32nd Annual SOMP Conference, September 8-14, 2022, Windhoek, Namibia.
- Xenaki, A., Zhang, H., Schafrik, S., Agioutantis, Z., Nikolaidis, S. (2021), Roof Bolting Module Automation for Enhancing Miner Safety, 5th International Future Mining Conference, December 6-10, 2021, Melbourne, Australia.

### 5.1.3 Conference Presentations

- Kolapo, P.**,** Zhang, H., Schafrik, S., & Nikolaidis, S., (2023). Application of Cobot Technology in Roof Bolter Machine Automation**.** SME 2023 Annual Conference and Expo, Denver, CO February 26 – March 2, 2023
- Schafrik, S., (2022), Enhancing Roof Bolter Operations with Robotics, NIOSH Robotics Interest Forum, June 29, 2022.
- Schafrik, S. (2022), Autonomous Roof Bolter Operations Using Robotic Operations, Central Appalachian Section of SME, Spring Meeting, Lexington KY, April 25-27, 2022
- Schafrik S. (2022), Advances in an Autonomous Roof Bolting Module, 13th Annual PE Seminar, Metallurgical Coal Producers Association, Southwest Virginia Community College, March 31, 2022

- Xenaki, A., Zhang, H., Schafrik, S., Nikolaidis, S., & Agioutantis, Z., (2022). Concepts for the Development of an Autonomous Roof Bolting Module for Enhancing Miner Safety**.** SME 2023 Annual Conference and Expo, Salt Lake City, Utah February 27 – March 2, 2022.
- Xenaki, A., S. Schafrik, Z. Agioutantis, (2020), Roof Bolting Module Automation for Enhancing Miner Safety, PCMIA Poster Competition, December 19, 2020, Virtual Presentation

# 6 Conclusions

This report described the process of developing a demo of an automated roof bolter module that performs most of the bolting cycle with the primary goal of moving humans away from the most dangerous activities. The automated roof bolter machine that was developed can perform a sequential bolting operation, including drilling, drill steel removal, resin placement, and bolt installation without human intervention. The human operator is assigned a new role of supervising one or more automated components and also controlling the whole automation process via the HMI. Apart from the 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.

The automation process is achieved by integrating of the six-axis robotic arm into the system to mimic human tasks during the roof bolting operation. The robotic arm imitates all human movements and functions which in turn enhances operators' safety, aid in the continuing increase in productivity, and reduce operational costs in underground coal mines. The robotic arm has the potential to adapt and work effectively in harsh conditions such as underground mining environments. During the automation process, the robot performed human functions such as grasping, moving, lifting and positioning of drill steels, inserting simulated resin membrane, and installing bolt. A reliable communication system was established between the robot arm and other components. This is crucial as it prevents collision and manages the movement of the arm and other automated units during the bolting process.

An operator-friendly HMI was developed for the operator to control and monitor the automated process away from the active face. The MD-4 touchscreen produced by Parker Hannifin is used in this project to interact with the automated roof bolter machine. The researchers successfully developed user-friendly interface to override the action of the machine in the event of unsafe acts. Other component functions of the automated roof bolter systems were built in the HMI. The entire roof bolting process is automated and controlled from the touchpad HMI device, which allows operators to remotely supervise and control the bolting process.

The PLC controls the roof bolter, which is connected to the operator touchpad and linked to the robotic arm and hydraulic bolter. The manipulation of the hydraulic bolter was done in iQAN software. The iQAN software allows the users to monitor different components that are connected through a CAN network which is used to transmit and receive data. The iQAN interface communicates to the programming panel, ABB and PLC through the Anybus CAN to Ethernet/IP. 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.

Some novel technologies were developed as components of the automated roof bolting machine. These technologies were built to prevent human intervention during the automated roof bolting process. These technologies include the plate feeder, the bolt feeder and the tool interchanger, which is known as the wrench system. Each system was linked to the PLC and controlled by the HMI touchpad. Other components of the roof bolting machine comprise the robot controller, the

PLC, the Anybus communicator, the HMI, the robotic arm, and the hydraulic roof bolter module. Integrating all the components through an established reliable communication path led to the automated roof bolting system.

Under ideal conditions the operator only needs two buttons to supervise and control the roof bolting process. From the laboratory testing of the automated roof bolter machine, the robotic arm has the potential to mimic human activities during the roof operation by performing basic grasping of consumables, holding, lifting, placing, and removal of drill steels during the roof bolting process. The outcome of this project shows that human operators can be moved away from the hazardous area to a safe distance and control the roof bolting operation via an HMI touchpad. It is important to state that human operators are still relevant and an integral part of the automated roof bolting process.

## 6.1 Recommendations For Future Work

Automation of machines in mining operations has witnessed rapid development and still has some gray area that offers many opportunities for innovation and improvement. Developing automated mining equipment requires cross-disciplinary skills and expertise in mining, mechanical, electrical and computer science.

This project has highlighted some key areas that deserve attention in developing an automated system for underground mining environments for future research and continued development. A notable contributing factor that ensures the development of automated roof bolting machine is the availability of suitable components that fit into the machine design. For instance, the researchers can only modify technologies built in their laboratory. The design of other systems that formed the automated system, such as the MD-4 touchscreen produced by Parker Hannifin, cannot be adjusted by researchers. Therefore, developing a proficient and reliable automated roof bolting machine with a rapid and efficient system depends on the available components. From the findings of this project, the following recommendations are made for future studies to develop reliable automated systems for mining operations.

- Improving the Random Access Memory (RAM) and other features of the current HMI device. During the automation process, the researchers found out that the performance of the HMI reduced drastically as more features were added to the HMI, such as pictures of different stages of the automation process. Thus, the manufacturer of the HMI touchpad should improve the memory storage capacity of the HMI to adopt more features such as photographs and video livestream.
- Introducing wireless HMI to promote remote operation. Another potential area of focus is developing remote operations systems that allow operators to remotely control mining equipment from a safe location. This could involve developing advanced communication systems allowing the operator to command the machine without wire connections. The current HMI is connected to the PLC via cables; instead, the connection could be achieved with advanced wireless communications, which allows operators to control equipment in real-time without defects.
- Provision of adequate training and support. Developing automated mining equipment requires skill sets that can operate and maintain the systems effectively. Providing adequate training and support for operators and maintenance personnel is essential to ensure the systems are used correctly and safely. There is a need to provide adequate training for the end users of the automated machine. This can be in the form of user manuals and technical support services to help mining companies adopt and implement new automated technologies. There is practical training provided by Parker Hannifin designing and developing control systems using iQAN software. Before editing the technology, the operators will need to be trained to control and interact with the input and output objects used on the automated machine. Training the maintenance personnel will improve productivity by reducing the downtime in mining operations and allowing customization.

# 7 Appendix A: Computer Programs for the Automation Process.

This Appendix shows the interface of the Robot Studio and iQAN computer programs used for the automation of the roof bolter machine.

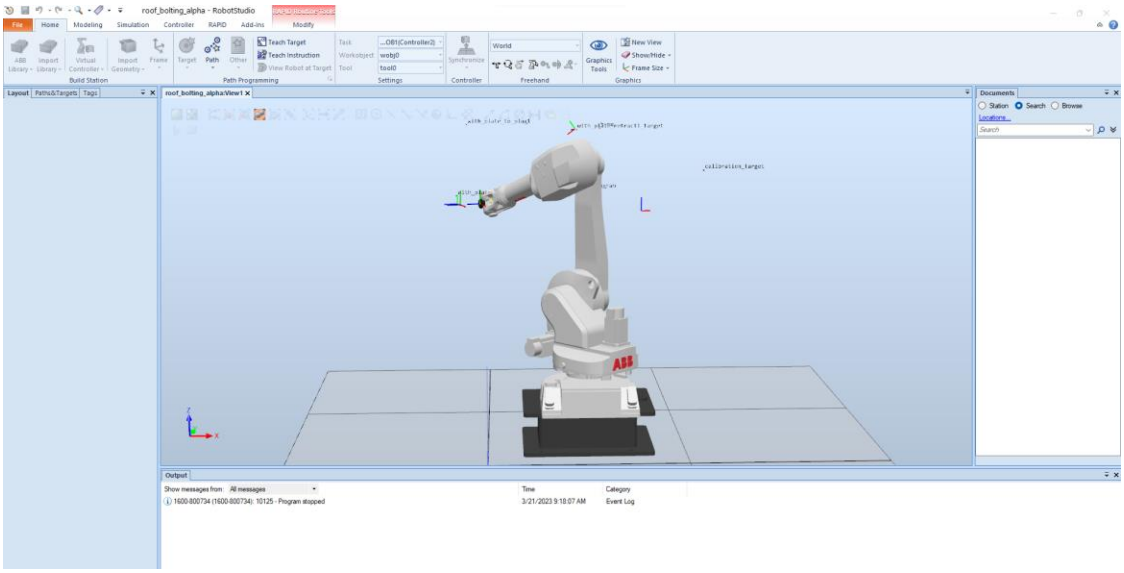


Figure A1: Interface of iQAN System for the Automation Process

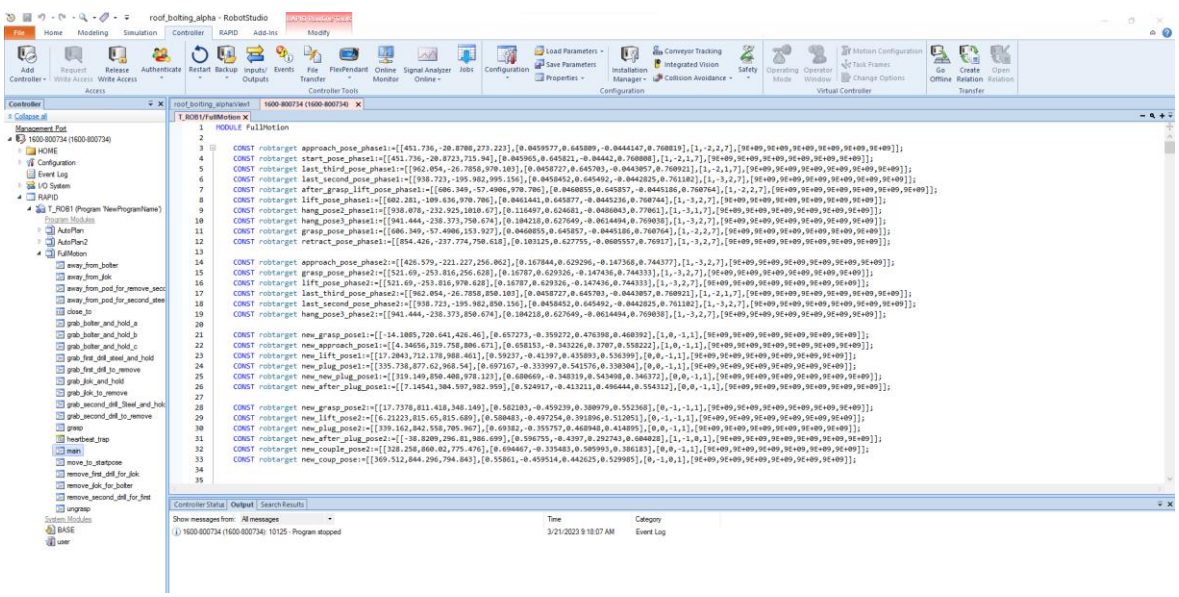


Figure A2: Motion and Planning Interface in Robot Studio.

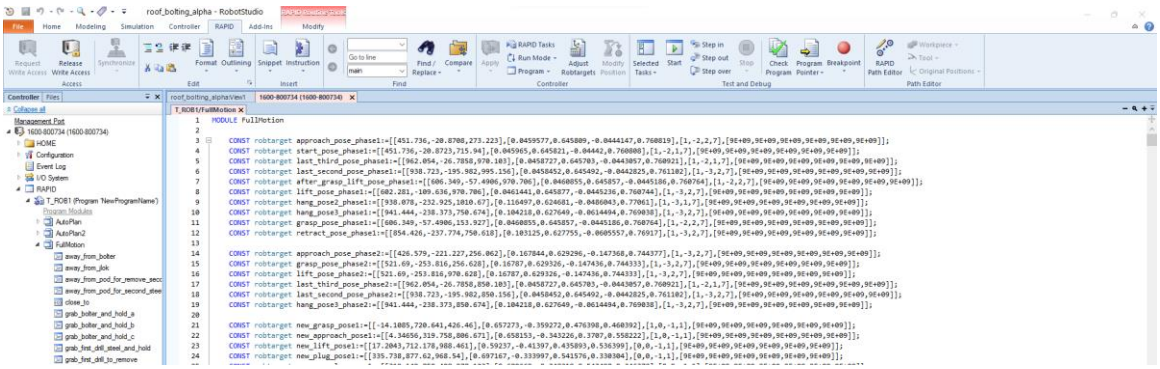

Figure A3: RAPID Interface for automated movement of IRB 1600 Robot

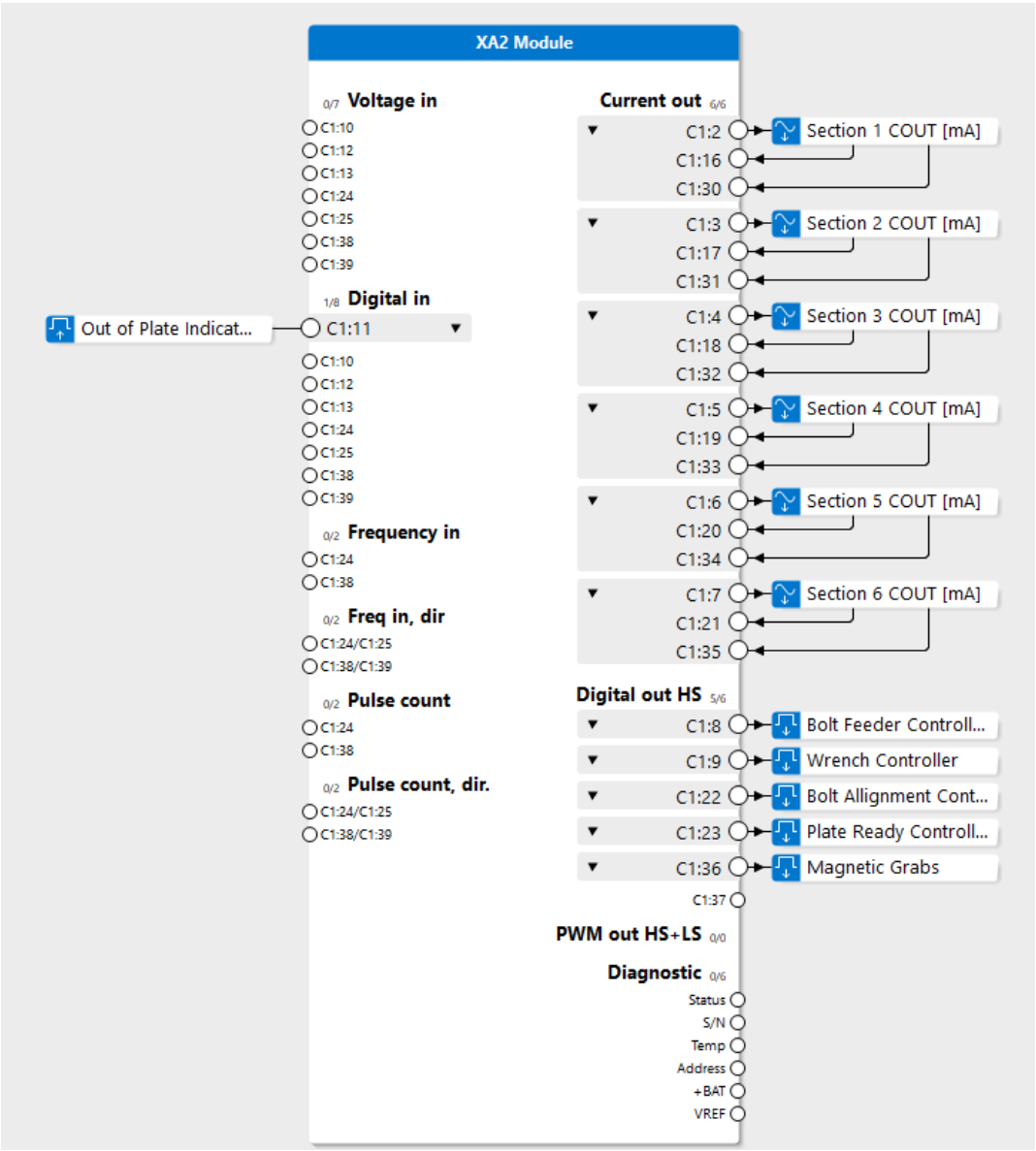


Figure A4: Modular control system connection on iQAN program

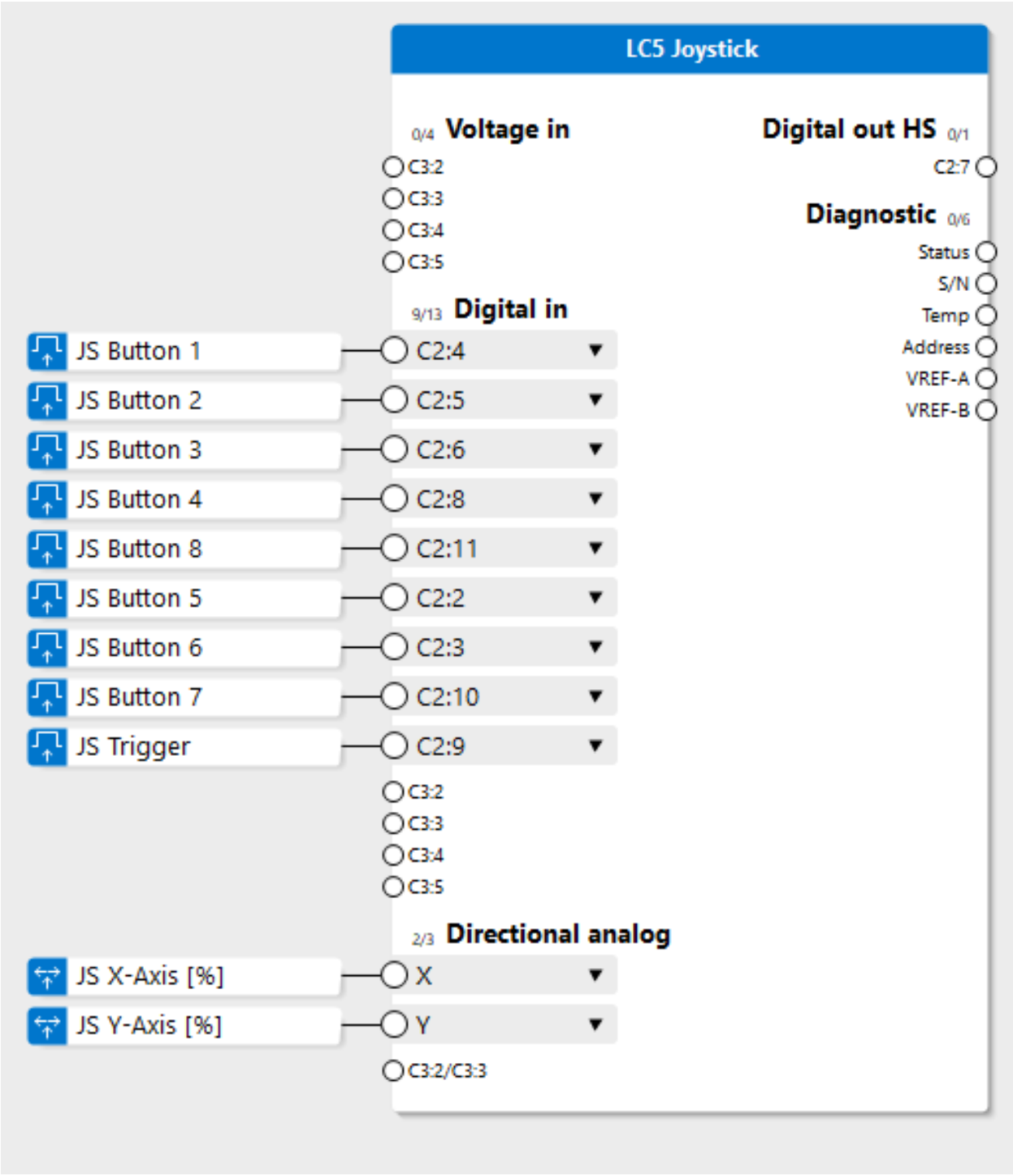


Figure A5: Joystick buttons connection on iQAN program for a manual control

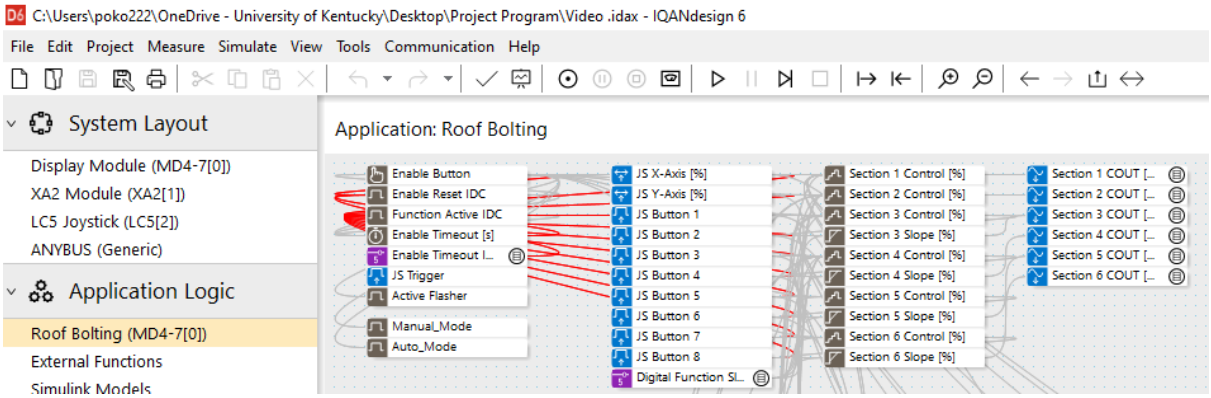

Figure A6: Application logic for programming modular control system

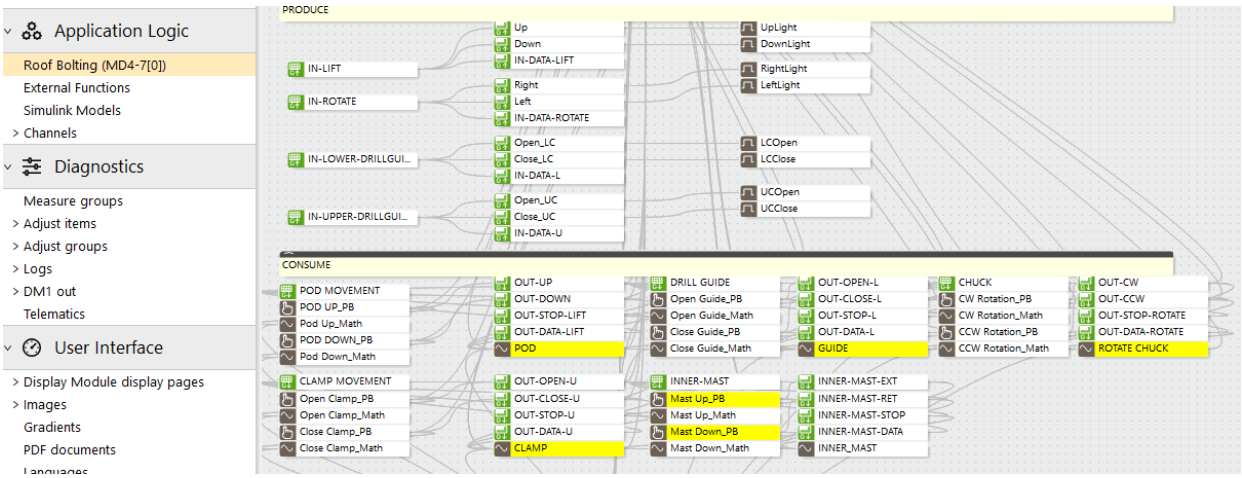

Figure A7: Application logic for programming the hydraulic roof bolter machine.

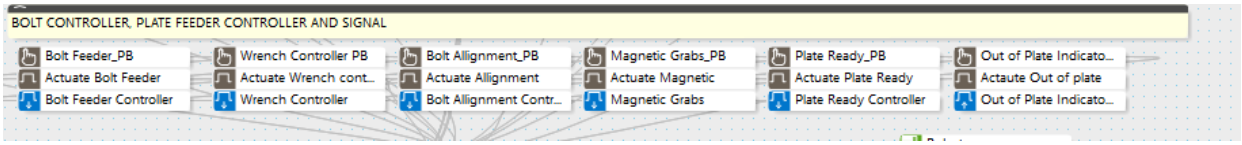

Figure A8: Application logic for components of the automated roof bolter machine.

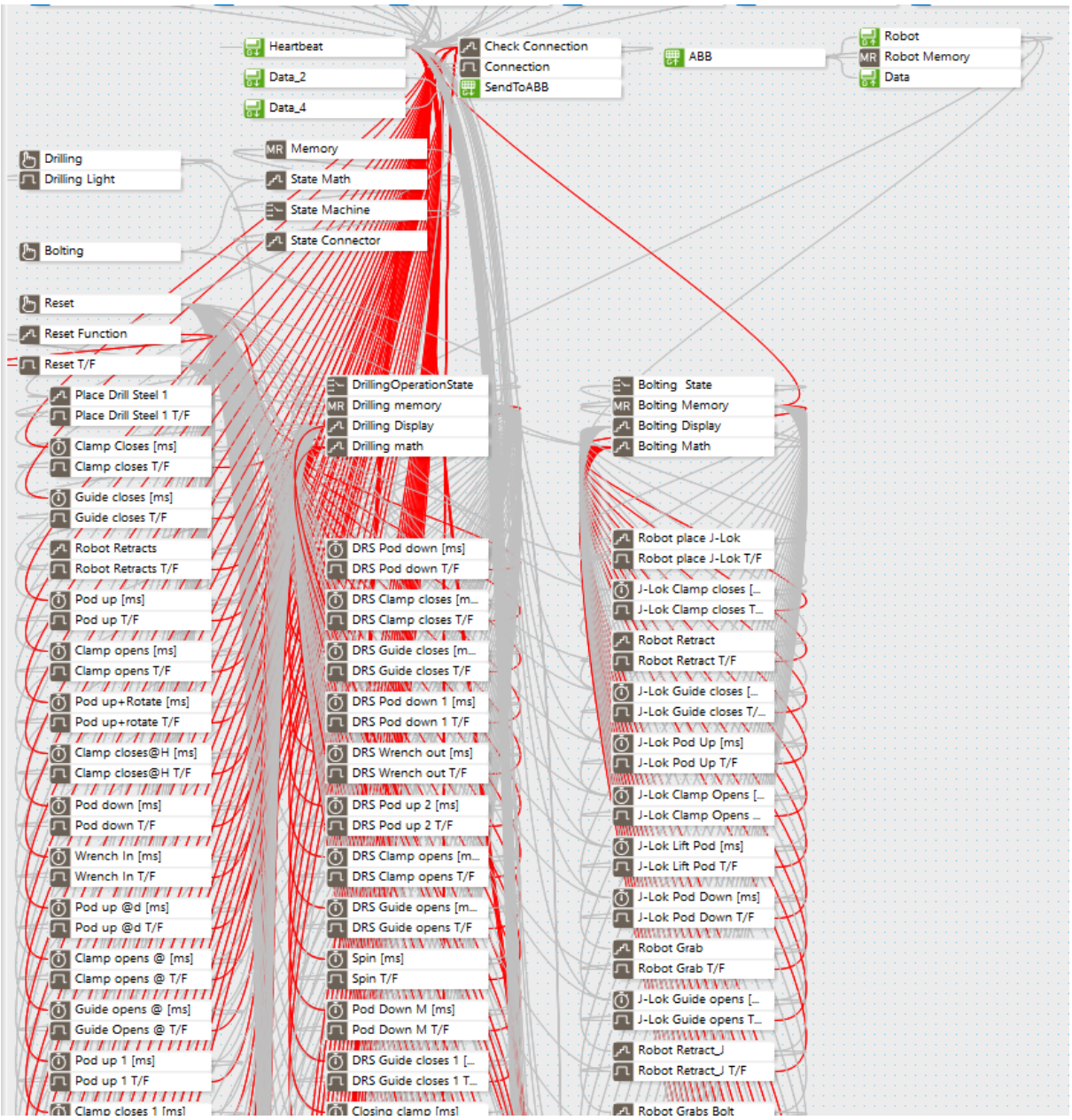

Figure A9: iQAN Interface for Autonomous operation

# 8 Appendix B: Anybus Device Configuration Manager Architecture

The Anybus communicator is a device installed in the PLC which receives, translates, and sends a CAM message into a signal the robotic arm will understand.

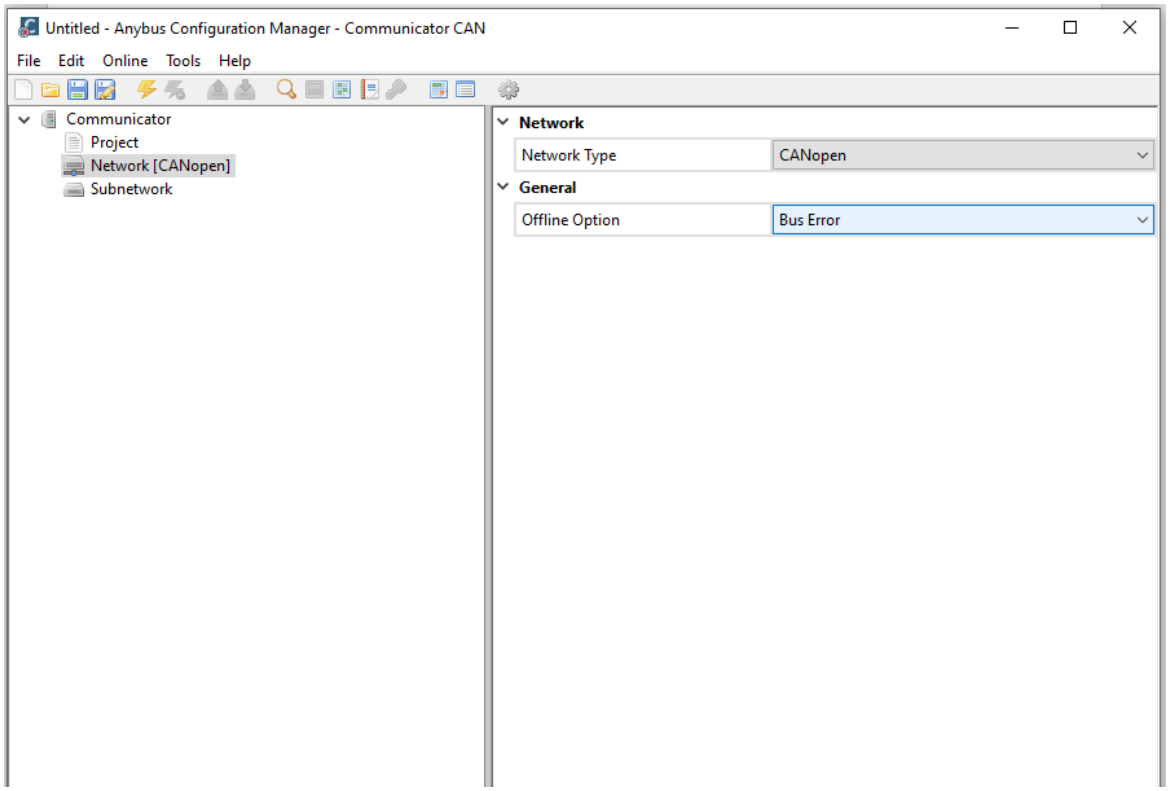


Figure B1: Anybus Communicator interface

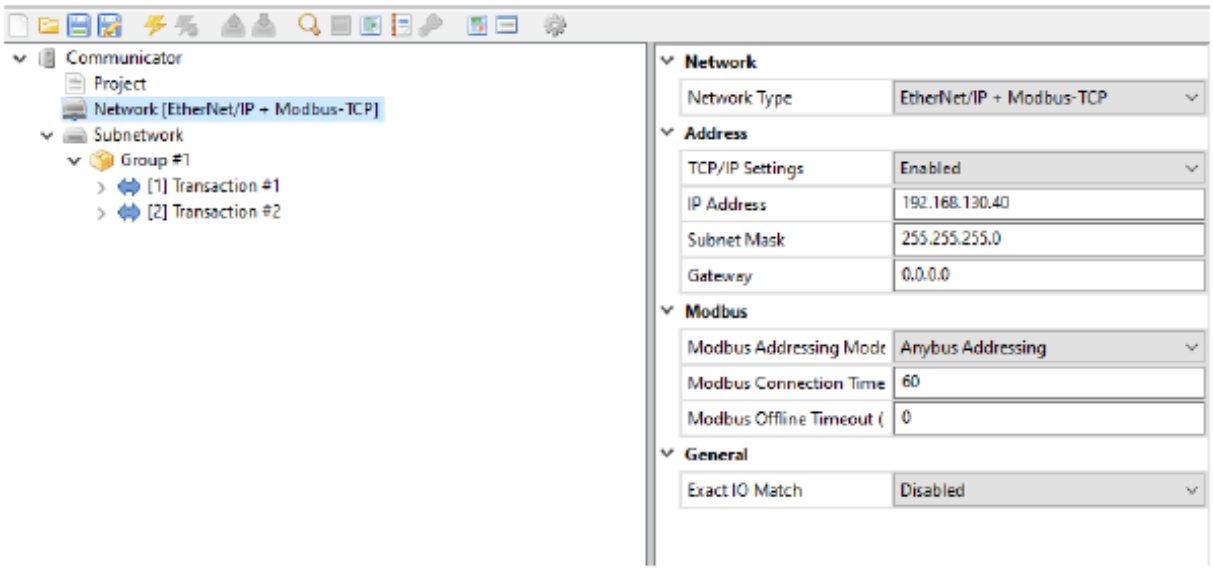


Figure B2: AnyBus system configuration

# 9 Appendix C: Other Components of Automated Roof bolting Machine

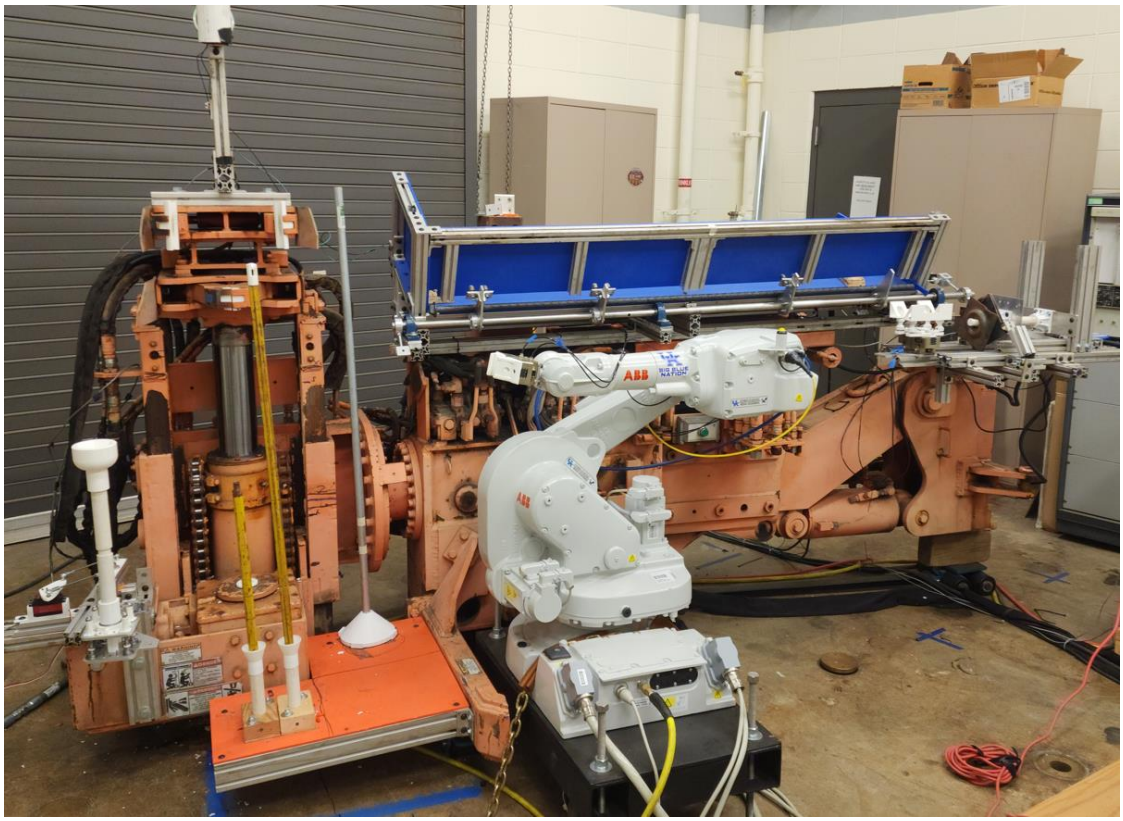


Figure C1: Automated roof bolter machine set up

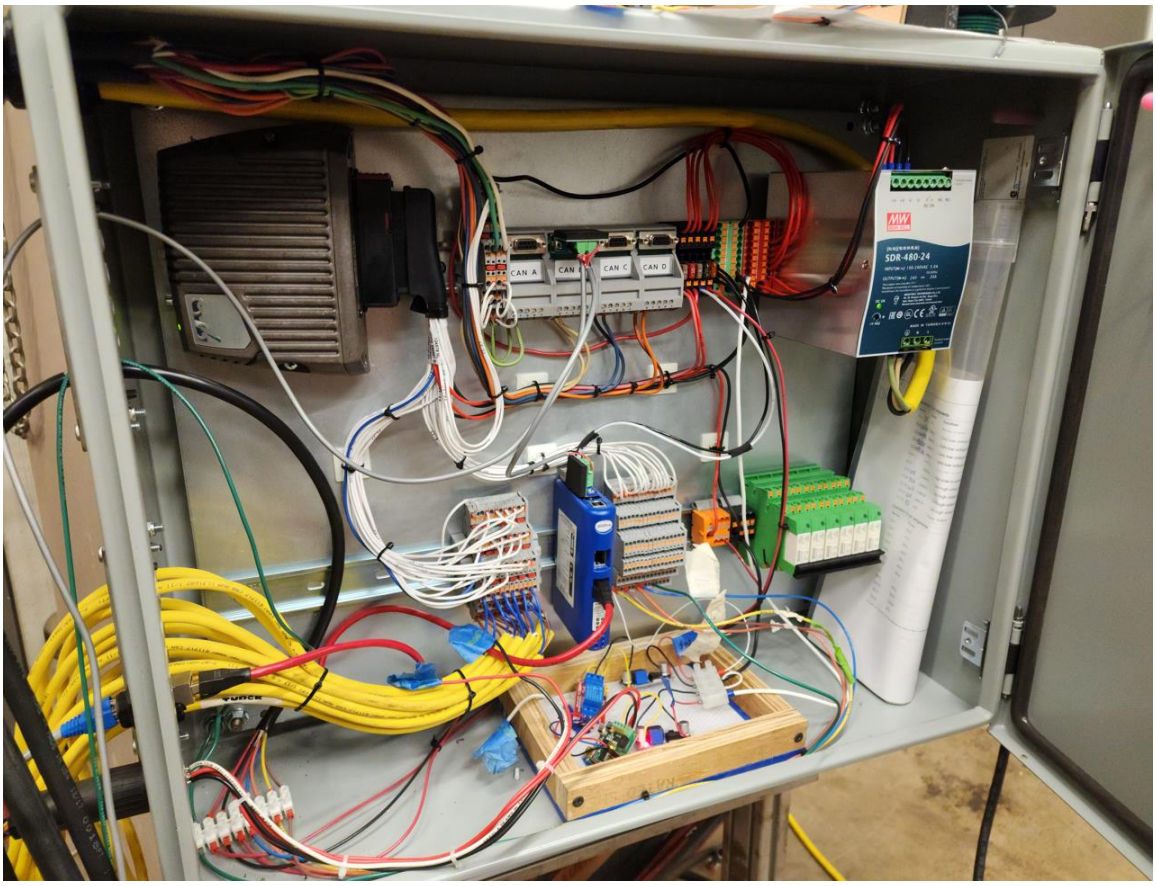

Figure C2: Control box layout

Figure C3: Robot controller

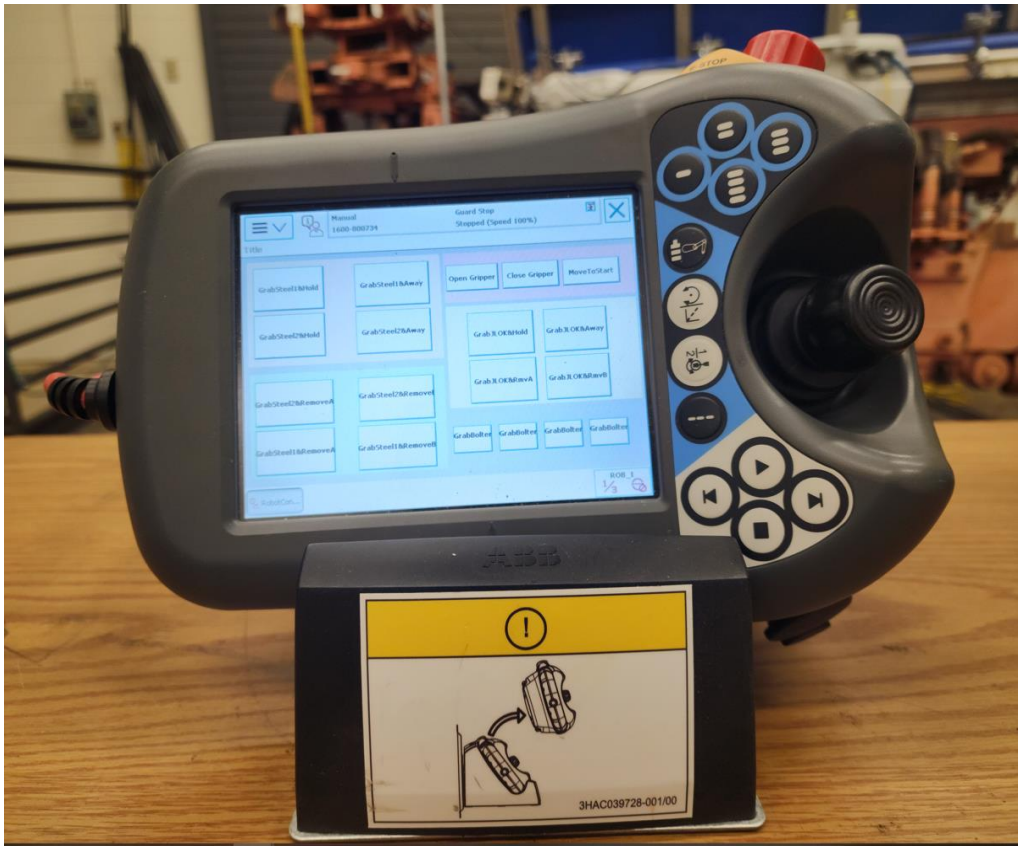

Figure C4: Flex pendant


Figure C5: Operator HMI

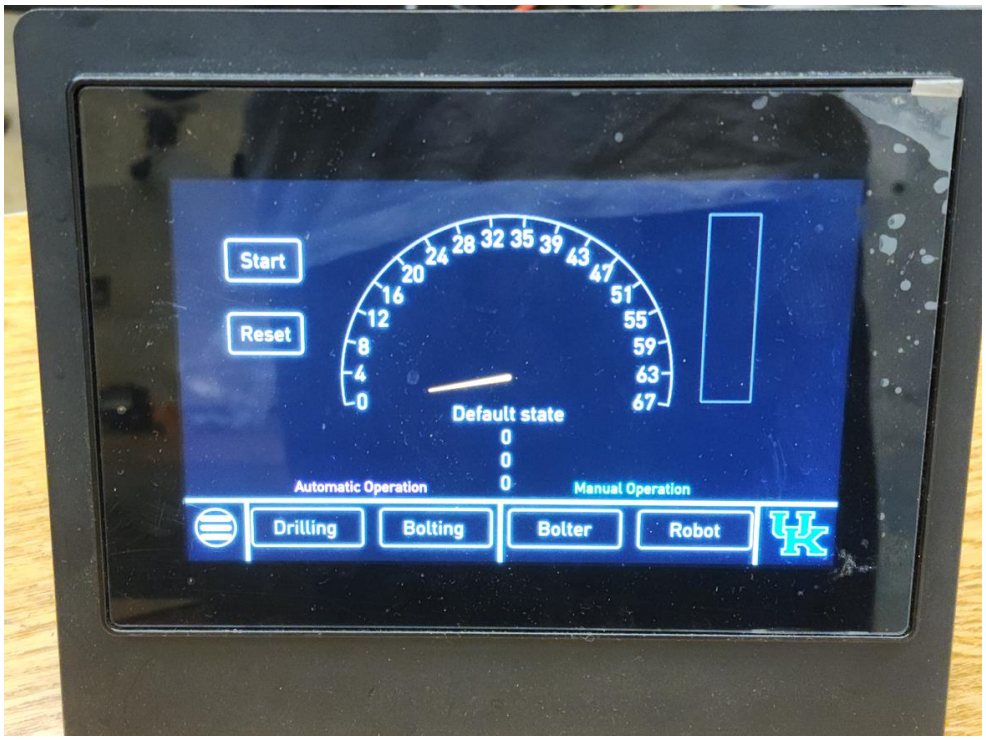


Figure C6: Automated drilling interface

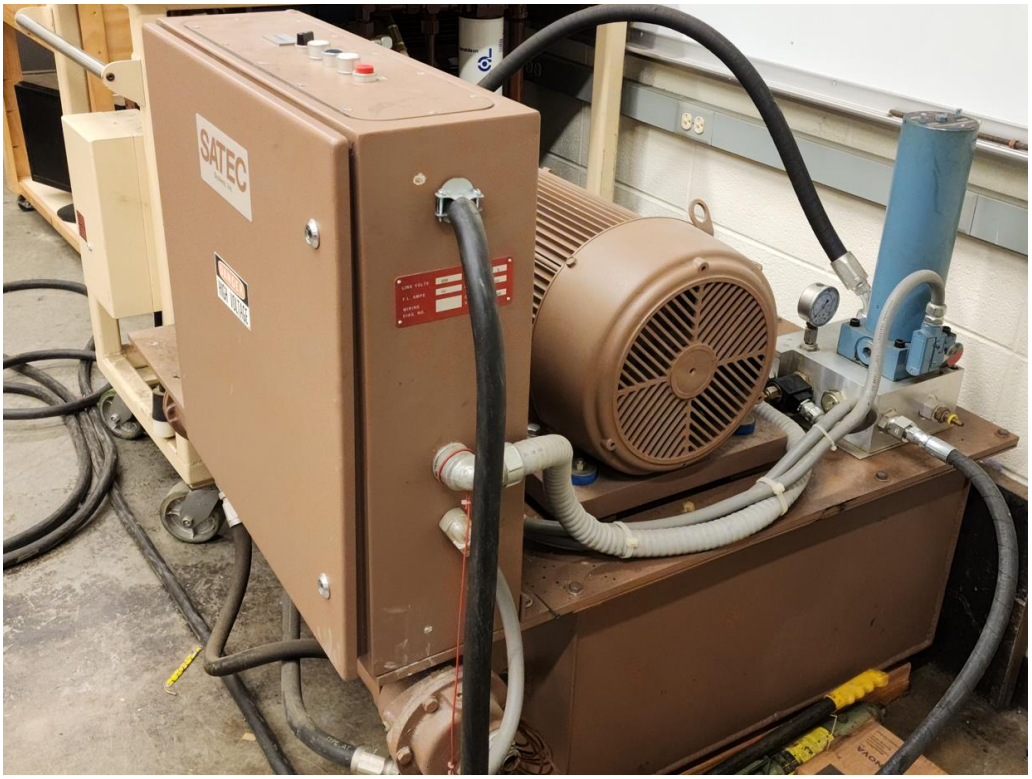

Figure C7: Hydraulic pump

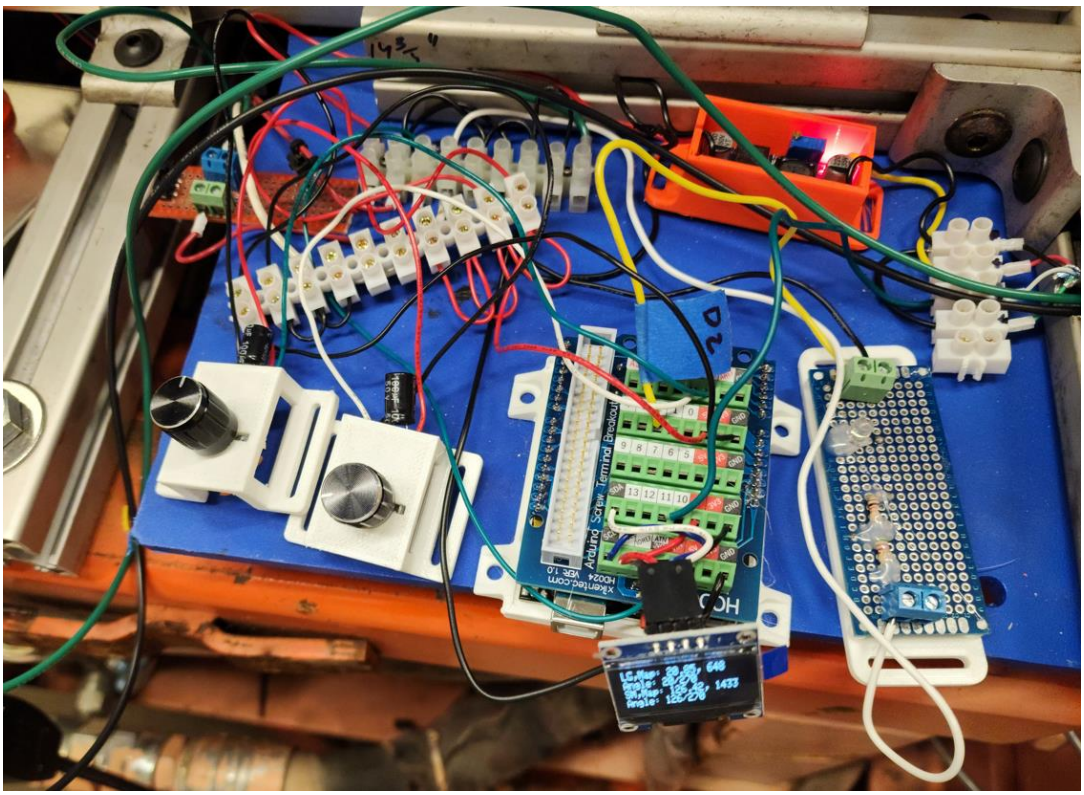

Figure C8: Wrench mini control

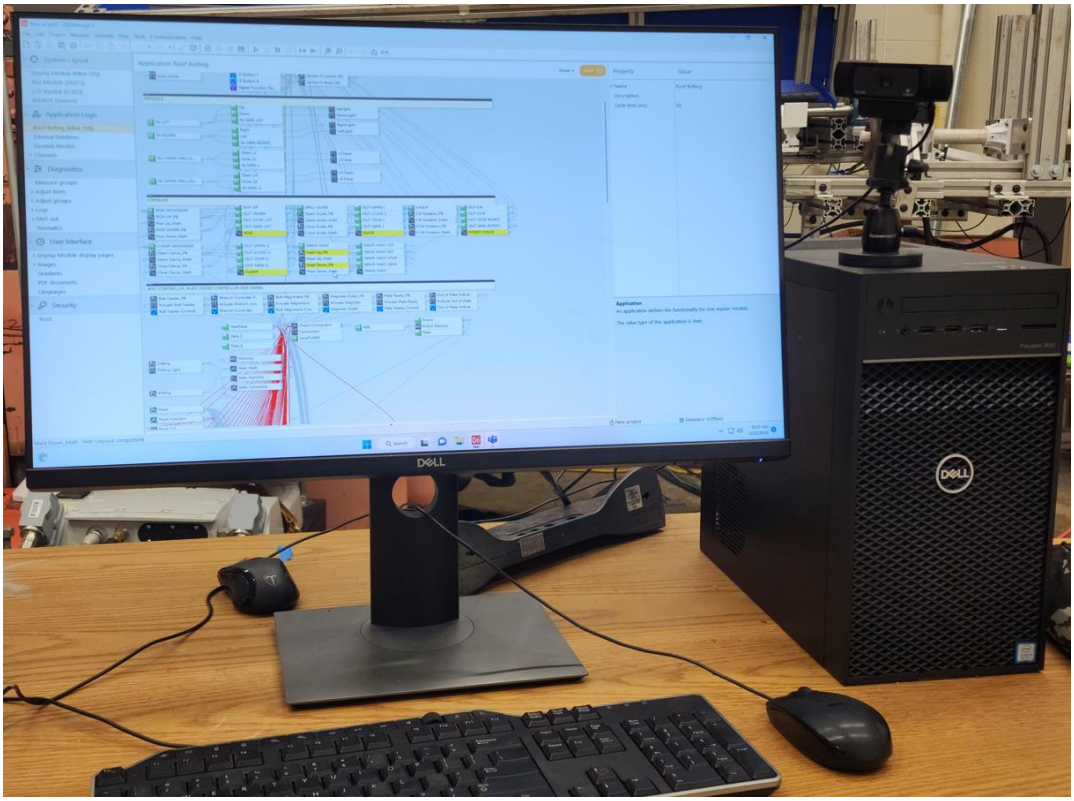

Figure C9: Desktop computer at the work station

# 10 Appendix D: Literature Review

## 10.1 Motivation and purpose

Literature review provides an insight on the information, technologies, constraints, challenges, applications etc., related to the research work presented in this report. The purpose of this review is to gather additional information about the concept of automating mining equipment to move miners away from the dangers roof bolting creates. A major emphasis of this research paper is reviewing mining technology which improves roof bolter productivity and fosters safer, more sustainable working conditions for miners.

This literature review mainly covers the following topics:

- Various challenges that are addressed by various authors related to the robotic design around mining automation systems currently in use.
- Working processes and technologies being proposed by various researchers and authors related to the topic of interest.
- Automated equipment available in existing coal mines, their benefits, their capacities, their specifications etc.
- Studies of the human-machine interaction with emphasis on the selection of the industrial manipulator and ways to trigger or operate this manipulator are the main focus of this section of the review. More specifically it will cover the topics of:
    - The benefits and challenges of selecting the industrial manipulator.
    - Studies on triggering the industrial manipulator during an emergency.

The construction of an autonomous robotic vehicle and/or manipulator-hand depends on the development of a robust remote calibration-diagnostics and a self monitoring system, the configuration of the robot-specific remotely-triggered actions, the use of optimized plan and control techniques, as well as the integration of the robotic spatial perception. Moreover, various considerations need to be made when developing and installing the communication system. The underground mine infrastructure may have possible effects on the signal transmission and propagation system.

Previous attempts at solving and optimizing those tasks have been challenging, yet modern automation system technologies have improved and been applied in a range of industrial processes, including the underground mining industry.

## 10.2 Industrial robots

Industrial robotics has emerged as a popular manufacturing methodology in several areas in recent years, including welding, materials transport, assembly, and spray finishing operations. Industrial robots are defined as complex machines that combine three basic components: an operative element to perform the actions, a central processing unit (CPU) to store and execute the control programming, and a power source.

Over the last few decades a new type of industrialized robotic system has emerged. The definition of the collaborative robots or cobots can be interpreted accordingly depending on the application context. The term was first introduced by the researchers Peshkin and Colgate (1999). Bitonneaou et al. (2017) defined cobots as a robot that physically interacts with humans, while De Santis (2008) added that these cobots physically interact with humans in a dedicated workstation. The main task of these robots is to directly actuate with the workforce, to assist them with task completion, and to support and relieve human operators from difficult or dangerous tasks (Restrepo et al, 2017; Koch et al, 2017).

Table 4 gives a condensed summary of the main characteristics of industrial traditional robots and compares them with the industrial collaborative robots based on the study of Hentout et al. (2019). The main difference is that a cobot can give assistance to employees when the work is too dangerous, strenuous, or tedious for them to complete. By doing so they create a safer and more efficient workspace without replacing human work. On the contrary, industrial robots are used to automate the manufacturing process almost entirely without human help. The use of an industrialized robotic system provides a safer working environment by removing the employees from mundane and highly dangerous tasks.

Table 4: A synthesis of the characteristics of Industrial traditional robots in comparison with the Industrial collaborative robots completed by the literature review of Hentout et al. (2019).

| Industrial Traditional Robots | Industrial Collaborative Robots (Light-Weight Cobots) |
|---|---|
| Fixed installation | Flexibly relocated (manually or on mobile robots) |
| Heavy structure, weighs around 250kg for 3kg payload | Light-Weight structure, weighs as little as 11kg for 3kg payload |
| Periodic, repeatable tasks; infrequently changes | Frequent task changes; tasks infrequently repeated |
| Online and Offline programming by a robot specialist | Online instructed by a process expert and supported by offline methods |
| Not easy to teach | Easy to teach |
| Rare interaction with the human, only during programming | Frequent interaction with the human, even force/precision assistance |
| Human and robot separated through perimeter safeguarding | Workspace shared with human |
| Hazards prevented by not allowing human robot interaction | Safe interaction with human |
| Profitable only with medium to large lot size | Profitable even at small lot size |

| | |
|---|---|
| Cannot reduce cost and footprint to justify new applications | Reduce cost and footprint to justify new applications |
| Not required risk assessment | Requires a risk assessment |
| Usually 6-axis with last three intersecting in wrist | Usually 6 or 7-axis with many offsets |
| No ability to provide support to the human | Provides power support to the human |
| Does not provide a virtual surface to constrain and guide human | Provides a virtual surface to constrain and guide human motion |
| Cannot adjust their configurations in real time to fit with the human physique | Automatically adjust their configurations in real time to best fit with the human physique and fastening task features |
| Does not provide an artificial force to the human | Provides an artificial force to the human to perform hazardous activities |
| Not able to reduce the ergonomic risk of strenuous tasks | Reduces the ergonomic risk of strenuous tasks |
| Set up takes days or weeks | Quick set up (less than a day) |
| A robotic programmer needs to be hired which might require additional investment | Easy to program without special skills; anyone who can work a smart phone can use it |
| Requires large and separate enclosures | Requires less floor space |
| Small or bug and fast | Small, slow, easy to use and easy to move |

An example of a mobile robotic manipulator is displayed in Figure 1. Based on the study of Grehl et at. (2015), the Julius robot consists of an articulated three-finger hand mounted on a robotic arm. His preliminary survey is to explore co-working scenarios, where Julius is deployed to assist the miner using its robotic and the three-finger gripper with demanding, precise or risky tasks. To achieve his goals, Julius carries wi-fi stations and uses his gripper to place them on the floor to extend the network range when the wi-fi signal becomes weak.

His arm is used in various applications, such as collecting water samples in abandoned areas, handling the mine ventilation system and investigating the underground area for loose rocks debris using his gripper's camera.

## 10.3 Automation and autonomous systems of mining equipment.

Automation in the mining industry is not novel. Robotic and Autonomous Systems (RAS) are playing an important role in today's mining industry. For example, automation systems have been deployed in most mineral-processing plants and coal preparation plans and are often semi-

automated. Many other application areas require the use of RAS technologies to assist with human activities due to the harsh working environment created by extracting and transporting minerals. Automation is nowadays being utilized in nearly all phases of mining including extraction and drilling. Some examples are going to be presented in the following paragraphs. LASC Longwall Automation technology was used to increase productivity in underground mines and to remove the employees from exposure to high respirable dust levels (Ralston et al, 2015; Ralston et al, 2017).

Other examples include the use of autonomous haul and dump trucks to transport materials in mines. Scheding et al. (1999) using results of field trials conducted in an underground mine in Queensland, Australia, suggested a navigation system capable of making large heavy industrial machinery much safer and more efficient in uneven terrain. Roberts et al. (2002) introduced the term opportunistic localization, a technique that allows the vehicle to make appropriate decisions when driving through intersections.

Figure D1: An articulated three-finger gripper allows Julius to operate devices designed for human hands. The precision and endurance of the robotic gripper increases the measurement quality. Figure retrieved from https://www.ausimmbulletin.com/feature/mining-futures-research-perspective-mobile-robots-in-underground-mining/

This implies that the vehicle is travelling while knowing the segment of the route and at the same time identifying the next node. Larsson et al. (2006) proposed a fully automated navigation system using the fuzzy behavior-based approach to navigate underground Load-Haul-Dump (LHD) vehicles. Marshall et al. (2016) presented an automated way to load materials using draglines and shovels.

### 10.3.1 Robotic miners.

Automation capabilities continue to increase as a result of advances in machine sensing and vision which aides in balancing the scales between humans and ma- chines. Hardware and software advances have greatly expanded the opportunities for adopting automation to many human-machine systems, resulting in much more complicated decisions about choosing levels of automation for different machine functionalities. The mining industry is currently in a stage of adopting more automation, and with it robotics. The area of development being researched, which concerns the content of this review, includes the automated installation of ground, roof and rib supports and robotic rock cutting machines.

### 10.3.2 Automated technology

#### *10.3.2.1 Localization*

The underground environment is particularly challenging when it comes to improving positioning accuracy. Several methods have been proposed to address this problem in the longwall context. One method is based on measuring the three-dimensional shearer path of the shearer directly through an inertial navigation-based system (Billingsley and Brett, 2015).

Xu and Wang (2010) implemented a shearer working path system based on three-machine position and dynamic-static fusion. This approach collects dynamic data of the shearer, static data of the conveyor shearer, and data from the hydraulic supports, in order to acquire the shearer's three-dimension location information.

Horizontal position information is collected using the Inertia Navigation System (INS) technology (Reid et al 2011). This system provides high short-time accuracy and robust autonomy, but shows an increasing error growth over time (Ruiz 2009). To solve this problem Fan et al. (2014) developed the wireless sensor network. Even though their approach showed a decrease in the position drift error, the position coordinates of the anchor nodes couldn't be determined in an accurate manner because of the movement of the roof support system.

Xie et al. (2017) installed tilt sensors on the shearer body and armored face conveyor (AFC). The main disadvantage of this method was that it demonstrated one-dimensional positions of the shearer instead of three-dimensional positions. In yet another approach, Wang and Wang (2020) and Xie et al (2017) used a shearer positioning system based on an INS and added an axial encoder, which is used to calculate the shearer's moving trajectory. They also used shearer motion constraints to improve the accuracy of positioning.

Navigation of commercial Automated Guided Vehicles (AGVs) is nowadays accomplished through inertial navigation, magnetic navigation, electromagnetic navigation, lidar navigation, visual navigation and other navigation methods. Localization methods that are available on AVGs till this date, include laser triangulation methods, ceiling mounted bar codes, range or camera-based wall-following, using floor markers or magnets as guidance while in vehicle updates its exact location, and following magnetic tape.

Houshangi and Azizi (2006) integrated the robot's position and orientation using a fiber optic gyroscope and the Unscented Kalman Filter (UKF), which estimates a probabilistic distribution using small range of numbers taken from specifically chosen test points. This approach assures better position and orientation accuracy in comparison with the Extended Kalman Filter (EKF) approach.

#### *10.3.2.2 Motion planning and control*

There are many aspects of the operation of a typical industrial manipulator or vehicle that must be planned and coordinated. Planning includes the determination of an optimum and safe no-collision path that the vehicles will have to follow while ensuring high precision docking with conveyors or other equipment. Advanced planning operations includes the positions of tools and material in specific locations.

Until recently, vehicles modified their trajectories in order to enable coordinate motions and ensure obstacle avoidance using an offline approach. However, future research aims on enabling the vehicle to modify its trajectory while operating. That implies highly intelligent control architectures and suitable sensor feedback.

Planning coordination using centralized computation methods are not suitable for AGVs and mobile robots used in mining industry, where the environment is less structured, and the tasks are not known in advance. The decentralized estimation schema or distributed approach seems to be more appropriate in such locations. While the paths that are planned in this environment are not fixed, special attention must be taken for high-accuracy docking maneuvers, in order to increase the flexibility and adaptability of the robotic configuration modifications (Herrero et al, 2013). For manipulators, appropriate joint planning configurations are needed to fulfill certain coordination tasks. In order to operate the robotic manipulator with absolute precision even at higher speed, control strategy has to be well defined.

Robot dynamics, payload, operating environment are the main challenges in designing the control system. In figure 2 an overall sequential engineering procedure of a control design of a manipulator is displayed (Ajwad et al 2015). The control design of a manipulator depends greatly upon the studied application scenario. Recent advances in manipulator control have been categorized into three sub-domains: Intelligent Proportional–Integral–Derivative (PID) control, robust control and adaptive control.

There is a continued interest in modifying a simple PID control to improve control performance and functionality (Blevins, 2012). Some of the possible ways to modify a PID control are presented in Fei and Wu (2006) study, where they cascaded through multiple controllers. Advancements in PID control include the combination of PID control with modern control techniques and algorithms to achieve optimum performance, improvements on tuning methods (Foley et al. 2012; Nagaraj and Murugananth, 2010), modifications with non-linear and adaptive control approaches (Iqbal et al 2014a, b).

Regarding the robust trajectory tracking techniques, Ullah et al. (2014) approach is based on the Computed Torque Control (CTC) algorithm which was used in a 6 Degree of Freedom robotic arm with 5 revolute joints. This control technique cancels out possible nonlinear behaviors of the

studied system and then uses linear modelling dynamics to accomplish the desire position and orientation. The combination of Computed Torque Control (CTC) with PD and PID has been reported by Piltan et al. (2012). Nguyen-Tuong et al. (2008) demonstrated a comparison between Locally Weighted Projection Regression (LWPR) and Gaussian Process Regression (GPR).

#### *10.3.2.3 Robotic arms for underground mining*

Robots equipped with robotic arms can improve the performance of human workers in harsh working environments like underground mines. Lösch et al. (2018) showcased a robotic system that has a UR5 robotic arm and a 3-Finger Adaptive RObot Gripper from Robotiq with which the system can then install, rearrange and remove Smart Sensor Boxes (SSBs) of an Internet of things (IoT) infrastructure. Robotics researchers also work together with mining experts to autonomize existing machines in the mining industry. Bonchis et al. (2013) adapted a mechanical manipulator from a Palfinger truck crane for the explosive charging tasks. They designed an end-effector that carries a laser range-finder for detecting the location of the blast holes and a number of video cameras and LED lights used to support the automatic and manual host insertion process. To insert the tool into the blast hole, the manipulator is first controlled by a planning algorithm and then teleoperated by a human operator to refine the position and direction of the end-effector. To perform different tasks underground, the robotic manipulator can be very different from traditional robotic arms. To replace human coal miners in Korea, Huh et al. (2011), designed a tele-operated mining robot that has a boom, an arm and a bucket.

Moreover, to heavy-duty tasks, most robotic manipulators are equipped with hydraulic actuators which propose unique challenges in controlling (Zhou 1995; Singh et al 1995; Sepehri et al 1994). Hydraulic actuators can be direct drive for linear or rotary motions. Lu (2009a,b) shows how a bucket wheel reclaimer can be converted into a robotic arm and then can be controlled automatically. In his work, he first modelled three joints of a typical BWR based on which the kinematics and dynamics are modelled. In the study of Peshkin and Colgate (1999) the authors conclude that Lagrangian dynamics models and Newton-Euler dynamics-based models for hydraulic robotic manipulators, provide superior control performance and give solution to highly nonlinear behavior of energy inefficient hydraulic systems (Figure D2).

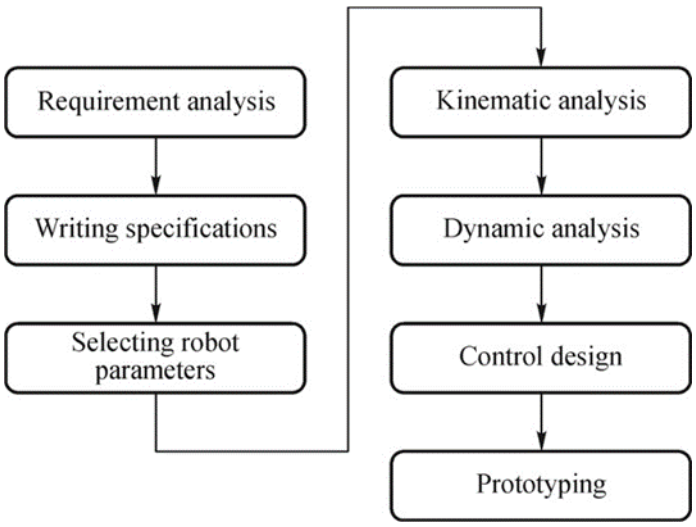


Figure D2: Manipulator control design - Sequential engineering approach. Figure retrieved from Ahwad et al (2015)

## 10.4 Human–robot interaction in underground robots

The term Human-Machine Interaction (HMI) is attributed to the low level of autonomy and complexity of interaction with industrial robots (Vaughan et al, 2012). The introduction of autonomous machines and robots on large scale mines is a new trend in the mining industry (Grehl et al, 2015; Thrybom et al, 2015). Robotic systems and mine automation applications have already been well developed in open pit mines (Rizos et al, 2011; Boulter and Hall, 2015; Dadhich et al, 2016; Lindmark and Servin 2018), while in underground mines, robots are used primarily on well-developed infrastructures (Plotnikov et al, 2020) and the majority of them include the development of automobile vehicles (Polotski and Hemani 1997; Roberts et al, 2022; Androulakis et al, 2020). Typically, mine sites host large numbers of independent equipment and systems. Each piece of equipment generates its own information and has its own interfaces. These machines complement human capabilities and relieve him of arduous tasks, as well as reduce energy costs in remote locations while limiting safety issues.

### 10.4.1 Basic technological approaches

It is becoming more common for human and robot co-workers to work on a dedicated workstation as collaborators, in order to accomplish tasks in industrial environments. An industrial robotic system may include one or several robots and one or several humans collaborating in conjunction to accomplish tasks. Moulieres-Seban et al. (2017) asserts that the design of a robotic system involves a clear understanding of the possible humans, tasks, robots and system interactions.

This has led to the need for advanced human-robot communication which can combine cognitive skills, intelligence, flexibility and decision-making of humans (Modares et al, 2015; Djuric et al 2016). The goal is to combine robotic strength, endurance and accuracy with human intelligence and flexibility (Kruger et al 2009; Muller et al 2016).

Argall et al. (2011) proposed a method of teaching in which primitive components of motions are learned by a robot through teleoperation. This method can be used to help robots perform a complete task without the operator having to determine all aspects of the task.

Farry et al. (1996) respected the principles of the detailed myoelectric signal processing approaches in order to create a complex robot hand that reproduces the motions of the operator's hand in real time.

According to Pedersen et al. (2012), a mobile manipulator can use gestures to determine whether to pick up and where to place an object. This method requires the definition of gestures. Those have to be easily distinguishable by the sensors on the mobile robot, as well as communicable by humans. Other researchers have tried to improve human safety by creating robots that determine where and who can ask for help (Rosenthal and Veloso, 2012; Veloso et al, 2015).

Sisbot et al. (2007) presented a solution for safeguarding the workforce near robot locations. The approach consisted of a path algorithm that computes the comfort and expectations of people that may be near the robot. This path planning technique assures a safer distance between the robot and the workforce and positions the robot in a clear and wide field of view in order to prevent surprise appearances.

### 10.4.2 Safety in underground industrial robotics

Safety and security issues related to industrial robots should always be addressed upon control development. Vasic and Billard identified a range of different threats to all humans surrounding robots. Guiochet (2016) studied the catastrophic consequences of a failure or extreme environmental conditions and how life threatening those situations can be. According to De Santis et al. (2008), safety tactics can be broken down into:

1. Intrinsic safety
2. Preventative collision techniques (pre-collision)
3. Techniques activated when a collusion occurs (post-collisions)

Colgate et al. (2008) addressed the problem that it is almost impossible for heavy conventional industrial robots to behave in a gentle and safe manner, when realistic conditions are taken into consideration. The following paragraphs are assigned to the various attempts of different authors to design an intrinsically safe robot based on the aforementioned conditions.

As specified by Bicchi et al. (2008), the first step in increasing safety performance, is to introduce compliance at the level of mechanical design. Other researchers have proposed increasing the robot's sensorial apparatus in order to mitigate the risk of an accident Colgate et al (2008). Other researchers have proposed increasing the robot's sensorial apparatus in order to mitigate the risk of an accident (Colgate et al 2008; Wilkinson 2004). The first lightweight arm named whole-arm manipulator (WAM) was proposed in Salisbury et al (1988). Recent examples of human-safe robots are the ABB YuMi (ABB, 2023), the Rethink Robotics Baxter and Sawyer (Rethink Robotics 2023a,b) and the KUKA LBR (Kuka 2023).

It is noted that safety in human-robot interaction extends beyond physical contact. Previous work (Lasota et al, 2014; Mumm et al 2011; Butler et al 2001) has shown that a robot's appearance, embodiment, gaze, speech, and posture can have negative psychological effects.

#### *10.4.2.1 Pre-collision systems*

It is necessary to achieve higher safety standards by preventing unexpected collisions between humans and robots. Those collisions must be determined and avoided before any injury occurs. Current practice in industrial robots is the use of proprioceptive/exteroceptive robot sensors to detect the presence of moving obstacles or humans, and stop the task execution to avoid contact. Based on real-time detection techniques and reactive planning algorithms, researchers have allowed a higher degree of coexistence and interactions between humans and robots (Ebert et al, 2005; Schiavi et al, 2009; Flacco and De Luca 2010; Fenucci et al. 2014). Green (2012) examined sensing technologies that could enable the development of underground autonomous vehicles. By combining three-dimensional cameras and a thermal imaging sensor, they created 3D thermal models of narrow mining stopes which can be used in determining the risk of rock fall in an underground mine. Kulic and Croft (2005) also presented a strategy for improving the safety of human-robot interaction by minimizing a danger criterion during the planning stage. Table 5 summarizes the pre-collision approaches as considered in this review.

Table 5: Summarized and categorized related works in pre-collision approaches, based on Hentout et al. (2019)

| *Research categories* | *Robot/Approach* | *Sensors* | *Applications* | *Ref* |
|---|---|---|---|---|
| *Reactive Control* | *LWRII* | *Joint-torque sensors* | *Detect and distinguish unexpected collisions. The operator has total control of the robot* | *Haddadin et al 2008* |
| | *3D simulation of a robotic cell* | *ROS compliant sensors* | *The robot moves at a reduced speed in the event of impending collisions* | *Fenucci et al 2014; Hentout et al (2019)* |
| | *KUKA/ LWEIV Real time collision avoidance* | *Microsoft Kinect sensor* | *Avoid collisions while executing at best the original Cartesian motion task.* | *Flacco et al 2012* |
| *Proprioceptive sensor-based control* | *The robot uses only the information already available (proprioceptive sensors, dynamic model)* | *Internal proprioceptive sensors* | *Adaptable behavior of the procedure to the current work conditions. The robot stops immediately when a collision occurs.* | *Indri et al 2015* |
| | *Fanuc 200iC/ Kinematic model and AR environment (ARToolKit)* | *Native 2MP sensor* | *Improves existing approaches by adding the Hybrid EKF pose estimation method* | *Ibari et al 2015* |
| *Exteroceptive sensor-based control* | ABB IRB140/ *Assessment of the risk level caused by the robot using sensor outputs* | *Exteroceptive distributed LED-based distance sensor* | *Provide a hardware/software solution* | *Ragaglia et al 2014* |

| *Research categories* | *Robot/Approach* | *Sensors* | *Applications* | *Ref* |
|---|---|---|---|---|
| | *Safety helmet. Localize human position in real-time using industrial wireless equipment* | *Combination of the Inertial Measurement Unit (IMU) and the Received Signals Strength Indication (RSSI)* | *Improvement of interactivity and usability when working on a flexible manufacturing system* | *Meziane et al 2014* |

#### *10.4.2.2 Post-collision approaches*

In real case scenarios is almost impossible for humans to collaborate with the robots without a certain level of physical contact. Post-collision techniques detect a collision as it occurs. The purpose of this method is to minimize the impact after an unexpected collision has occurred. Different approaches on this topic are reported in (Heinzmann and A. Zelinsky, 2003; Cirillo et al, 2013; Sangiovanni et al, 2018). Table 6 summarizes the post-collision approaches as considered in this review.

Table 6: Summarized and categorized related works into post-collision approaches, based on Hentout et al. (2019)

| Approach | Ref |
|---|---|
| Safe robot impact behavior based on human-pain tolerance database. | Yamada et al, (1997) |
| Analysis of injuries using different robots by considering the severity of injuries to a human caused by a collision with a robot. | Haddadin et al, 2008 |
| Biologically-inspired non-linear elastic force deformation response model. | Courreges et al (2016) |

### 10.4.3 Tele-operation

Human-robot communication interface is crucial for safe deployment of robots in underground mining because of its complex and various environments. Ideally, humans should be able to monitor and interrupt the working progress of robots remotely in a safe place. In Huh et al. (2011), a tele-operation system is implemented as a remote-control station where humans can control the robot with joysticks. It is also important to inform humans about the status of robots and the working progress in a human-friendly way. In Huh et al. (2011), the remote-control station has two monitors that show the robot and obstacles in the work area. To enable an equipment sharing scenario, Wilkinson (2004) suggests a new, cooperative approach to teleoperation in mining environments. He also proposes an interactive telemining simulator to help quantify the interaction between operators in a dual operator configuration.

### 10.4.4 Shared Autonomy

In direct teleoperation, users provide inputs that are then directly converted to robot actions. However, direct tele-operation is often tedious and time-consuming, especially for robotic arms that have a lot of degrees of freedom. Previous approaches on shared autonomy have combined teleoperation with autonomous assistance, where the system predicts the goal of the operator and then assists the operator for that goal (Dragan and Srinivasa 2013; Kofman et al 2005; Yu eta al, 2005; Hauser 2013; Javdani et al (2015), Nikolaidis (2017). Haptic interfaces

have been particularly effective in adapting the automation to allow the user to regulate the control authority delegated to the system (Abbink et al, 2012). Researchers have regulated the stiffness of the control system so that the user can opt to delegate control or initiate taking back control (Goodrich et al, 2008). A continuous transitioning of autonomy can be achieved by accounting for control effort (Passenberg et al 2011), criticality of the task (Abbink and Mulder, 2009) or user habituation in the task (Rakita et al. 2018). Shared control approaches have been extended also for bimanual manipulation using an action vocabulary (Rakita et al. 2019).

## 10.5 Other issues and challenges

Other constraints and challenges related to industrial robotic systems can be outlined as follows:

1. develop robust detection of human movement to build good predictive models,
2. ensure robust detection of contact between robots and workforce in multiple points
3. develop fast responsive controllers for real-time local trajectory replanning for complex underground mining environment
4. ensure satisfactory real-time constraints
5. develop a reliable system structure for fault tolerance, by including three main principles: error detection, error diagnosis and recovery.

## 10.6 Discussion

Mining is no different from other sectors in that automation is often largely driven by the goal of making equipment operator activities safe by removing humans from a hazardous environment and increase operational efficiency and production capability. Mining can take advantage of lessons learned by other sectors and industries. Efforts on introducing automation in mining requires mining-specific research, but the research can focus on providing alternate solutions to specified problems such as the control and monitoring of automated equipment rather than more fundamental research. Areas of development, currently being researched, include and are not limited to:

1. Monitoring and control of autonomous haul and dump trucks.
2. Establishing centrally located control rooms.
3. Developing automated underground longwall systems.

4. Automating materials handling systems and palletizing equipment.

## 10.7 References


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