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THE METHODOLOGY FOR INTEGRATING ROBOTIC SYSTEMS IN UNDEGROUND MINING MACHINES

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THE METHODOLOGY FOR INTEGRATING ROBOTIC SYSTEMS IN UNDEGROUND MINING MACHINES

DISSERTATION

A dissertation submitted in partial fulfillment of the
requirements for the degree of Doctor of Philosophy in the
College of Engineering
at the University of Kentucky

By
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2023

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ABSTRACT OF DISSERTATION

THE METHODOLOGY FOR INTEGRATING ROBOTIC SYSTEMS IN UNDEGROUND MINING MACHINES

Roof bolting is a critical operation in ensuring the safety and stability of underground mines by securing the roof strata with bolts. The process involves moving and manipulating heavy tools while being vigilant about the safety of the area. During the installation of roof bolts, operators are exposed to hazardous conditions due to challenging working conditions in underground mines, extensive working hours, and demanding shift schedules leading to personnel fatigue and influencing operators to take shortcuts that may increase the risk of injuries and fatal accidents. The successful completion of roof bolting tasks depends heavily on operator judgment and experience to perform these tasks. To mitigate the occupational hazards inherent in roof bolting operations, a six-axis ABB IRB 1600 robotic arm was integrated into the roof bolter machine to imitate human functions during the roof bolting operation.

The integration process involves selecting a suitable robot that can perform human activities and has the potential to handle the tasks at hand. The ultimate goal of implementing the robotic system into the roof bolter machine is to minimize human involvement during the roof bolting operation by converting the machine from manual operations to a partially automated roof bolter machine. The integration enhances the safety of personnel by moving humans away from the face where roof bolting takes place to a safe distance. The operator is then assigned a new role to control and supervise all the operational tasks of the automated roof bolting operation via a human-machine interface (HMI).

During the laboratory testing of the automation process, the robotic arm cooperates with some novel specialized technologies to imitate human activities during roof bolting operations. The developed systems include 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 Programmable Logic Controller (PLC) and controlled by the HMI touchpad. An HMI was developed for the operator to control and monitor the automated process away from the active face.

This study establishes robust communication paths among all the components. The design communication network links the robotic arm and other components of the roof bolter machine, leading to a smooth and sequential roof bolting process. The EtherNet/IP protocol is used to pass messages between the components of the automated roof bolter machine through a Controller Area Network (CAN) bus device 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 developed automated systems during the bolting process.

The outcome of the study shows that the robotic arm has the potential to mimic human activities during the roof bolting operation by performing bolt grasping, holding, lifting, placing, and removal of 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 Human Machine Interface (HMI) touchpad. 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.

KEYWORDS: Automation, underground mining operation, robotic arm, roof bolter machine, mining machines, human-machine interface

Peter Kolapo

December 13, 2023

Date

THE METHODOLOGY FOR INTEGRATING ROBOTIC SYSTEMS IN UNDEGROUND MINING MACHINES

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DEDICATION

This work is dedicated to God Almighty, the Alpha and the Omega, and those who believe in themselves.

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1. INTRODUCTION

1.1 Background

The goal of technological integration is to minimize human interventions in mining operations, which has been a transformative development for the industry, significantly driven by the automation of mining processes. More importantly, the introduction of digital technologies in mining operations has the potential to reduce the exposure of personnel to occupational risks and hazards. Statistical trends from the mining industry have shown that the safety of mineworkers' has tremendously improved as mining-related accidents and injury rates continue to decrease. Despite automation's significant influence on mine health and safety, the expectation of achieving zero harm in mining operations necessitates a continuous demand for further improvements. The need for safety improvement motivates the deployment of a new generation of robot technologies and digital systems to enhance personnel safety.

The fundamental goal of automation is to develop machines that can perform repetitive or hazardous tasks, thereby improving the safety of humans. Robots' ability to perceive their surroundings and think like humans is dependent on the integration of various sensors. In other words, robots' ability to perceive their surroundings and think like humans is dependent on the integration of various sensors. These sensors significantly influence the ability of robots to make decisions for navigation, mobility, and intelligent manipulation of objects without compromising safety standards. Recent advancements in the field of robotics technology, including the development of more efficient algorithms, encourage the creation of sophisticated robotic systems (Munaretti, et al., 2012). Some recently developed robots are faster and more reliable, with stronger robot manipulators capable of performing tasks efficiently and accurately.

As previously mentioned, the main benefit of integrating automated technologies in mining operations is improving the health and safety of the miners. The World Economic Forum (WEF) predicts that the implementation of digital systems into the mineral extraction process would significantly improve the health and safety, potentially preventing 1,000 fatalities and avoiding 44,000 injuries (World Economic Forum (WEF), 2017).

Implementing digital technologies in mining operations would not completely eliminate the presence of humans from the mining process but instead assign them new roles. Consequently, these new roles would allow humans to work in a safe environment, improving their health and safety while increasing operational efficiency and productivity. In general, the main potential benefit of integrating robots in underground mining operations is to improve personnel safety. More importantly, operators can be moved away from potentially unhealthy and hazardous areas to safer environments.

1.2 Problem Statement

Mining is a labor-intensive operation that is generally carried out by manually operated equipment or hand-digging methods with simple tools such as shovels, chisels, and hammers (Rupprecht, 2017). Working with manually controlled equipment at a close range is physically demanding, and exposure to hazardous conditions could lead to accidents and near misses. The roof bolting operation is a task that requires a significant amount of labor and involves multiple functions, including drilling, resin placement, and bolt installation. During bolt installation, the operators are involved in physically demanding work over long periods in unfavorable environments, thereby increasing the probability of unsafe actions leading to accidents or near misses. For instance, the extraction task in underground coal mining operation involves repetitive processes in confined and hostile environments. As a result, machine operators, especially roof bolter operators, are prone to exposure to hazardous conditions due to their proximity to the unsupported roof and dust and noise exposure. This hostile work environment contributes to the operator fatigue, influencing operators to take shortcuts that could lead to injuries and fatal accidents.

Despite the number of risks operators are exposed to during the roof bolting operation, most underground mines still use human-driven manually operated roof bolter machines. Kyslinger (2017) argued that roof bolting is the most dangerous equipment-related operation in underground mining. Roof bolting accidents account for 39 percent of equipment-related accidents in U.S. coal mines. Similarly, Sammarco, et al., (2016) reported that the roof bolter operators had the second highest number of machinery-related injuries, accounting for 64.7 percent at underground coal mines, although the industry has implemented various safeguards to minimize fatalities in its operations. However, challenges still remain evidenced by the persistent recurrence of accidents (Esterhuizen & Gürtunca, 2006). Considering these concerns about the health and safety of personnel working in underground mines, these long-standing problems can seriously threaten the mining industry's sustainability. For this reason, these hazards need to be controlled. Roof bolter machine operators need to move from the active mining face to a safe distance where they can remotely control the operation than operate the equipment directly.

1.3 Research Questions

Since the introduction of roof bolting technology to underground coal mines in the 1940s and 1950s, there have been continuous improvements in the roof bolter machine (Mark, 2002). Despite these significant improvements in the machine, injuries and fatalities still happen during roof bolting operations. Therefore, there is a need to move humans away from tedious and unhealthy environments and allow automated systems to perform roof bolting tasks. However, the introduction of automated technologies in roof bolting operations has raised concerns that must be addressed. The main question posed by this research is, "Can cooperative robot systems and other automated technologies perfectly perform human functions in roof bolting operations?" Consequently, this leads to the following sub-questions:

- Can we develop a roof bolter that can be operated remotely?
- Are there any specifications for implementing a cooperative robot to automate roof bolting tasks?
- Can humans move away from an active mine face during roof bolting operations?
- Can humans remain relevant in the roof bolting cycle with the integration of cobot technologies?
- Can robots make timely and sound decisions in roof bolting process?
- Can robots be controlled in the event of unexpected or unsafe actions?

1.4 Research Objectives

This research will address the following objectives:

- Objective 1: Develop specifications for implementing cooperative robotics for partial automation of roof bolting tasks in underground mining.
- Objective 2: Develop concepts for safe and efficient collaborative robot (cobot) interaction with humans during the roof bolting. This objective includes the design of a human-machine interface (HMI) for controlling the automated roof bolter machine.
- Objective 3: Design intermachine communication protocols for components not originally designed to work together. Establishing a robust communication protocol is crucial for the sequential movement of each component during autonomous operations.
- Objective 4: Apply the above-mentioned concepts to develop a partially automated roof-bolting machine.

1.5 Innovation of Dissertation

Integrating automated systems in mining machines has significantly reduced operator exposure to risks, especially in extremely hostile environments such as underground coal mines. An example of this automated machinery is the roof bolter machine used to install roof bolts to prevent roof fall in underground coal mines. The roof bolter machine remains a notable piece of equipment that exposes operators to several occupational risks. Therefore, human operators need to be moved from these hazardous working conditions by automating the roof bolter machine. It is important to note that converting the manually operated roof bolter machine to an automated machine will not completely remove humans from the roof bolting process but instead assign a new role of remotely monitoring and controlling the bolting cycle from a safe distance. It will improve the health and safety of the roof bolter operator by moving humans away from hazardous working conditions.

The following are the innovative contributions of this dissertation:

- The conversion of a manually operated roof bolter module to an automated machine

- Design of specialized components used in the automation process of the roof bolter machine.
- The integration of components and systems that are not originally designed to work together, such as a high-precision system (robotic arm) and a low-precision machine (hydraulic roof bolter).

1.6 Dissertation Outline

This dissertation is organized according to the following chapters:

Chapter 2 presents a comprehensive literature review of different applications of digital and automated technologies in mining operations. It further discusses several attempts to automate mining machines for both open pit and underground mining operations. The chapter extensively discusses the challenges of implementing automated systems in underground mining operations.

Chapter 3 discusses specifications that need to be considered when selecting a robotic system capable of performing human activities during roof bolting operations. The standard industrial configuration of the robotic arm was taken into account to ensure the success of the automation process. These include the weight capacity of the robot, the extended reach of the robotic arm, the axes movement specifications, and its ability to fit within the task area. In addition, this chapter explains the three major areas that must be taken into account for the successful integration of robotic systems in underground mines: the people (miners), the process (work instructions and plans), and the technology.

Chapter 4 presents interaction concepts between the developed automated machine and the human. It describes the design and development of a human-machine interface system that allows operators to override the action of the roof bolter by requiring them to approve each task before machine execution.

Chapter 5 presents an approach to designing intermachine communication protocols for components not originally designed to work together. Establishing a reliable communication path is critical in controlling the movement of components, especially the robotic arm, during the roof bolting operation process.

Chapter 6 explains integration of the above-mentioned concepts to develop a partially automated roof bolting machine. It discusses the assembly of components and the robotic arm that led to the partially automated roof-bolting cycle. The development and testing of the partially automated roof bolting machine were done at the rock mechanics laboratory of the Department of Mining Engineering at the University of Kentucky.

Chapter 7 presents a summary of the research and the resulting conclusions. The chapter also offers recommendations for future work in this field of research.

2. LITERATURE REVIEW

This chapter presents a comprehensive literature review of various applications of digital systems and automated technologies in mining operations. It provides an overview of the state-of-art and behavior of robotic systems in their immediate environment. Several attempts to automate different mining machines in underground mining environments are also explored. Finally, the challenges facing the implementation of automated systems and the reason for the slow adoption of automated mining operation technologies are discussed.

2.1 The State-of-Art and Behavior of Robotic Systems

Robotic systems are becoming popular and increasingly being applied in several engineering and industrial fields to perform various tasks. The applications are predominantly in fields like manufacturing, agriculture, exploration, and intelligent transportation to perform welding, material transport, spray finishing, assembly, and finishing operations. In recent times, new types of industrialized robotic systems have emerged with advanced features that aid in automation. These robots are primarily designed to work closely with the human employees, providing task support and helping human operators complete their assignments while simultaneously taking on challenging and hazardous tasks to alleviate the workload and ensure safety (Ralston, et al., 2015). The key benefits of deploying robotic systems include enhancing personnel safety, improving operational efficiency, and increasing task accuracy. In mining operations, automation enables the personnel involved in the task to work remotely without being physically near the equipment (Salvador, et al., 2020).

This type of robot, which is designed to work alongside humans in the same workspace, is called a cooperative robot, or cobot. Cobots are equipped with sensors that modify their path to avoid obstacles and collisions with humans. This makes them ideal tools for performing assembly tasks like grasping, placing, holding, and core complex assembly processes involving multiple components and intricate movements (Pedrocchi, et al., 2013). The main distinguishing feature between cobots and industrial robots lies in their respective roles in the workplace. Cobots can offer valuable assistance to employees, particularly when the work is hazardous, physically demanding, or monotonous. As a result, they help to create a safer and more efficient workspace without replacing human labor. On the other hand, industrial robots are primarily used to automate the manufacturing process with little to no human intervention. Doing so eliminates the need for employees to perform routine and highly dangerous tasks, thereby creating a safer working environment.

The development of cobot machines is the transformation needed to perform a repetitive working process. The technology can interact and work with operators in close proximity to accomplish tasks such as picking and placing, assembly, screwing, loading, and unloading industrial machines. They are often equipped with cameras, sensors, and robust vision systems to detect the surrounding and perform unstructured tasks. These features and other improved characteristics allow the cobots to share space with humans and guarantee their safety (Javaid, et al., 2022). Due to their safety-centered design and accuracy, cobots have been seen as an exciting companion to perform tedious, repetitive, and physical staining tasks, which in turn helps to improve ergonomics and safety in operations.

In the past, robots were not allowed to operate in the same vicinity as humans due to safety concerns. Then, robots were caged or placed in cells to perform specific tasks. Today, the isolation of robots from humans has been eliminated in the workspace; robots now serve as tools to perform tasks side by side with humans without being considered a danger. However, as technology advances, robots are increasingly becoming more intelligent and adaptable, enabling them to work alongside humans in a wide range of tasks. In the context of cobots and operators sharing the same working space, these features ensure operators' safety by preventing collisions between humans and robots (Scoccia, et al., 2020). They also address the psychological aspect of the interaction (Lasota, et al., 2014). However, contrary to societal perceptions about cobots and autonomous technologies, cobots can work side by side with operators in the same space instead of replacing them. Generally, the goal is not to replace the operators but to integrate them into operations, so they can assist humans in performing repetitive and heavy tasks.

The human-robot interaction (HRI) is another critical characteristic of cobots that must be considered before deploying the system into operations. The reason for considering HRI is to develop robots that can interact with humans in their social environments. The HRI also involves various stages of robotics, such as design, development, communication, and evaluation of robot behavior and its interaction with humans and environments. For humans and robots to successfully collaborate to achieve a common goal, humans must trust the robot as a co-worker, ready to protect their common interests and the welfare of every individual working around them. Trust is a critical factor that significantly influences the acceptance of robots as assistants to humans, as well as the provision of information required for sound decision-making. HRI presents an opportunity not to see robots as tools but as collaborators and interaction partners. In addition, the interaction between humans and robots promotes optimal skills in operations (Hancock, et al., 2011). Therefore, it is important to focus on how the HRI characteristic affects quality performance, reliability, and other factors, as illustrated in Figure 2.1. When HRI is appropriately managed, it can positively impact human-robot trust, thereby increasing human confidence in automation systems.

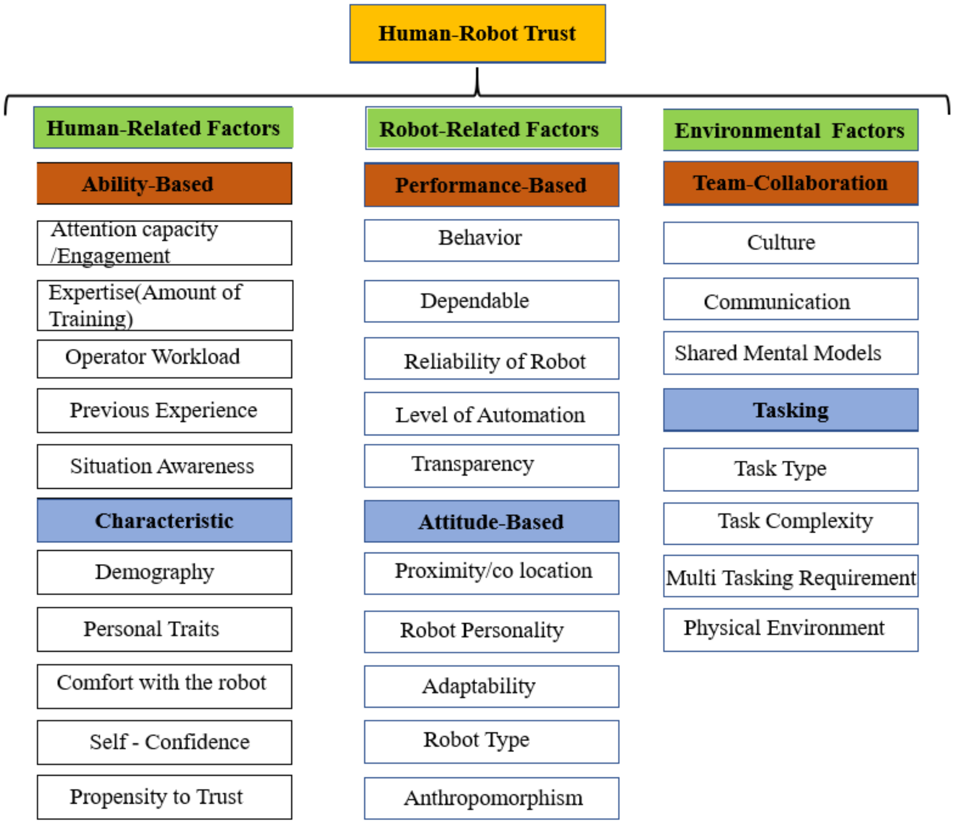


Figure 2.1: Factors influencing trust development in HRI (Hancock, et al., 2011).

When robots are integrated into operations, the system becomes automated; consequently, the robot will have operational control of the system. This is one of the major reasons why operational size and ergonomics should be considered at the design stage; this might increase the level of acceptance of cobots in operations. Other concerns that must be addressed to inspire and facilitate effective interaction include robot appearance, behavior and object sensing. Specifically in mining operations, the diversity in this field such as variation in mining methods and the extremely harsh mining conditions, acidic water, and exposure to rockfall, might serve as barriers to the implementation of robot and digital technologies in mining operations. This is unlike an industry such as automotive industry, which is relatively uniform across the country. The unhealthy underground mining operations may cause the failure of sensors and the robot communication network. With this, robots and other digital technologies should be designed based on their application. The technology should be designed and built to meet technical and operational demands and standards (António, 2013).

Additionally, ergonomics abilities are another significant feature of cobot systems. That is their precision, strength, and endurance in performing tasks which helps to reduce human physical and cognitive functions. These attributes allow operators to dedicate decision-making skills to value-added activities. The fundamental prerequisite to be considered during the development of cobots is the safety of humans working around robots. Recent advances in digital technologies have also impacted the actual industrial robots, making them more autonomous and effective in performing specific functions in public places without compromising safety. An example is the mobile Julius robot presented in a study by Grehl, et al., (2015). This robotic system consists of a robotic arm and an articulated three-finger hand, illustrated in Figure 2.2. The Julius robot's primary objective is to assist miners by deploying its robotic arm and specialized gripper to perform demanding, precise, or hazardous tasks in co-working scenarios. The robot carries Wi-Fi stations to extend the network's range and deploys its gripper to position them on the floor in response to weakening Wi-Fi signals to achieve its goals. Integrating robotic systems and other automated technologies is now more prevalent than ever before and is proving to be an indispensable component of modern mining practices. The mining industry has a well-established track record of employing automation across various phases of mining operations, such as drilling and extraction. According to Ragaglia, et al., (2014), the application of automated systems in underground mining operations was used to increase productivity and to remove the miners from exposure to highly respirable dust.

Figure 2.2: An articulated three-finger gripper "Julius" designed to operate like human hands (Grehl, et al., 2017)

Over the years, extensive studies have been conducted on the advancement of cooperative robot technologies for various engineering fields. For instance, collision detection algorithms for motion planning tasks are used to avoid contact and limit impact forces in the worst case. According to Scoccia, et al., (2020), a certain degree of redundancy is necessary for kinematic reconfiguration when the robot works in environments with potential obstacles. The redundant manipulator is listed as the best feature in collision avoidance. Redundancy in robot manipulators is crucial in cluttered environments containing obstacles. It enables the robot to reach its goal while successfully avoiding those obstacles. However, to achieve real-time path planning capabilities for manipulators with a high number of degrees of freedom (DOFs) operating in unstructured environments, it becomes necessary to integrate redundancy control frameworks with attraction and repulsion vector fields. Cobots are gaining attention even in heavy industrial settings.

However, despite its application in manufacturing and other sectors, the mining industry has yet to see the same advancement due to its harsh working conditions and inherent difficulties in navigating the robot through uneven and rough terrain in mineral extractive operations (Green, et al., 2011).

Robots are deployed to replace or assist humans in accurately performing various repetitive and tedious tasks (Akli & Bouzouia, 2015). Due to the rapidly evolving field of robotics and AI, robots are not only sharing the same workspace with humans but also using robots as assistants. According to Javaid, et al., (2022), the integration of robotic system in production lines allows operators to have access to real-time information, estimation of production demand, and provision of proactive, predictive and prescriptive maintenance using new big data analytics. Figure 2.3 shows various applications of cobot technology for industrial usage.

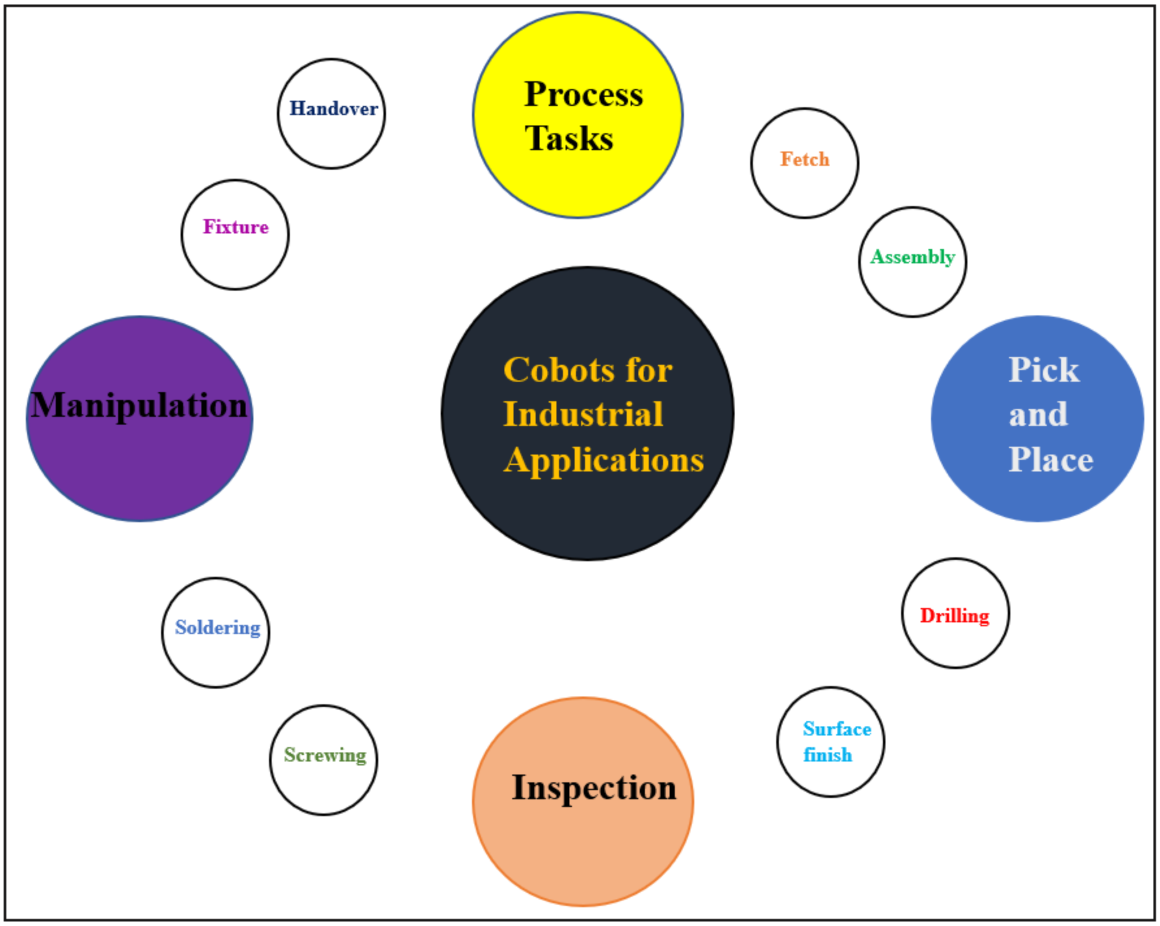


Figure 2.3: Qualitative features of cobots for industrial applications (Javaid, et al., 2022).

2.2 Applications of Robotic and Digital Systems in Mining Operations

The primary goal of any mining company is to extract as many minerals as possible in an economical manner without compromising the health and safety of the personnel. Since the introduction of cobots and automated technologies in mining value chains, there has been significant improvements in the overall mine productivity and the safety of the miners (Salvador, et al., 2020). The adoption of robotic systems in the mining value chain was predicted to increase over time as mining companies are likely to improve mine sites' safety and health performance. Different types of robots are being introduced into mining operations to perform various tasks such as robotic dozing, excavation, drilling and blasting, and transport of fragmented rocks. The emergence of many adaptative mobile robots equipped with sensors to perform human tasks in mining operations motivates the industry to implement more mining robots into their operations. Also, considerable technological improvements and reduced costs, introducing new approaches for remotely operated equipment to extract minerals, expanded utilization of automation and fostered the application of robotic systems across the mining value chain (Paredes & Fleming-Muñoz, 2021). In addition, existing mining robots and autonomous technologies have recorded significant improvement by increasing productivity, enhancing safety and reducing operational costs.

The fluctuation in the profit margin of mining operations due to increased operating expenses and production costs encourages the implementation of automated systems in mining operations. The use of autonomous equipment in mining is primarily driven by the benefits that their applications provide to various mining operational stages. These stages include prospecting, exploration, development, exploitation, and reclamation. Notably, the advantages of automation in mining can be divided into three significant areas; productivity and efficiency, health and safety, and cost savings. There is no doubt automation can equate to increase efficiency,

A study by Lopes, et al., (2018) compared human and robot efficiency in performing mining tasks, the results of which are shown in Table 2.1. Compared to humans, the strength of autonomous systems is that they can work for more extended periods repetitively, making them suitable for mining operations. Also, machines do not need breaks or changing shifts, which saves time in operations.

Table 2.1: Comparisons between Human and Robot in executing mining tasks and features (Lopes, et al., 2018).

Mining Features	**Humans**	**Robot**
Mining in harsh environments	Impossible	Possible
Actions in narrow or confined place	Impossible	Possible
Transference of heavy loads	Up to 50kg (110.23 lb.)	Up to 200kg(440.93 lb.)
Speed of manipulation	Low	High
Integration and exchange of information	Difficult and limited	Simple and fast
Stable work without intervals	Impossible	Possible
Sensing capacity	Hard visual, acoustic (50-1200Hz), tactile, olfactory	Visual in non-optic range, acoustic in non-audible range, exact measurement of speed, temperature, depth, forces etc.

The mining industry is gradually undergoing significant changes as mining operations are becoming more autonomous through the integration of digital systems to improve miners' safety and increase productivity. Some of these autonomous systems that are gaining ground in the mining industry include haul trucks, automated drilling and tunnel boring systems, drones, smart sensor technologies, electric power trucks, autonomous equipment monitoring, loader and long-distance haul trucks. Automation also facilitates the use of battery-operated equipment because it allows for different types of sensors to be deployed on the equipment. The invention of mini robots programmed to navigate, explore and perform human tasks in underground mines are technological innovations that have changed the mode of operations in mining. Recent studies suggest that the introduction of robots and autonomous technologies in the mining value chain will address the prolonged miners' health and safety issues in mining operations (Green, et al., 2011; Salvador, et al., 2022; Sanmiquel, et al., 2018; Paredes and Fleming-Muñoz, 2021). It was long predicted that the adoption of autonomous machines in mining operations could add up to US$56 billion to the industry by 2025, because machines can enable the mines to operate for longer hours, at higher levels of productivity and lower personnel costs (World Economic Forum (WEF), 2017).

The automation and digitization of mines are mutually reinforcing trends. The increase in the rate of integrating robotic systems into mining operations shows that mining companies are moving from manual labor to autonomous machinery as a solution for safety, efficiency, and increased productivity (Lopes, et al., 2018). Examples of mines that have adopted automated technology in their operations are the iron ore mines operated by Rio Tinto in the Pilbara region in Australia. The mine is equipped with an autonomous train of three locomotives that transport around 28,000 tonnes of iron ore for over 280 kilometers (174 miles) from their mining sites in Tom Price to the port of Cape Lambert (Rio Tinto, 2023). Similarly, another iron ore mining site in Australia is regarded as the global industry leader in mining automation. The Roy Hill iron mining site owns the world's single largest autonomous haulage system (AHS) (Moore, 2023). Also, the Diavik diamond mine in northern Canada, owned by Rio Tinto, deployed AHS machinery for fleet operations. One of the significant benefits of the AHS machinery to the conventional haul truck fleet is that AHS trucks can operate for nearly 24 hours every day of the year in dedicated autonomous operating areas. Interestingly, the AHS can interact with excavators and numerous ancillary vehicles at the intersection, waste dumps, and load areas. In the Rio Tinto Pilbara iron ore mine site in Western Australia, the company also operates autonomous drill systems (ADS) to drill production blast holes. These automated drill rigs can drill blast patterns more quickly and accurately than any human or human-operated equipment. These machines are controlled remotely by people from another operations center (Rio Tinto, 2023). The autonomous fleet outperforms the manned fleet by an average of 14% and has 13% lower operating costs (Motion Metrics, 2019).

Another innovation in mining operations in recent years that deserves attention when discussing automation in mining operations is the noticeable improvement in sensing and monitoring systems in real time. The sensing attribute of digital technologies is considered one of the major features in control and operational decision support, especially in autonomous systems. The advancements in sensors and GPS technologies make automation more practical and efficient. The integrated sensors in various autonomous machinery provide real-time data that can be used in making sound decisions regarding safety and equipment performance. Examples of these sensors include:

- Ultrasonic sensors for recording distances.
- LiDAR for mapping and navigation of autonomous equipment.
- Radar to determine objects' location, angle, and velocity.

Autonomous vehicles are fitted with various sensors which transmit the locations of their operation and vehicles' engine information through the Wi-Fi network and issue alerts when maintenance is needed (Sam-Aggrey, 2020). The motive for the application of these smart sensors is the drive to collect data in real-time to make sound decisions on mine safety and locate the position of equipment and personnel in underground mines. Secure communication is crucial for the success of sensors facilitated by installing multiservice, secured IP throughout the mine and enabling reliable Wi-Fi connectivity underground.

According to Sam-Aggrey (2020), the successful integration of AHS in mining operations depends on many factors, including the mine design, available local infrastructure, topography, and the size, scale, longevity and remoteness of mining operations. One of the notable challenges of using autonomous equipment in underground mines can be the frequent failure of the electronic components, such as sensors of the autonomous equipment, which can affect the system's performance. Also, environmental factors such as temperature could affect the deployment of autonomous systems in mining operations. Mining companies in colder climate countries may be skeptical about deploying AHS because of difficulties due to cold weather. Despite these challenging factors, the statistical trend in mining automation shows a continuous, incremental growth in the testing of these autonomous technologies in various mines.

The design of autonomous equipment is based on the integration of sensors used for positioning, recognizing surrounding objects, decision making and autonomous vehicle steering control. These sensors are based on configurations that should be accurate and robust to make sound decisions about their immediate surroundings. A favorable condition assists the sensors to perform optimally and generate accurate results (Rowduru, et al., 2019). Unfortunately, extreme temperatures and harsh working conditions are common in underground mining environments. Current changes in the pattern of weather events and future climate impact can also affect digital technologies. These conditions degrade the performance of digital systems and autonomous systems, like accuracy, delay in response time, residual life, and reliability. Therefore, it is imperative to carry out regular preventive maintenance, testing, diagnosis, and other technical analyses to check the reliability and performance of the installed digital systems.

However, the growing demand for mining products, especially those identified as critical minerals for industrial sustainability and economic breakthrough, has given rise to the application of robots and digital technologies across the mining value chain to enable easily accessible ore reserve that is gradually depleting. The decline in ore grades and profitability margins in mining operations necessitates companies to mine deep to reach new deposits, resulting in higher operational costs and lower profit margins. As a result, underground mining will continue to progress to a deeper level to meet the demand for minerals. This implies extraction from the greater depth, posing risks to the miners due to the hostile work environments. The hazardous work environment is becoming increasingly unattractive to mineworkers as the depth and location of these minerals expose mineworkers to various occupational hazards. Also, gaining access to the deposit is becoming difficult because of poisonous gases, dust, high temperature, poor ventilation, complex and challenging mining conditions. For instance, high temperatures in underground mines will not only affect miners' physical and mental health by reducing their work efficiency and causing accidents, but also trigger the thermodynamic effect of rock masses and produce unexpected mine disasters (Li & Cai, 2021). The potential solutions to these challenges lie in removing humans from hazardous working conditions and relocating operators to a safer environment. The drive to reduce costs, increase efficiency, and gain access to new and profitable reserves has triggered a surge in the global mining industry to accept and deploy automated technologies in their operations (Keenan, et al., 2019). That is, there is a need to implement autonomous equipment that can be controlled remotely and perform human tasks accurately.

Most mining companies are trying to improve safety by removing people from the immediate vicinity of their operations, thereby increasing productivity (O'Connor & Sertic, 2020). Several studies predict that applications of digital and autonomous technologies could transform the mining industry by improving worker’s performance in harsh working environments such as in underground mines. In recent decades, the mineral extractive industry has introduced new technologies that have significantly lowered the total number of fatalities and incidence rates (Ruff, et al., 2011). Recent statistics on mining-related accidents have shown tremendous improvements as injury rates continue to decrease. Despite the notable improvement in safety performance in mining operations, the common expectation of achieving zero harm promotes a continuous demand for further improvements. The need for improvement in safety motivates the development of new generation of robot technologies that can potentially enhance the health and safety of the miners.

2.3 Relevant Studies on Mining Machine Automation

Since the introduction of automation into the mining industry, there has been an increase in mining productivity over the years, as shown in Figure 2.4. Thereafter, automation of mining machines has advanced over time. In the past, the classification of automated machinery was limited to those that were teleoperated. Nowadays, automated equipment can now be categorized as teleoperated, semi-automated, and fully automated machine (Ghodrati, et al., 2015). Todd, et al., (1993) reported that in the early 1990s, significant attention was given to the automation of drilling operations. However, with the current advancement and innovation in technology, as well as automation efforts in mining operations, the full automation of deep mines can be achieved in the next decades (Rogers, et al., 2019).

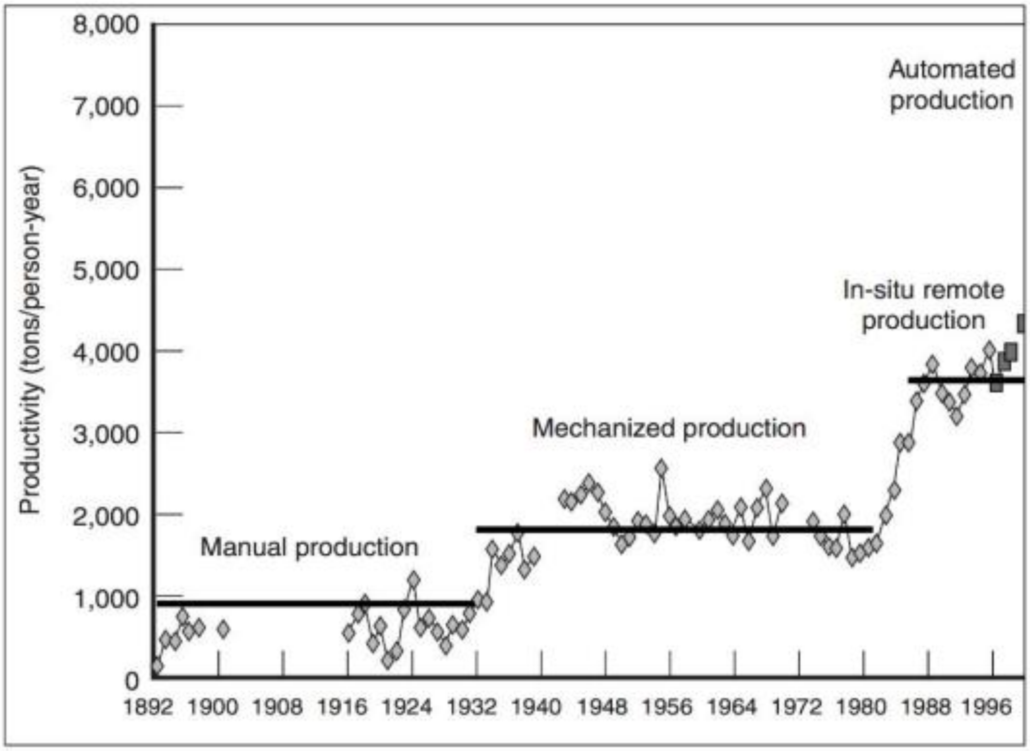


Figure 2.4: Increment in productivity as a result of change in technology (Cosbey, et al., 2016).

Apart from the increase in production, automation of mining equipment can substantially reduce exposure to risks, especially in extremely hostile environments such as underground coal mines. In this light, robots and automated technologies can become valuable tools for detecting these hazards before failure. The introduction of robots and automated technologies in the mining value chain has changed the design of workflow. Automating tasks previously performed manually by miners is now a viable option; tasks done manually by miners can now be achieved with automated systems. Scholars predicted that adopting autonomous technologies would disrupt the world labor market. According to Paredes and Fleming-Muñoz (2021), the adoption of automated technologies could affect the labor market in the future as mining is regarded as a capital-intensive economic process. The implementation of autonomous systems in the mining value chain does not remove humans from mining operations, but instead allocates them to a new task that might require new skills. Therefore, deploying robots and autonomous equipment would increase the high-skilled labor force. The system would require a workforce with a suitable background and technical know-how, such as computing and coding, to operate the automated technologies. Unfortunately, the application of robots and autonomous systems in underground mines is still limited compared with other engineering fields (Zimroz, et al., 2019). A number of studies can be found in the sections below discussing various attempts to automate mining equipment using digital systems in all phases of mining operations.

There have been growing efforts to automate loading hauling and dumping (LHD) vehicles due to the rapid technological advancement in research and development of underground mining machines. The LHD is the most common equipment used in underground mining. Several researchers have conducted extensive studies on designing and developing autonomous LHD machines for underground mining environments. According to Tatiya (2013), the LHD is used in more than 75 percent of haulage equipment in underground mining operations. Despite its usage, LHD automation remains a much less developed area (McKinnon & Marshall, 2014). Automating LHD machines is challenging, but automation will enhance operational efficiency, cost efficiency, and safety. Larsson et al. (2006) proposes a fully automated navigation system using the fuzzy behavior-based approach to navigate underground LHD vehicles. Marshall, et al., (2016) also presented an automated way to load materials using draglines and shovels. The task in the automation of a loading system is the development of excavation algorithms that imitate how operators work by tilting the bucket intermittently while excavating to penetrate the material. Another initiative was discussed by Tampier, et al., (2021) on detecting wheel skidding using LiDAR-based odometry and internal measurement of the LHD's actuator.

Marshall, et al., (2008) study lists challenges facing the development of autonomous robotic excavation equipment and most of them depend on the interaction between the bucket and fragmented rock. During excavation, bucket-rock interaction forces affect the bucket motion through the material, ultimately defining the amount of ore loaded. The geometry of the rock mass and particle sizes and shapes create resistance for the bucket as it attempts to scoop the fragmented rock pile depending on the properties of the rock, such as the density and hardness of the rock. Another significant challenge in developing autonomous LHD equipment is the issue of developing hydraulic actuated steering, which controls the vehicle at high speed.

A recent study by Rowduru, et al., (2019) mentions some of the problems facing the development of autonomous LHD, including the positioning of the vehicle, signal processing and communication in underground mines, maintaining a constant distance from side, location of the loading and dumping points, modeling of vehicle and path tracking controller and vehicle stability analysis. The outcome of their study addresses the challenges of hydraulic-actuated steering in an autonomous vehicle. One of their suggested solutions is using variable frequency drive (VFD) to control the motor's variable speed. The method applied VFD to control the flow entering the cylinder to achieve the desired actuation. Apart from the abovementioned solution, there are other suggested approaches to control the automatic steering mechanism of an automated vehicle, including the use of a proportional direction control valve to control the flow entering the steering cylinder, application of a variable displacement pump to close the loop and lastly, the application of a stepper motor to generate the required torque to regulate the flow to the steering cylinder.

Moreover, the environmental conditions in most underground mines can also influence the automation process of the machine. Hemminghaus (2005) stated that humidity could increase cohesion forces making the overall LHD process difficult. Other conditions, such as the uneven terrain and water around the draw point, can make the loading process challenging. These factors make it difficult to design an exact bucket for future excavation prior to the execution of any particular operation. Thus, during the design of the autonomous LHD machine, the autonomous system must consider these features to perfectly mimic the operators deal while driving the LHD, such as detecting an accurate enough position of the rock pile before charging at it for effective navigation within the drifts while pulling back from the rock, and estimating if the bucket is full enough (Tampier, et al., 2021).

In addition, larger fragmented rocks can be present at the draw points, which operators can detect as the LHD approaches the draw point. While in autonomous LHD, the system might not be able to maneuver the loading, which might abort the loading operation if the rock is too big. Chadwick (1996) reported that Caterpillar and Komatsu attempted to automate haul trucks in the mid-1990s. Marshall, et al., (2016) stated that the first commercial driverless truck was seen at the Gaby Mine in Chile. Thereafter, several attempts have been recorded in efforts to automate the equipment. Larsson, et al., (2008a) successfully tested an automatic LHD for backfilling operation. Gu, et al., (2019) proposed an optimal trajectory planning method for LHD in turning maneuvers, reducing the vehicle's driving time. Larsson, et al., (2006) developed a cheap and robust automated navigation system using a fuzzy behavior approach to navigate the LHD. Larsson et al., (2008b) installed sensors and control systems for autonomous navigation of the LHD vehicle, as shown in Figure 2.5. The study developed algorithms to detect cross cuts on each side of the tunnel and compute a rough estimate of the direction of the tunnel relative to the robot. The detection algorithm provides input for topological localization and matching topological artifacts to enable navigation.

Figure 2.5: LHD vehicle incorporated with sensors and control for autonomous navigation (Larsson, et al., 2008b).

In recent times, the use of robots for inspecting mining equipment and real-time machine monitoring in underground environments has been gaining more prominence. Mechanical systems in underground mining require adequate supervision and monitoring to prevent downtime in operations. One of the mechanical systems in underground mining operations is the conveyor belt. In most mines, conveyor belts transport bulk material for considerable distances, consisting of the belt running over rollers installed on a fixed frame. Traditionally, machine monitoring is performed by human operators based on perception. The introduction of robots to inspect and monitor is the game-changer that improves working conditions as identification of issues that might have caused the delay in operations are addressed on time.

Rocha, et al., (2021) and Szrek, et al., (2020) performed an autonomous conveyor belts inspection process using a robotic device. Rocha, et al., (2021) deployed a wheel-tracked mobile platform robot named ROSI to monitor conveyor belt performance, such as adjusting the contact force for touching the conveyor structure. The robot has a total of 15 degrees of freedom (DOF) that contains four traction modules, four tracked flippers, and seven joints of the anthropomorphic manipulator for automatic anomaly detection. In their experiment, the ROSI robot uses a hybrid wheeled locomotion mode to overcome obstacles, including climbing stairs. The result of their field test demonstrated that the robot has the potential to withstand harsh operating conditions while executing the inspection task. On the other hand, Szrek, et al., (2020) developed an inspection robot mounted on an unmanned ground vehicle (UGV) platform to collect data that will be used for conveyor belt maintenance. This robot has an RGB camera to see the conveyor route and to identify hot spots using infrared thermography, as shown in Figure 2.6. The video fed is wirelessly transmitted using a selected channel at a frequency of 5.8 GHz to a remote-control panel. In fault detection operations, the robot's GPS module facilitates the determination of fault location with high accuracy. However, a localization system based on ultra-wideband (UWB) transceivers is utilized when operating in underground mines where GPS signals are unavailable.

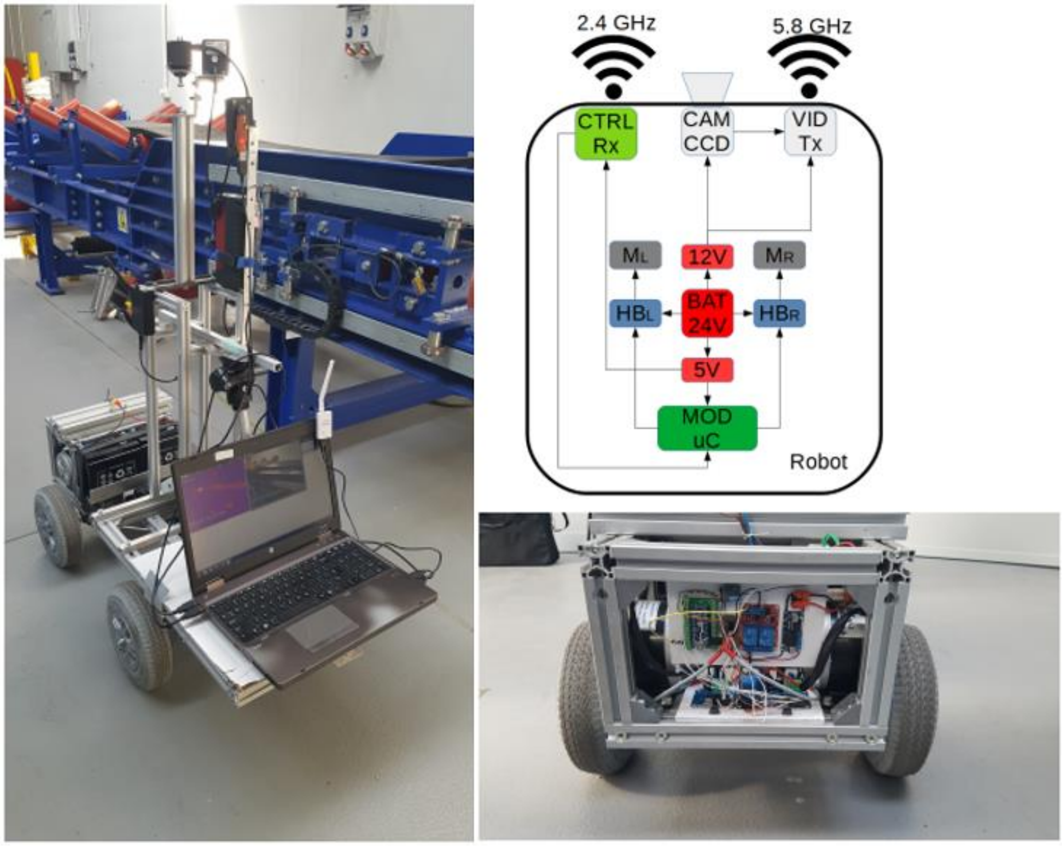


Figure 2.6: An inspection robot for monitoring conveyor belt (Szrek, et al., 2020).

In addition to integrating sensors in mine machinery, the implementation of global positioning system (GPS) technology has also played a key role in mining equipment automation. This technology has been useful for controlling navigation and collision prevention in mining haulage equipment. One of the common applications of GPS in surface mining methods is the self-positioning of drilling rigs in rock fragmentation operations. An example of this is the GPS-based blast hole system that eliminates the need for a manual survey of the mine to provide guidance for the navigation of the drill rigs. Likewise, integrating GPS systems in mining fleet vehicles has enhanced fleet management systems by providing real-time tracking and monitoring of haul trucks. Also, it reduces accidents resulting from low visibility conditions and blind spots of trucks by providing 3D information about the truck's surroundings based on the GPS. Today, GPS is widely used in open pit mining operations for fleet management, localization and positioning of equipment, and mine vehicle collision prevention.

In the study by Chaowasakoo, et al., (2015), they used GPS to track and manage the truck fleet at the Adaro coal mine in Indonesia. Their study examined the benefits of using GPS in a coal-hauling operation. The study outcome presents an opportunity for the GPS to maximize the efficiency of fleet trucks and increase production while removing the overburden. Similarly, Gaber, et al., (2012) installed GPS on driverless AHS to control and navigate without human intervention. The AHS relies on robust wireless communication for control while using GPS-derived coordinates from a detailed map for navigation. Apart from creating a detailed map, the GPS signals also provide haul vehicle dispatch information and haul road information in real-time through wireless communication infrastructure and tracking of the current location of the dump truck. Likewise, Baek, et al., (2017) developed a Bluetooth beacon-based underground navigation system (BBUNS) to identify haul roads in an underground mine. The BBNUS device provides information on trucks, such as the real-time location, construction of three dimensions (3D) of the geographic information system (GIS) database of the haul roads in an underground mine, and calculation of travel time for each section. The advancement in positioning technology brought about the application of Simultaneous Localization and Mapping (SLAM). The SLAM is used to locate the position of equipment on a map. Thrun, et al., (2004) and Nüchter (2009) successfully mapped an abandoned mine using the SLAM algorithms. Lösch, et al., (2018) deployed an autonomous robot that integrates an Inertial Measurement Unit (IMU), lighting, two RGB cameras, a laser scanner, and a SLAM algorithm to map and navigate underground mining environments. SLAM has been a valuable tool in determining the location of robots in underground mines due to the absence of GPS. However, the SLAM algorithm still requires further improvement to its robustness and accuracy among degraded scenes with less structure and low illumination (Tardioli, et al., 2019).

In underground mining operations, localization and positioning of equipment and personnel have been challenging tasks since the signal cannot pass through the earth. This is a major drawback for researchers in this area. However, much effort has been placed on the navigation and guidance of mining vehicles in underground environments. One of the trials in Australian mines was discussed in Batterham (2017) study. The work reported that 2D laser scanning technologies were used to navigate a 30 t LHD. Similarly, Bissiri, et al.,

(2008) used the combination of a laser scanner and INS as a new automated surveying instrument. In Chi, et al., (2012) work, autonomous navigation and positioning of LHD and scrapper were achieved for underground tunnels with laser scanning systems, barcode theory, and special beaconing.

Another application of automated systems is in gas detection robots in underground mining operations. Nowadays, robots are widely used in detecting gas and dust explosions in underground coal mines. Li, et al., (2019) built a coal mine rescue robot (CMMR) to detect gases in underground coal mines. Kasprzyczak, et al., (2012); Reddy and Krishna (2015) developed a mobile inspective robot to monitor explosive and toxic gases in underground coal mines. The communication between the robot and the operator is only limited to wired connections, as the radio waves are attenuated by the rock mass and isolated dams (Kasprzyczak, et al., 2012). A study by Murphy, et al., (2009) highlighted the importance of deploying mobile robots in mine rescue in the United States. The robot was developed with 3/8 in clearance which is approximately 8 inches wide, 19.5 inches in length and an additional 14.5 inches. In one of the experiments conducted with the robot to search for missing miners, the robot was able to search the ledges and the mine floor for the victims.

Green (2011) reported that the Council for Scientific and Industrial Research (CSIR) in South Africa built a mine safety robot to inspect hanging walls in deep underground gold mines. The mine safety robot was developed to address the challenges by enhancing miners' safety in South African hard rock mines through sense and navigation in harsh underground stope environments. The authors used thermal imagery and 3D structure to create a 3D model of the mine. In one of their attempts to model the mine, an IR camera to evaluate hanging wall risk was insufficient for complete analysis as rock mass protruding into the stope will also be cooled by the passing ventilation air. But the 3D topographical information would be a critical parameter for assessing the rock mass stability. The outcomes of the study showed that the addition of 3D sensors made it possible to register the 3D surface of the thermal texture, which in turn could be used to determine the stability of the rock mass.

Moreover, considerable progress has been recorded in automating the drilling process in mining operations. The primary objective is to remove human involvement from these operations by enabling autonomous drilling fleets to execute drilling tasks independently. Autonomous drilling fleets are equipped with advanced technologies such as Global Navigation Satellite Systems (GNSS) and machine learning algorithms for making decisions and carrying out operations, as shown in Figure 2.7. Satellite-based positioning drilling machines is increasingly preferred for accurate and efficient hole positioning and alignment in mining operations. In traditional hole navigation systems, a drilling operator is aided by precision sensors and a satellite positioning receiver that compares the boom's position and attitude to the predetermined drilling plan. On the other hand, the new satellite-based approach provides superior hole accuracy compared to conventional methods where the boom is manually positioned using rig controls (Pirinen, et al., 2014). The operator receives support from a system that includes a satellite positioning receiver and precision sensors for the boom in such a setup. The automated drills are renowned for their convenience and accuracy, resulting in improved blasting quality, increased productivity, and reduced costs (Pirinen, et al., 2014). Rio Tinto has 26 autonomous drills that can safely and accurately drill blast holes from a remote location (Rio Tinto, 2023). Operators are located at the company operation center during autonomous drilling operations to plan drilling activities rather than manually operating the machine.

Figure 2.7: Automated drilling machine receiving signal from GNSS (Liebherr, 2023).

Similarly, a team of researchers from the Australia CSIRO developed an automated vehicle called the robotic explosive charging system (RECS) for charging blast holes. The machine is designed to insert primers and detonators into already drilled holes in the roof and walls of development drives and fill the holes with liquid explosives. The study uses a robotic arm equipped with sensors such as laser ranger finders and a camera installed in the end effector to automatically insert the emulsion into pre-drilled holes (Bonchis, et al., 2014). Rio Tinto introduced the technology into their operations to automate the process of pumping explosives into drill holes. According to Rio Tinto (2023), the machine is equipped with a computer system to determine the right amount of explosives to use for each drill hole, which helps to reduce wastage and improve the effectiveness of the blast.

In a recent development, a collaboration between ABB and Swedish mine operators Boliden and LKAB developed and tested an automated explosive charging robot designed to detect and fill already drilled holes with explosives and detonators. The test was conducted in a pilot project at Boliden Garpenberg, an underground zinc mine in northern Stockholm, Sweden (Evans, 2023). The developed technology comprises vision systems and automation solutions that establish communication with the truck, crane, and ABB robotic arm, as shown in Figure 2.8.

Figure 2.8:Automated explosive charging robot (ABB, 2023)

The technology is constructed by integrating an industrial robotic arm into an existing truck to mimic the human functions of assembling detonators and primers, which led to the automation of the charging process of all the boreholes in underground mining operations. Traditionally, the charging of explosives into drill holes for blasting is done by humans, which presents many risks to personnel filling the holes with explosives. Introducing an automated explosive charging robot minimizes personnel exposure to health and safety risks by moving humans away from potentially charged explosives and increases opportunities to optimize this task repeatably.

The robotic arm has cameras to scan and detect boreholes within the designated scanning area. The charging process of the boreholes begins with the robot grabbing the detonator cassette from the detonator magazine and fixing it to the primer, which is connected to the charging hose. The charging hose is then moved to the position of the first hole, and the charging hose is inserted into the bottom of the drilled hole. Subsequently, explosives are pumped through the hose, and the hose is retracted. Upon detonating the initial hole, the robotic arm systematically advances to the next drilled hole to start the process again.

In recent times, the roof bolter machine has gained significant attention due to the hazards that operators are exposed to while carrying out the roof bolting process in mining. In underground coal mining operations, the roof bolter machine is regarded as the second-highest fatality rate among U.S. employment sectors, with 15.1 fatalities per 100,000 full-time equivalent workers (Sammarco, et al., 2016). Since its introduction into underground coal mines in the early 1970s, several attempts have been made to automate the machinery to move operators from active mining faces. One significant improvement was incorporating Automated Temporary Roof Support (ATRS), which serves as a roof support system (Hammons, et al., 2009). The ATRS was developed to prevent roof skin failure during roof bolting operations. The development of the deflector system has improved the safety of the operator during bolting operations. However, there are still dangers lurking overhead that can pose risks to the roof bolter operator. Likewise, Finfinger, et al., (2000) developed a monitoring and control system that identifies different rock properties during the roof bolting drilling operation; Kyslinger (2017) designed and manufactured a roof bolting machine to drill and install six bolts simultaneously with a limited number of operators. To reduce roof falls injuries on roof bolter operators, Robert and Prosser (2007) developed a system that can be used to collect data related to torque, thrust, and rotational speed during drilling operations. They used a real-time device with a Fletcher Information Display to examine the roof condition during the roof bolting operations.

There are also notable improvements in the automation of longwall mining equipment. The gamma-ray coal thickness sensor in longwall was developed from late 1989 into the early 1990s (Peng, et al., 2019). Ralston, et al., (2017) reported the application of inertial navigation technology in underground environments for accurately positioning and guiding a longwall machine. Reid, et al., (2016) stated that the integral inertial guidance system for automation of the longwall coal mining process was developed by Longwall Automation Steering Committee (LASC). Wang and Huang (2017) categorized automation development in LASC in recent years as 3D remote monitoring video feeds, the 3D position of the shearer, keeping the conveyor and support straight and level, and raising the shearer drum automatically. Another significant effort to automate the longwall mining operations is the measurement of the shearer path in three-dimensions using an inertia navigation system (INS) (Billingsley & Brett, 2015). In the work of Wang and Wang (2020), the authors installed the INS to know the exact shearer position in a longwall mining face. Similarly, Xu and Wang (2010) developed a shearer working path system using the sensor information of the shearer, scrapper conveyor and hydraulic support to define the shearer position. This approach involves collection of real-time data from the shearer's movements, alongside static data from the conveyor shearer and hydraulic supports, to obtain the three-dimensional location of the shearer.

Also, Xie, et al., (2017) installed the tilt sensor and strapdown inertia navigation system (SINS) on the shearer body to measure the shearer body pitch angle and the scrapper conveyor shape, respectively. The main limitation of this approach was its ability to indicate only the shearer position in one-dimension instead of a three-dimensional position. Boloz and Baily (2020) also discussed an attempt to automate the MIKRUS longwall system to extract thin coal seams. In the studies by Ge, et al., (2012), one can find the applications of autonomous technologies in drilling and defragmentation of oversize lumps. Li and Zhan (2018) developed equipment with independent intellectual property rights for unmanned control technologies for rock-drilling jumbos, down-the-hole (DTH) drills, underground scrapers, underground mining trucks, and underground charging vehicles. Marshall, et al., (2016) introduced an automated way to load material using draglines and shovels. Similarly, Dunbabin and Corke (2006) proposed an automated approach to detect and avert dipper stalls in an electric rope shovel. Another notable attempt is the automation of a continuous mining system for underground block caving mining method, as reported by Castro, et al., (2015).

In conclusion, the automation of mining machines has received notable attention recently. Historically, innovation in technology and the conversion of manually operated mining machines to automated machines have been driven by equipment manufacturers and vendors (Rogers, et al., 2019). The implementation of automated technologies in the mining value chain has grown exponentially due to numerous benefits provided since its introduction in recent decades. Notably, mining costs are drastically reduced, and most important, the safety of operators is improved (Chi, et al., 2012).

2.4 Challenges Facing Automation in Underground Mining Operations

The need for automation in mining operations is the result of the inability of humans to perform specific functions due to risks associated with the tasks. The fundamental goal of automation is to develop machines that can perform repetitive or hazardous tasks, thereby improving the safety of humans. Advancements in machine sensing and vision influenced the design and development of automated technologies that behave and act like humans. Notably, automation has significantly impacted three critical areas in the mining industry: productivity and efficiency, health and safety, and cost savings.

Despite the progressive impacts and benefits of integrating autonomous systems with the long-term target of an unmanned mine are confronted with numerous difficulties. Mining companies are still skeptical of deploying these smart technologies into their operations due to some of the factors mentioned below.

2.4.1 Complexity in geology and harsh underground mining conditions

Underground mines are challenging workplaces, not only for humans but also for machines. Natural hazards, limited space, lack of illumination, dust, humidity, high temperature, and mine atmosphere hinder the automation process. These hazards pose risks not to operators but can also be detrimental to digital systems. Günther, et al., (2019) reported that, the environmental conditions of underground mines are highly dependent on the depth of the mine; the mineral extracted, the surrounding rock and geology, the mining technology or current use of the mine and several other factors, which are unique to each mine. Typically, underground mine temperatures range from 8^0 C to 50^0 C, which defines the high temperature requirement for material and machine durability. The demanding mining conditions in mining operations that threaten miners survival often motivate the deployment of robots. Despite its success story in manufacturing and other sectors, the mining industry has not seen the same advancement due to its harsh working conditions and inherent difficulties in navigating the robot through uneven and rough terrain in mineral extractive operations (Green, et al., 2011). The effects of these challenges in the mining industry can be seen as the factors that influence the level of technological development in mining compared to other sectors.

Apart from high temperatures underground, the presence of water either dripping or remaining stagnant on the floor of the mine, combined with acid mine water can lead to corrosion or electrical short circuits in mining machines. In addition, the absence of natural lighting causes complete darkness without artificial light in underground mines. This creates challenges, particularly for detection algorithms reliant on optical characteristics which contend with highly variable lighting conditions. In underground mines, these challenges can be attributed to the location of deposits, harsh environment (dust, temperature, and humidity), seismic events, and the presence of suffocating and hazardous gases. The release of methane gas (CH_4) underground mines, especially in underground coal mines, can create explosive environments, making it imperative to prevent potential ignition sources.

Also, mining at greater depths has imposed a greater burden on the mine ventilation systems to maintain acceptable and safe work conditions. There are many heat sources that cause the increase of temperature and humidity of air during its travel through mine airways and production workings. However, these harsh environmental conditions could also affect the performance of autonomous machines. For instance, an increase in humidity can increase the cohesion forces, making the overall LHD automation process difficult (Herminghaus, 2005). Lastly, complexities in geology influence the continuous change in mine layout and mine designs. Hence, this could affect the mine operational cost as the existing autonomous systems may not be relevant to the new mining methods.

2.4.2 Technological and Technical Challenges

Navigation of autonomous equipment in underground mines is one of the most researched areas in developing underground mining automation systems and machinery. The unavailability of satellites in underground mining makes it challenging to create accurate maps of the roads with GPS, which should have assisted in tracking autonomous vehicle positions and states in underground mines. The absence of GPS in underground structures poses significant limitations to the applications and deployment of autonomous technology in underground mining environments (Gallo & Barrientos, 2023). At a minimum, an autonomous vehicle must possess information regarding its surrounding area, which is typically acquired through techniques such as laser scanning. While its geo-referencing within the mine can be considered an optional feature, it can significantly enhance the performance of the robot's mapping algorithms.

Autonomous systems accuracy, strength, and robustness in path planning and obstacle recognition lie in creating accurate maps. The map is an important parameter for autonomous fleet management to compute and forecast travel time between locations. Although, technological advances have brought about the development of LiDAR scanners known as the SLAM algorithm, which is a suitable replacement for GPS in locating autonomous vehicles on the map. However, one of the defects of using SLAM in underground mining environments is the issue of poor visibility due to dust and poor lighting conditions in the roadway. In addition, undulating floor, reflections on bodies of water, or shifting cross-sections, pose significant obstacles to autonomous navigation.

Some other technological hindrances confronting the application of autonomous equipment in the mining industry were discussed in Marshall, et al., (2016). These include lack of skilled workers to operate the autonomous systems; difficulties in developing proper infrastructure to mine in extreme environments; lack of technical support for robotics (e.g. automation of LHD); lack of adequate training and skills; difficulties in human-machine interface and interaction that can lead to sabotage of the systems; fail-safe operations; and variation in time taken to deploy systems in the field.

2.4.3 Economical Challenges

It is believed that a continual implementation of autonomous technologies in the industrial space will change the role of humans in the industrial workplace. This also holds for the mining industry. However, there must be a distinction between reducing human positions and eliminating human tasks in mining operations. Having the human role removed from the industrial system significantly changes the design and implementation of automation. Traditionally, the mining industry is a conservative sector, and workers resistance to change originates from their fear of being replaced by automation and subsequently losing their jobs. The fear of job losses contributes to the state and vision of accepting the integration of new technologies, which will take some time to change. While some scholars predicted that adoption of automated technologies could lead to job losses, it is expected that such technologies would create new high-paying jobs that require a new set of skills.

Currently, the mining industry is witnessing a need for new skills to operate autonomous systems, which may make it difficult for the operator to accept the technology. Therefore, the manufacturer deploying the autonomous systems needs to invest in people and the technology at the same time by playing a role in defining new skill requirements, providing educational opportunities to prevent skill shortages, and empowering the community at large (Global Mining Guideline Group, 2019). There is a need to define the workforce's needed skill sets, talent, and adaptability. From there, identifying newly required skills and discovering new skill pathways for individual employees in local and regional geographical areas can be set up. This approach would promote the retraining of existing employees that would work on the automation and determine the opportunity for cross-training.

Furthermore, integrating human factors in equipment deployment in mining operations would solve the automation problem for operators. This is why Haight, et al., (2021) suggested a series of workshops that would connects the stakeholders, academia, and industry to discuss if the equipment manufacturer addresses human development, as the operator will continue to interact with the autonomous equipment. This tendency is aggravated as robotics applications are used more to increase productivity and cut costs. Companies will likely have to invest more in the education and training of their local workforce.

Lynas and Horberry (2011) stated that overreliance on robotics systems could result in riskier behavior from mining workers, leading to hazardous situations. Another risk for mining companies is committing significant investments in unproven technologies, consequently holding back the spread of new technologies. They suggested that mining companies which are trying to deploy new technology into their system should learn from the mistakes of other industries where automation and tele-remote operation have already been used on a large scale. In most cases, the automated system loses situation awareness which may reduce the need for certain skills to operate the system. This does not necessarily mean a complete deskill in the workforce, but instead, it may lead to a shift in skills and knowledge required, such as programming code and data analysis. Also, Horberry, et al., (2010) recommended that mining companies should learn from other industries' mistakes by considering human factor issues, such as displaying equipment status for operators and maintainers to control and work on the equipment. This will solve many human-related issues that can lead to problems such as improper use of the equipment, employee distrust, and sabotage of the device.

2.4.4 Ethical Challenges (Human-Machine Relationship)

Autonomous equipment is designed to enhance safety and improve productivity. According to Lopes, et al., (2018), automated machines requiring a robust and consistent ethical and regulatory background is a crucial challenge and gap that can hinder the acceptance of automated systems in the near future. Despite the predicted benefits of robots in the mining industry, human behavior toward robots and other ethical questions about the technology and implementation needs further elaboration.

The change in the feedback mechanism in automated systems is another factor affecting operators with experience working with machines that require manual operation. Timely feedback is important for human-machine relationships. The designer and manufacturer of the automated technology should consider this parameter during the design and development phase. The change in feedback mechanism and design can have an adverse impact on the operator's performance and understanding of the automated processes. The lack of understanding of the feedback mechanism can reduce operators' ability to detect failures in automation (Rogers, et al., 2019). Due to the implementation of automation, operators must fulfill new training and knowledge prerequisites to gain a more comprehensive understanding of the system's capabilities. This necessitates supplementary training.

Rogers, et al., (2019) stated that before integrating automation into a mining operation, there are obstacles that need to be addressed for effective and sustainable performance of the technology. Their study used the human factor engineering (HFE) approach to describe the challenges and complexities of implementing automation in a social-technical system. The HFE method, based on its core perspective on automation, needs to be human-centered and not technology-centered. Moreover, when the designer tends to define the role of an operator as a by-product of automation, this can cause abuse of the automated equipment. The consequences of this can lead to misuse or disuse of the equipment by human operators (Parasuraman & Riley, 1997). Therefore, an operator must be assigned automation-related tasks to successfully integrate and use an automated device.

2.4.5 Regulatory and Legal issues

Currently, no generally accepted legal framework or guideline covers the behavior of intelligent autonomous and for the deployment of autonomous technology for underground mining. Lopes, et al., (2018) stated that the three principal legal requirements for robotics include liability, responsibility, and privacy. Responsibility would address the issue of autonomous robot acts against the law, which might result from poor development or manufacturer defects. Suppose the issue of who is responsible and what kind of penalty should be applied for the technology failure can be addressed; in that case, it will improve the performance of the autonomous systems. In most cases in robotics, the designers or manufacturers are held responsible since the autonomous system cannot be held accountable for their actions, such as failure or accident.

Also, the issue of privacy is another critical concern that needs to be addressed. Integrating automated systems leads to a substantial rise in the number of sensors deployed, generating a vast amount of data. However, in order to comply with legal regulations, it is necessary to collect and process this data in accordance with the extent to which personal data can and should be collected, in addition to determining the appropriate anonymization of such data in specific cases. Furthermore, the large volume of data collected presents challenges that must be addressed through the selection, evaluation, processing, and storage of the data utilizing appropriate algorithms. These considerations must be resolved before the initiation of data acquisition.

Specifically, in the mining industry, where there is no standardization of robotic mining equipment, the issue of data sharing with different levels of automation (fully autonomous, mixed autonomous, manual, or remote equipment) needs to be discussed. Where there are defined standards and regularities, data can be exchanged among systems developed by the manufacturers. According to Marshall, et al., (2016), legal concerns and insurance-related challenges could impede the adoption and implementation of autonomous equipment in the mining industry. The difficulty in making a proper risk analysis for autonomous machines can be a hindrance. Legal issues in mining can include the intellectual property of technology, data privacy, or environmental issues. Technology in mining represents a significant advantage and thus is likely to be targeted by other players in the industry aiming to replicate it, earning an unfair advantage. Mining companies are producing huge amounts of data due to automation; hence, there is a need to protect it; however, this is costly. Legal standards need to be leveled to raise environmental standards offered by automation to the mining industry for a sustainable mining sector.

2.5 Summary of the Unaddressed Areas in Literature

Sections 2.2 to 2.3 conducted a comprehensive literature analysis to ascertain the integration of various robotic and digital systems in mining equipment. A condensed overview of the critical knowledge gaps identified during this literature review, which directly align with the aims and research questions addressed in this dissertation, are summarized below.

1) Current studies on the application of robotic systems and automated technologies in mining machines focus mostly on the ability to execute specific tasks without emphasis on features to be considered in selecting suitable robotic systems for operations. For instance, the maximum length the robotic arm can extend to perform tasks and the operational environment, such as the confined spaces in underground mines.
2) Only a few articles discuss the method used in designing an effective human-machine interface for controlling and monitoring the state of the automated machine.
3) The literature does not discuss approaches adopted in establishing communication paths and control of the system units of the automated machine.
4) There is also a notable absence of real-time operation visualization to identify system failures or unpredicted activities that can lead to injuries and accidents. Visualization enables seamless collaboration between humans and robotic systems, which is crucial for safety and productivity.

2.6 Conclusion

Robotic systems offer valuable assistance to humans, particularly when the work is hazardous, physically demanding, or monotonous. An overview of state-of-art and behavior of robotic systems with its immediate environment has been discussed along with the comparisons between humans and robots executed tasks. This chapter also examined several attempts to automate various mining machines in surface and underground mining. Traditional machines were converted into automated equipment by integrating sensors to function autonomously. Examples of these sensors include:

- LiDAR for mapping and navigation of autonomous equipment;
- GNSS and INS for precise geospatial location and orientation of the equipment;
- Ultrasonic sensors for recording distances;
- Cameras; and
- Radar to determine objects' location, angle, and velocity.

Some mining equipment that has recently received notable attention include the LHD, AHS, DTH drills, continuous miner machine, LASC, roof bolter machines, underground scrappers, underground mining trucks, underground charging vehicles, draglines, and shovels. Also, the chapter has discussed some of the challenges facing the deployment and acceptance of automated technologies in underground mining operations.

Chapter three discusses some factors to consider when selecting a robotic system to integrate into existing underground mining machines. The robotic system's standard industrial configurations and specifications will be duly examined to ensure the appropriate selection of a robotic arm that can mimic human activities during roof bolting operations.

3. DEVELOPMENT OF SPECIFICATIONS FOR PARTIAL AUTOMATION PROCESS OF THE ROOF BOLTER MACHINE.

This chapter discusses specifications that must be considered when selecting a robotic system capable of performing human activities during roof bolting operations. The three major areas that must be taken into account for successful integration of robotic systems in underground mines are explicitly discussed: the people (miners), the process (work instructions and plans), and the technology. More importantly, the standard industrial configurations of the robotic arm are considered to ensure the success of the automation process. These include the robot's weight capacity, the robotic arm's extended reach, the axes' movement specifications, and its ability to fit within the workspace.

3.1 Roof Bolter Machine

The roof bolting technique is a primary support system used in underground mines critical to the safety of all workers underground. This approach has become a standard practice in ground control due to its effectiveness in reinforcing the ground and improving the stability of underground structures. The process involves installing roof bolts to mitigate any potential ground control issues. The installed bolts constitute a ground support system comprising a plain bar installed in a rock mass to prevent loosened keyblocks from moving from their positions by bonding them together. According to Elwawy, et al., (2020), a rock bolting tool is designed to enable a rock mass to support itself through the application of suspension and reinforcement of the rocks around the underground opening to support the rock mass.

The roof bolter machine is a specialized drilling machine in underground mining operations used to install roof support bolts (Matetic, et al., 2008). This machine is predominant in underground excavation projects, especially in underground coal mines, to support the freshly excavated subsurface structures from collapsing. In underground coal mine openings, the continuous miner machine creates the access road by cutting and extracting the coal, leaving behind a tunnel in the coal seam. As the continuous miner machine advances, the roof bolter installs bolts in the freshly excavated tunnel to secure the roof and prevent it from collapsing. While the continuous miner machine excavates coal from the seam, the roof bolter machine reinforces the tunnel roof and ensures it remains stable and safe for miners. During roof bolts installations, the roof bolter machine drills holes into the roof and inserts the roof bolt to prevent the movement of a jointed rock mass. As of today, the majority of roof bolters in coal mines in the United States are manually operated, and this involves the following steps:

- Positioning the drill steels by the operator into a designated chunk (drill head), then initiating the manual control to drill a hole in the roof to the desired depth. After successfully drilling the hole, the operator then withdraws the drill steel from the hole.
- Subsequently, the operator manually controls the machine to remove the drill steels and drill bit from the drilled hole.
- This is then followed by resin insertion, which contains a resin and a hardener mixed during installation, creating a strong reinforcing material between the rock and the bolt installed.
- The last step involves the operator placing the bolt on the chunk (drill head) and manually controlling the roof bolter machine to insert the bolt in the hole.

During the bolting process, operators are involved in moving heavy tools in awkward conditions, and at the same time, being vigilant about their safety. The operator uses one hand to feed the consumables on the hydraulic roof bolter machine and uses the other hand to control the machine. Due to the demanding nature of the work, the operator can be exposed to risks that lead to injuries or death. The roof bolter operators are not only exposed to rock falls but also other safety hazards such as dust inhalation and continuous exposure to noise levels above the prescribed threshold (Schafrik, et al., 2022). Besides the extreme environmental conditions in underground mines, the long working hours combined with rigorous shift-work schedules of mining work can cause fatigue in mine personnel, inevitably leading to accidents and injuries. Furthermore, operators are susceptible to an increase in fatigue as a result of the working conditions such as dim lighting, loud noise, hot temperatures, limited visual acuity, early morning awakenings, long work hours, long commuting times due to mine site remoteness, and long work hours (Legault, 2011). A combination of these factors contributes to the operator’s fatigue, which influences operators to take a shortcut that could lead to injuries and fatal accidents. To address this issue, this study integrated a six-axes robotic arm into the roof bolting system to mimic human tasks during roof bolting operations. It is envisaged that the integration of the robotic arm into the roof bolting cycle will enhance human tasks, leading to an increase in productivity. The robotic arm is a replica of a human hand envisaged to perform the functionality of a human hand in a machine.

However, the primary aim of this chapter is to discuss the specifications and properties (features) considered in choosing a suitable robotic system for partial automation of the roof bolting operation. The selection of appropriate robotic systems is crucial for the performance of the automated machines. When planning to integrate cobot technology into an environment such as underground mining operations, it is imperative to understand the human tasks the robot is replacing. A detailed study of human functions and activities during the roof bolting process must be carried out to design and know the kind of robot that can perfectly imitate such functions. As discussed earlier, the conventional roof bolting process heavily relies on the operator's judgment and experience to perform the bolting process. The roof bolter operator places the drill steels and drill bit on the machine for drilling; removes drill steels and bits from the machine after drilling; injects resin into an already drilled hole; and positions the bolt on the machine for installation.

3.2 Key Considerations for Successful Implementation of Automated Technology into Mining Operations.

Integrating autonomous systems is a complex process involving planning, designing, and implementing various layers of deployment. Due to the complexity of these systems, it is crucial to conduct a proper planning process before deployment. However, as technology advances, it is essential to remain flexible in adapting plans, recognizing that technological change is a continuous process.

The mining industry has seen a rise in adopting automated technology to improve operational efficiency, reduce costs, and increase productivity. By successfully implementing automated technologies into mining operations, organizations can achieve greater efficiency, reduce costs, and increase productivity. However, successfully implementing automated technology requires careful consideration. During the planning process, it is important to examine the key areas that could impact the successful integration of the robotic system into underground mining machines. For the integration of automated technology to be successful, attention is required in these three key areas:

- People;
- Processes; and
- Technology.

The three elements mentioned above for successfully implementing digital technologies in mining operations have been around since the early 1960s (Khanduri, 2022). The people do the work; the processes make the system more efficient; and the technology assists people in performing their functions and automates the process, as shown in Figure 3.1. Moreover, it helps to provide complete control of the system and to optimize operations. These factors are applied in mining and other fields to improve the operational efficiency of operators and equipment.

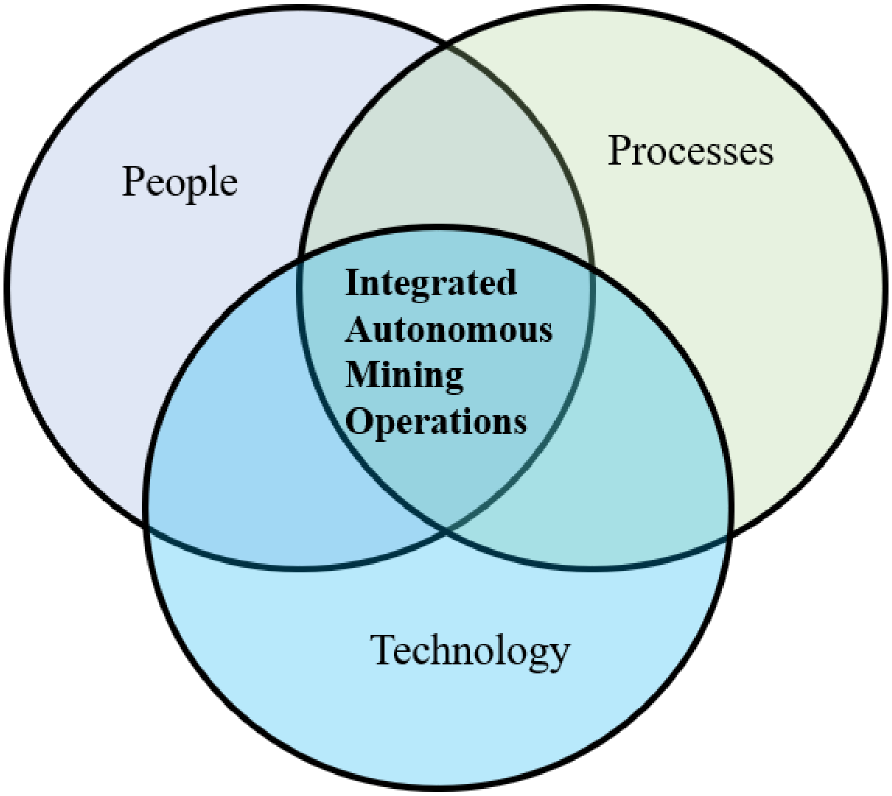


Figure 3.1: Relationship between the key three elements for automated systems implementation (Mottola, et al., 2011).

3.2.1 People (Miners)

The “people” are the human resources available to interact and share the same workspace with the technology. These people instruct the system to execute specific tasks defined in the process, which may involve utilizing technology. As part of the implementation process, the people working around the technology must be properly trained to control the system. One of the main tasks is to bring onboard the right people. Technology manufacturers must identify the right skills, experience, and attitude to operate digital technologies. The people also need clear role definitions, so everybody knows their responsibilities. This will help to make sound decisions, technology selection, process deployment, and personnel hiring. According to Lynas and Horberry (2011), significant human factors remain a concern in mining equipment automation, even with a slightly different emphasis. Recent attention has been placed on interface design, acceptance of new technologies, and the evolving skill requirements for those responsible for operating and maintaining the newly introduced equipment rather than solely on manual tasks and environmental ergonomics. As technology advances, new skills will be necessary to operate the equipment, potentially making it challenging for people (miners) to accept autonomous technology.

Therefore, the manufacturer deploying the autonomous systems needs to invest in people and the technology at the same time by playing a role in defining new skill requirements, providing educational opportunities to prevent skill shortages, and empowering the community at large (Global Mining Guideline Group, 2019). There is a need to define the workforce's necessary skill sets, talent, and adaptability of the workforce. From there, the identification of newly required skills and discovering new skill pathways for individual employees in local and regional geographical areas can be set up. This approach would promote the retraining of existing employees that would work on the automation and determine the opportunity for cross-training. This is why it is essential to establish a relationship between mining equipment manufacturers and mining companies not only for training mining personnel, but also to develop equipment suitable for the adopted mining methods in their operations.

3.2.2 Processes

Integration of automated systems will significantly transform the operational aspects of the mine. This will change the operation and workflow of the mine, as the process defines how the tasks will be achieved with the help of the technology. Usually, processes are repetitive actions that aim to achieve the same outcome, regardless of who executes them. Introducing an autonomous system is a holistic change that may affect the mining process, such as safety management plans, traffic management plans, work instructions, interfacing between autonomous areas, maintenance, and operational shift management. The deployment of autonomous systems would change the workflow in mining operations. For instance, there may be potential for increment in remote service tasks, which may introduce new organization processes and challenges, such as managing changes in time zones. To successfully implement autonomous technology, these changes must be identified, properly addressed, and tailored to fit the existing mine layout, mine design, and mine plan.

However, while robust planning is required, technological change is an ongoing process, and plans must also be adaptable to those changes.

3.2.3 Technology

Technology provides the tools people can use to implement the process. It also helps automate some parts of the process. Mine management and mine designers and planners should understand the limitations of the autonomous mining technology they will use and the differences between manual and autonomous operations. Ultimately, mining companies must ensure that the technology fits and works perfectly into existing mine design or mining operations. The mine design should be compatible with autonomous equipment and potential combinations of autonomous, semi-autonomous, and manual equipment. Traditional designs for one type of equipment may need to be improved, and the entire design should be optimized for automation in new projects or complete redesigns. The strength of a successful implementation of autonomous systems in mining operations lies in existing technology at the mine. In most cases, implementing automated technology requires the application of other technology, such as the availability of a reliable wireless communication network and control rooms. These must be identified and be part of the operational readiness planning and deployment process. However, the people and process must fit into the new technology. The people must be trained, and the process requirements must be identified. Successful technology integration is possible when the right people follow the appropriate processes to support it. If people don’t know how to use the technology or fail to follow the processes appropriately, the technology will not be efficient. Thus, the manufacturer of the autonomous system must understand the relationship between these three elements before integrating it into the mining value chain.

3.3 Specifications for Selecting a Robotic System for Partial Automation of Roof Bolting Operations.

Integrating robotic systems in underground mining machines is a staged process that requires proper planning, design and implementation. The implementation process should not be seen as a "plug and play" procedure due to the complexity of the system and the mining conditions in underground mining operations. Integrating robotic systems brings a new approach to mineral extraction process and material movement, which might necessitate adjusting an existing mine design, system infrastructure, and operational process. More importantly, automating any mining process brings numerous challenges due to the dynamic and hostile nature of the underground mining environment. This is the reason why mining companies must carefully evaluate why they want to implement automated technologies in their operations. However, equipment operating repetitively is typically easier to automate compared to equipment that continuously needs human input.

However, there is a need to integrate robotic systems in roof bolting operations to reduce the risks the machine operators are exposed to during the roof bolting process. Due to the multiple tasks performed by the operators, they are exposed to different levels of injuries depending on the phase of the roof bolting cycle. During the roof bolting process, machine operators work in the proximity of potentially unstable roofs, loose bolts, and a heavy spinning mass which are significant contributors to operator's injuries in the underground mining space. The bolter operator is exposed to roof falls and elevated dust levels, but the drilling and bolting processes are often noisy. It is envisaged that integrating robotic systems into the roof bolting cycle will move operators away from the active mining face to a safer location. It is anticipated that this will change human activities during the roof bolting process to a supervisory role where the operator can monitor and control the roof bolting process via a touchpad.

Before integrating the robotic system into a conventional roof bolting machine, it is important to consider the specifications of the robot to ensure that it can perfectly perform human activities during the roof bolting operation. This step is crucial to ensure the robot behaves safely and predictably when deployed in an underground mine. The overall objective of this study is to partially automate a roof bolting operation by deploying a robotic arm to mimic human activities during the roof bolting cycle. That is, a robotic system that can perform a complete cycle of drill steel positioning, drilling, bolt orientation and placement, resin placement, and bolt securing was studied in detail. The robotic arm was used to perform each process that makes up the roof bolting cycle.

Ideally, robots are designed to perform a specific task and are developed to function efficiently. An example is a robotic arm used in an assembly line to carry out repetitive tasks, such as picking and placing objects with the help of sensors. However, these robots are programmable and can move in two axes. In selecting a suitable robotic system that can mimic human activities during the roof bolting operation, the following standard industrial configurations were considered:

1) Weight capacity of the robot;
2) Extended reach;
3) Axis movement specifications; and
4) Fit-in to an existing machine (compatible)

3.3.1 Weight Capacity of the Robotic Arm

The weight capacity of the robot describes the strength of the robot. This is often referred to as the payload. The payload describes the maximum amount of weight a robotic arm can lift. The robot's load-carrying capacity depends on the capacity of the actuators (Korayem, et al., 2010). The robot manufacturer ensures that the payload capacity is designed based on specific applications. The payload capacity varies (0.5 kg to 1000 kg) among robots depending on the application. The payload capacity of the robot is influenced by various factors like the choice of materials utilized in the end effector, its mechanical strength, and the effectiveness of its gripping mechanism.

When selecting an industrial robot for a specific task, the robot payload is a crucial parameter that requires careful consideration. It is one of the primary specifications provided by robotic manufacturers and frequently becomes a defining characteristic of a robot. The payload capacity of a robot pertains to the maximum mass that its wrist can effectively accommodate. The payload capacity is usually expressed in kilograms, a widely adopted unit of weight measurement by most robot manufacturers. Although some may perceive payload solely in terms of the weight of workpieces manipulated by the robot, it also encompasses the weight of any end-of-arm tooling (EOAT) and bracketing seamlessly integrated with the robot wrist. To accurately assess the payload capacity of a robot, it is essential to consider every component that might be affixed to the robot's wrist, including (EOAT). This careful consideration is necessary because these attachments directly influence the robot's ability to carry, and handle loads effectively. An accurate evaluation of the robot's payload capacity can be achieved by considering all potential attachments.

However, in this study, the roof bolt and plate used for the laboratory testing of the automated roof bolting machine is a standard roof bolt used in typical underground mining environments. The bolt weighs around 5.44 kg (12 lbs), and the plate weighs 1.4 kg (3 lbs). Thus, the expected weight to be lifted by the chosen robotic arm is 6.8 kg (6.8 lbs). However, roof bolt lengths in underground coal mines typically range from 1.8 m (6 ft) to 3.6 m (12 ft). The roof bolt lengths used for the laboratory testing of an automated roof bolting machine are approximately 178 cm (5.83 ft), as shown in Figure 3.2. These characteristics are essential in selecting a robot for the roof bolting process, as this can significantly affect the productivity and performance of the robot. Conversely, selecting a payload capacity lower than the required capacity can result in decreased productivity, longer cycle times due to inefficiencies, and even damage to the robot. In particular, choosing the wrong payload capacity to replace human activities on the roof bolting operation can affect the overall time to complete the bolting cycle (Kroeger & McGolden, 2007). Selecting a robot with an appropriate payload capacity will optimize the machine’s overall performance, promote smooth workflow, and foster the desired outcomes in applications.

Figure 3.2: A roof bolt waiting for grasping by the robot during the laboratory testing.

3.3.2 Extended Reach of the Robotic Arm

The robot’s reach refers to the maximum length the robotic arm can extend to achieve or perform tasks. The robot’s reach and joint ranges determine the scope of its work envelope representing a 3D shape or volume in space. The robotic arm’s reach gives the robot an advantage over the human arm as the robotic system can be designed to carry out desired tasks based on the nature of the work environment. More importantly, most robotic systems are built to work in environments that are unsafe or inaccessible for humans (e.g., deep water excavation, planetary exploration, confined areas) or the prevalence of hazardous conditions (e.g., nuclear radiation, toxic gases). For instance, during the roof bolting operation in underground coal mines, the operator uses one hand to feed the consumable to the machine and the other to control the roof bolter machine. The operators are involved in moving heavy tools in awkward and confined conditions, while being vigilant about their safety. Physically demanding jobs over extended periods in unfavorable environments also increase the probability of unsafe actions, leading to accidents or near misses.

When selecting the reach of the robotic system for this project, underground coal mining conditions were considered for the automation process. Due to confined working conditions in underground coal mines, it is essential to consider the vertical and the horizontal reach of the robotic arm. The reach of the robotic arm can be measured in vertical and horizontal axes, as shown in Figure 3.3. The vertical reach of the robotic arm measures the maximum height or vertical distance the robot arm can attain when extended from its base. In contrast, the horizontal reach describes the maximum distance the robot can attain from its base.

Figure 3.3: Vertical and horizontal reach of a robotic arm performing tasks.

Likewise, the radial reach specification of the robot was studied during the selection process. The radial reach describes the maximum distance from the robot's base to any point on the arm. That is, the maximum distance between the robot's wrist center and the axis of joint one (1). It is often referred to as the robot workspace or working range. The reach of the selected robot is 1.45 meters (4.76 feet), shown in Figure 3.4.

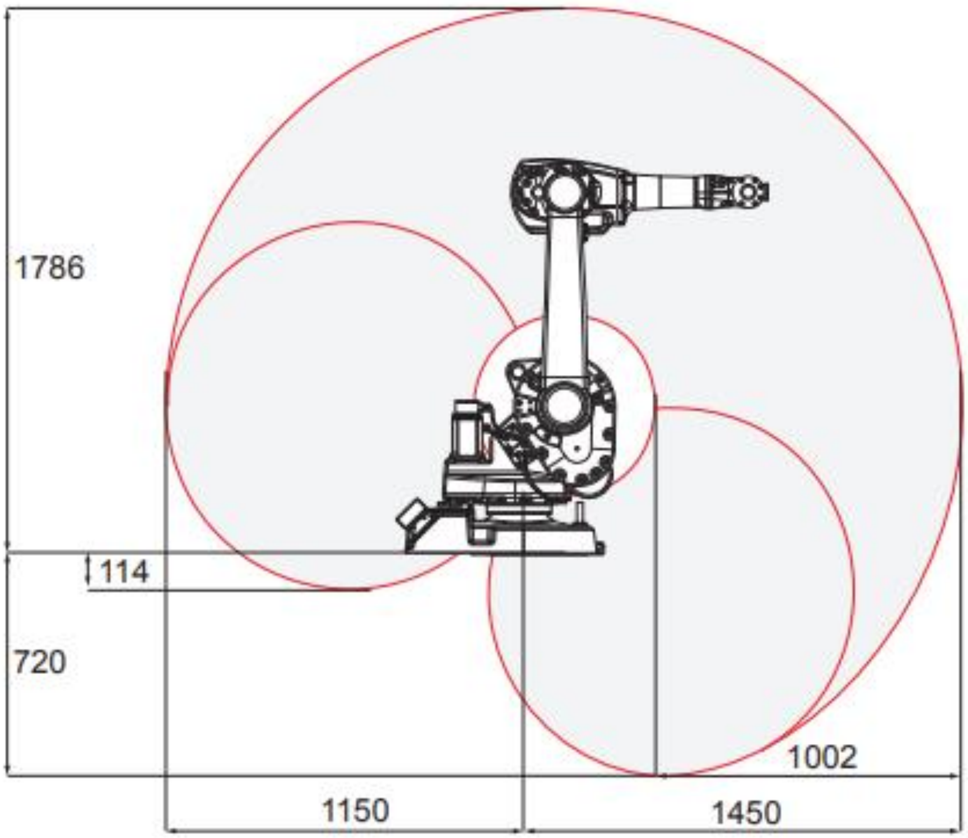


Figure 3.4: Working range of robotic arm ABB IRB 1600 -10/1.45 (ABB, 2019).

3.3.3 Axis Movement Specification of the Robotic Arm

The axis movement specification of the robot is another vital feature which was considered during the selection of the robotic arm due to the confined areas present in the underground mining method. In the robotics context, an axis defines the mechanical joints of the robot that are intrinsically connected to its segment providing pivotal axes that facilitate the robot's movement. An axis is frequently interpreted as the robot's degree of freedom (DOF). For instance, a robot with three DOF can only operate in the X-Y-Z planes; however, the robot cannot tilt or rotate. While a six DOF robot has the X-Y-Z planes and orientation angles (roll, pitch, and yaw), as shown in Figure 3.5. It is important to know that when a robot is purchased with a given number of axes; it is difficult to incorporate additional axes after purchase. Increasing the number of axes or the DOF on a robot creates more space than a robot with a lesser number of axes.

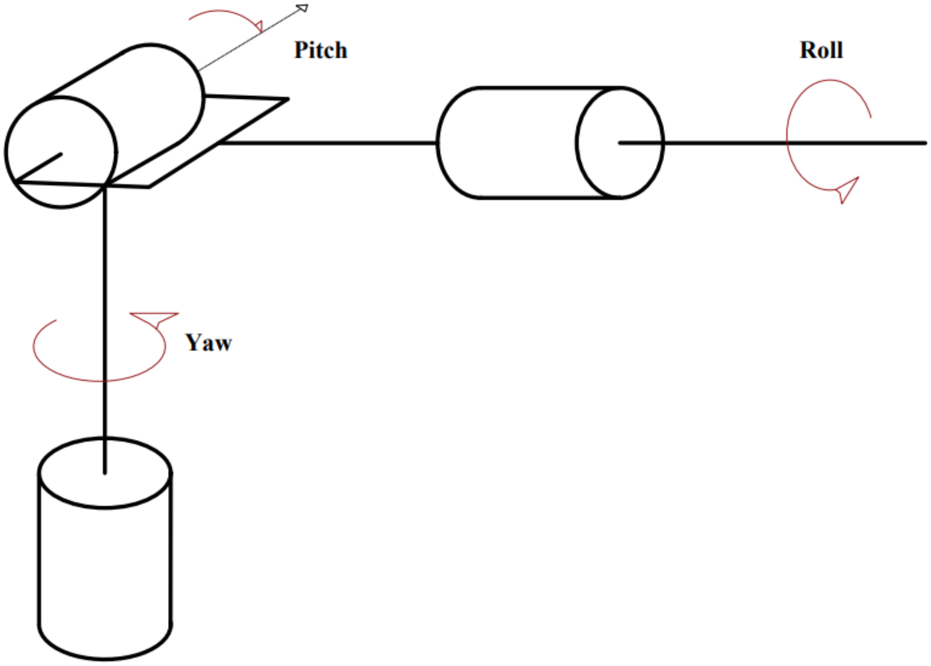


Figure 3.5: Description of the orientation angle of a robot

One way to identify the DOF of a robotic system is by counting the number of motors (Bélanger-Barrette, 2015). The most common method to determine the number of DOF is by examining the type of joint motion. That is, the DOF of a robot is directly influenced by its number of joints. The joint can be rotary (revolute) or linear (prismatic). For instance, a robot manipulator with six joints robot has six DOF: three for positioning (X-Y-Z) and three for orientation (roll, pitch, and yaw angles). A manipulator with less than six DOF cannot reach every point in its work environment with arbitrary orientation. Thus, it is important to consider the DOF of the robot based on the tasks at hand, as specific tasks may require more than six DOF. Another critical factor to note about the robot's axes is that the more the number of axes, the greater the maneuverability. If you need a robot to perform complex tasks, a manipulator with more axes would be a preferred choice. The number of axes is dependent on the application. Generally, most industrial robots have a six-axis of movement, which gives them the ability to perform various tasks compared to robots with fewer axes. The six-axis industrial robot is commonly used due to its high payload capacity, flexibility, and robust programming. Figure 3.6 shows the description of the axes of a six DOF robot.

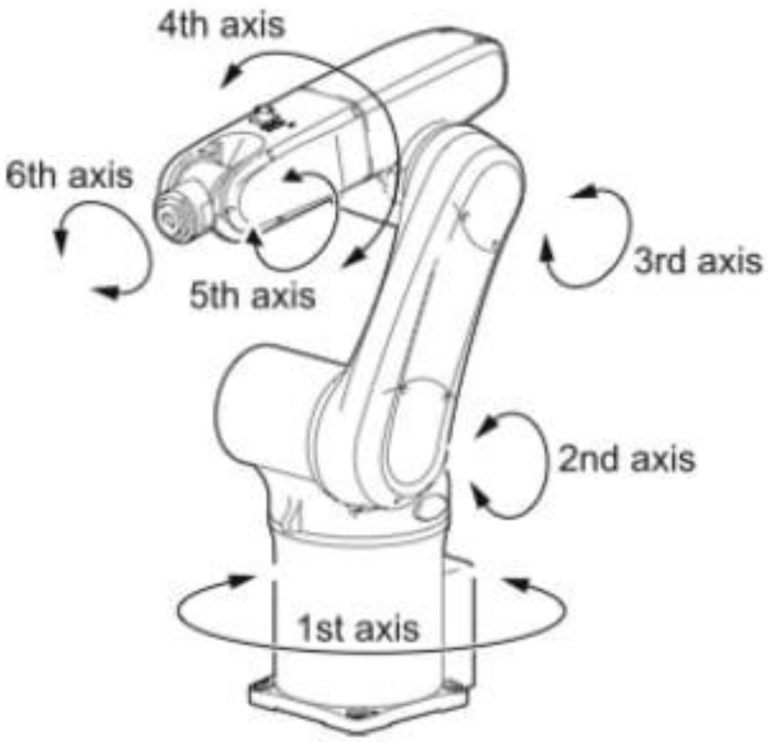


Figure 3.6: Description of a six-axis industrial robot.

This study integrates a six DOF robotic arm to mimic human activities during the roof bolting tasks. The six-axis robot allows the robot wrist to rotate freely in a circular motion, similar to that of human wrist. The robot is suitable for complex movements that can simulate activities performed by human arms such as grabbing, holding, placing, and positioning of consumables during roof bolting operations.

Similarly, the robot's motion range is an important factor when selecting a robot for a specific task. The robot's motion range describes the extent to which a robot manipulator can move its end effector or perform various motions. It represents reach and mobility of the manipulator in the workspace which defines features like joint limits, workspace boundaries and mechanical constraints. The range depends on the DOF that the robot has. However, each DOF corresponds to a distinct axis, each axis equipped with a motor to generate a precise motion. Notably, the more complex application will require a greater range of motion. Although a narrow range motion robot offers enhanced stability when lifting heavy loads, part repositioning is often needed. Conclusively, the number of axes is an important parameter to consider when selecting an industrial robot as it will determine its range of motion.

The robot's speed is another parameter to evaluate, as it determines the efficiency and overall roof bolting cycle time. Consequently, the speed can influence the productivity of the automated roof bolter machine. The cycle time of a roof bolting operation in underground coal mines is critical for ensuring the safety of underground workers, as the freshly excavated roof has a stand-up time without a support system which is prone to fall of ground. Hence, optimizing the time the robotic system takes to complete a roof bolting task can significantly improve safety of miners and increase the efficiency of the automated roof bolter machine. However, it is envisaged that the automated roof bolter machine will enhance performance and productivity during roof bolting operations. The robot's speed can impact the overall cycle time to install a bolt. The faster the robot moves on average, the more quickly jobs are done and the higher. A faster robot can process more units or perform more tasks, leading to higher throughput and improved productivity. The selected robot for this study has up to 50 percent shorter cycle times than competing robots in material handling, machine tending, and process applications. It speeds up and slows down faster than other robots, saving time while moving between tasks. This is possible due to the manufacturer's patented second-generation QuickMove motion control, the robot's strong motors, and low friction losses in the spur gears. Usually, most robots will cut corners at high speed. With this robot, the path will be the same regardless of speed.

3.3.4 Fit-in to An Existing Machine (Compatibility)

Selecting a robot that fits into the hydraulic roof bolter requires careful consideration. The goal of this study is to integrate a robotic system that can perform human activities in roof bolting operations. The task entails identifying a robotic arm that can fit perfectly into the roof bolting module without redesigning the bolter to accommodate the robot. Implementing robots to collaborate with machines requires careful consideration. It is important to consider a robot that can fit in the operator-designated space of the hydraulic roof bolter machine. The outcome of this study is not to develop a new machine but to automate the machine to enhance the safety of operators. In underground coal mines, operators and machines are always close to one another. The position of the machine operator is critical in determining the size and workspace available for the robot. The operational environment should be considered when selecting robots to replace humans. For instance, operators of the roof bolter machine work in confined spaces in underground coal mines. This must be considered when selecting a robotic arm that replaces humans for automation operations. The confined space in underground mines is a constraint for the types of machines to be implemented in underground mining operations.

Integrating a robot into another machine typically involves ensuring compatibility of hardware and software interfaces between the robot and the existing machine. The robot, the roof bolter machine, and other components must work together to automate the roof bolting operation. The specific integration process will depend on the type of robot and the machine it is being integrated with. The robot and other machines were integrated for autonomous operation using the iQAN systems developed by Parker Hannifin. The iQAN system enables the robot and other components of the automated roof bolter machine to be integrated and controlled by the operator. To effectively perform sequential roof bolting operations, the robot must be fully compatible with and controllable by the iQAN system. Identifying the robot's purpose and tasks would help to determine the type of robot that can fit for the automation process. Considering these factors will assist in selecting a robot that can fit with other machines. The robot's ability to fit into the existing roof bolter module will enable the robot to perform human tasks during the roof bolting operation without colliding with the walls or roof due to limited maneuverability.

3.4 Description of ABB IRB 1600 Robotic Arm

The selected cobot system for this study is ABB robot IRB 1600. This robotic arm is made up of two main parts, namely the manipulator and the controller. 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 1600 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). In this study, 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 (axes) and five revolute joints shown in Figure 3.7. The robot arm can imitate human intelligence during bolting operations by performing the operator tasks such as grabbing drill steels for drilling, removing drill steels after drilling, installing pumpable resin, and placing bolt for installation.

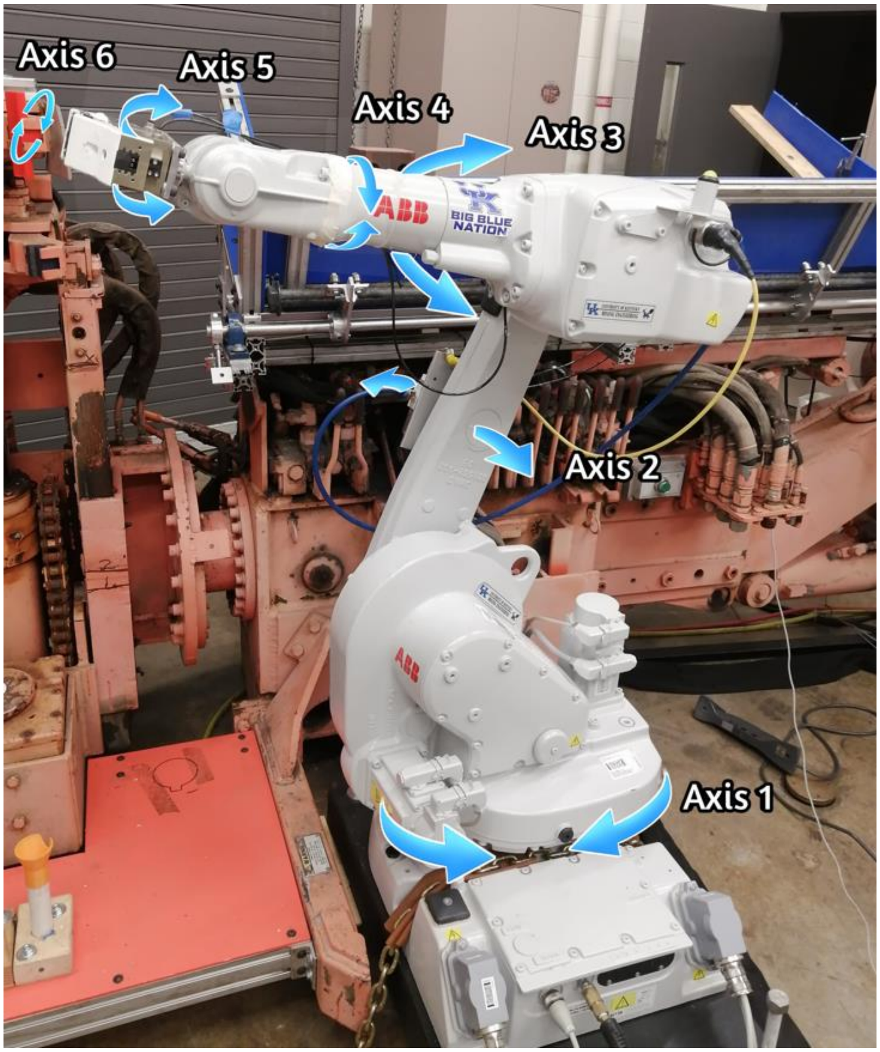


Figure 3.7: Axes description of the ABB IRB 1600 Robotic Arm.

Furthermore, the robot controller controls the movement of the robotic manipulator. The controller manages the robot's wrist and prevents interference within the robot's vicinity. To enable operational capabilities, it is customary for the robotic arm and controller to be paired together in most cases. That is, the controller is designed to control the robot and to ensure that the robot performs optimally. The robotic arm comprises a series of mechanical linkage designed to simulate the functionality of the human arm. The robotic arm is also just one component in an overall robotic system, as illustrated in Figure 3.8, which consists of the robotic arm, external power source, end-of-arm tooling or end effectors and control computer. Moreover, the programmed software (ABB RobotStudio) should be recognized as an essential component of the entire system, as it significantly influences the performance of the robot and its potential applications.

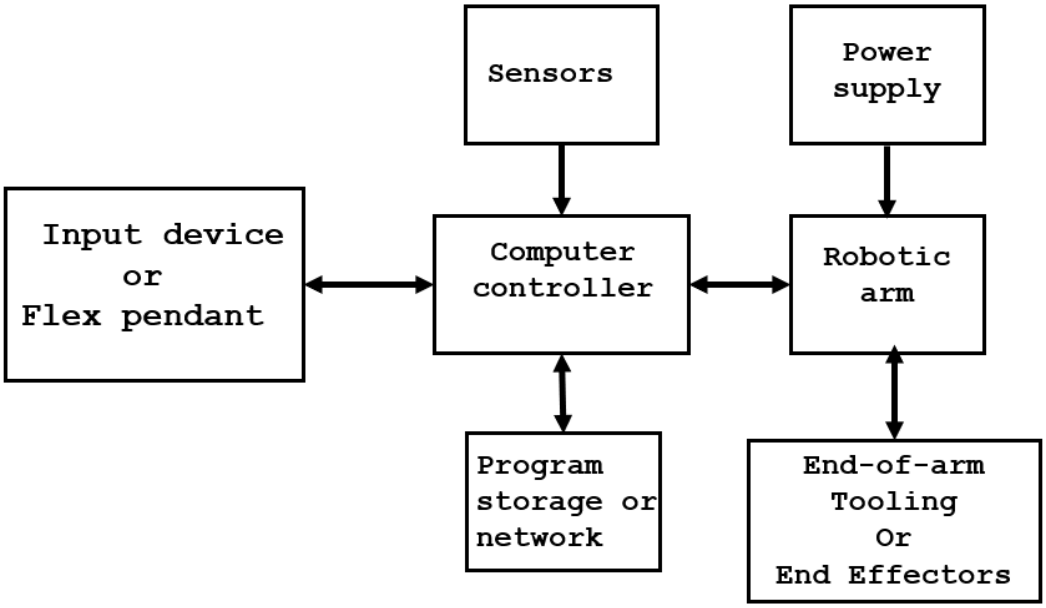


Figure 3.8: Components of a robotic system

The IRB 1600 robot is equipped with RobotStudio software that manages and controls the robot's movement. The software provides an interface that controls every aspect of the robot, such as creating the motion trajectories and the development and execution of program communications. In this study, the robot is programmed to move in a particular path during the roof bolting operation. Before the establishment of robot motion trajectories, simulations were performed to mimic how the robot would perform the roof bolting cycle in underground mining conditions with undulating surfaces, inadequate lighting, and power cables laying on the floor. The simulation involved all the steps the robot took to execute tasks, from grabbing drill steels to installing the bolt. The simulation showed clear robot motion paths that prevent a collision. How the robot is programmed and controlled plays a crucial role in determining its capabilities and the breadth of tasks it can effectively undertake.

The basic technical specifications of the ABB IRB 1600 robotic arm are tabulated in Tables 3.1 to 3.4. These tables present technical information and the standard industrial configurations of ABB IRB 1600. The robot arm has various versions depending on the reach, axis movement, and axis maximum speed (ABB, 2019). The ABB IRB 1600 robot version 10 with a 1.45 meter (3.28 feet) reach selected for this study has the potential to mimic human activities during the roof bolting operation by performing bolt grasping, holding, lifting, placing and removal of drilling steels during the roof bolting operations.

Robot Specifications	**Ream (m)**	**Payload (kg)**	**Armload (kg)**
IRB 1600 - 10/1.45	1.45	10	20.5
Number of Axes	6 +3 external (up to 36 with MultiMove)		
Protection	Standard IP54 Option Foundry Plus 2 (IP67)		
Controller	IRC5 Single cabinet / IRC5 Compact		

Table 3.1: ABB IRB Robot specifications based on payload capacity (ABB, 2019)

Table 3.2: ABB IRB Robot specifications on environmental adaptability (ABB, 2019).

Ambient temperature for mechanical unit	
During operation	+ 5°C (41°F) to + 45°C (113°F)
During transportation and storage	- 25°C (- 13°F) to + 55°C (131°F)
During short periods (maximum 24 hrs)	up to + 70°C (158°F)
Relative humidity	Max. 95%
Safety	Double circuits with supervisions, emergency stops and safety functions, 3-position enable device
Emission	EMC/EMI shielded

Table 3.3: ABB IRB Robot specifications based on movement (ABB, 2019).

Axis movement speed	**IRB 1600-10/1.45**
Axis 1 rotation	+180° to -180°
Axis 2 arm	+120° to -90° +150° to -90°^{2}
Axis 3 arm	+65° to -245°
Axis 4 rotation	Default: +200° to -200° Max. rev: +190° to -190°
Axis 5 bend	+115° to -115°
Axis 6 turn	Default: +400° to -400° Max. rev: +288 to -288

Table 3.4: ABB IRB Robot specifications based on axis maximum speed (ABB, 2019)

Axis maximum speed	**IRB 1600-10/1.45**
Axis 1 rotation	180°/s
Axis 2 arm	180°/s
Axis 3 arm	185°/s
Axis 4 rotation	385°/s
Axis 5 bend	400°/s
Axis 6 turn	460°/s

3.5 Conclusion

Before implementing robotic systems, it is necessary to consider three crucial areas that could impact the successful integration of the technology. These include the people that would work and share the same workplace with the technology (miners), processes (work instructions and tasks to be achieved with the automated system), and technology (the system that performs the automation). The relationship between these three factors regarding the integration of automated technology has been explicitly discussed in this chapter. Selecting robotic systems that mimic human tasks during roof bolting operations must follow standard industrial configurations. The specifications of the robotic systems must be carefully evaluated, considering the task to be accomplished by the robotic arm, the autonomous operation of the roof bolter machine, and the dynamic and hostile nature of the underground mining environment. Some factors that need to be considered in selecting a robotic system for underground mining operations have been discussed in this chapter. These include:

- the payload capacity of the robotic arm;
- the maximum reach of the robotic arm (vertical and horizontal distance covered);
- the robot's axes movement specification; and
- the compatibility with existing (host) machine.

For this study, the ABB IRB 1600 robotic arm was selected to successfully mimic human activities during the roof bolting operation. This robot is envisaged to accomplish a roof bolting task with the support of the surrounding machine. The robot performs sequential roof bolting tasks and successfully collaborates with a conventional roof bolter machine.

In chapter four, the interaction between humans and the developed automated machine will be discussed extensively. The design and development of a human-machine interface (HMI) allow the operator to control and manually approve the machine’s tasks in the event of unpredicted actions. In addition, the developed HMI device controls the automated machine and presents task features that enable the operator to make sound decisions on the roof bolt bolting operation.

4. DEVELOPMENT OF CONCEPTS FOR SAFE AND EFFICIENT HUMAN-MACHINE INTERACTION (HMI) DURING PARTIALLY AUTOMATED ROOF BOLTING OPERATIONS.

A human-machine relationship is one of the overall considerations in integrating automated technologies in underground mining operations. The acceptability of automated technologies depends on operators' involvement in using and controlling digital systems. This chapter explains the design and development of a safe and efficient human-machine device that enables the operators to monitor and control the automated roof bolting operation from a safe distance. The link between the HMI device, Programmable Logic Controller (PLC), and other system components will be discussed.

4.1 Human-Machine Interaction (HMI) in Automated Machines

Modern automated machines usually have a human-machine interface to deliver information from the machine to the operator, allowing them to control and monitor the machine. This interface provides reliable and real-time information about the behavior of the machine via a graphical user interface (GUI) that enables the operator to assess the machine’s status, monitor the performance, and adjust their operating parameters with reliability. The HMI system is crafted with a high degree of operator-friendly interface between humans and machines to foster the operators' acceptability of the technology. In a typical industrial machine, the design of the HMI can be programmed on a Windows-based PC or on a touchscreen controller that runs on an embedded operating system like Windows CE or Linux computer operating system. In general, the standard features of the HMI include:

- Touch screen operation;
- Tools for entering data (buttons or keypads); and
- Pages with navigation control and logs for alarms and events.

When selecting an HMI device for a particular machine, it is essential to consider the range of devices that can be controlled. Other factors that deserve attention include the device's dimension, work environment and area, operating temperature, operating humidity, vibration, and shock rating (Zhang, 2010). Traditionally, HMI design uses light-emitting diodes (LEDs) for flat panel displays, which usually depends on the material used. Due to technological advancements, the HMI with a flat panel display now make use of liquid crystal display (LCD) or plasma technologies. The LCD works based on the passage of electric current through a trapped liquid crystal solution between the sheet of polarizing material. The aligned crystals ensure that light is blocked, and an image is created on the screen. The differences that exist between HMI are performance specifications (hard drive capacity, processor type and RAM), and input/output (I/O) ports (ethernet, RS-232, RS-422, RS-485, small computer system interface, and USB port).

The advent of automated machines enables humans to delegate tasks to machines. However, this delegation does not entail a complete transfer of work responsibilities to machines; machines are still controlled by humans. The introduction of automated technology does not usually replace humans; instead, it changes the nature of human work from direct operations to a more supervisory role. These automated machines are still managed and controlled by humans; in the event of abnormal scenarios for which the machines are not designed, operators must be able to override the machine actions using the HMI device. The HMI bridges humans and machines, allowing for seamless communication between the operator and the machine. The device provides operators with an interface to control automated systems. The most notable function of the HMI is to manage and regulate how the automated systems behave. The device controls the system instead of operating the system directly by flicking a switch, engaging gears and joysticks, turning the steering wheel, and stepping on a pedal.

The HMI device comprises the hardware and software systems communicating between the end operator and the automated systems. HMI's software systems are components and functionalities that allow effective communication between the operators and the automated system. These include the GUI, input and output (I/O), data visualization, and communication protocols. Meanwhile, the hardware component comprises the touchscreen (display), memory, and communication interfaces (the serial and ethernet port). A well-designed HMI interface fosters effective communication and builds trust by presenting information, commands, and intentions to operators. Also, it can decrease downtime in operation and improve productivity, as it provides operators with control functions and information. More importantly, it gives operators the proper context and feedback on the results of actions and information on system performance needed to make sound decisions during autonomous operations. Examples of HMI designs that influence operator judgment and decision-making are;

(1) Designing the interface using a specific color palette can help the operator identify important information that may require urgent and immediate attention, such as creating alarm notifications.
(2) Creation of additional visual features to notify the operator when parameters are changing and whether the automated machine is performing within a desirable range. These features will assist with making sound decisions by highlighting potential hazards in operations.

Conversely, poorly designed HMIs have been identified as one of the significant factors contributing to abnormal situations, downtime in operations and a major cause of accidents and fatalities in autonomous machine work environments (Gruhn, 2011). Likewise, poorly designed HMIs can restrain rather than assist operators, as the device does not provide the user with the information the operator needs to understand to work with the automated machine. To eliminate any ambiguity in the design of the HMI, it should be as understandable and user-friendly as possible. Besides, it will also foster the acceptability of the technology by the miners. The effectiveness of the HMI can affect the acceptance of the entire technology; in fact, it can impact the overall success or failure of the system. Therefore, the manufacturer of automated machines should focus more on HMI interface design, acceptance of new technologies, and the changing skill requirements for those who operate and maintain the new equipment rather than the traditional focus on manual tasks and environmental ergonomics. In addition, the HMI needs to perform to the operator's satisfaction. One of the major tasks of the designer of the HMI is to create an interface that meets the defined usability requirements for a specific HMI system.

4.2 HMI Display Layout and Design Considerations

The fundamental tasks of the HMI system are to communicate information from the machine to the operator and from the operator to the machine. The machine and the operator share a mutual objective of controlling the process and offering solutions to potential problems. Controlling autonomous processes depends on the effectiveness of interface design. Hence, it is important to have an effective HMI screen that would be able to present the process, instructions, and commands necessary to operate the machine at the appropriate time. Designing an operator-friendly interface requires a combination of modern design features and layout considerations, including style, color, tactile feedback, and ergonomic and intuitive operation, resulting in an optimal operator experience that determines customer satisfaction with the system.

Thorough knowledge of technical ergonomics, design, and mining operation standards is fundamental to HMI system design. The designer of HMI should provide the operator with an effective and efficient interface that will aid the control and monitor the autonomous operation of the machine. The device's designer must understand the operator's goal, tasks, and mental model to design a robust HMI. Understanding the user's workflow and tasks is the first step in HMI design (Rockwell Automation, 2019). The display of the HMI is primarily designed for the operators to interact with the automated machine. Therefore, it is important to consider how the operators interact with the machine. Operator means of interaction can be in various forms, including input devices such as a mouse or trackball, a touch-enabled display (accommodating touch tools like a touch pen, hand, gloved hand, etc.), and a keyboard.

Ultimately, the display information on the HMI connects the operator to the machine. Operators technically work with information on the screen to monitor the state of a process and to manually override the actions of the machine in the event of an unplanned action. Usually, the operator relies on the display information to send commands that instruct the machine on a specific action. The display information can be in form of graphs, charts, dashboards, and alarms for proper monitoring. According to Rockwell Automation (2019), the display information on the HMI should:

(1) Meet the need of the operators;
(2) Ensure that the operators understand the mode of operations and how information is related;
(3) Present the necessary information for the task;
(4) Facilitate users' rapid comprehension of both present and future status and the system's response to their actions; and

(5) Reduce visual complexity.

This study identifies the following steps as important factors to consider when designing a generic HMI for an automated system.

4.2.1 Describing Operator’s Goal, Task, and Work Environment.

Creating an HMI for automated machines requires knowing the operator's role and the tasks to be performed by the machine during the autonomous operation. Gaining insight into operators' objectives, tasks, workflow, and cognitive framework will help decide the input requirements best suited for the task at hand. Operators' understanding of autonomous operations and how to execute tasks can influence the design of the HMI. Also, in-depth knowledge of relevant ergonomics, component selection, safety control, and industry compliance are critical to designing a highly reliable HMI system. However, it is important to consider the environment and condition of the HMI; this will help select components, proper display type, housing, and mounting apparatus. For instance, the manufacturer of HMI for underground mining machines needs to consider a system that can withstand a harsh environment like explosive gases, groundwater leakage, and dust. Touchscreen HMI interfaces are not recommended for use in environments where the surface is prone to exposure to oil, condensation, or airborne debris. For exterior use, attention must be given to the effect of prolonged exposure of the HMI screen to ultraviolet (UV) radiation. Considering these will assist in designing a robust HMI system best suited for an application.

4.2.2 Display of Necessary Information and Controls

Before deciding on the type of information to display on the HMI devices, it is necessary to consider displaying information that aligns with the operators’ mental model and task flow. Reducing visual clustering and displaying unnecessary information should be avoided, leaving only the information needed with appropriate format and information grouping. This will create a higher level of reliability and help the operator monitor the operation's status and successful execution of the tasks. The screen should present only the operator’s essential interface, such as responsive tactile touch and color illumination. Relying solely on color to convey information is not advisable. The HMI should have illumination features that can incorporate multiple colors using widely available RGB LEDs. The designer must avoid using too many colors or flashing alarms.

Usually, the HMI displays contain both data and non-data pixels that can be used in designing an interface. The non-data pixel includes icons, lines, and shapes, while the data pixel comprises photographs, image boxes, panels, track bars, etc. The data pixel consumes the HMI Random Access Memory (RAM), which can affect the device’s speed. Thus, limiting the quantity of data pixel information utilized on the HMI is advisable. A key strategy to maintain focus on critical information involves employing techniques such as strategic sizing and placement of elements on display.

4.2.3 Information Presentation

The format of presenting information on HMI depends on the data type, the tasks at hand, the intended message, and the operator’s needs. Only information linked to the specific task the operator is performing should be displayed on the touchpad. Cluttering the screen with irrelevant information can increase response and potential errors. The designer must be familiar with symbolic colors and know where to use specific colors when creating the HMI. For instance, red color is often used to indicate a fault condition, and amber color represents a caution sign or sense of alertness for an action that is about to be triggered. At the same time, green signifies the satisfactory completion of a process. Also, the interface must have a consistent set of menu buttons and functions to assist the operator in navigating from screen to screen. Ensuring consistency in the display of information across multiple screens can make the operator intuitive and logical. It is important to create buttons to navigate between previous and subsequent screens.

4.2.4 Contextual Information

Determining the contextual information to be displayed on the HMI would present a robust and friendly interface. To manage an operation effectively, the operator needs to anticipate potential problems and proffer solutions to them. The interface design should maintain essential options and materials relevant to a particular task while avoiding unnecessary or redundant information that might distract the operator. Good designs do not overwhelm operators with too many alternatives or confuse them with unneeded information (Zhang, 2010). The contextual data provides operators with the necessary information that can support operator decision-making. This information includes the display of graphs and charts to show the current state of the machine. Graphs and charts are commonly used in HMIs to present data and information in a visual format. Sometimes, the graphical presentation of information can be better understood than icons, as the graph can reveal a trend or comparison. This can provide context to operators of whether the autonomous operation is working according to the trajectories programmed in the computer software. The best way to enhance the HMI is to effectively translate data into visual feedback and highlight vital information that requires the operator's attention. Finally, the interface design must communicate clearly and simply in the operator's language for seamless control of the automated system.

4.2.5 Grouping of Information

Grouping of similar information presents the operator with visual clues, values, and states of the automated machine. Grouping of buttons aims to reduce visual clutter using the least visible means. The HMI screen layout should be designed in a way that the operator can change positions and organize the controls in a logical sequence based on their anticipated usage, grouping related controls together. Grouping can be achieved by strategically positioning related items in close proximity, utilizing lines, or employing background shading. For example, it is crucial to ensure that emergency-stop and safety control buttons are prominently displayed on the HMI screen, arranged in a grouped manner. This visibility allows operators to quickly access and utilize these controls in the event of unexpected or unplanned actions. Other essential buttons that need to be identified and grouped are the manual and automatic machine operating modes. Grouping information based on the HMI interface can assist the operator in identifying and tracing issues quickly without having to look for more information or wait for an alarm.

4.3 Development of An HMI for a Partially Automated Roof Bolter Machine

Developing an operator-friendly HMI for the partially automated roof bolter machine is one of the critical features for controlling the robotic arm, the hydraulic roof, and other components of the machine. The primary purpose of this display is to allow the operator to communicate with the roof bolter machine during autonomous operations. The HMI provides 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. The device is precisely crafted so that the interface shows the real-time countdown of each step and allows the operator to monitor the operation through a taskbar. Technically, the HMI is designed and developed for more cognitive interaction between the operator and the automated machine, as shown in Figure 4.1. Video streaming serves as 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 ABB Robot Studio Application Program Interface (API) module. The API module is connected directly to the robot and listens continuously for connection with an operator interface through a static IP.

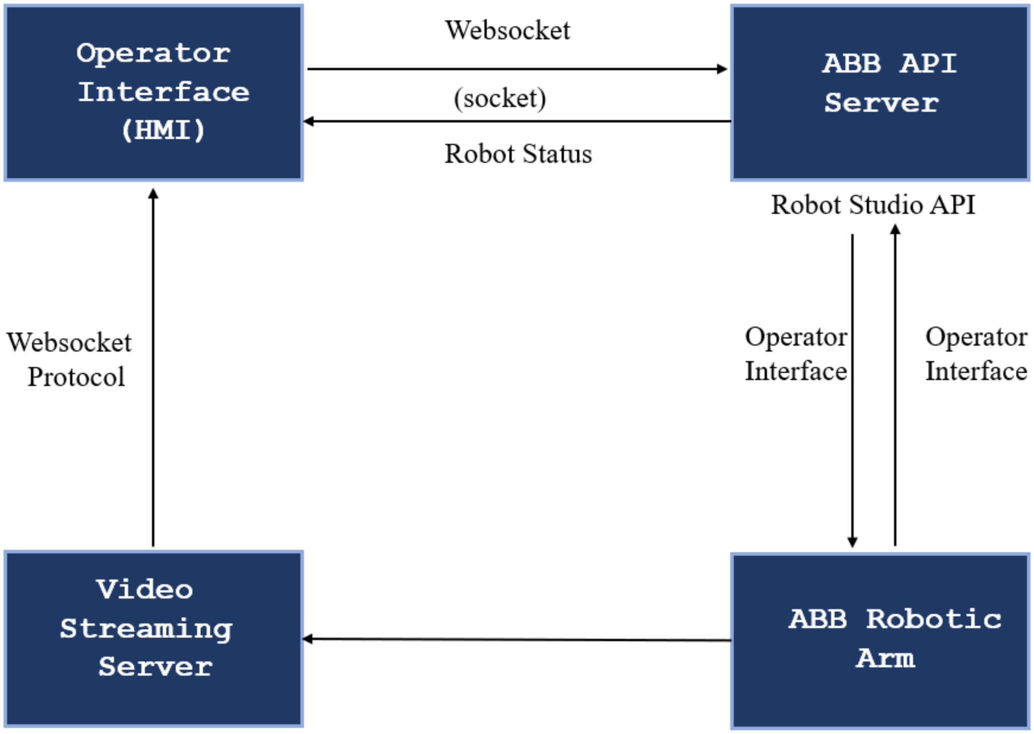


Figure 4.1: Human-robot interface for computer environments

Before developing an HMI that controls the automated machine, the robotic arm was being controlled with ABB IRC5 FlexPendant that comes with the robot. The FlexPendant device is purpose-built to withstand the demands of harsh industrial environments and ensure uninterrupted operation. The production screen on the FlexPendant introduces the smartphone interface logic, resulting in an efficient production environment that empowers an operator with control and facilitates heightened productivity. This innovative integration enhances the operator's ability to work efficiently and effectively. The touch screen is easy to clean and highly resistant to water, oil, and other liquid splashes. The ABB IRC5 FlexPendant is designed to work with only the ABB-authorized API (RobotStudio) in running programs, jogging the manipulator, modifying robot programs, etc.

The FlexPendant 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 emergency or unexpected events. The FlexPendant is a handheld operator device that performs many of the tasks involved when operating a robot system, especially, when creating robot trajectories like grasping, holding, placing and removing consumables from the hydraulic roof bolter module. In this study, the FlexPendant is used as 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 FlexPendant was developed using the ABB Screen Maker software. During the motion planning, twenty (20) buttons were created to provide an interface that controls and manipulates the robot’s motion to perform specific tasks such as grasping, positioning, moving, and lifting objects through a programming language called RAPID as shown in Figure 4.2.

Figure 4.2: ABB IRC5 FlexPendant for controlling the robotic arm

The FlexPendant comprises hardware and software that make it look like a computer system. These components form the core of the FlexPendant. The full description of the FlexPendant is presented in Figure 4.3. The device is linked to the robot controller by an integrated cable and connector to either operate the robot in automatic mode or continue running it using the FlexPendant.

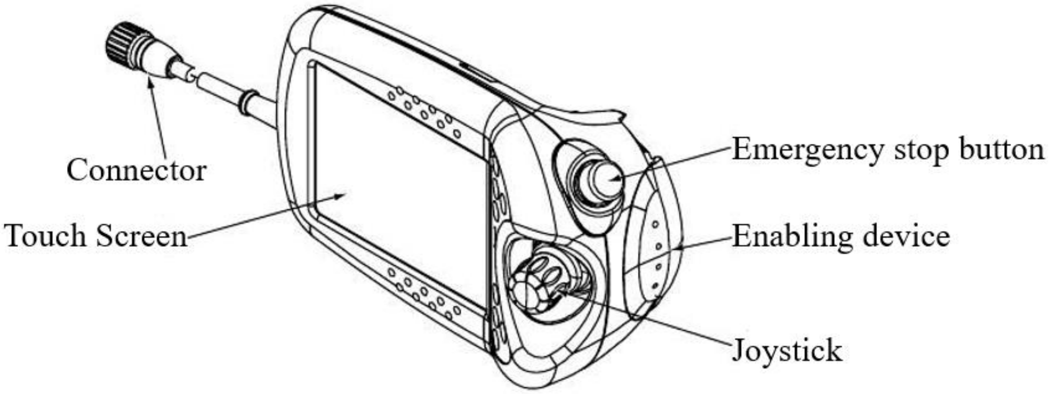


Figure 4.3: The description of ABB IRC5 FlexPendant

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. The Parker Hannifin Master Display module (MD4) iQAN system is connected to the iQAN control systems to monitor the individual progression and groups of individual commands of the programmed tasks. The MD4 HMI system offers a variety of visualization software and hardware solutions to provide features such as graphics, alarm, and networking modules, as presented in Figure 4.4. The HMI device has an interactive touch interface for controlling and monitoring the performance of automated machines. The technical description of the MD4 HMI stated by the manufacturer is summarized in Table 4.1. The table shows various properties and capacities of the device. It has a rugged mechanical design with no moving parts and is completely sealed. Notably, the screen of the MD4-HMI is designed with bonded glass that improves readability, avoids light refraction, and also eliminates possible condensation since there is no air between the glass and the LCD (Parker, 2019).

Despite the provision of IP camera support to livestream the autonomous operation of the roof bolter, the study did not use video streaming; instead, the photographs of each action of the robot and other components were added to the iQAN program, where the operator interface can display them as automation progresses.

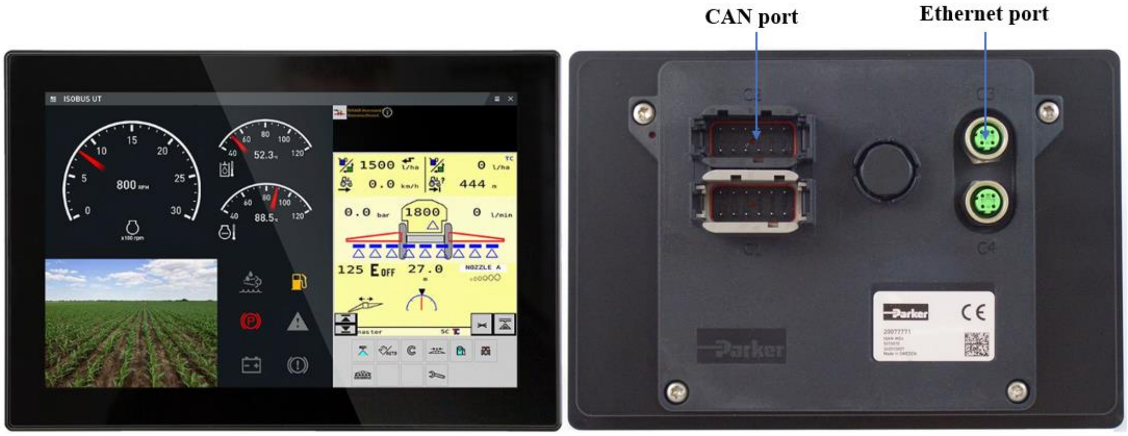


Figure 4.4: Parker Hannifin HMI display unit from using iQAN.

Table 4.1: Basic Technical specifications of iQAN-MD4 (Parker, 2019).

Technical specifications	**Descriptions**
Screen size	7 inches (Landscape or portrait)
Screen type	16:9 / LCD (LED backlight)
Resolution	800 x 480 pixels
Power supply voltage	9 - 32Vdc
Operating temperature range	-30^0 C to +70^0 C
Number digital outputs	4
Number digital inputs	2 voltage /10 digital/ 1 encoder
Display type	PCAP touchscreen
Maximum operating temperature	60^0 C
Ingress protection rating	IP65
Electrical connection	Deutsch DTM
Communication interface	4xCAN, 2xEthernet
Video in	IP-camera support

During the design of an HMI for the automated roof bolter machine, specific clusters of individual commands originating from the basic robot and machine actions are created and transferred to the automated interface. The functions from the manual operation, such as the joystick and other physical operating push buttons, are transferred to the HMI. This enables the operator to send commands that control the machine from the HMI touchpad rather than humans operating the machine directly. Each hydraulic roof bolter action from traditional roof bolter push buttons is assigned a corresponding button created on iQAN software to perform the same function when uploaded on the MD4 via the PLC.

However, the push button can be set as either a momentary, maintained or latch push button. The momentary push button is used when starting an operation by sending a signal value that can be high or low depending on the configuration of the system when pressed and another signal value when released. The maintained push button is used when it remains active (either pressed or released) after being pressed once until it is manually reset or released. It is designed to maintain its position or status until further action is taken. It toggles between two values by sending one value to the tag when pressed and a second value the next time the button is pressed and released. In contrast, the latched push button is a toggle switch function that remains activated or deactivated once after being pressed until it is manually toggled or latched in the opposite position. When pressed, the push button sends a signal to the system and retains its value until reset (unlatched) by the handshake connection.

Creating an HMI begins with establishing a welcoming home page that greets the operator and requests their authorization before granting access to the menu page. The HMI should be designed in a way that the operator must energize the hydraulic system at the menu page by pushing the “hydraulic” button. After pressing the hydraulic button, a red light will continue flashing to warn the operator that the hydraulic roof bolter machine is active, as shown in Figure 4.5. This is one of the functional safety actions against unplanned events when operating the hydraulic roof bolter. From this HMI interface, the operator can run the machine manually or automatically.

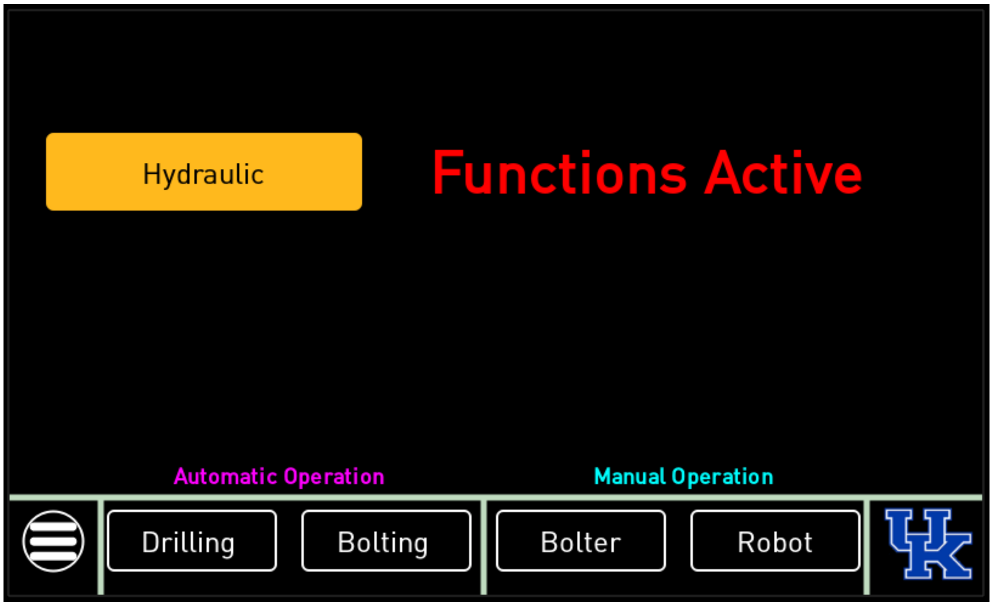


Figure 4.5: Designed menu page for partially automated roof bolter machine.

4.3.1 Development of Manual Operation Interface

The manual mode of operating the hydraulic roof bolter is the same as the traditional method of running the machine. The difference is that the machine will be controlled from an HMI touchpad. This approach enables the operator to control the machine remotely, eliminating the need for direct physical operation. When designing a manual mode of operation interface on the iQAN logic program, careful attention must be given to the arrangement of push buttons, which can be done by grouping related buttons next to each other. Grouping will reduce the visual clustering of buttons and improve the HMI's usability by reducing cognitive load. This also makes it easier for the operator to quickly identify and access the button they need, leading to a more efficient and intuitive operator experience. An example is the grouping of the hydraulic roof bolter machine push buttons in an interface to perform functions like:

(1) Closing of the upper clamp
(2) Opening of the upper clamp
(3) Closing of the lower clamp (Guide)
(4) Opening of the lower clamp (Guide)
(5) Lifting the pod (drill head)

(6) Lowering the pod (drill head)

(7) Rotating the chunk clockwise

(8) Rotating the chunk counterclockwise

Each of the functions listed above is assigned to a push button on the HMI for human-machine interactions, as presented in Figure 4.6. Creating these push buttons on the HMI enables the operator to control the machine from the touchscreen device.

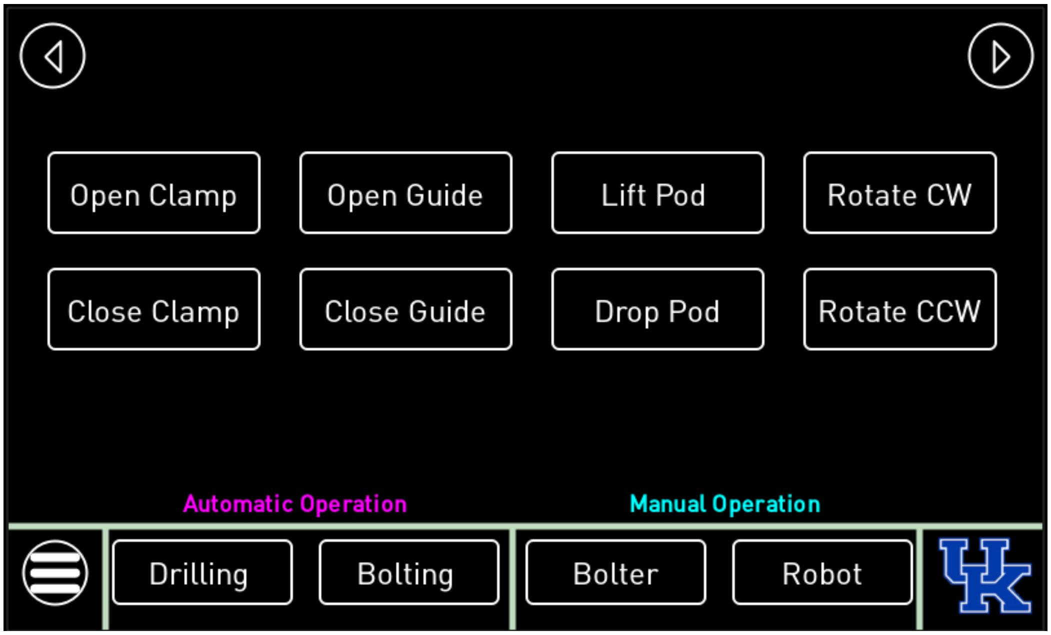


Figure 4.6: Hydraulic roof bolter push button interface of the MD4-HMI.

Figure 4.6 shows the previous and next arrows pointing to the left and right, respectively. The previous arrow presents the operator interface to navigate the screen to the preceding interface. On the other hand, the next arrow indicates that the screen can be flipped to the next showing the continuation of manual operation. The page consists of push buttons to control other automated roof bolter machine components, as shown in Figure 4.7. These components include the wrench, the bolt feeder, the plate feeder, and the pneumatic Schunk system.

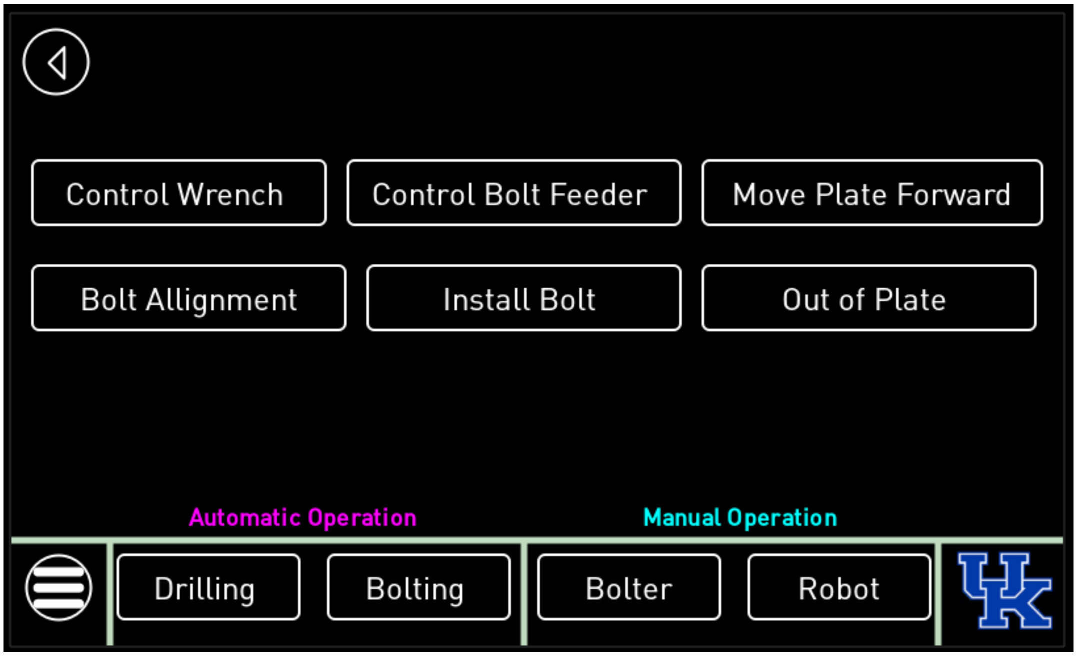


Figure 4.7: HMI interface for other components of the partially automated roof bolter machine.

However, the second interface in manual operation is the robotic arm function. The HMI interface for robot operation represents different push buttons for various robot functions. Technically, the interface comprises buttons migrated from the FlexPendant, as shown in Figure 4.8.

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 movements that can pose risks to the safety of the personnel working near the equipment.

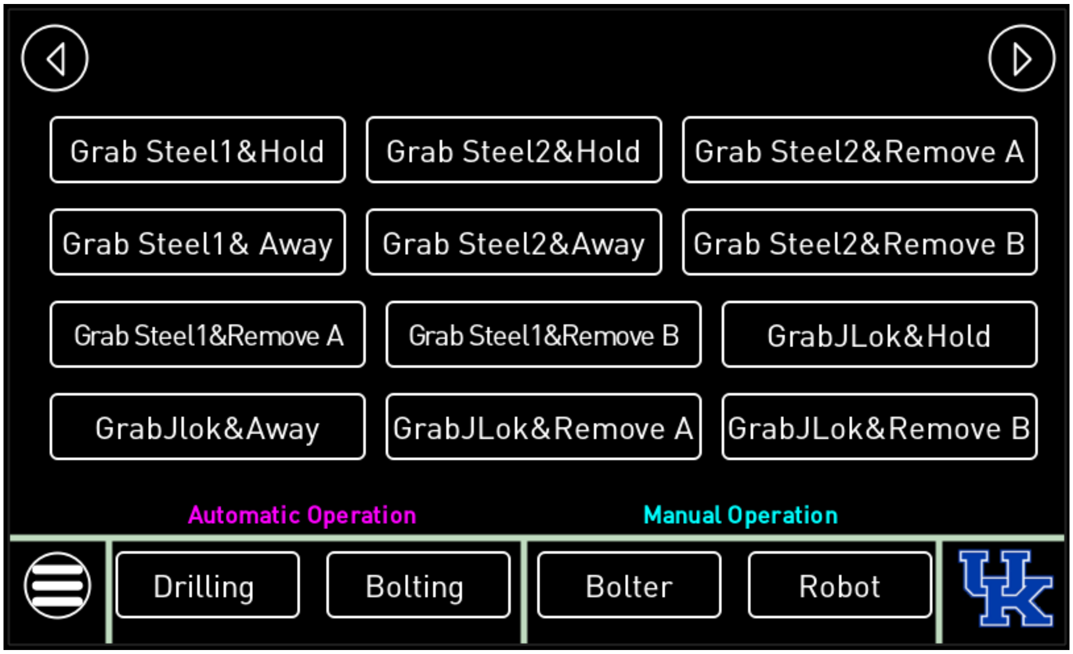


Figure 4.8: HMI interface for the robotic arm tasks.

4.3.2 Development of Automatic Operation Interface

The automatic operation is referred to as the autonomous operation. This mode of operation allows all the machine components to run with little or no human intervention. The automatic operation interface only has two primary operations; these are automatic drilling and bolting operations. The automatic drilling operation is the first tasks of the autonomous roof bolting task, where the robot arm, the hydraulic roof bolter machine, and other components perform drilling operations with human intervention. Figure 4.9 shows the drilling interface of the autonomous drilling operation. The HMI is designed so that the device requires the operator to approve every task before being executed by the automated machine.

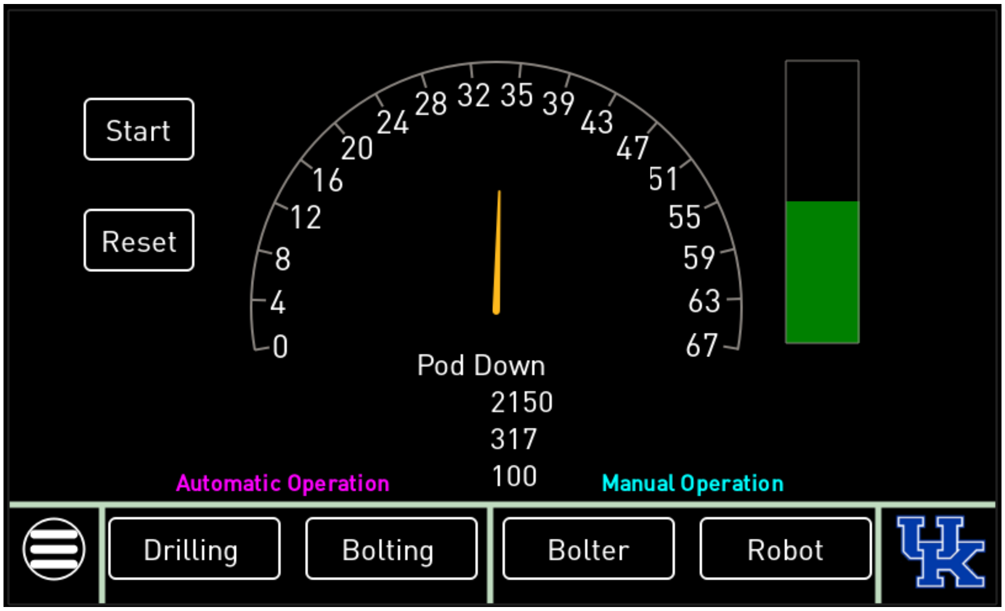


Figure 4.9: HMI interface for automated drilling operation.

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 can 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. In addition, the interface has a timer countdown for tasks performed during the automated roof bolting operation. For instance, the interface in Figure 4.9 shows the current task as “pod down” with the current timer as 2150 milliseconds. When the time counter reaches zero, the machine will perform the next task according to the PLC ladder logic on the iQAN program. Upon completing the drilling of the roof, the subsequent operation entails the insertion of pumpable resin and then, subsequently followed by the installation of bolts. These two tasks are seamlessly integrated and carried out consecutively within the framework of automated bolting operations. The HMI interface used for automated bolting closely resembles that of automated drilling. When the operator is required to perform some hydraulic bolter functions, the HMI is designed in such a way that the operator can easily change to manual operation.

4.4 Connection Between HMI and Automated Roof Bolting Machine

A robust connection between the HMI device and PLC is critical to the overall success of the automated system. 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. Integrating the iQAN system and ABB robot controller allows the operator to send commands to 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 HMI is connected to the PLC to control the robotic arm and the hydraulic roof bolter through the iQAN system. Also, the HMI device contains other components like the wrench, the bolt feeder, and the plate feeder. When a button is pressed on the HMI, a CAN message is generated from the PLC and translated for immediate execution of the task. After creating 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 illustrated in Figure 4.5 is connected to the computer while the CAN port is linked to the PLC. Upon establishing this connection, the computer gains the capability to upload the programmable ladder logic onto the MD4-HMI device.

The HMI and PLC are integral components of the automated roof bolter machine, with each component performing distinct roles and offering specific capabilities. The HMI creates a seamless link between the operator and the machine, enabling manual control over the system's operation. On the other hand, PLCs autonomously provide instructions to the machines, thus eliminating the need for human input. Both components have a crucial role in ensuring that industrial operations run smoothly, but it is important to know their differences to maximize efficiency.

4.5 Conclusion

One of the goals of this study is to design a user-friendly interface that presents the user with the progress of the roof bolting process while providing the user with options to override the process. The designed HMI provides an easy-to-use operator interface to control the autonomous operation of the roof bolter machine. The development of the HMI put together several display layouts and design considerations to foster the development of a robust HMI interface, as stated in Rockwell Automation (2019) report. The connection between the HMI and the automated systems through the iQAN system has been discussed. The method of sending signals from various push button types was fully explained. The outcome of this chapter developed a user-friendly MD4-HMI with both manual and automatic modes of operation. The developed HMI can adapt and work under high ambient temperatures, as described in Table 4.1. The specifications listed above show that the device is suitable for underground mining conditions.

Chapter five explains the establishment of a control network that manages the movement of each component of the automated roof bolter machine. The planning and creation of robot motions and the development of various system components will be thoroughly discussed. Chapter five also presents some specialized machines connected to the PLC to automate the process by providing instructions to machines without human intervention.

5. THE DESIGN OF INTERMACHINE COMMUNICATION PROTOCOLS FOR MACHINES NOT ORIGINALLY DESIGNED TO WORK TOGETHER.

Designing an effective intermachine communication protocol between machines that are not designed to work together depends on the requirements, constraints, and characteristics of the automated machine. This chapter describes the development of various types of machines that serve as the components of the automated roof bolter machine. This study then presents an approach used in designing an intermachine communication network between various components and the PLC of an automated roof bolter machine. Establishing a reliable communication path in controlling the movement of these components, especially the robotic arm, during the roof bolting process will be illustrated in this chapter.

5.1 Development of Components of the Automated Roof Bolter Machine

The essence of automated machines lies in their capacity to independently generate and regulate motion without human intervention. The ability to control various machine components involves sending signals to actuators and motors to obtain the desired response in an automated system. The successful integration of different machine components, originally not intended for collaborative operation, heavily relies on effective communication to facilitate the exchange of information through the transmission of commands, which is essential for the automation process. As far as control of automated systems is concerned, establishing a robust communication network between different system units will enhance the potential for intelligent control. In addition, creating an effective communication network in an automation system can foster interaction between various machine parts to achieve specific tasks without human involvement.

Before establishing an efficient communication network for an automated roof bolter machine, it is important to provide a comprehensive description of the construction of different machine types that comprise the fundamental components of the automated roof bolter machine. This study developed some specialized novel technologies that serve as components for the automation process of the roof bolter machine. These technologies were built to minimize or have no human intervention during the roof bolting operations.

This study ensures minimal usage of sensors in the automation process of the roof bolter to prevent challenges related to equipment failure, which is regarded as one of the critical considerations in underground coal mines. These specialized components of an automated roof bolter machine typically include the following three elements

1. The bolt feeder;
2. The plate feeder; and
3. The wrench system.

5.1.1 The Bolt Feeder

Operators of underground mining equipment are exposed to numerous hazards that can lead to injuries and accidents. By introducing automated technologies to mining operations, any potential risk to mining personnel is lowered. To reduce the risks for underground mineworkers, there must be a reduction in human involvement in operating machines. This study designs and develops an automated bolt feeder machine that stores and supplies bolts for robot installation during roof bolter operations. Despite the advancements of mining machines in recent years, the current roof bolting machine available in the mining industry still needs to be further developed into a prototype that can store bolts. In this study developed a bolt feeder, which is strategically placed at a position where the robotic arm can grab for installation, as shown in Figure 5.1. Before constructing the bolt feeder machine, this study considered several aspects that need to be controlled to ensure repeatable results. These include the size of the bolt feeder, the positioning of the bolt feeder, the types of mechanical motion-control systems to be installed, and the directional movement of the actuator. The primary function of the bolt feeder is to house multiple bolts and position a bolt for grabbing at a time. The current prototype of the bolt feeder was designed to allow the bolt to slide without frictional force. 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.

During the design evaluation, 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. The idea of placing the bolt in a position where the robot can grasp it would improve cycle time and the autonomous process.

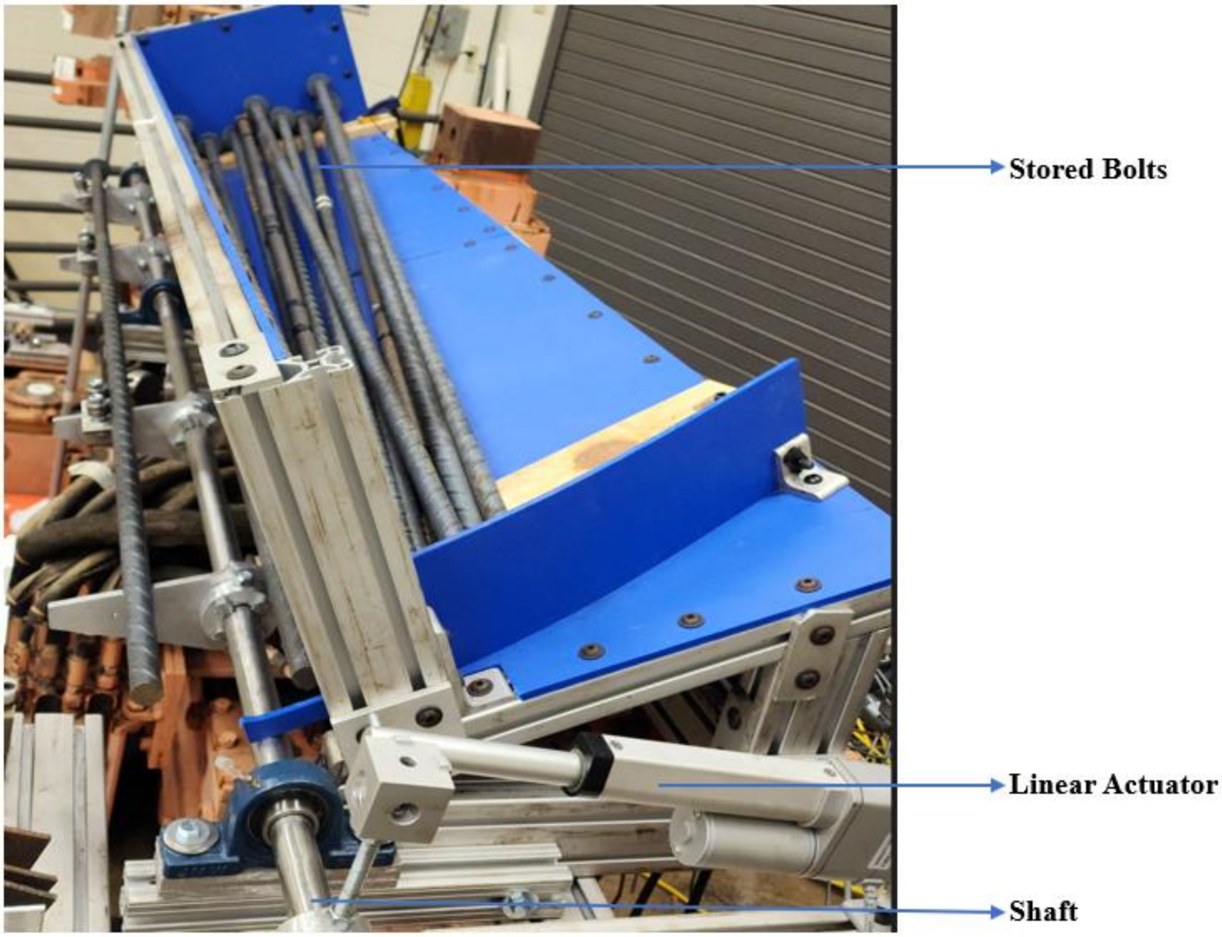


Figure 5.1: The bolt feeder with a linear actuator showing bolts waiting for installation .

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 linear actuator drives 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 positioning of the bolt. The manufacturer specifications of the linear actuator installed on the bolt feeder are summarized in Table 5.1. The performance of the actuator was examined during the laboratory testing of the automated roof bolter machine. An evaluation of the bolt feeder's performance entailed a comprehensive analysis of the linear actuator's operational speed and load capacity.

Table 5.1: Technical specifications of the linear actuator installed in 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] 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

5.1.2 The Plate Feeder

The plate feeder is designed to perform the primary function of fixing the plate on the bolt. 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 has been one of the most challenging steps for the operator during the roof bolting process, as shown in Figure 5.2. Similar to the bolt feeder, the plate feeder incorporates a linear actuator to initiate the motion. It achieves this by pushing the square plate, causing it to advance towards the white PVC shaft, where it awaits installation.

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 allows 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.

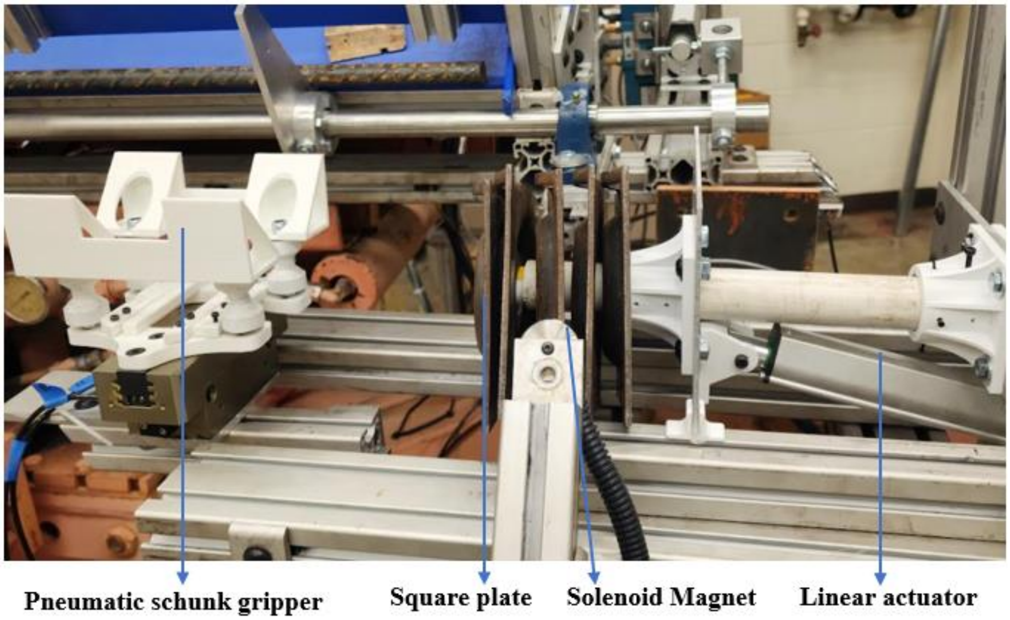


Figure 5.2: The plate feeder component of the automated roof bolter machine

5.1.3 The Wrench System

During the roof bolting process, the operator uses a hand to hold consumables like pumpable resins and drill steels while using the other hand to operate the machine. Several roof bolting accident reports have shown that this leads to the bolting machine operator developing unsafe practices, such as holding the drill rod while rotating. Operators frequently trap their hands against the roof when inserting or tightening the roof bolt. Hence, the best approach to avoid these accidents and injuries is to move humans away from the roof bolting operation and allow automated systems to perform hazardous tasks. This study constructed a wrench system to prevent human involvement during the automated roof bolting operation. The wrench system performs the human tasks of supporting the operation. The wrench system was designed and developed to quickly change tools and hold consumables 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 5.3.

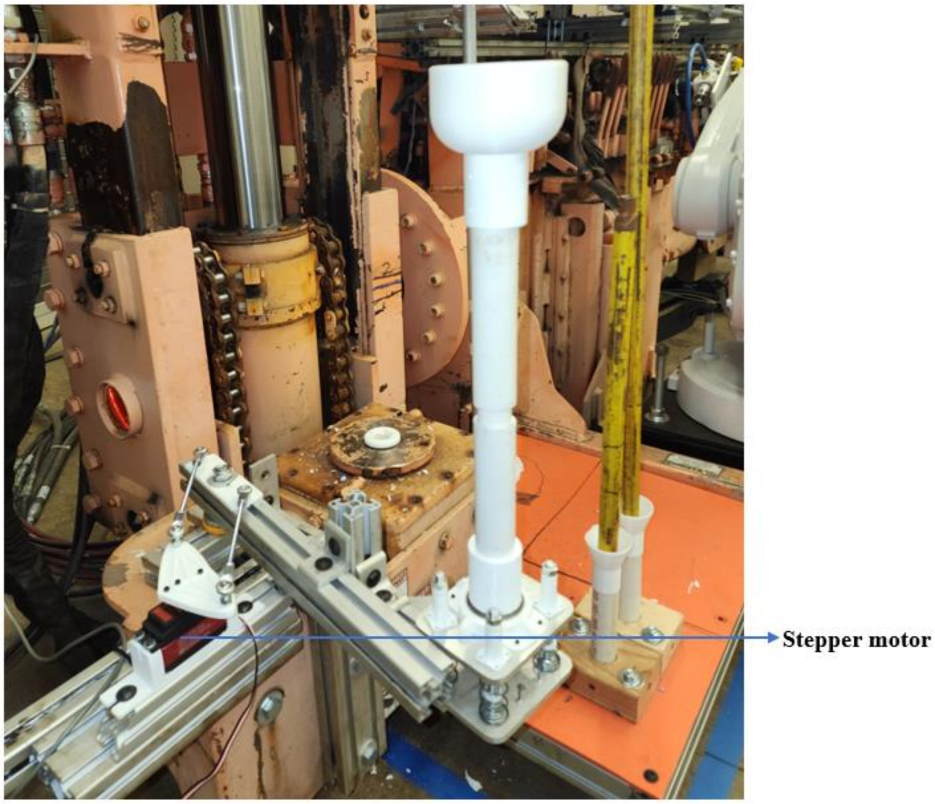


Figure 5.3: The wrench system of an automated roof bolter machine

The wrench system 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 the desired 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 stepper motor enables the movement of the wrench system, which is activated in response to signals transmitted from the HMI device. The stepper motor is connected to a microcontroller linked to the iQAN XA2 module to control the flow of current to the motor via the touchpad. In addition, the established network between the wrench controller and the PLC controls the directional movement of the wrench in and out of the drill head. Also, the ability of the wrench controller to communicate with the PLC presents the possibility of integrating all other components of the roof bolter into the IQAN program for the automation process.

The iQAN XA2 Module generally controls the linear actuator and stepper motor on these specialized components by regulating the voltage across its terminal using pulse width modulation (PWM). The microcontrollers are connected to the XA2 module to control the movement of the motor and actuators using high and low digital signals. The iQAN software presents an interface to set the digital signal that controls the components on high and low signals. For instance, the extension of linear actuators on both plate and bolt feeders is set high while the retraction is set to be low. Similarly, the same approach is used to control the movement of the stepper motor that drives the wrench system. The wrench microcontroller illustrated in Figure 5.4 controls the wrench's motion by sending programmable input and output signals as high and low signals to the iQAN XA2 module for task execution.

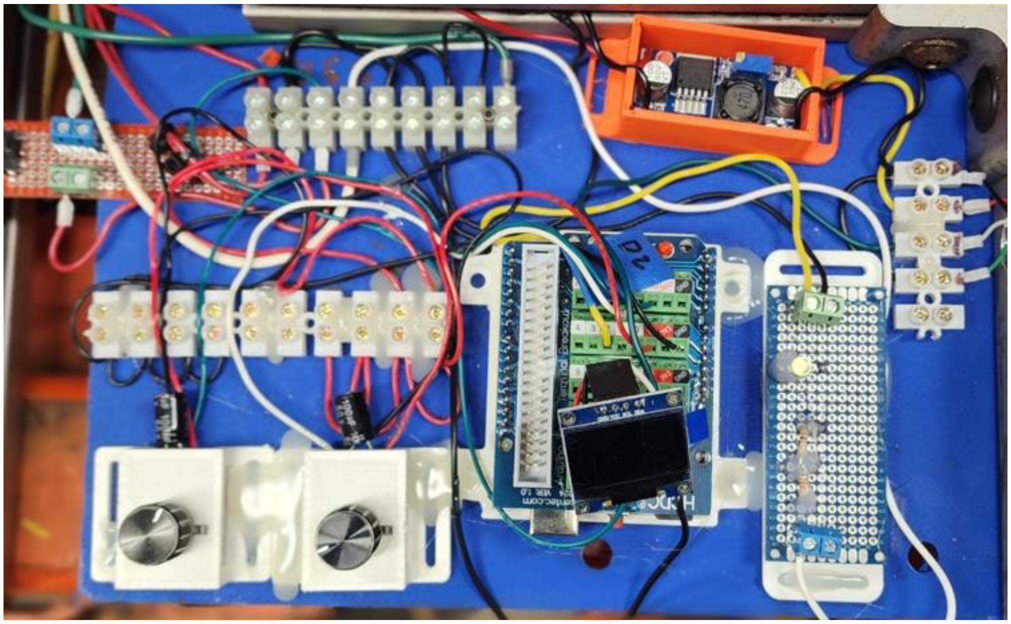


Figure 5.4: Microcontroller for coordinating the movement of the wrench system

In summary, the addition of the PLC and robot is not sufficient for the automation of the machine's task. Components need to be developed that will put the consumables and other objects to be manipulated by the robot in predictable and repeatable locations. The components as described in this chapter are all controllable by the PLC as illustrated in

Figure 5.5 but operate independently of the PLC. In this way, they can be replaced in a production machine with equivalent components that perform the same task, but may be hydraulically controlled like the rest of the machine.

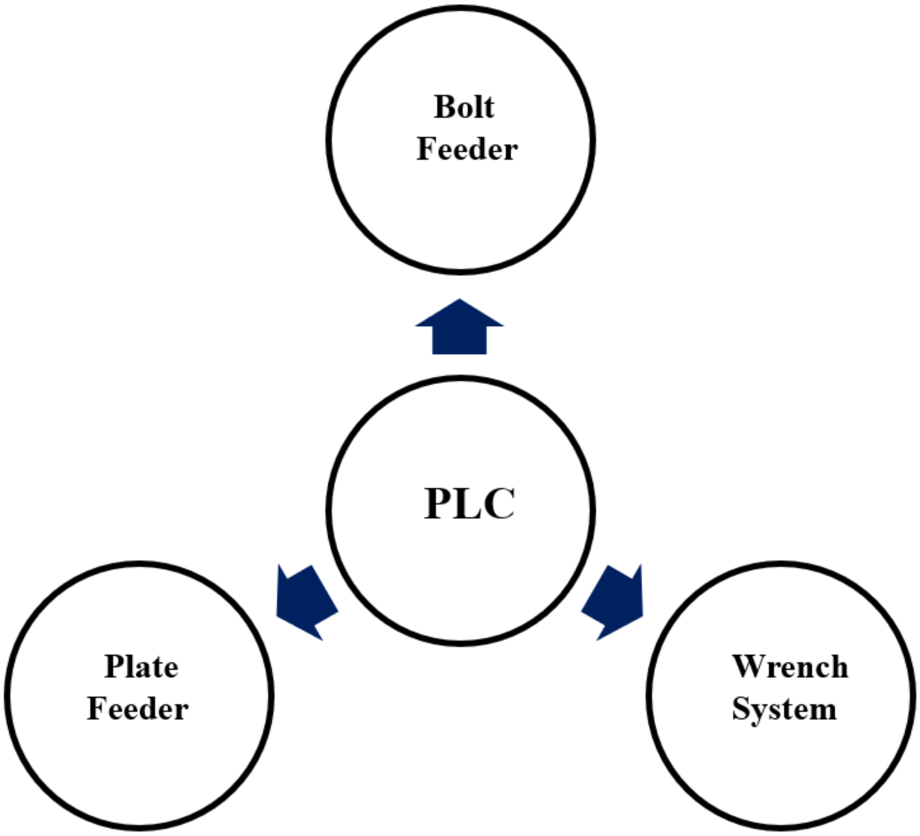


Figure 5.5: Integrating components to the PLC.

5.2 Robotic Arm Task and Motion Planning for the Automated Roof Bolting Process

Robot task and motion planning involves developing algorithms that enable the creation of trajectories that allow robots to achieve desired tasks autonomously. The process entails creating a sequence of actions and motions required for a robotic arm to execute given tasks. When a robot performs a task, firstly, it needs to find feasible plans to accomplish the goal; then, during plan execution, it has to consider the surrounding complex and changing environment before stepping ahead. This process is summarized as task and motion planning. It plays a significant role in ensuring that the robot navigates and interacts with their environment safely without collision. Once the motion and task are established and saved on the dedicated robotic arm software, the robot can move precisely and execute the plans repeatedly.

This study developed algorithms to generate task-and-motion plans for the ABB robot to manipulate drill steels, bolts, and the simulated pumpable resins autonomously. The goal is to allow the ABB robot, the roof bolter module, and other developed systems to collaborate seamlessly to automate the roof bolting tasks. During the planning phase, the study manually created robot paths to pick up the drill steel, the simulated pumpable resin, and bolts and place them on the roof bolter module. However, the manually created paths will be infeasible when the robot works autonomously during the roof bolting process. This study also considers the situations where the ABB robot has to manipulate obstructing objects, like drill steels, the wrench system, and roof bolts, during autonomous operation. This assists in preventing collision during roof bolting operation tasks.

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) as discussed in Zhang, et al., (2023), where the study 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 drill steels and installing it into the roof bolter, while motion planning is used to compute the actual paths the robot should execute.

This study considers the roof bolter and the ABB robot multi-robot systems. As a result, the study defines the problem as a multi-robot geometric task-and-motion planning problem, where the objective is to collaboratively move multiple objects to specific regions while accounting for the presence of movable obstacles. During laboratory simulations, the roof bolter was simplified as a single-degree-of-freedom robot. This configuration allows the drill base to perform vertical movements, specifically 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, the collaboration between the roof bolter and the manipulator is required. The planner generated collaborative plans so the manipulator could pick up the required objects and hand them to the roof bolter. To achieve this goal, the robot is programmed to identify and remove any objects from the roof bolter from the RobotStudio software.

5.2.1 ABB RobotStudio and Robot Trajectory

The IRB 1600 robot is equipped with RobotStudio software that manages and controls the robot's movement. The software provides an interface that controls every aspect of the robot, such as creating motion trajectories and the development and execution of program communications. In this study, the robot is programmed to move in a particular path during the roof bolting operation. Before the establishment of robot motion trajectories, simulations were performed to mimic how the robot will perform the underground mining conditions where there are undulating surfaces, inadequate lighting, and power cables laying on the floor, shown in Figure 5.4. The hydraulic roof bolter consists of yellow, pink, and green components, with the red object indicating the drill head. The simulation involved creating all the steps that the robot would take to execute tasks, from grabbing drill steels to installing the bolt. The simulation showed clear robot motion paths that prevent a collision.

The goal of planning an algorithm is to generate robot executable motion paths to install the drill steel into the roof. To achieve this, the study developed an algorithm that identifies and moves away obstacles that may be found in the working environment. In the environment shown in Figure 5.6, the robotic arm follows the path created to place the bolt on the drill head for installation. The RobotStudio enables humans to create a target in space, defined by its coordinates and additional information like the position, orientation, and configuration for which the robot must reach.

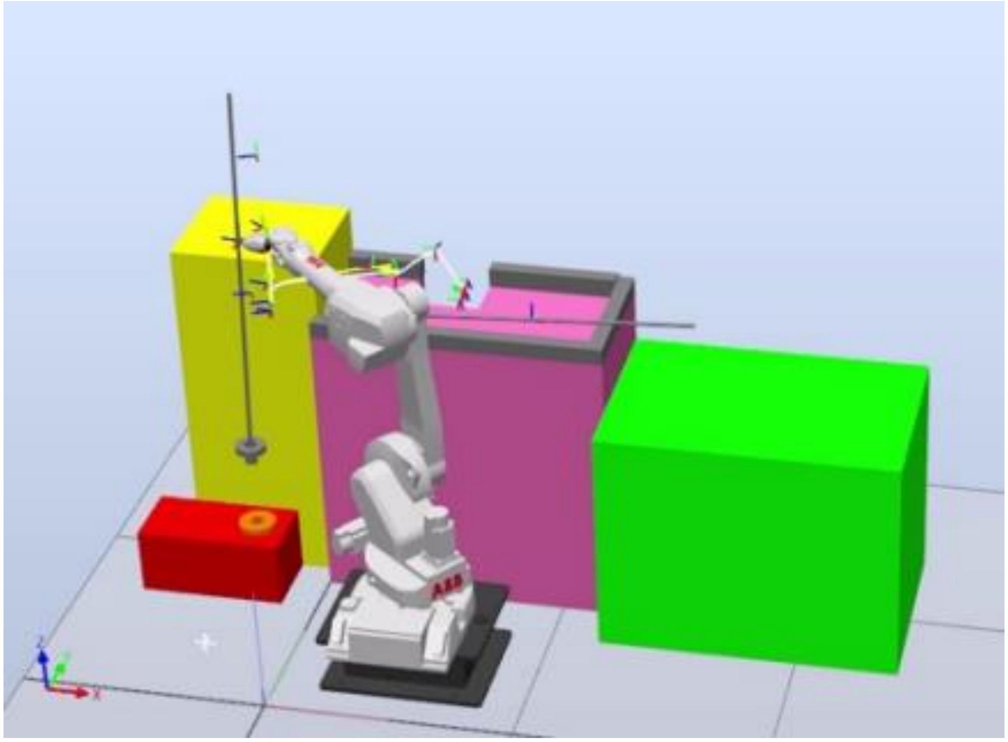


Figure 5.6: Simulation of robotic arm path creation in ABB RobotStudio

The RobotStudio comprises a high-level programming language called RAPID to control the IRB 1600 robot. The RAPID program consists of several instructions that describe the task to be performed by the robot in a Pascal-like syntax. These instructions represent various commands such as grabbing drill steels, removing drill steels, lifting pumpable resin, and grabbing and placing bolts. Applying commands built into the algorithm makes the robot imitate human efforts in bolting operations. The robot trajectory was created in the RAPID using the flex pendant to drive the robot. The base coordinate of the robot is defined as the origin of the robot's workspace. The coordinates of the robot are recorded and safe in the RAPID as the robot moves from one position to another. The measured coordinates represent the robot's base coordinate and the first joint's centerline.

The RAPID uses a four-point method to present the coordinate of the robot's position, which is usually in linear motion. The interface of the RAPID is programmed in C# with three different modules, namely the server, the client, and the RobotStudio API module. The RobotStudio API module is connected directly to the robot controller on the computer, which is physically connected to the robotic arm. The server connects the user to the RobotStudio API module through a static IP address, enabling external users to control the robot remotely. The user represents the GUI interface where commands are sent to the robot by pressing a button. The RAPID program must be carefully written to allow remote application control of the robot's motion. Although, the remote access operator needs permission from the physical operator to be able to access and control the robot's movement. When all the paths and tasks of the program are completed, the robot returns to its home position.

5.3 PLC Setup with iQAN System

The PLC is a digital control unit specifically designed to manage the digital input and output (I/O) in an automated system. A PLC must accommodate multiple discrete inputs and outputs, allowing for expandability while maintaining real-time control over the monitored process. This study developed a PLC to monitor and control the automated roof bolting operation. The hydraulic holes from the hydraulic roof bolter machine are connected to the modular control unit, which is linked to the PLC. The primary function of modular control is to create customized control solutions for easy integration of systems to the PLC.

In this study, the modular control is used to connect the conventional hydraulic holes from the roof bolter machine to an adaptable, responsive control system that can easily be controlled from the HMI device. The black cable is the hydraulic hole from the roof bolter machine, while the yellow cable is the bulk cable (programmable cable) that links the modular control to the PLC, as shown in Figure 5.7. The modular control converts 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 the clamp and guide, the up and down movement of the pod, and rotating the chunk in clockwise and counterclockwise directions. The hydraulic holes are also 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.

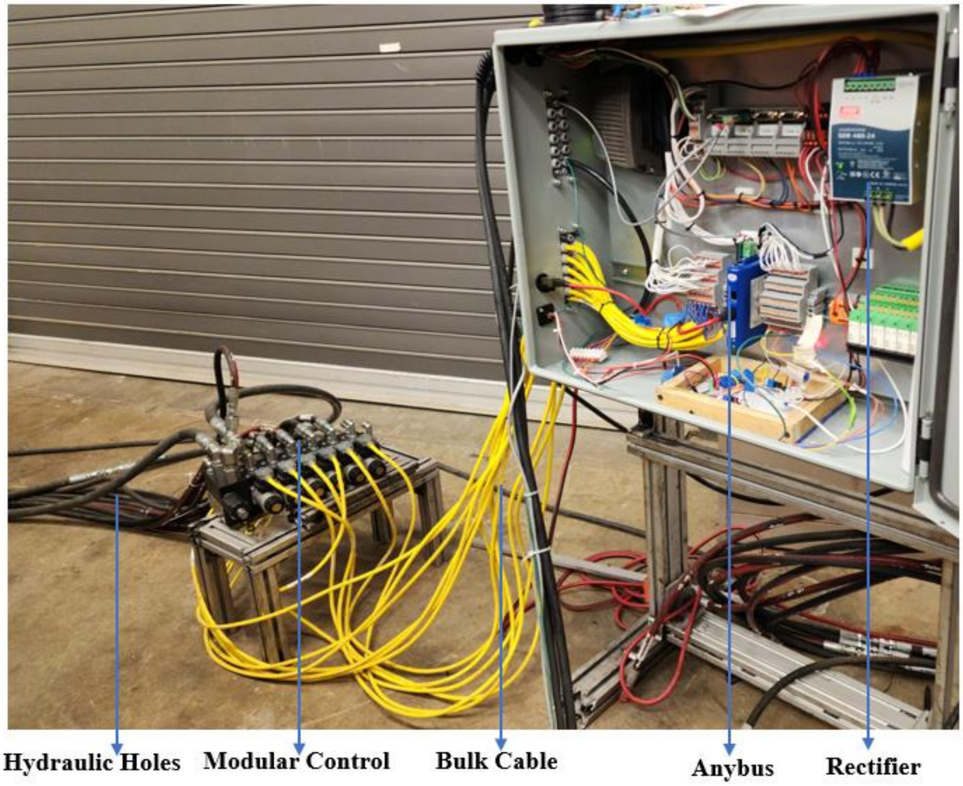


Figure 5.7: Connection between the hydraulic holes and the PLC.

The iQAN logic is built to perform these functions from the I/O devices and generate control signals that allow the machine to be automated. The iQAN interface communicates to the programming panel and the ABB and PLC controller through the AnyBus CAN to Ethernet/IP interface. The iQAN software interface provides a programming outlook that facilitates the transmission of messages to the PLC. The primary advantage of using the iQAN program is its seamless communication protocol over a CAN bus using the IQAN CAN protocol. In addition, the software offers a user-friendly interface for accessing the CAN communication protocol, allowing users to interact with various components, including the robot, the hydraulic roof bolter machine, and others. The CAN message enables the operator to control the bolting process through Parker Hannifin's iQAN system. A practical illustration of this interaction involves assigning specific time values to perform certain tasks. For instance, in the IQAN program, the time taken to close the upper clamp is configured to be 3500 milliseconds, while the time taken to close the guide is 3850 milliseconds. The primary function is to monitor and control the machine's behavior, ensuring optimal performance and functionality. The HMI device is connected to the PLC to control the robotic arm and the hydraulic roof bolter through the iQAN system.

The diagram in Figure 5.8 shows the XA2 module interface connecting hydraulic valves to the modular control system for specific tasks. For instance, section one from the hydraulic valve controls the rotational movement of the chunk; 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 is not connected, as only five sections are required to control the machine for the automated roof bolting operation.

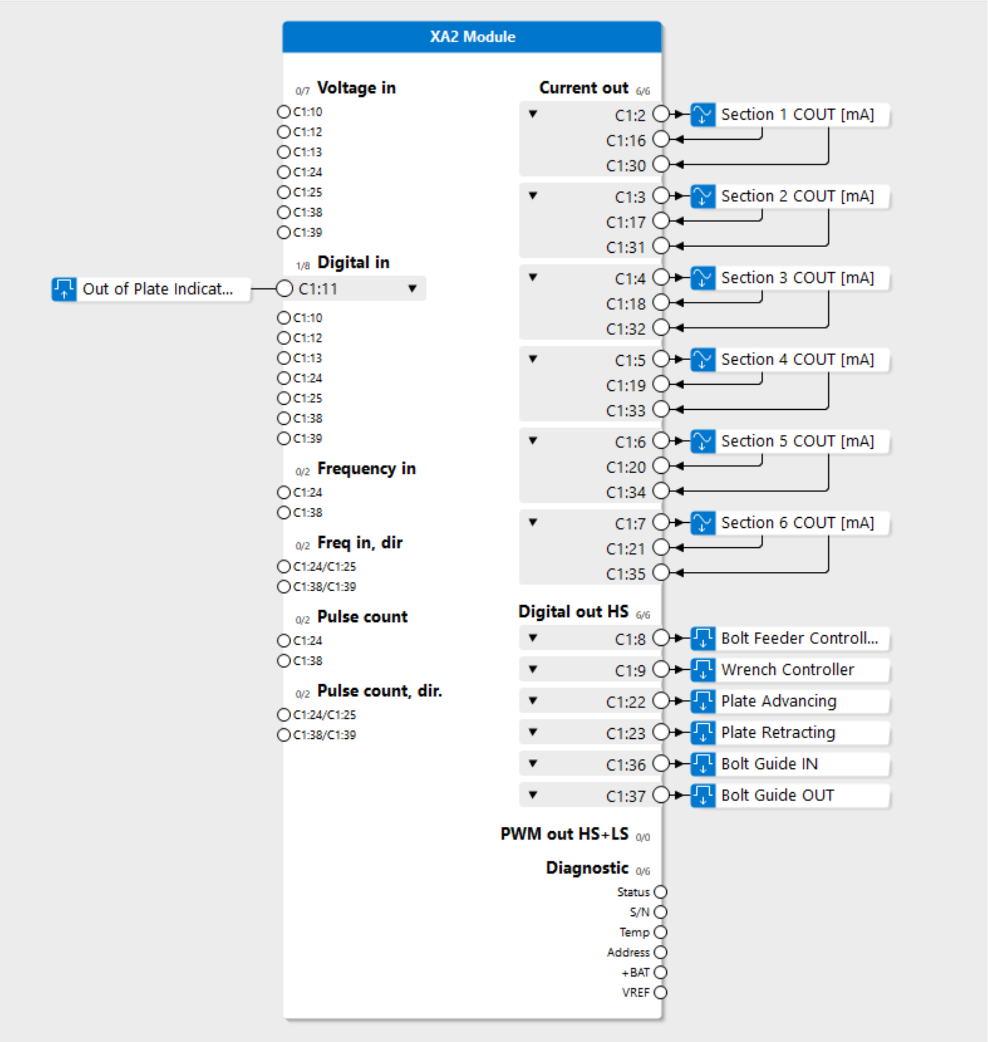


Figure 5.8: iQAN XA2 module connection with roof bolter and other machines

5.4 Establishing Communication Protocols between Anybus Device and the iQAN system

The Anybus device is installed in the PLC cabinet. This device allows the robotic arm to be incorporated successfully with the iQAN systems. 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 5.9. 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 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. The model of the Anybus communicator employed for the communication between the robotic arm and other machines to automate the roof bolter machine is the AB7317 Anybus communicator.

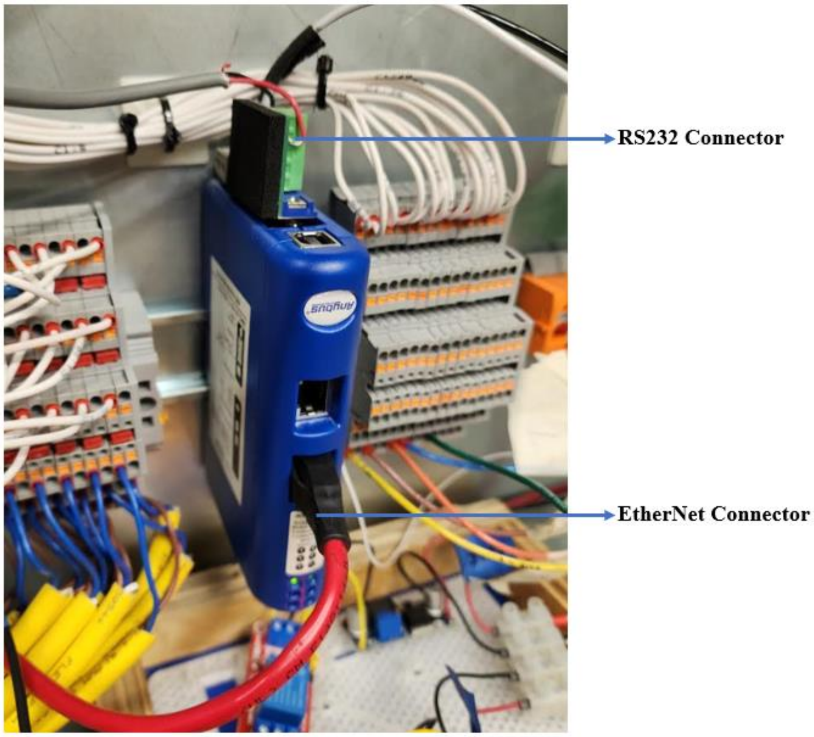


Figure 5.9: AB7317 Anybus Communicator

The Anybus communicator is connected to EtherNet/IP to control the automation process of the roof bolter machine. The device serves as gateway to perform intelligent protocol conversion and presents the CAN data to the PLC as easily processed I/O data. The device is a stand-alone gateway designed for IP20 and DIN-rail mounting, requiring a 24-volt power supply, as shown in Figure 5.10.

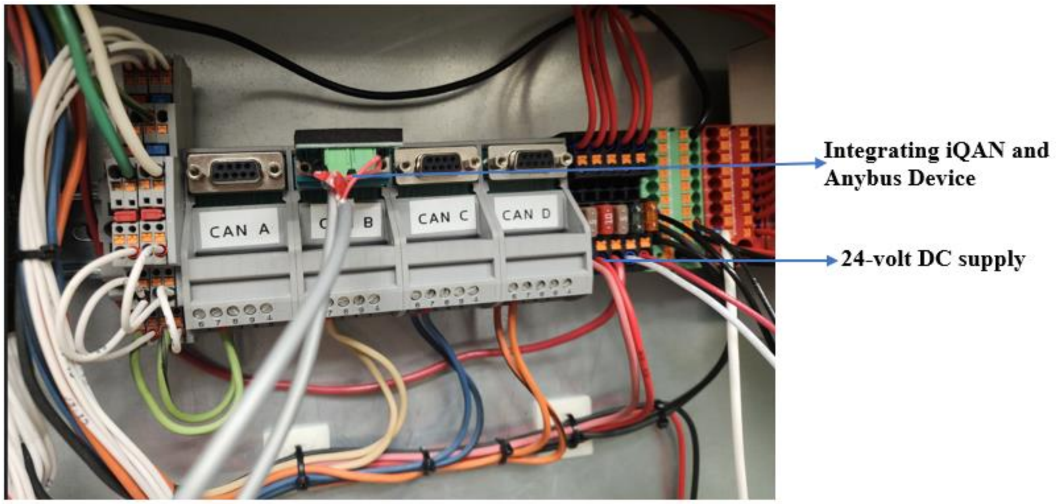
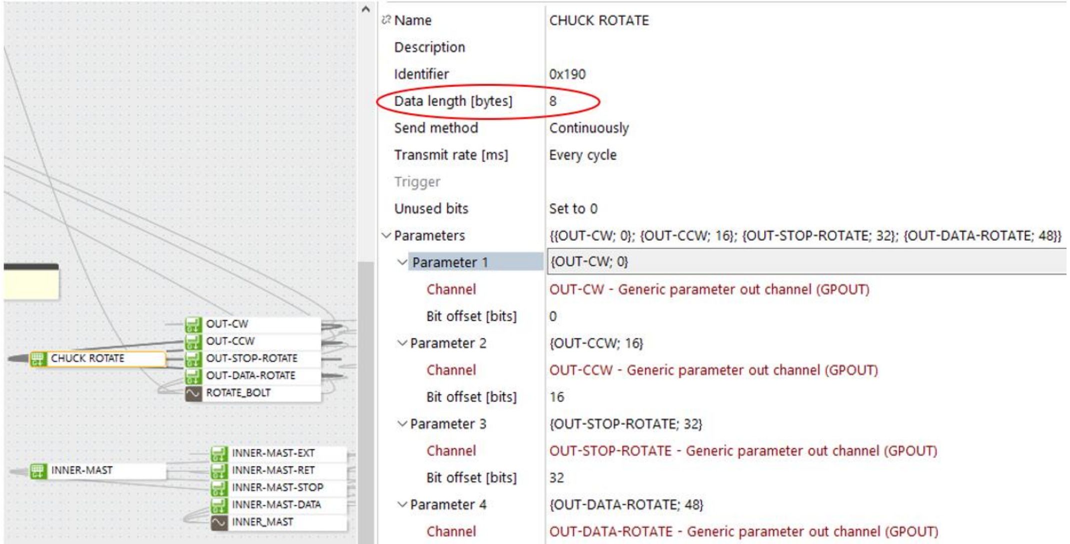


Figure 5.10: CAN Bus system showing integration of RS232 connection from Anybus and iQAN

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. Then, a CAN bus interface is integrated directly into the valve section to connect to the master control unit and control the roof bolter's hydraulic system. Using the CAN bus as the primary communication interface makes the communication network more accessible to sensors and other devices. This study 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. In a CAN Bus network system, multiple nodes communicate by sending messages to designated nodes using specified identifiers. All nodes operate as masters, eliminating the need for a central master controller to supervise the bus. This network configuration ensures a highly reliable connection and minimizes the occurrence of faults. The bus network topology of the CAN Bus reduces the points of failure since a single data line is used to handle all communications.

In this study, the CAN from Parker Hannifin's iQAN system is a message-based protocol that allows messages to be sent in form of a packet of data known as a CAN frame. The CAN frame can send 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 as shown in Figure 5.11. 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 CAN identifier for the first task in the roof bolting automation process is drilling which 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.

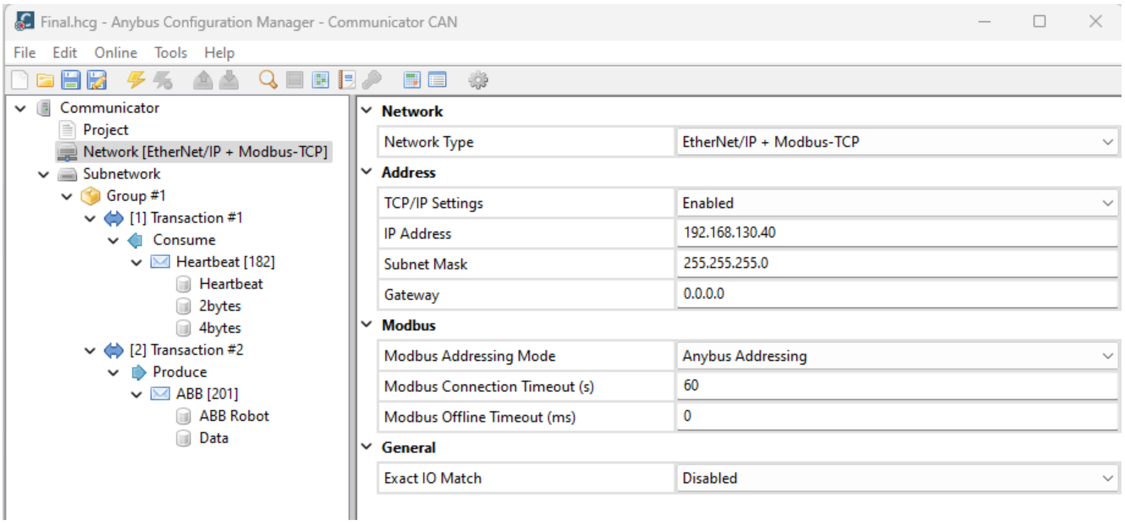


Name	CHUCK ROTATE
Description	
Identifier	0x190
Data length [bytes]	8
Send method	Continuously
Transmit rate [ms]	Every cycle
Trigger	
Unused bits	Set to 0
Parameters	{{OUT-CW; 0}; {OUT-CCW; 16}; {OUT-STOP-ROTATE; 32}; {OUT-DATA-ROTATE; 48}}
Parameter 1	{OUT-CW; 0}
Channel	OUT-CW - Generic parameter out channel (GPOUT)
Bit offset [bits]	0
Parameter 2	{OUT-CCW; 16}
Channel	OUT-CCW - Generic parameter out channel (GPOUT)
Bit offset [bits]	16
Parameter 3	{OUT-STOP-ROTATE; 32}
Channel	OUT-STOP-ROTATE - Generic parameter out channel (GPOUT)
Bit offset [bits]	32
Parameter 4	{OUT-DATA-ROTATE; 48}
Channel	OUT-DATA-ROTATE - Generic parameter out channel (GPOUT)

Figure 5.11: Maximum data length allowed in a frame from iQAN program

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. The Anybus device gateway software solution is developed by the HMS network to facilitate communication between different devices, notably devices that use other protocols. Using different protocols, it acts as a bridge between devices, enabling them to exchange data and communicate effectively. 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 the fault since a single data line is used to manage all communications. In the Anybus device configuration setup, the IP configuration allows the device to connect to a network, enabling communication with other components of the roof bolter machine. The IP configuration is crucial because it determines how the Anybus device is identified and accessed on the network. The device becomes reachable by assigning a unique IP address, and data can be exchanged between it and other network-connected devices. As shown in Figure 5.12, an exemplary configuration has been allocated for the automation of roof bolting. This configuration encompasses assigning an IP address, specifically 192.168.130.40, to the Anybus communicator, alongside a corresponding subnet mask of 255.255.255.0.

The Anybus communicator can convert almost any type of serial protocol such as Modbus RTU, ASCII, DF1, or any other type of proprietary Query/Response or Produce/Consume protocol. In this study, the consume transaction is the heartbeat, providing instructions to the robot and other components for task execution. In contrast, the produce transaction delivers feedback to the operator upon completing the task. Essentially, the consumer represents the request, while the produce represents the response.



Network	
Network Type	EtherNet/IP + Modbus-TCP
Address	
TCP/IP Settings	Enabled
IP Address	192.168.130.40
Subnet Mask	255.255.255.0
Gateway	0.0.0.0
Modbus	
Modbus Addressing Mode	Anybus Addressing
Modbus Connection Timeout (s)	60
Modbus Offline Timeout (ms)	0
General	
Exact IO Match	Disabled

Figure 5.12: Anybus gateway configuration interface.

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 connected to the iQAN systems. This study communicates the signals based on the CAN protocols assigned to service ports A and B (CAN Bus), as shown in Figure 5.13. 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.

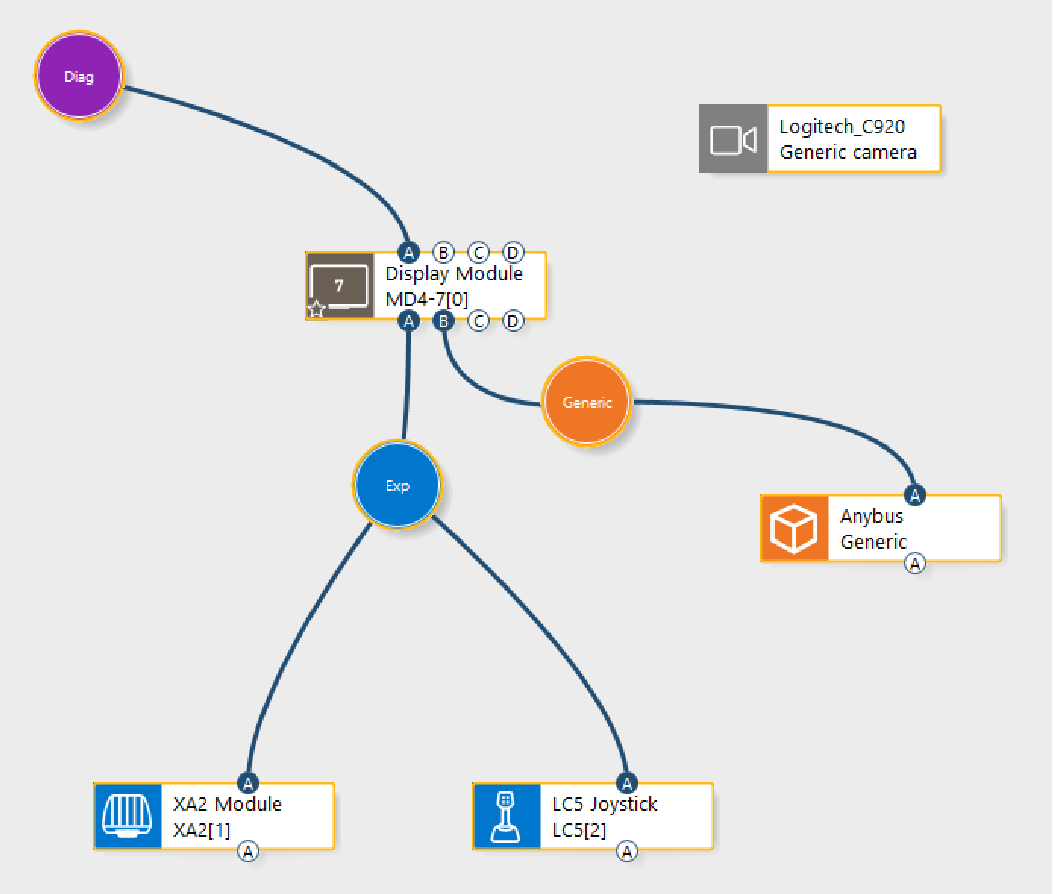


Figure 5.13: iQAN system communication interface.

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. Apart from minimizing physical connections, other benefits include high communication speed, reliable network, error resistance, and low-cost implementation. The system provides easy access to interfere with the CAN communication protocol between the robot and other components. The CAN communication protocol employs a carrier-sense, multiple-access approach incorporating collision detection and arbitration based on message priority. In contrast to conventional networks like USB or Ethernet, CAN does not send large blocks of data point-to-point from node A to node B under the supervision of a central bus master. In CAN communications protocol, messages are passed between machines by the physical medium which is defined in terms of the physical layers of model.

The iQAN program 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. Although some of the sensors connected to the PLC work with voltage below 24V, a microcontroller (voltage divider) was built to power these components. For instance, the linear actuator that drives the shaft on the bolt feeder and the linear actuator for the wrench movement is powered with 12Vdc.

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 programmable time sequence in the iQAN program allows for the movements of various components. The application of the time-based logic program prevents collision between the hydraulic roof bolter, the robotic arm, and other components of the automated roof bolter machine. However, the time-based logic does not only make it easier to estimate the cycle time but also optimizes the bolting operation which in turn influences the performance of the bolting process. Whenever a change is made on the iQAN program, the program is uploaded to the PLC for the update.

5.5 Conclusion

Establishing an intermachine communication process for machines designed not to work together is the basis of autonomous operation. This study constructed various devices that serve as automated roof bolter machine components. A robust network was developed that enables these components to perform sequential roof bolting operations. Notably, the Anybus communicator in the PLC receives, translates, and sends a CAN message into a signal the robotic arm will understand. The integration and autonomous movement of various components are achieved with the programmable time sequence in the iQAN program.

The assembly of various components and the robotic arm that brought about the partially automated roof bolter machine are discussed in chapter six. The concepts of integrating these technologies and developing communication between the devices led to automated roof bolter machines. Chapter six also discusses the development and the laboratory-scale testing of an automated drilling operation, automated bolting process, and several modifications made for a successful automated bolting operation.

6. THE CONCEPTS OF DEVELOPING A PARTIALLY AUTOMATED ROOF BOLTER MACHINE.

Integrating the six-axis robotic arm with other specialized machines led to the development of a partially automated roof bolter machine. This chapter discusses assembling the developed specialized machines that serve as the components of the automated roof bolter machine. These components are linked to the PLC and controlled by the HMI touchpad. This study focuses on the laboratory testing of subroutine automated tasks such as the drilling operation, removing drill steels, inserting the pumpable resins, and installing the bolt for a successful automated bolting operation. The developed HMI interface offers the operator essential functionalities such as the start and stop push buttons to initiate and terminate the automated roof bolting processes.

6.1 Integration of the Robotic Arm, Hydraulic Roof Bolter, and Other Components

The arrangement of different components of the automated roof bolter fosters the integration process. The position of the machine components holds great importance in the realm of automation by ensuring optimal performance, efficiency, and safety of automated systems. Although component positioning can be tricky, getting it right is crucial to the optimization of workflow and speed of the automated assembly system. The automated roof bolter machine integrates several components, indicating their precise position, orientation, and direction of movement to avert any complications and inefficiencies in the automation process, ensuring optimal performance and productivity. The assemblage of these components is the key element in the design and conversion of a manually operated machine to an automated machine. Notably, strategic positioning of components enhances system speed, while concurrently mitigating redundancy in the machine by preventing the need for additional systems.

Another factor to consider before the integration process is the space facility for the automated roof bolter machine assembly and test. All the automated roof bolter machine components were built and tested in the Rock Mechanics Laboratory located in the Department of Mining Engineering at the University of Kentucky, USA. Figure 6.1 shows the arrangement of all the automated roof bolter machine components in the laboratory.

The choice of selecting the space lies in the amenities available in the laboratory for the automation process. Similarly, the selected space must demonstrate features that are replicas of the underground mining method. The Rock Mechanics Laboratory selected for testing the automated roof bolter machine is equipped with amenities like a high voltage electrical power supply for the hydraulic pump, heavy lifting equipment for installing heavy components such as the roof bolter module and robotic arm, compressed air to supply air to pneumatic devices, and 3D printers for printing machine parts. The laboratory space is suitable for assembling and testing automated roof bolter machines.

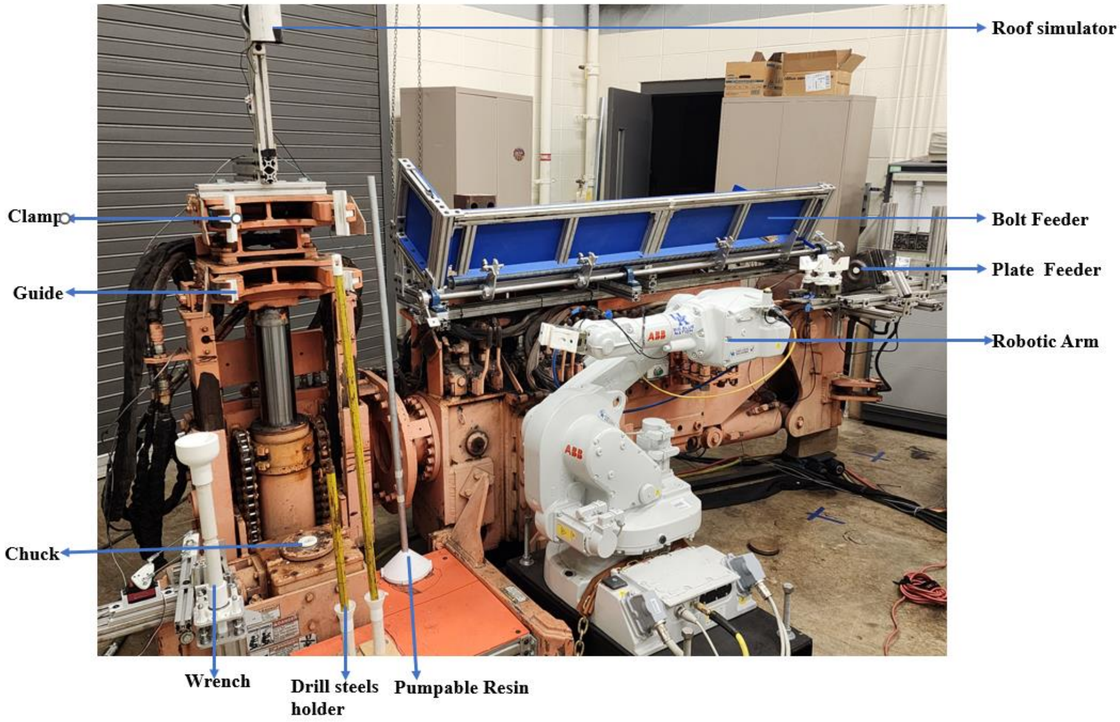


Figure 6.1: Arrangement of different components for the automated roof bolting process.

Moreover, achieving a successful automated roof bolter machine requires seamless coordination among the ABB robotic arm, hydraulic roof bolter module, and all other relevant components. Integrating all components of the roof bolter machine is the most critical phase of this work, as individual component needs to execute assigned tasks without collision. The integration was done in the iQAN program. This software program provides a platform to control and monitor the behavior of machines such as hydraulic systems, which makes it suitable for this study. The iQAN program allows the operator to monitor different iQAN-units connected through a CAN network. One of the main reasons for using the iQAN program for this study is the easy access communication protocol of the CAN network. Several ongoing communication protocols are not revealed to the operator. Within the automated process, there are several ongoing communication protocols remain undisclosed to the operator. The operator can only see the progress of the automation process via the HMI device. The integration of all components and technologies enables the proper sequencing of the automated roof bolter operations controlled by the HMI device. The HMI is connected to the PLC to enable control of the automated roof bolter machine using IQAN technology.

The communication between the robot and other components is critical to the automation process. The establishment of a secure communication protocol between the components and the robotic arm enables control of various parts into their desired position, which in turn led to the development of an automated roof bolting process. However, during development, several testing and prototyping communication methods were developed. 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 so 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 commands 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. The communication architecture illustrates that the Anybus communicator controls the communication in the form of the 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 6.2.

Additionally, it is imperative to develop a cohesive communication strategy that can effectively integrate the ABB robot with various interconnected components; C # scripts (.NET framework) have been developed that use the RobotStudio API to control the robot directly. Other C# scripts have been developed to use the Kvaser CAN interface (a USB-to-CAN connection) to communicate directly with the PLC. 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. Using CANBUS as the primary communication interface makes the communication network more accessible to sensors and other devices.

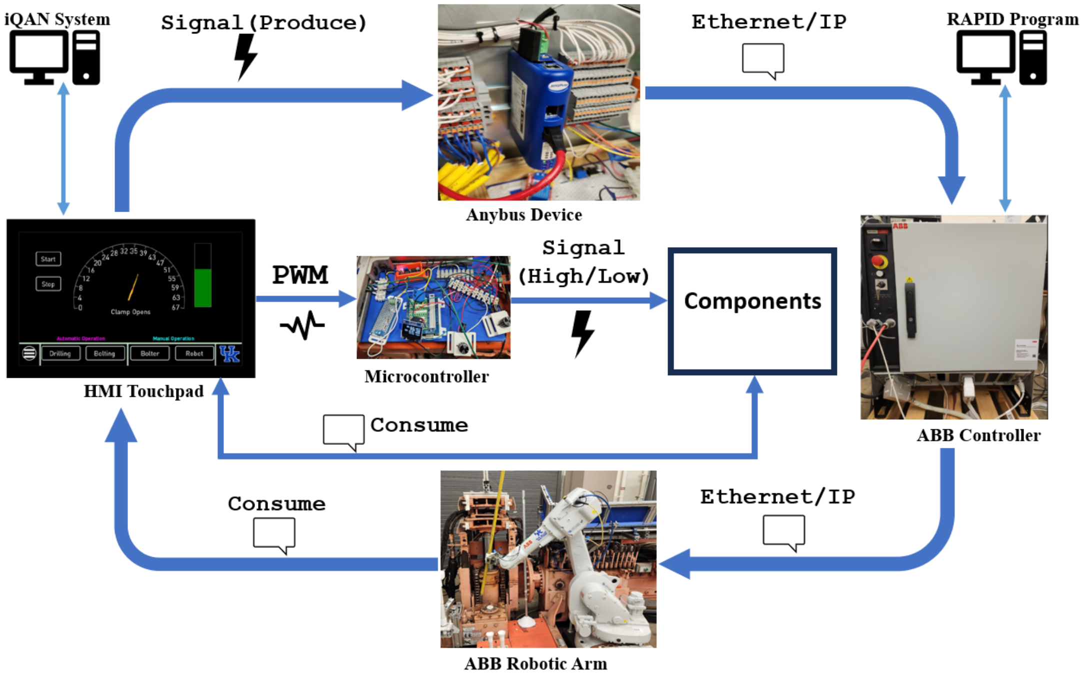


Figure 6.2: Automated roof bolter machine communication architecture

The robot uses the EtherNet Industrial Protocol (EtherNet/IP) to communicate with other bolting process components. As previously discussed, this process is industrial EtherNet/IP based, with the ability to communicate between the robot and the control system in real-time. 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. Establishing a reliable communication path between the robot and the PLC is vital in the automation process.

Traditionally, the roof bolting operation is categorized into four major steps. These include:

1. Hole drilling into the overhead roof;
2. Removal of drill steels;
3. Insertion of pumpable resins; and
4. Bolt installation.

In this study, the entire process of testing the automated process in the laboratory was structured into major two steps. These include the drilling and bolting operations. The drilling operation in the roof bolting process entails penetrating the roof and removing consumables such as the drill steels and drill bit. On the other hand, the bolting operation involves inserting the pumpable resin and installing the bolt.

6.2 Automated Drilling Operation

The automated drilling section of an automated roof bolting operation comprised of drilling the roof and removing drill steels from the holes. The ABB robotic arm is used to position and remove drill steels upon task completion. The automated drilling task is conducted by allowing the robotic arm to perform human tasks in roof drilling. The robotic arm's action not only imitates 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. As discussed in chapter five, the robotic arm trajectories are created using the flex pendant, and the paths are saved in the Robot Studio software. The Robot Studio provides an interface that controls and manipulates the robot's motion to perform specific 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 6.3. 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.

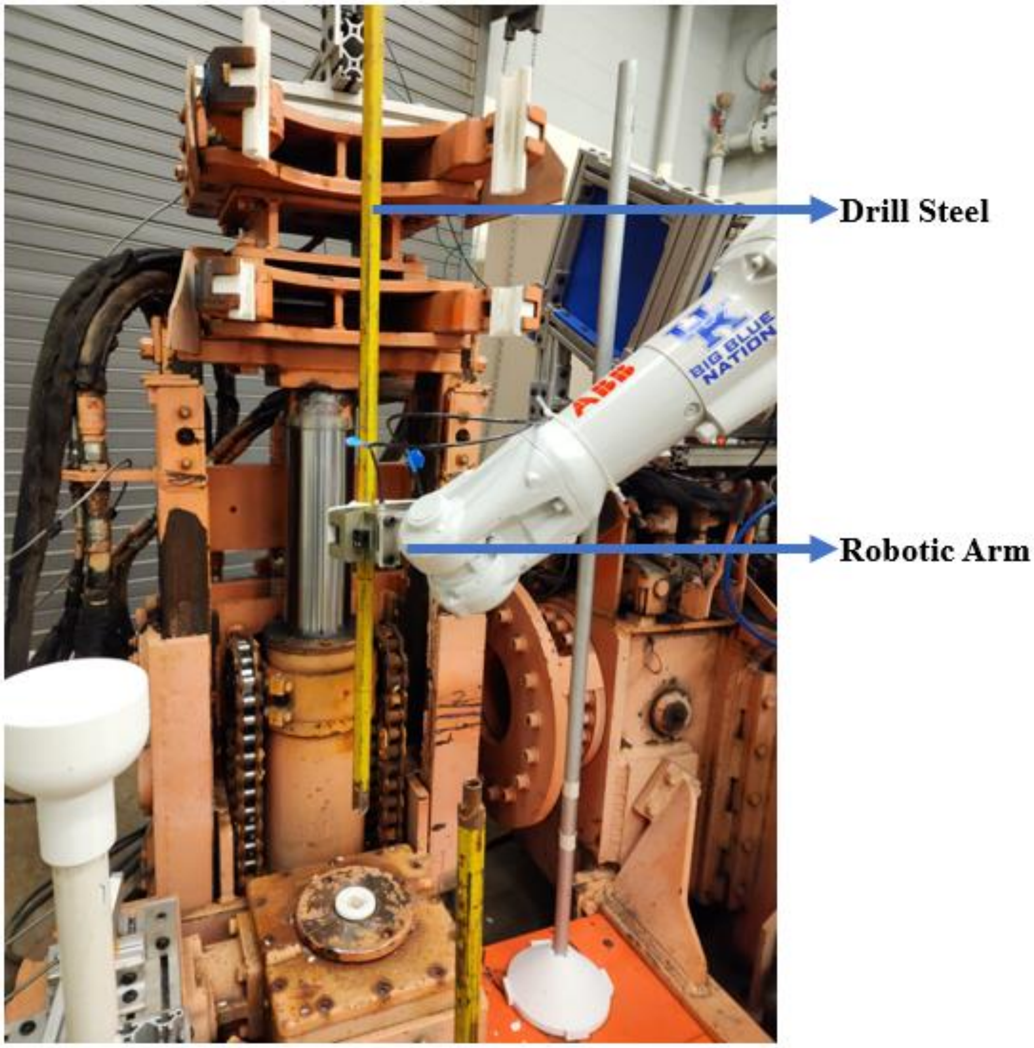


Figure 6.3: Placement of first drill steel for drilling operation by the robotic arm.

It is important to note that before the robotic arm can perform an automated operation, the RAPID program in the RobotStudio has to be carefully planned, programmed and tested to ensure the safety of operators and equipment. Before starting the automated operation, the operator ensures 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 operator monitors the automated operations. During the roof bolting operation, if the operator notices any irregularity in the movement of the robotic arm, the hydraulic system or 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. The software presents easy access to the communication protocol of CAN and enables the users to interact with both the robot and the hydraulic roof bolter. The CAN message allows the user to control the bolting process through Parker Hannifin's iQAN system. When the PLC generates a CAN message, the message is sent to the Anybus communicator, which translates and sends it to the robotic arm controller for the robotic arm to execute. The Anybus device controls the communication between the robotic arm and the hydraulic roof bolter through an Ethernet/IP interface. All the components are connected to the PLC through the iQAN program. The HMI is connected to the PLC to control and supervise the automated roof bolting process.

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 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. Although, human operators will be required to approve primary operations, such as moving the bolting head or starting a new drilling sequence, while also maintaining the ability to operate the robotic arm and the hydraulic system. Based on the laboratory test, the robotic arm performs and improves the automation process.

6.3 Automated Bolt Installation

The automated bolt installation section of the automated roof bolting cycle contains the pumpable resin insertion and installation of the roof bolt. Installing bolts in underground mining operations traditionally relied on operator experience and judgment. 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. Ideally, the resin insertion is done with a pumpable resin comprised of two components, a resin and a hardener, mixed during installation, creating a strong reinforcing material between the rock and bolt installed. The resin serves as a bonding agent between the bolt and the surrounding rock. 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. Pumpable resin systems are designed so that little to no reaction occurs until the bolt is inserted and rotated through the cartridge, mixing the components and initiating the curing action. In this study, a pumpable resin as presented in Figure 6.4 was employed to simulate the pumpable resin in the roof bolting machine.

Figure 6.4: Simulated pumpable resin for the automated roof bolting machine.

In a manually operated roof bolting operation, human operators use 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 soft nature of the pumpable resin poses challenges for the robot to grab. Also, the material handling issues associated with the resin cartridge are challenging for a single robot to grip the cartridge and the other items the robot must handle. To address these shortcomings, the study developed a surrogate to simulate the pumpable resin similar to the Jennmar J-Lok system, which would enhance the laboratory testing of the automated roof bolter machine. As shown in Figure 6.5, the plastic base is designed and printed from the 3D printer to stabilize the simulated resins. This device then allows the robotic arm to grab the simulated resin for positioning effectively and also suitable for the hydraulic roof bolter to perform the installation. 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 by inserting the resin into the hole.

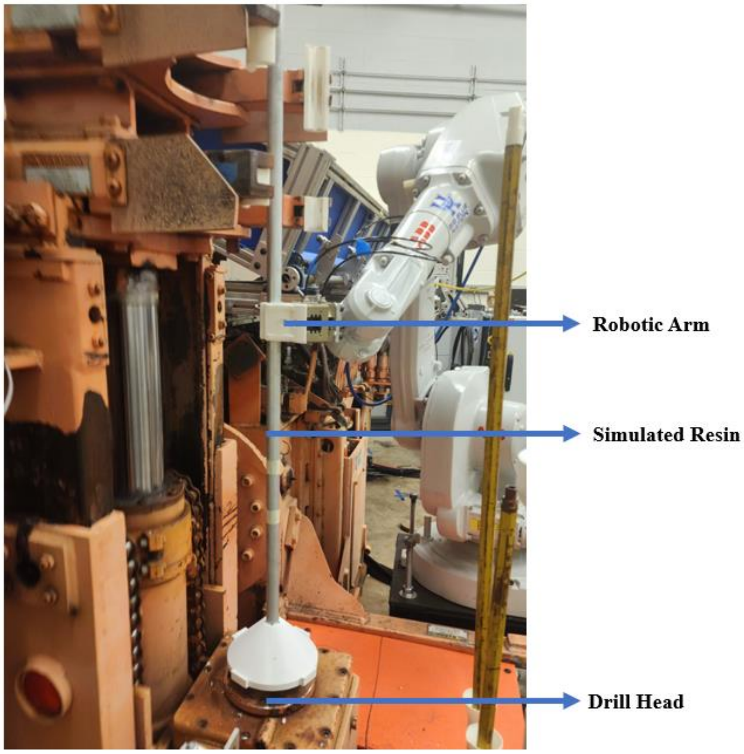


Figure 6.5: Robotic arm placing the surrogate pumpable resin during laboratory testing

After installing the simulated resin, the next task is for the robot to grab the bolt and position it on the roof bolter for installation. Before placing the bolt on the hydraulic roof bolter, the robot grabs the bolt and fixes the square plate on it, as shown in Figure 6.6. After fixing the plate on the bolt, the robot moves the bolt with the plate and places it on the hydraulic roof bolter machine for installation. Then, the robotic arm moves back to its resting position. The hydraulic roof bolter finalizes the installation process, which raises the drill head to insert the bolt into the hole. It is important to know that the operators initiate the entire bolt installation process by pressing the start button on the HMI touchpad. This action triggers the robotic arm and other machinery to execute the entire bolting operation seamlessly. Thus, the robotic arm can perform the entire roof bolting sequence instead of the human operator.

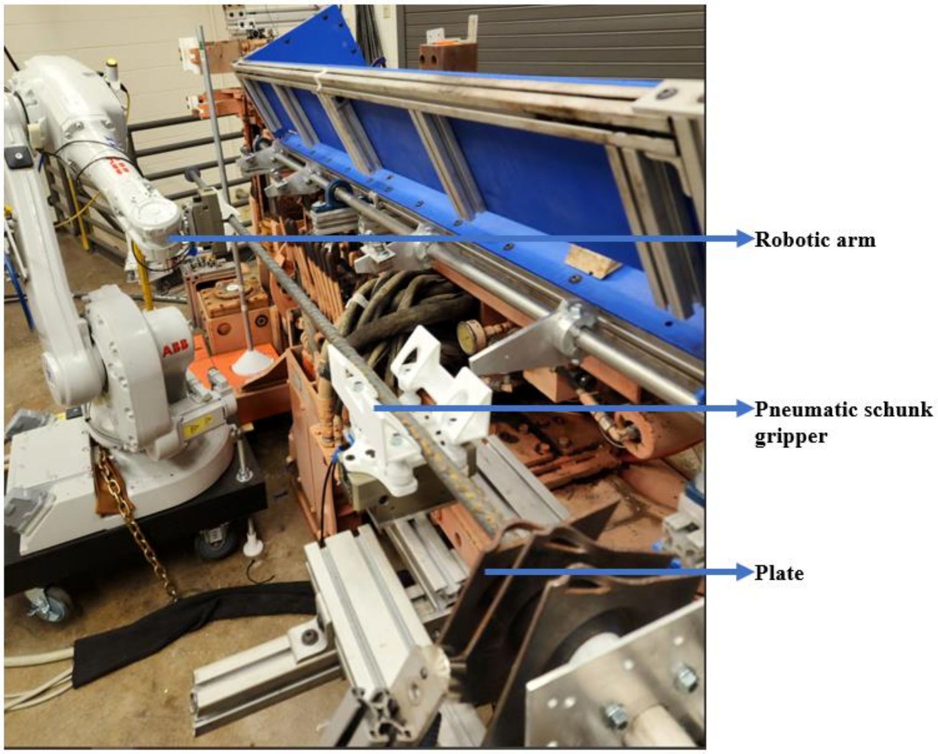


Figure 6.6: Fixing the plate on the bolt

6.4 Modifications of Hydraulic Roof Bolter Parts

Before integrating various systems for laboratory testing, several adjustments were made to the conventional roof bolter machine for seamless automation process. The roof bolter module selected for this study needs modification in its various parts to be fit for laboratory scale testing. For example, the study reduces the drill size to one inch from the default machine design of one and half inch drill using a chunk, as illustrated in Figure 6.7. Additionally, the default clamp and guide could not perform their functions effectively for the laboratory scale testing. This study redesigned and constructed the clamp and guide on the roof bolter for effective drilling and bolting operations. The modifications were made using a 3D printer to develop desired parts for seamless roof bolting process. The newly designed clamp was able to effectively mimic the human hand in holding consumables during the roof bolting process.

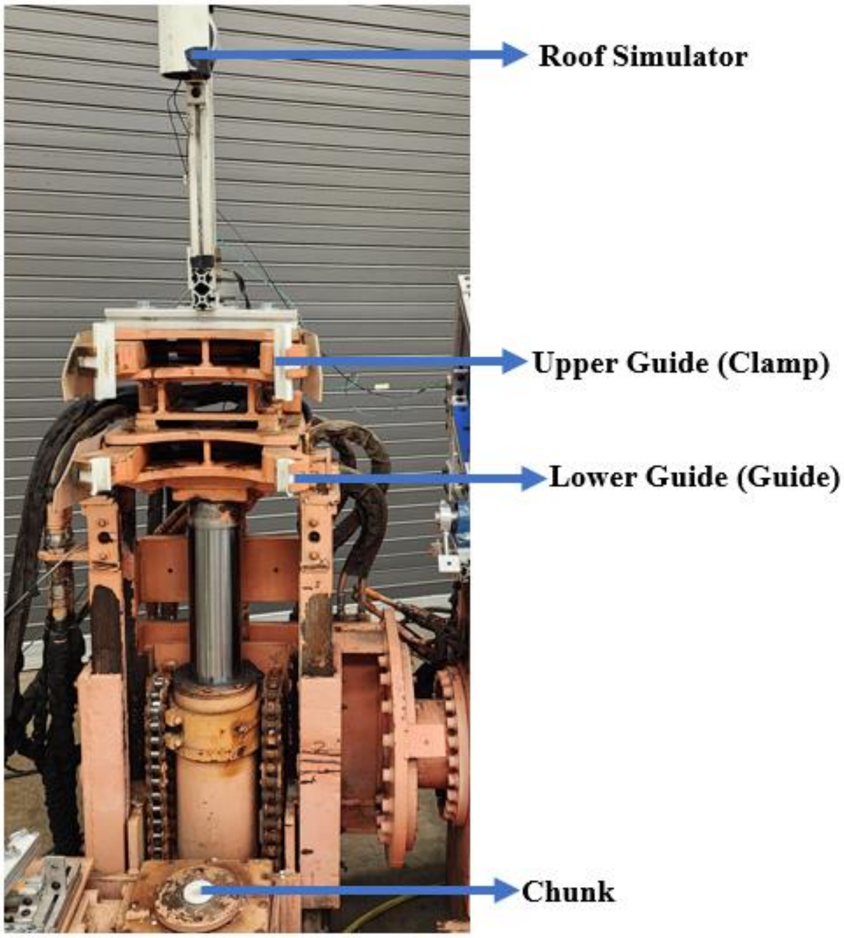


Figure 6.7: Modifications made on the hydraulic roof bolter

Likewise, the chunk was reconstructed to properly engage the drill steel while spinning during drilling and removing drill steel. The robot places the drill steel in the clamp, and the chunk 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 redesign parts also works perfectly for resin injection and bolt installations. Another significant modification to the hydraulic roof bolter was the installation of the roof simulator presented in Figure 6.6. The purpose is to demonstrate the working in a typical underground mine roof bolting automation process, 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 pumpable resin and runs bolts into the hole. The specific details of the mechanical systems of the roof bolter that require modification were worked on to suit the automation process.

6.5 Outcome of Integrating Several Components of an Automated Roof Bolter Machine

The outcome of this study presents the integration of several components that led to the development of an automated roof bolter machine that can perform a complete roof bolting operation with no human intervention. This revolutionizes the approach towards installing roof bolts in underground mining methods where the proficiency of human operators plays a crucial role. The robotic arm was introduced into a manually operated hydraulic roof bolter machine to mimic human activities during roof bolting operations. A notable benefit of utilizing a robotic arm in the underground mining operation include the potential to adapt and operate efficiently under challenging conditions, such as high ambient temperatures that can negatively impact human performance. Incorporating a six-axis robotic arm has revolutionized the roof bolt installation process, effectively replicating human actions. This advanced technology adeptly performs critical tasks such as precise positioning and feeding drill steels, removing drill steels, inserting pumpable resins, retrieving bolts, fixing plates onto bolts, and precisely positioning bolts while instructing the bolting module to execute the entire bolting process.

The study was able to build some components of the automated roof bolter, establish a strong communication link within systems and develop a program in the iQAN programming environment that allows integration of all the components that form the automated roof bolter machine. A robust communication network was established between systems and created a program in the iQAN programming environment that facilitates the integration of all the components, resulting in the formation of 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.

The final deliverable of this study 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 work, 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. Integrating 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. However, automating the operation of the roof bolter presents a significant challenge due to the need for the manipulator arm to execute specific functions within a confined space. The precise positioning of the robotic arm in relation to the roof bolter machinery is of utmost importance, as it must have unobstructed access to all necessary consumables for the bolting operation. Moreover, careful planning and implementation are required to ensure that the introduction of the automated roof bolter does not adversely affect or cause any delays in the ongoing roof bolting operations.

The robotic arm is best for performing dirty, dull and dangerous tasks, posing health and safety risks to humans. The robot is a manipulator that mimics the actions of humans and is often programmable to perform specific tasks and actions. These features make it suitable to replace human tasks during the bolting operation. The laboratory testing showed that the robotic arm has the capability to successfully carry out the entire roof bolting sequence without human intervention. Each of the actions of the robotic arm 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 6.1.

Table 6.1: Summary of robotic arm movement during the automated roof bolting process.

Robotic Arm Involvement	Description of movement
Drilling operation	
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 grasps and places drill steel two for the hydraulic to couple it with drill steel one to complete the drilling task.
Removal of drill steels	
Robot removes drill steel two	The robot moves to take away drill steel two after completing the drilling tasks. The hydraulic bolter drops down 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.

Table 6.2 Continued: Summary of robotic arm movement during the automated roof bolting process.

Simulated pumpable resin insertion	
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 resin is retrieved and positioned in its initial position.
Bolt installation	
Robot grabs bolt to fix the plate on it	The robot travels to grasp the bolt after sliding the bolt 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.

Contrary to the robotic arm, the movement of the roof bolter module and other components were 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 study examined the mechanism iteratively to minimize the time required for safe operation towards reducing the overall operation cycle time. For instance, during the laboratory testing, precise instructions are provided to the iQAN program regarding the duration for closing the clamp, which is set at 3500 milliseconds, and the duration for closing the guide, which is set at 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 6.2. All the functions in the table use specified timeframe to perform their tasks in the iQAN logic program.

Table 6.3: Hydraulic roof bolter movement and involvement during the automated roof bolting 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 is no 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 chunk	The chunk 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 chunk can either move in a clockwise (CW) or a counterclockwise (CCW) direction.

6.6 Determining the Success Rate of the Robotic Arm in Performing Automated Roof Bolting Operations.

The ability of the robotic arm to consistently, precisely and accurately perform tasks such as placing and removing drill steels was carried out to determine its success rate. During the experiment, all robot tasks related to handling the drill steels were repeated 20 times to examine their reliability in positioning the drill steel (DRS) accurately both for usage and storage. This included the most complicated task the robot performs which is separating the DRS 2 from DRS1. The experiment results are presented in Table 6.3 and Table 6.4. ”

Table 6.4 Result of the experiment showing the robotic arm positioning of drill steel 1 on the chunk.

Tasks	**Attempts**	**Success**	**Failure**	**Succes Rate**
Robot positioning of DRS 1	20	20	0	100%

Table 6.5: Result of the experiment showing the robotic arm positioning of drill steel 2 on the chunk.

Tasks	**Attempts**	**Success**	**Failure**	**Succes Rate (%)**
Robot positioning of DRS 2	20	20	0	100%

The outcome of the experiment showed that the robotic system is able to grab and position the drill steels on the chunk to the same position and orientation. The robot was able to repeatedly perform the task over and over again. The result shows that the robot arm has 100% success rate in performing the task.

In the second phase of the experiment, the robot was used to remove drill steels (RDRS) to determine the success rate in performing the task. The result of the investigation is tabulated in Table 6.5 and Table 6.6.

Table 6.6: Result of the experiment showing the robotic arm removing DR2 from the chunk and place it in the drill steel holder.

Tasks	Attempts	Success	Failure	Succes Rate (%)
Robot removing RDRS 2	20	18	2	90%

Table 6.7: Result of the experiment showing the robotic arm removing DR 1 from the chunk and place it in the drill steel holder.

Tasks	Attempts	Success	Failure	Succes Rate (%)
Robot removing RDRS 1	20	20	0	100%

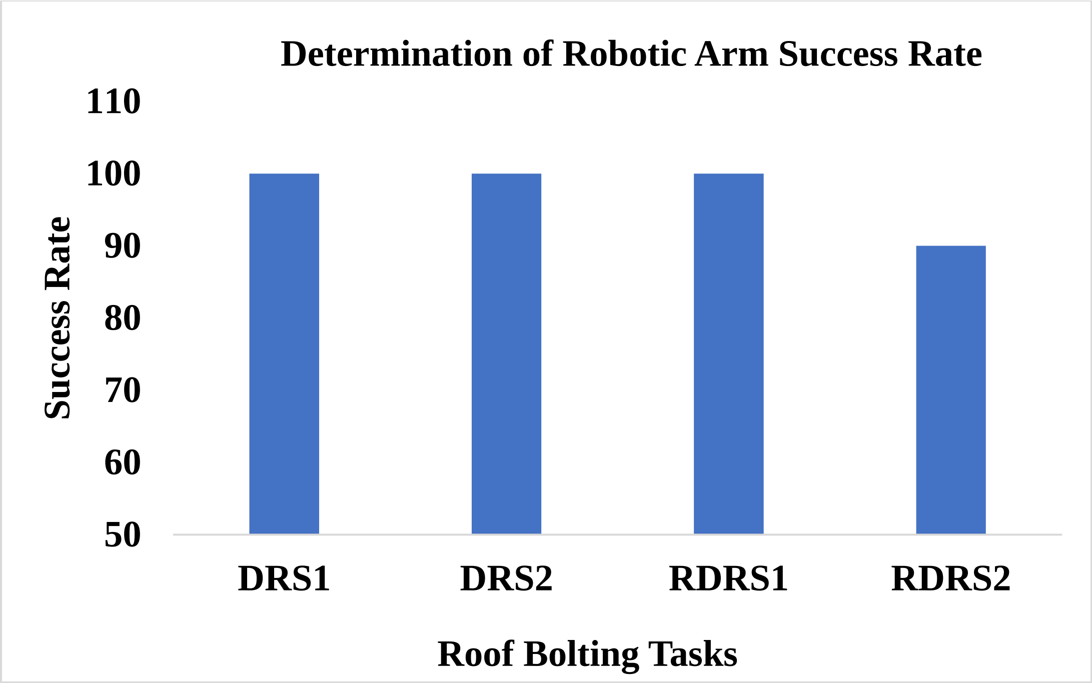


Figure 6.8: Graph showing repeatability of ABB IRB 1600 robot in performing automated roof bolting.

From the result, the robot arm failed twice in 20 attempts when removing the drill steel 2 from the chunk. The coupling mechanism of DRS 1 and DRS2 is the main source of the robot's missing drill steel. If the drill steel had encountered resistance, as the machine is designed, then the union would be more rigid and reliable for this operation. The failure in the robot grabbing the drill steel can be attributed to the position and orientation of drill steel 2 after detaching from drill steel one. The ability of the robotic arm to repeatedly achieve the same task depends on the orientation and the positioning of the drill steel. A notable factor that influences the orientation and positioning of drill steel 2 is the changes in the chunk's geometry, resulting in the slanting of the drill steel. Contrarily, the removal of drill steel is guided by the lower clamp, which keeps the drill steel in the same position for the robot to grab repeatedly.

6.7 Discussion

This study showed the conversion of a manually operated roof bolter machine to a partially automated roof bolter machine. The integration of a robotic system transforms the machine, enables it to perform tasks that were once exclusive to humans. However, integrating robotic systems into manually operated mining machines requires some careful considerations. Apart from the compatibility of the robotic system with the host machine, it is essential to ensure the technology can perform the unique needs for its integration. The integration of robotic systems involves incorporating an articulated robot, such as the ABB IRB 1600 robotic arm with five revolute joints, with other machines to form an automated machine. A successful integration process brings together all the components to operate seamlessly as a cohesive unit. In most cases, the components are not originally designed to work together. Various systems are interconnected and synchronized through careful design, programming, and configuration to work harmoniously towards a common goal. Establishing robust communication protocols and data exchange within these system components enables the coordination of different components to achieve seamless interaction and cooperation between the systems.

The aim of the study was to integrate a robotic system into a roof bolter module. The study integrated a robotic arm, the replica of a human hand, to mimic human functions during the roof bolting cycle. That is, the robotic system should be able to perform human functions such as the positioning of drill steels, removing the drill steels after drilling the roof, inserting the simulated pumpable resin in the perforated roof, and placing the bolt with the square plate on the chunk for installation. The robotic arm was deployed to perform the above-listed functions, which led to the development of the automated roof bolter machine. In this study, the robotic arm and other specialized components developed in the work were tested for motion under similar conditions of an underground mining scenario. Bringing together these systems to function as an automated machine involves considerations such as system compatibility, scalability, reliability, and safety measures. Combining the high-precision robotic arm with other low-precision machines, such as the hydraulic roof bolter and various components developed in this study, is the basis of the automated roof bolter machine.

Addressing the challenges of human involvement during autonomous operation requires the development of some technologies that serve as various components of the automated roof bolter machine. These components work together in an automated roof bolter machine by sending data back and forth to generate necessary signals that control the actuator on the machine to perform specific tasks. Some novel technologies were developed in the study as part 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, known as the wrench system. Each component was integrated with the robotic arm and the hydraulic bolter module and linked to the PLC to ensure effective control during automated roof bolting operation.

The system integration was done through the iQAN program. This 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 Anybus Communicator is an EtherNet/IP-based system that serves as a gateway between the 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 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. The PLC controls the roof bolter, which is connected to the operator touchpad and linked to the robotic arm and hydraulic bolter. The programmable valves from the hydraulic roof bolter are connected to the PLC to control the machine from the iQAN logic program. The manipulation of the hydraulic bolter module and other components of the automated roof bolter takes place in the iQAN software. 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. During the laboratory testing, 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. The iQAN program is linked with HMI via the PLC to control the automated roof bolter machine and provide communication using CAN protocol.

A human-machine interface was developed to enable the manual approval of the tasks and to override the system in the event of unpredicted or unsafe actions. The study developed an operator-friendly HMI for the operator to control and monitor the automated process away from the active face. The two fundamental tasks of the HMI device include communicating information from the automated machine to the operator and sending information or commands to the machine from the user. A fully programmable display MD4-7 touchscreen developed by Parker Hannifin is used as the HMI device to interact with the automated roof bolter machine. The interface of the HMI device contains all the functional buttons to perform the roof bolting cycle in automatic and manual mode. The HMI also comprises buttons linked to each of the components of the roof bolter machine. The HMI controls the bolting process with start and stop buttons from the subroutine of all the components to perform the roof bolting operation. The operator of the automated roof bolter machines must approve every task before the robot, or the hydraulic roof bolter machine executes it. For instance, the operator must authorize the hydraulic system at the menu page to activate the hydraulic roof bolter machine. This is one of the functional safety precautions to prevent unplanned events when operating the hydraulic roof bolter. The laboratory test's outcome showed that the entire roof bolting process is automated and controlled from the touchpad HMI device, which allows operators to supervise and control the bolting process remotely.

The entire automated roof bolting process is divided into two major steps: the automated drilling and the automated bolting operation. Traditionally, the roof bolting machine comprises four major processes: drilling the roof, removing drill steels, inserting the pumpable resin and installing the bolt. The iQAN program subroutines these four major processes into two main steps:
automated drilling (drilling the roof and removing drill steels from the machine) and automated bolting (resin insertion and bolt installation). Each of the two major steps in the automated roof bolting operation has a start and a stop button that initiates and halts the automated drilling and bolting operations. These start and stop buttons are prominently displayed on the HMI interface, allowing human operators to control the entire operation.

The outcome of this study shows that the ABB IRB 1600 was successfully integrated with other specialized technologies to automate the roof bolter machine. The cooperation between the robotic arm, hydraulic roof bolter module and other technologies enables the proper sequencing of roof bolter operation. 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 specific tasks like grasping of consumables, holding, lifting, placing, and removing the drill steels during the roof bolting process. This test 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. However, it is important to state that human operators are still relevant and an integral part of the automated roof bolting process.

6.8 Conclusion

The integration of all the components brought about the automated roof bolter machine. This study has demonstrated that the entire roof bolting process is partially automated and can be controlled from the HMI touchpad, which allows the operator to control the roof bolting process remotely. The automation process is achieved by integrating the robotic arm into a manually operated roof bolter machine to mimic human activities during the bolting process. The robotic arm and other specialized novel technologies developed in this study are components of the automated roof bolting process. The PLC controls the roof bolter, connecting to the HMI touchpad that manages and controls the automated roof bolter machine. The entire roof bolting is subroutined into automated drilling and bolting operations. These operations are displayed on the HMI touchpad for the operator to monitor and control the bolting operation. However, all the above-mentioned operations are subroutined into two (start and stop) buttons on the HCI touchpad to carry out the bolting operation. The laboratory testing shows that the robotic arm has the potential to imitate human functions during the roof bolting operation by performing bolt grasping, holding, lifting, placing and removal of drilling steels.

Chapter seven presents the summary of this study, draws conclusions and gives recommendations for future work in this field of research based on the knowledge gained from this study. The ABB IRB 1600 robot was integrated to imitate human intelligence in automating the roof bolting process.

7. CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

The following were the outcomes of this study;

1) The ABB IRB 1600 robotic arm was successfully integrated into an existing roof bolter machine, leading to a partially automated roof bolter machine. Some of the necessary factors to be considered when selecting a robotic system for an underground mining operation include the payload capacity of the robotic system, the maximum reach of the robot (vertical and horizontal distance covered), the robot's axes specification, and compatibility with the host machine.
2) This study designed and developed an HMI device for the automated roof bolter machine to interact with human operators using an MD4 touchscreen from Parker Hannifin. The MD4 HMI device is linked to the PLC for effective communication between the operator and the automated machine. This device enables the operator to monitor the progress of the automated roof bolting process while providing the operator with options to override the entire process.
3) The outcome of this study built several novel specialized technologies that serve as automated roof bolter components. These systems include the bolt feeder for housing multiple bolts and positioning them for the robot to grab, the plate feeder for fixing the square plate on the bolt, and the wrench system, which serves as the tool interchanger while the roof bolting process is in operation.
4) The laboratory tests performed in this study demonstrated the establishment of communication protocols and a control network using EtherNet/IP protocol to pass messages between the robotic arm, the hydraulic module, and the developed components of the automated roof bolter machine.
5) This study showed that the implemented robotic arm can effectively and efficiently perform human functions in the roof bolting process. As a result of the developed automated roof bolter machine, operators can be moved away from hazardous areas

to a safe distance and control the roof bolting operation via an HMI touchpad while allowing the automated machine to perform the roof bolting operations.

6) This study shows the importance of humans in automated systems. Humans remain relevant in an automated roof bolter machine. Operators are still needed to control, operate, and maintain automated technologies.

7) The conversion of a manually operated roof bolter machine and other technologies confirmed that it is possible to integrate machines not originally designed to work together. The study incorporates high-precision technology (the robotic arm) with other low- precision machines (hydraulic roof bolter, plate feeder, bolt feeder, and wrench system) to develop a partially automated roof bolter machine.

7.2 General Considerations to Automating Existing Underground Mining Machines

There are a large number of machines used in mining that are proven to suit their purpose. Automation of the machines, in many cases, means a completely new design for the machine. This has historically been the case for the roof bolter. This work has described an example of adding automation to an existing machine in a way that does not require a complete redesign and that still allows a human to operate the machine. Based on the outcome of this work, the following steps should be performed for automation of an existing mining machine:

1. Understand human motions and interactions with the controls during the operation of the machine. Identify what human actions should remain human to control. For instance, positioning a machine underground may remain the job of a human supervisor. But the machine's operation once at a place could be automated.
2. Identify what consumables will be used in the process of operating the machine.
3. Determine what the human is typically interacting with besides the controls. The PLC will control the electric and hydraulic systems and should not be considered what the human interacts with; it needs to be the basis for the end-of-arm tooling that is employed. The weight and location of the interactions are important to determine the size and strength requirements for the robot.

4. Simulate the selected robot and the end-of-arm-tooling to determine if the robot will be able to reach all of the areas that are necessary for performing the task. Repeat step 3 if necessary.
5. Determine how the robot will interact with the consumables. Most mining machines are designed to hold consumables for a human operator who is capable of identifying, sorting, and grabbing at an unpredictable location. Robots need to have consumables in predictable locations. Create consumable holders and distribution fixtures as necessary. The end-of-arm tooling must be able to interact with the fixtures and the consumables. Repeat steps 3-5 as necessary.
6. Reduce the actions of the human that will be replicated by the robot to the minimum number of individual actions. Repeat earlier steps as necessary.
7. Integrate the electric, hydraulic, consumables fixtures, and robot actions into individual task groupings. Use sensors and timing to synchronize the robot's actions with the other components. Groupings of tasks should be reasonable for the typical operator of the machine. When possible, return the robot to a generic resting position so that the human supervisor can launch as many tasks as possible without having to reset the robot.
8. Order the task groupings into a sequence of events that would complete an automated process. Allow the operator to interrupt the processes and take control of the individual task groupings made in step 7. Steps 7 and 8 combine into the HMI.
9. Consider regulatory requirements. Determine if any of the sensors, controls, robots, etc., that have been developed would prevent the machine from being useful. Evaluate steps 3-8 as necessary to adjust the design to be in compliance.

After this process, the machine has the capability for autonomous action with a human supervisor.

7.3 Novel Contributions of this Study

The following are the novel contributions made based on the outcome of this study.

1) Developing a partially automated roof bolting machine for underground mining operations. The study converted the conventional roof bolter machine to an automated machine that can perform the roof bolting process autonomously.
2) Defining specifications to be considered when selecting a robotic system for underground mining operations.
3) Developing several specialized technologies that served as components of an automated system.
4) Developing concepts for humans to interact effectively with the automated system. A human-machine interface was developed to control the automated roof bolter machine.
5) Demonstrating the potential of the robotic arm to mimic and improves human functions during the roof bolting process.
6) This work integrates machines and systems that are not originally designed to work together. That is, the study incorporates high-precision machines with low-precision systems to form an automated machine.

7.4 Recommendations for Future Work

This dissertation has highlighted some factors to consider when integrating robotic systems in underground roof bolter machines. A notable contributing factor that ensures the development of automated roof bolting machines is the availability of suitable components that fit into the machine design. The study only modifies the host roof bolter machine and integrates some novel technologies built to change the mode of operation. The development of an efficient and reliable automated roof bolting machine depends on the conformity of components.

From the findings of this study, the following recommendations are made for future studies that want to develop an automated roof bolter machine or employ the approach used in this study to convert manually operated underground mining machines to automated mining equipment:

1) Improving HMI features: There is a need to improve some features, such as improving the capacity of the storage device and other features of the current HMI

device. The Random Access Memory (RAM) of the current MD4 HMI device is too small to allow memory-intensive applications such as using photographs or images to denote different stages of the roof bolting operations or showing tasks in progress. Therefore, the MD4 HMI with high storage capacity should be deployed for the roof bolting operation.

2) Amenities availability at the assemblage physical space: Before deploying the robot and other systems, ensure that the designated area for constructing and testing the automated roof bolter machine is adequately equipped with features to facilitate component assembly.

3) Introducing wireless HMI system: Another critical area to improve 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 send information to the machine via the HMI device without wire connections. The current HMI is connected to the PLC via cables; instead, the connection could be achieved with advanced wireless communications, which would allow operators to control equipment in real time without defects.

4) Proper positioning of system components: Integrating autonomous systems is a complex process involving planning, designing, and implementing various layers of deployment. Due to the complexity of these systems, it is crucial to conduct a proper planning process before deployment. Proper placement of each component can ensure workflows, performance, impact efficiency and improve the overall system performance of the automated machine. For instance, proper positioning of the robotic arm can reduce the risks of collision and ensure the safe operation of a robotic arm with other components of the roof bolter machine.

5) Training and support: Specific skills are required when working with automated mining machines. Providing adequate training and support for operators and maintenance personnel is essential to ensure the systems are used correctly and safely. The training can be in the form of operator manuals and technical support to guide the operator and mining companies to integrate the technology into their

systems. For instance, a good understanding of mechanical and electrical systems might be an added advantage for an operator; the ability to analyze complex situations and proffer solutions; critical thinking, troubleshooting skills and an understanding of safety awareness protocols. Before operating the technology, the operators must 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.

7.5 Research Publications

Schafrik, Steven., Peter Kolapo and Zach Agioutantis, Development of an Automated Roof Bolting Machine for Underground Coal Mines, Proceedings, 32nd Annual SOMP Conference, September 8-14, 2022, Windhoek, Namibia.

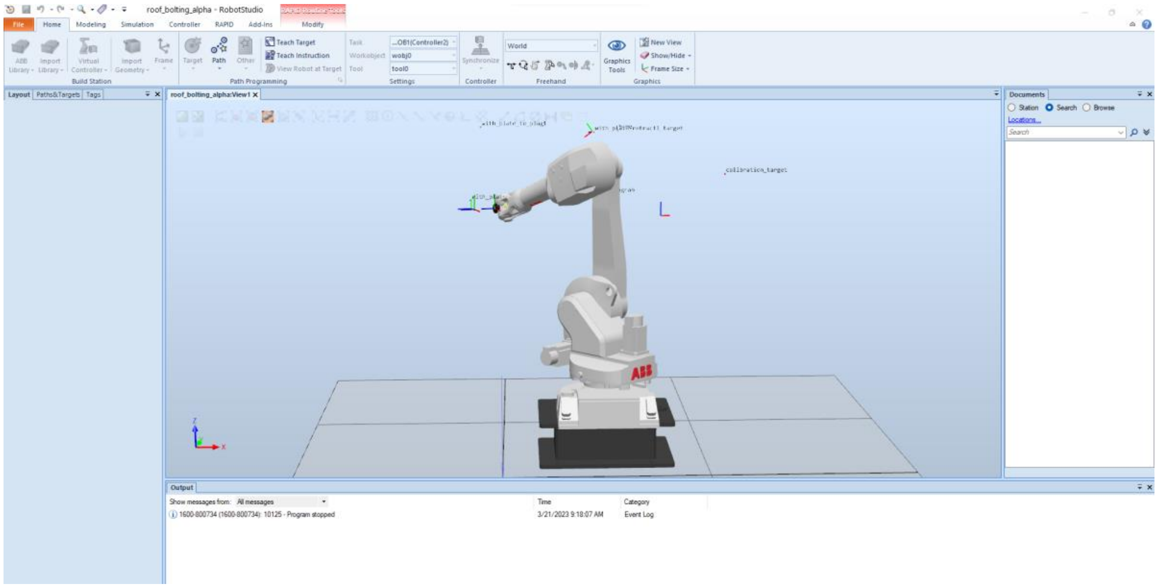
H. Zhang, S-H. Chan, J. Zhong, J. Li, P. Kolapo, S. Koenig, Z. Agioutantis, S. Schafrik, S. Nikolaidis (2023). "A MIP-Based Approach for Multi-Robot Geometric Task-and-Motion Planning". *Autonomous Robots.* DOI: 10.1007/s10514-023-10148-y

Kolapo, P., Schafrik, S., Zhang, H., Nikolaidis, S., & Agioutantis, Z., (2023). "A System Thinking Approach to Automating a Mining Machine**".** [Currently Submitted and Under review].

APPENDICES

Appendix A: Computer programs Interface for the Automation Process of the Roof bolting Process.

Appendix A presents the interface of the Robot Studio and iQAN computer programs for the integration of the ABB IRB 1600 robotic arm and other components of the automated roof bolter machine.



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Show messages from: All messages                               Time                  Category
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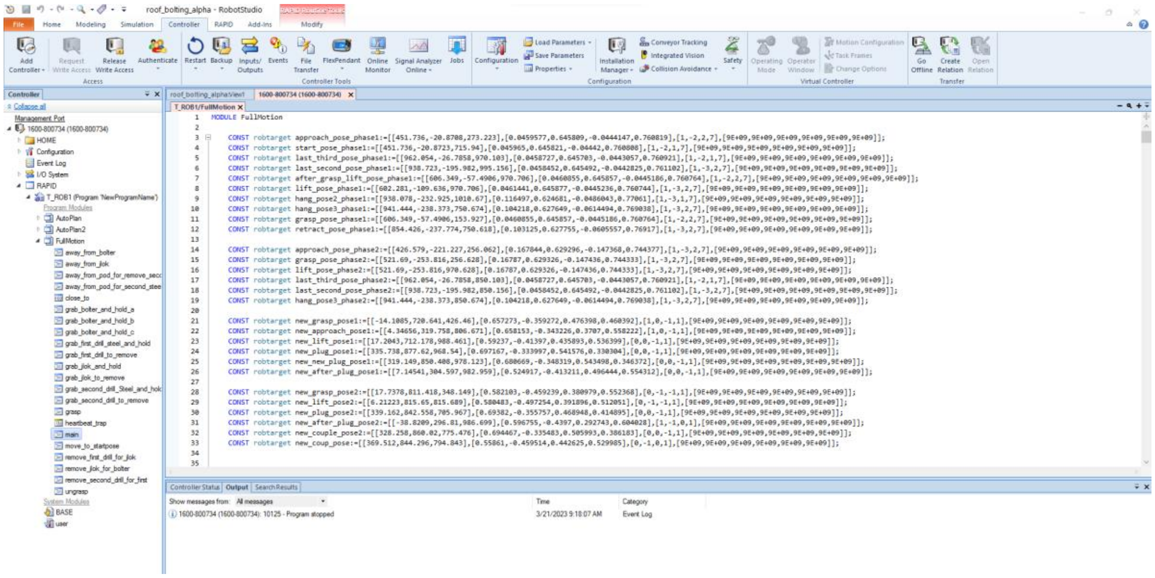
Figure A1: Robot Studio Interface for the Robotic Arm Intuitive Automation Process.



```
MODULE FullMotion

    CONST robtarget approach_pose_phase1:=[[451.736,-20.8708,273.223],[0.0459577,0.645809,-0.0444147,0.760819],[1,-2,2,7],[9E+09,9E+09,9E+09,9E+09,9E+09,9E+09]];
    CONST robtarget start_pose_phase1:=[[451.736,-20.8723,715.94],[0.045965,0.645821,-0.04442,0.760808],[1,-2,1,7],[9E+09,9E+09,9E+09,9E+09,9E+09,9E+09]];
    CONST robtarget last_third_pose_phase1:=[[962.054,-26.7858,970.103],[0.0458727,0.645703,-0.0443057,0.760921],[1,-2,1,7],[9E+09,9E+09,9E+09,9E+09,9E+09,9E+09]];
    CONST robtarget last_second_pose_phase1:=[[938.723,-195.982,995.156],[0.0458452,0.645492,-0.0442825,0.761102],[1,-3,2,7],[9E+09,9E+09,9E+09,9E+09,9E+09,9E+09]];
    CONST robtarget after_grasp_lift_pose_phase1:=[[606.349,-57.4906,970.706],[0.0460855,0.645857,-0.0445186,0.760764],[1,-2,2,7],[9E+09,9E+09,9E+09,9E+09,9E+09,9E+09]];
    CONST robtarget lift_pose_phase1:=[[602.281,-109.636,970.706],[0.0461441,0.645877,-0.0445236,0.760744],[1,-3,2,7],[9E+09,9E+09,9E+09,9E+09,9E+09,9E+09]];
    CONST robtarget hang_pose2_phase1:=[[938.078,-232.925,1010.67],[0.116497,0.624681,-0.0486043,0.77061],[1,-3,1,7],[9E+09,9E+09,9E+09,9E+09,9E+09,9E+09]];
    CONST robtarget hang_pose3_phase1:=[[941.444,-238.373,750.674],[0.104218,0.627649,-0.0614494,0.769038],[1,-3,2,7],[9E+09,9E+09,9E+09,9E+09,9E+09,9E+09]];
    CONST robtarget grasp_pose_phase1:=[[606.349,-57.4906,153.927],[0.0460855,0.645857,-0.0445186,0.760764],[1,-2,2,7],[9E+09,9E+09,9E+09,9E+09,9E+09,9E+09]];
    CONST robtarget retract_pose_phase1:=[[854.426,-237.774,750.618],[0.103125,0.627755,-0.0605557,0.76917],[1,-3,2,7],[9E+09,9E+09,9E+09,9E+09,9E+09,9E+09]];

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    CONST robtarget lift_pose_phase2:=[[521.69,-253.816,970.628],[0.16787,0.629326,-0.147436,0.744333],[1,-3,2,7],[9E+09,9E+09,9E+09,9E+09,9E+09,9E+09]];
    CONST robtarget last_third_pose_phase2:=[[962.054,-26.7858,850.103],[0.0458727,0.645703,-0.0443057,0.760921],[1,-2,1,7],[9E+09,9E+09,9E+09,9E+09,9E+09,9E+09]];
    CONST robtarget last_second_pose_phase2:=[[938.723,-195.982,850.156],[0.0458452,0.645492,-0.0442825,0.761102],[1,-3,2,7],[9E+09,9E+09,9E+09,9E+09,9E+09,9E+09]];
    CONST robtarget hang_pose3_phase2:=[[941.444,-238.373,850.674],[0.104218,0.627649,-0.0614494,0.769038],[1,-3,2,7],[9E+09,9E+09,9E+09,9E+09,9E+09,9E+09]];

    CONST robtarget new_grasp_pose1:=[[-14.1085,720.641,426.46],[0.657273,-0.359272,0.476398,0.460392],[1,0,-1,1],[9E+09,9E+09,9E+09,9E+09,9E+09,9E+09]];
    CONST robtarget new_approach_pose1:=[[4.34656,319.758,806.671],[0.658153,-0.343226,0.3707,0.558222],[1,0,-1,1],[9E+09,9E+09,9E+09,9E+09,9E+09,9E+09]];
    CONST robtarget new_lift_pose1:=[[17.2043,712.178,988.461],[0.59237,-0.41397,0.435893,0.536399],[0,0,-1,1],[9E+09,9E+09,9E+09,9E+09,9E+09,9E+09]];
    CONST robtarget new_plug_pose1:=[[335.738,877.62,968.54],[0.697167,-0.333997,0.541576,0.330304],[0,0,-1,1],[9E+09,9E+09,9E+09,9E+09,9E+09,9E+09]];
    CONST robtarget new_new_plug_pose1:=[[319.149,850.408,978.123],[0.680669,-0.348319,0.543498,0.346372],[0,0,-1,1],[9E+09,9E+09,9E+09,9E+09,9E+09,9E+09]];
    CONST robtarget new_after_plug_pose1:=[[7.14541,304.597,982.959],[0.524917,-0.413211,0.496444,0.554312],[0,0,-1,1],[9E+09,9E+09,9E+09,9E+09,9E+09,9E+09]];

    CONST robtarget new_grasp_pose2:=[[17.7378,811.418,348.149],[0.582103,-0.459239,0.380979,0.552368],[0,-1,-1,1],[9E+09,9E+09,9E+09,9E+09,9E+09,9E+09]];
    CONST robtarget new_lift_pose2:=[[6.21223,815.65,815.689],[0.580483,-0.497254,0.391896,0.512051],[0,-1,-1,1],[9E+09,9E+09,9E+09,9E+09,9E+09,9E+09]];
    CONST robtarget new_plug_pose2:=[[339.162,842.558,705.967],[0.69382,-0.355757,0.468948,0.414895],[0,0,-1,1],[9E+09,9E+09,9E+09,9E+09,9E+09,9E+09]];
    CONST robtarget new_after_plug_pose2:=[[-38.8209,296.81,986.699],[0.596755,-0.4397,0.292743,0.604028],[1,-1,0,1],[9E+09,9E+09,9E+09,9E+09,9E+09,9E+09]];
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    CONST robtarget new_coup_pose:=[[369.512,844.296,794.843],[0.55861,-0.459514,0.442625,0.529985],[0,-1,0,1],[9E+09,9E+09,9E+09,9E+09,9E+09,9E+09]];
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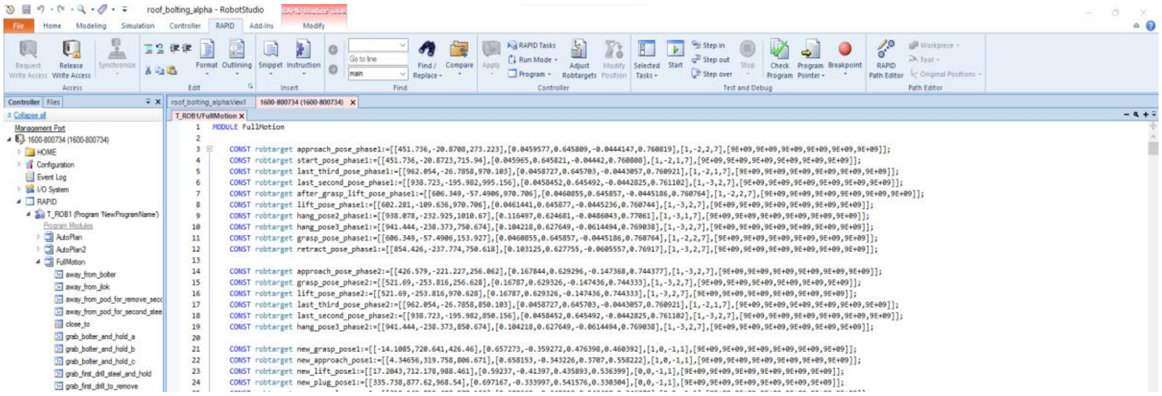
Figure A2: Motion and Tasks Planning Interface in Robot Studio.



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MODULE FullMotion

    CONST robtarget approach_pose_phase1:=[[451.736,-20.8708,273.223],[0.0459577,0.645809,-0.0444147,0.760819],[1,-2,2,7],[9E+09,9E+09,9E+09,9E+09,9E+09,9E+09]];
    CONST robtarget start_pose_phase1:=[[451.736,-20.8723,715.94],[0.045965,0.645821,-0.04442,0.760808],[1,-2,1,7],[9E+09,9E+09,9E+09,9E+09,9E+09,9E+09]];
    CONST robtarget last_third_pose_phase1:=[[962.054,-26.7858,970.103],[0.0458727,0.645703,-0.0443057,0.760921],[1,-2,1,7],[9E+09,9E+09,9E+09,9E+09,9E+09,9E+09]];
    CONST robtarget last_second_pose_phase1:=[[938.723,-195.982,995.156],[0.0458452,0.645492,-0.0442825,0.761102],[1,-3,2,7],[9E+09,9E+09,9E+09,9E+09,9E+09,9E+09]];
    CONST robtarget after_grasp_lift_pose_phase1:=[[606.349,-57.4906,970.706],[0.0460855,0.645857,-0.0445186,0.760764],[1,-2,2,7],[9E+09,9E+09,9E+09,9E+09,9E+09,9E+09]];
    CONST robtarget lift_pose_phase1:=[[602.281,-109.636,970.706],[0.0461441,0.645877,-0.0445236,0.760744],[1,-3,2,7],[9E+09,9E+09,9E+09,9E+09,9E+09,9E+09]];
    CONST robtarget hang_pose2_phase1:=[[938.078,-232.925,1010.67],[0.116497,0.624681,-0.0486043,0.77061],[1,-3,1,7],[9E+09,9E+09,9E+09,9E+09,9E+09,9E+09]];
    CONST robtarget hang_pose3_phase1:=[[941.444,-238.373,750.674],[0.104218,0.627649,-0.0614494,0.769038],[1,-3,2,7],[9E+09,9E+09,9E+09,9E+09,9E+09,9E+09]];
    CONST robtarget grasp_pose_phase1:=[[606.349,-57.4906,153.927],[0.0460855,0.645857,-0.0445186,0.760764],[1,-2,2,7],[9E+09,9E+09,9E+09,9E+09,9E+09,9E+09]];
    CONST robtarget retract_pose_phase1:=[[854.426,-237.774,750.618],[0.103125,0.627755,-0.0605557,0.76917],[1,-3,2,7],[9E+09,9E+09,9E+09,9E+09,9E+09,9E+09]];

    CONST robtarget approach_pose_phase2:=[[426.579,-221.227,256.062],[0.167844,0.629296,-0.147368,0.744377],[1,-3,2,7],[9E+09,9E+09,9E+09,9E+09,9E+09,9E+09]];
    CONST robtarget grasp_pose_phase2:=[[521.69,-253.816,256.628],[0.16787,0.629326,-0.147436,0.744333],[1,-3,2,7],[9E+09,9E+09,9E+09,9E+09,9E+09,9E+09]];
    CONST robtarget lift_pose_phase2:=[[521.69,-253.816,970.628],[0.16787,0.629326,-0.147436,0.744333],[1,-3,2,7],[9E+09,9E+09,9E+09,9E+09,9E+09,9E+09]];
    CONST robtarget last_third_pose_phase2:=[[962.054,-26.7858,850.103],[0.0458727,0.645703,-0.0443057,0.760921],[1,-2,1,7],[9E+09,9E+09,9E+09,9E+09,9E+09,9E+09]];
    CONST robtarget last_second_pose_phase2:=[[938.723,-195.982,850.156],[0.0458452,0.645492,-0.0442825,0.761102],[1,-3,2,7],[9E+09,9E+09,9E+09,9E+09,9E+09,9E+09]];
    CONST robtarget hang_pose3_phase2:=[[941.444,-238.373,850.674],[0.104218,0.627649,-0.0614494,0.769038],[1,-3,2,7],[9E+09,9E+09,9E+09,9E+09,9E+09,9E+09]];

    CONST robtarget new_grasp_pose1:=[[-14.1085,720.641,426.46],[0.657273,-0.359272,0.476398,0.460392],[1,0,-1,1],[9E+09,9E+09,9E+09,9E+09,9E+09,9E+09]];
    CONST robtarget new_approach_pose1:=[[4.34656,319.758,806.671],[0.658153,-0.343226,0.3707,0.558222],[1,0,-1,1],[9E+09,9E+09,9E+09,9E+09,9E+09,9E+09]];
    CONST robtarget new_lift_pose1:=[[17.2043,712.178,988.461],[0.59237,-0.41397,0.435893,0.536399],[0,0,-1,1],[9E+09,9E+09,9E+09,9E+09,9E+09,9E+09]];
    CONST robtarget new_plug_pose1:=[[335.738,877.62,968.54],[0.697167,-0.333997,0.541576,0.330304],[0,0,-1,1],[9E+09,9E+09,9E+09,9E+09,9E+09,9E+09]];
```

Figure A3: RAPID Programming Interface for Coding the ABB IRB 1600 Robotic Arm

Figure A4: Modular Control Connection Interface on iQAN Computer Program

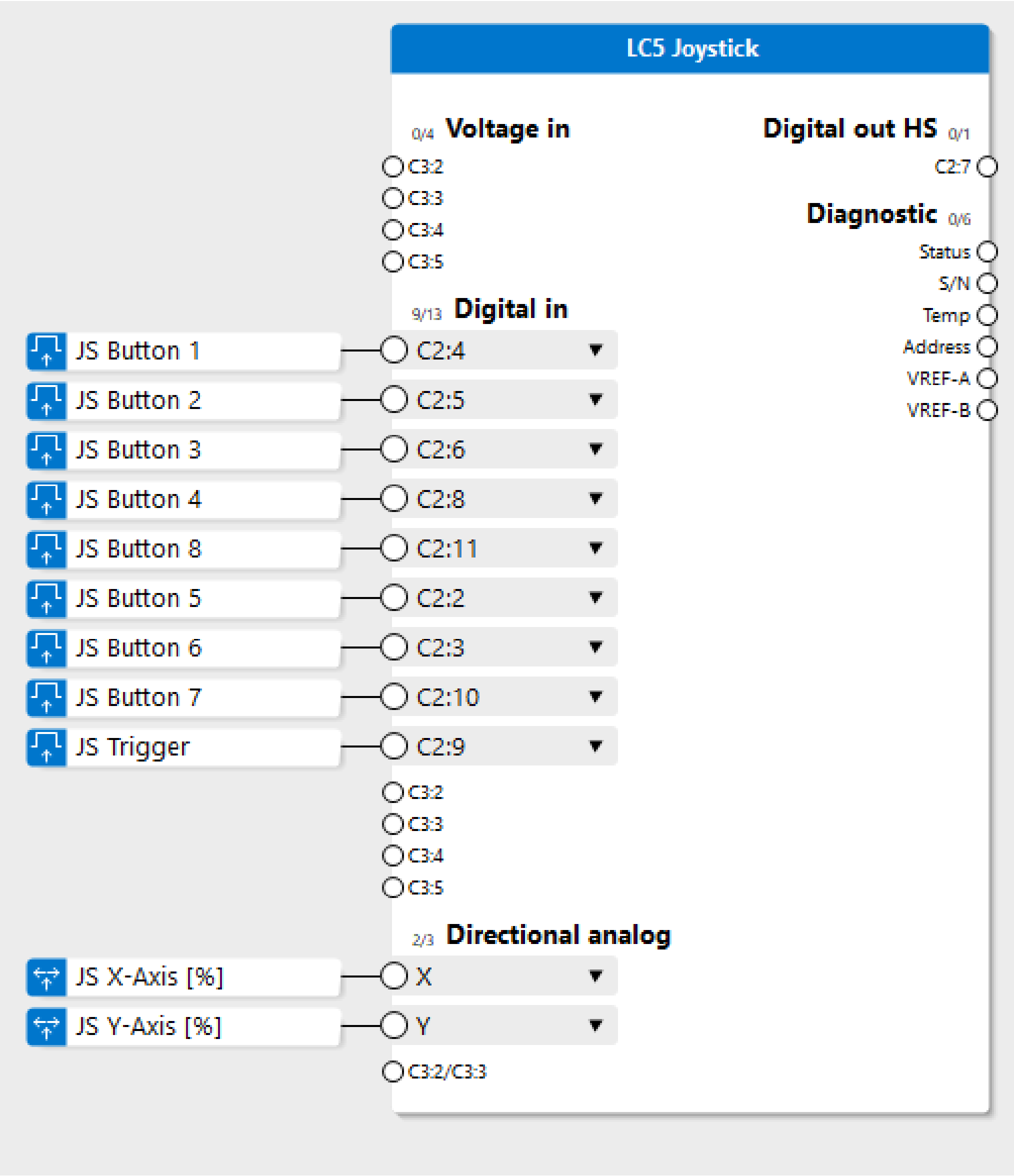


Figure A5: iQAN Program Interface Showing the Joystick Buttons Digital Connection for a Manual Control of the Hydraulic Roof Bolter Machine.

Figure A6: iQAN Program Interface Showing the Developed Systems Digital Connection to the Digital out on the XA2 Module.

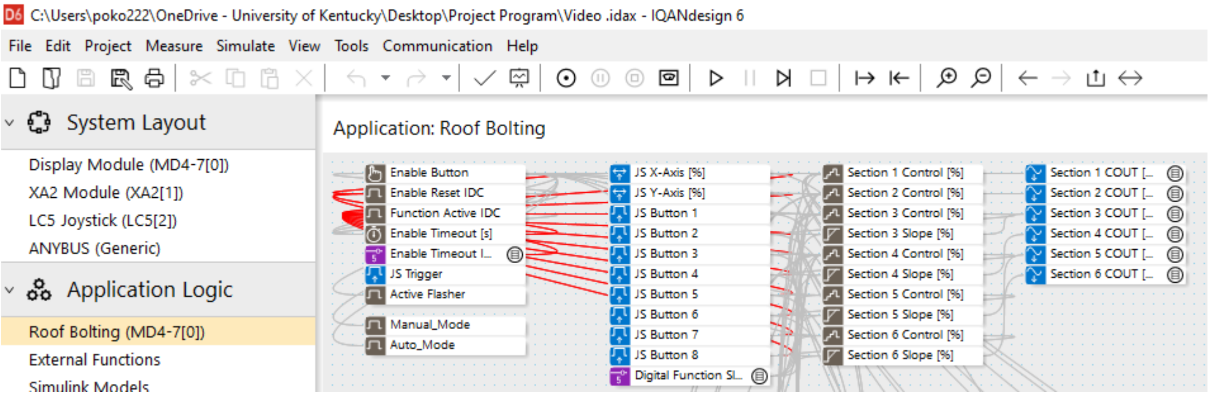


Figure A7: iQAN Programming Interface for Connecting the Modular Control System with the Hydraulic Roof Bolter Machine.

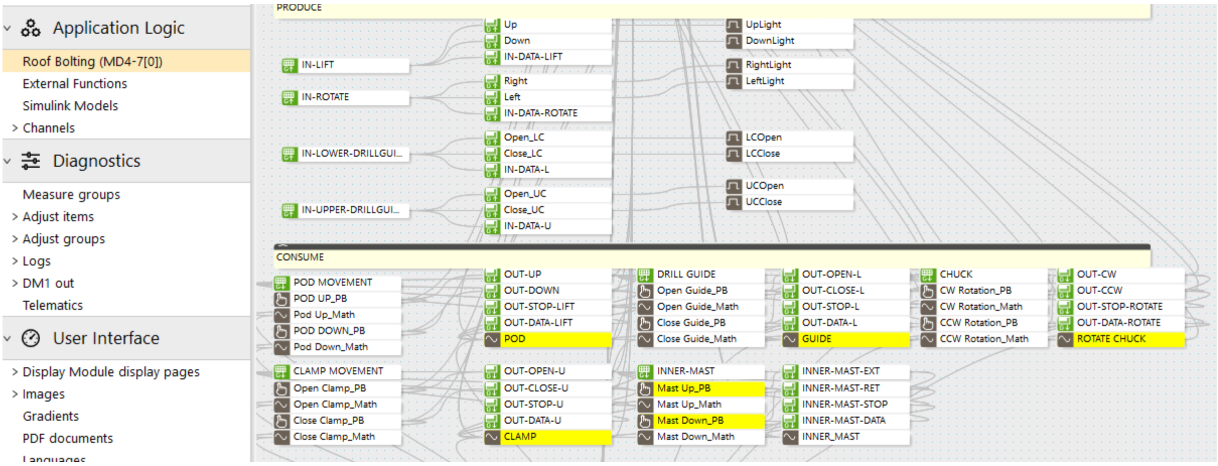


Figure A8: iQAN Programming Interface for Controlling the Hydraulic Roof Bolter Machine.

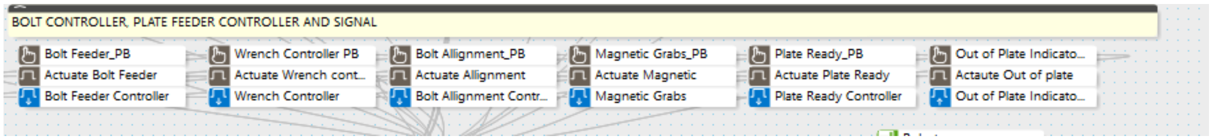


Figure A9: iQAN Programming Interface for Controlling Other System Units

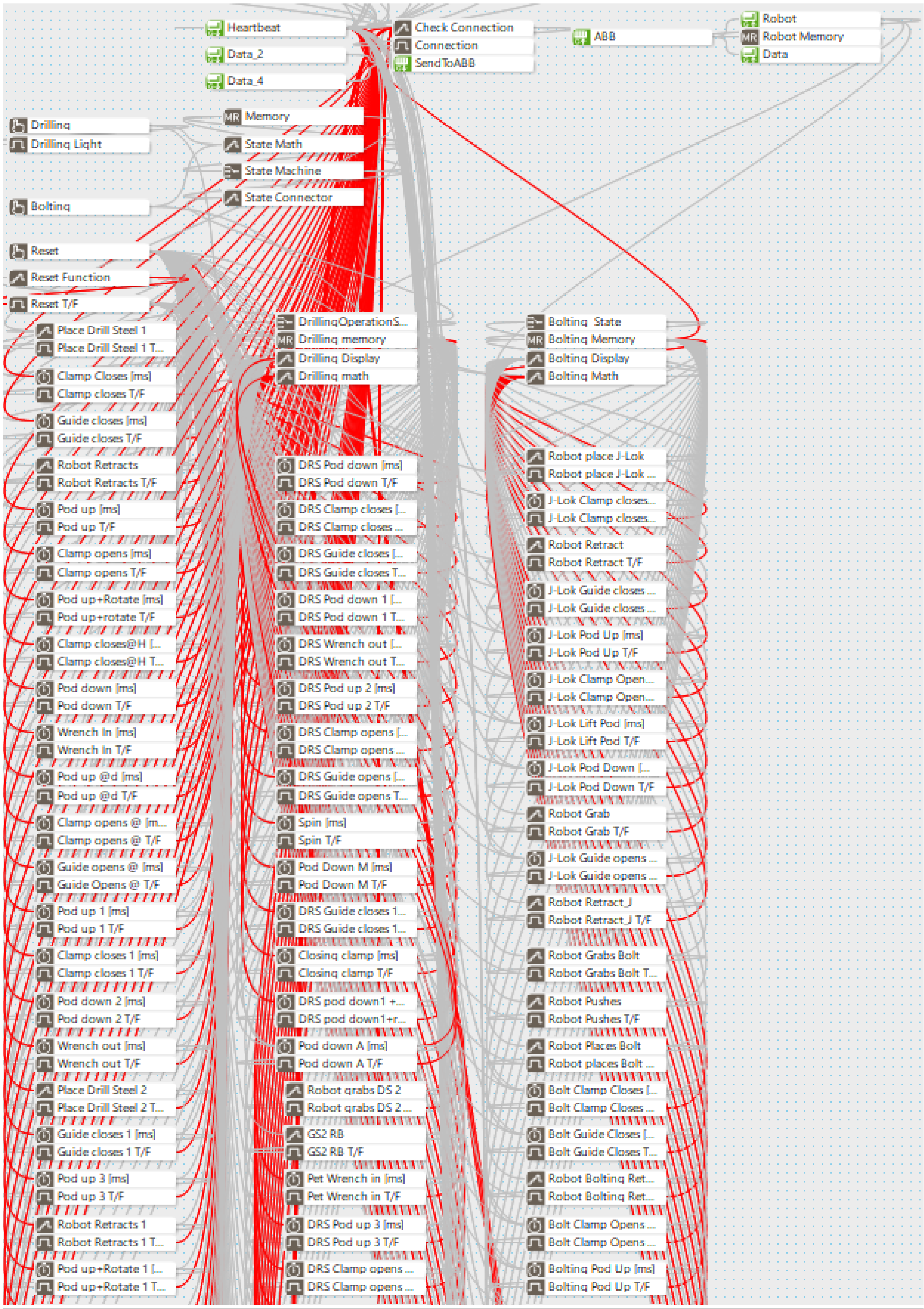


Figure A10: iQAN Logic Interface for Integrating all the System units to perform Automated Roof Bolter Machine.

Appendix B: AnyBus Device Configuration Architecture

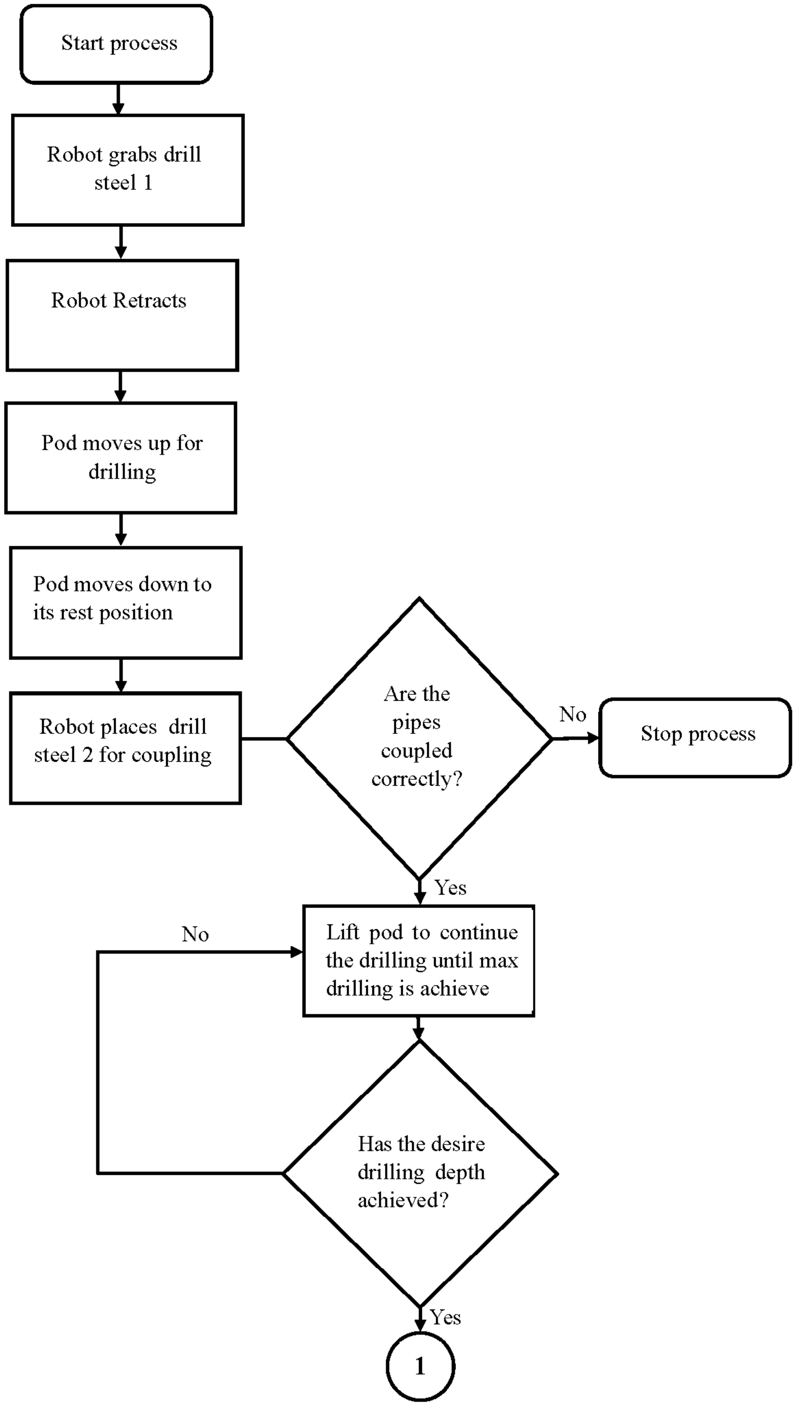


Figure B1 Drilling Process Flow Chart

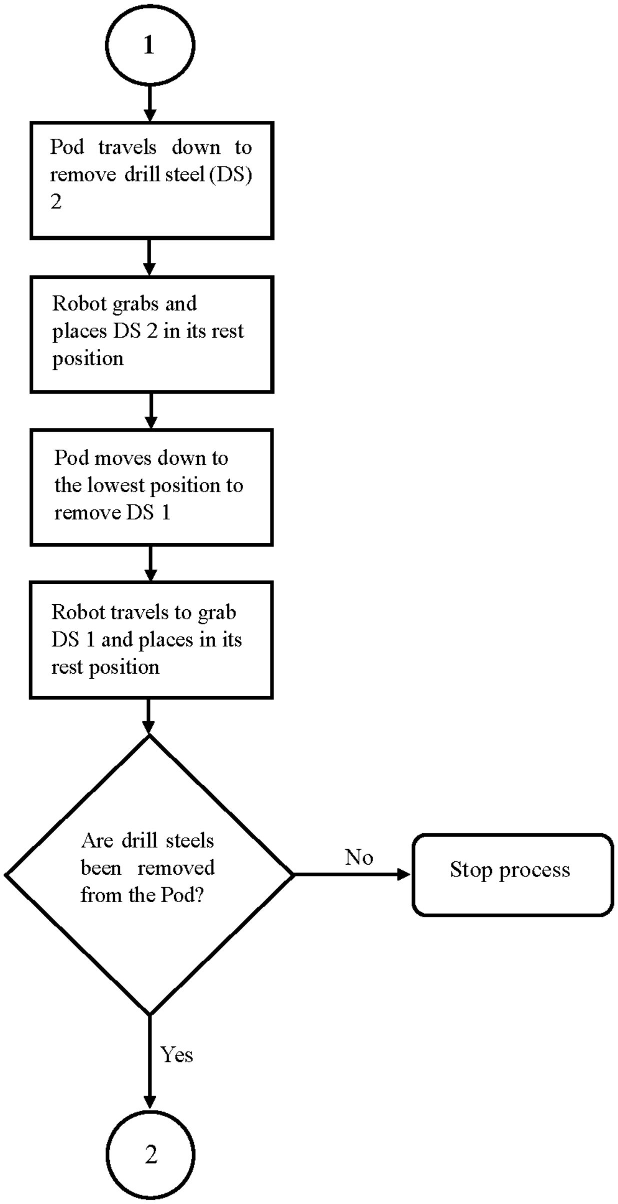


Figure B2: Removal of Drill Steels after Achieving the Desire Roof Depth

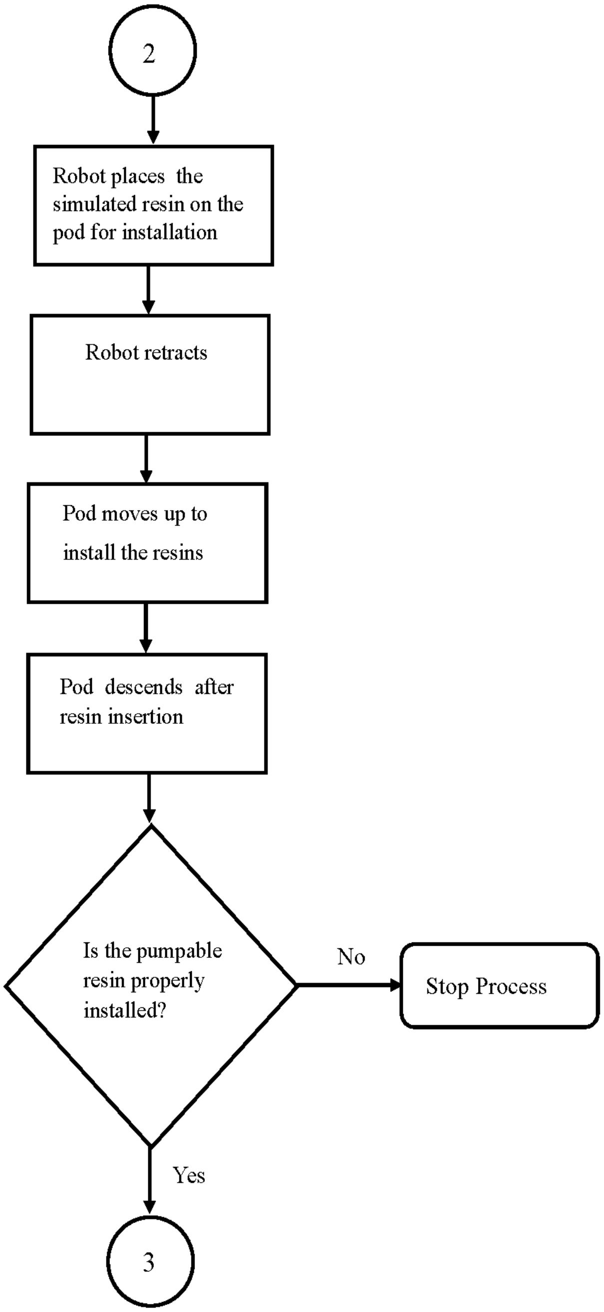


Figure B3: Insertion of Simulated Pumpable Resin

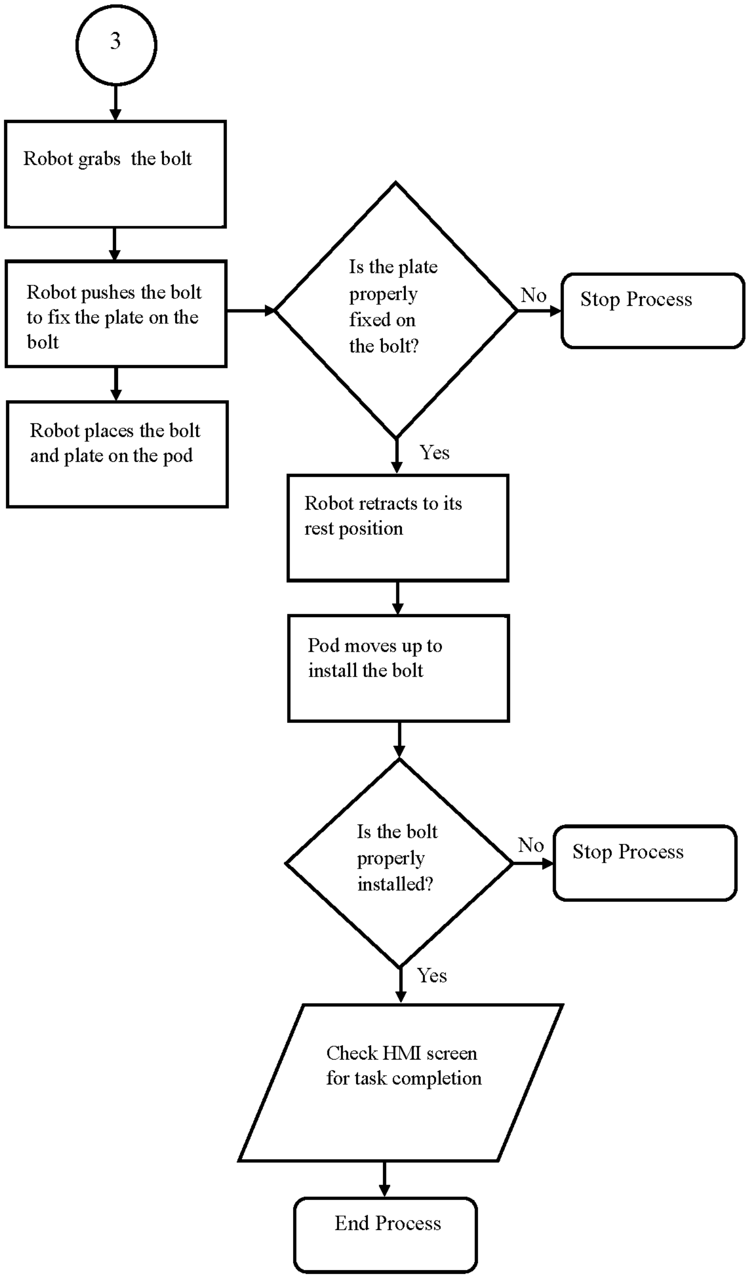
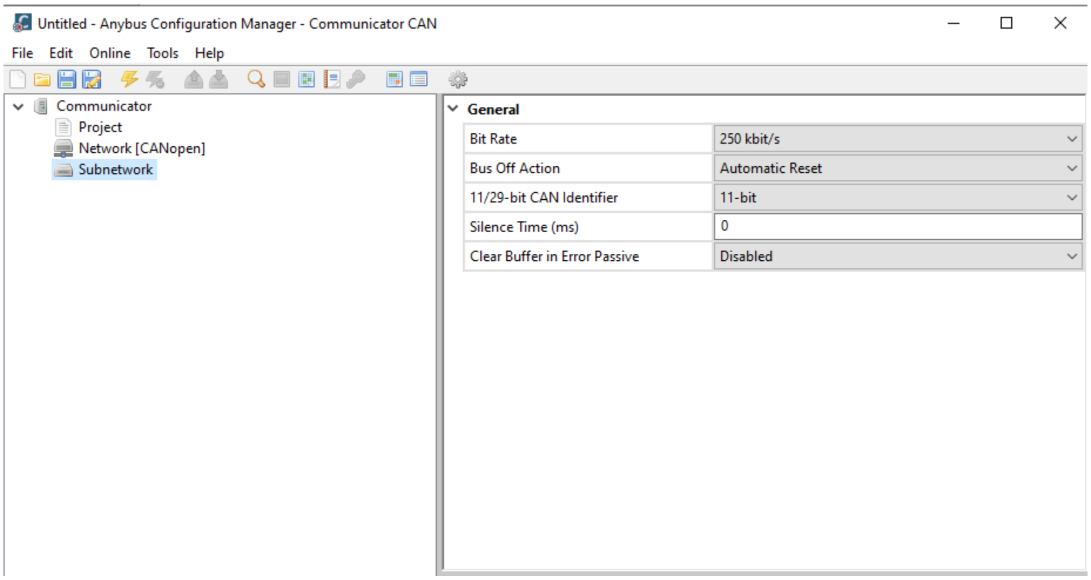


Figure B4: Bolt Installation Flow Chart Process

Appendix C: AnyBus Device Configuration Architecture

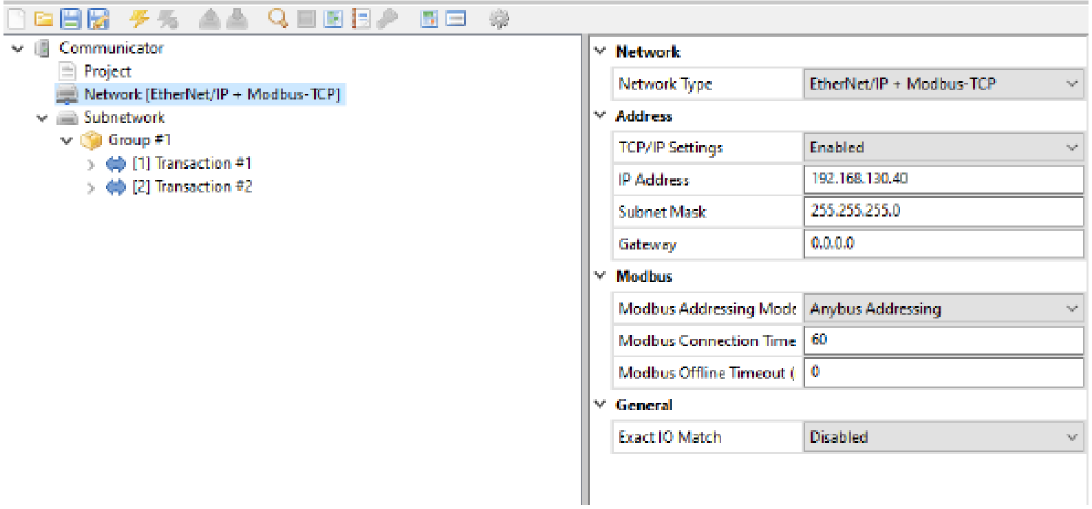
Appendix C shows the configuration interface of the Anybus communicator system. The Anybus device is installed in the PLC which receives, translates, and sends CAN messages into a signal the robotic arm will understand.



General

Bit Rate	250 kbit/s
Bus Off Action	Automatic Reset
11/29-bit CAN Identifier	11-bit
Silence Time (ms)	0
Clear Buffer in Error Passive	Disabled

Figure C1: Anybus Device Interface



Network

Network Type	EtherNet/IP + Modbus-TCP

Address

TCP/IP Settings	Enabled
IP Address	192.168.130.40
Subnet Mask	255.255.255.0
Gateway	0.0.0.0

Modbus

Modbus Addressing Mode	Anybus Addressing
Modbus Connection Time	60
Modbus Offline Timeout (	0

General

Exact IO Match	Disabled

Figure C2: Anybus Device Interface Network Configuration Parameters.

Appendix D: Additional System components of the Automated Roof Bolter Machine

Appendix D shows other components of the automated roof bolter machine.

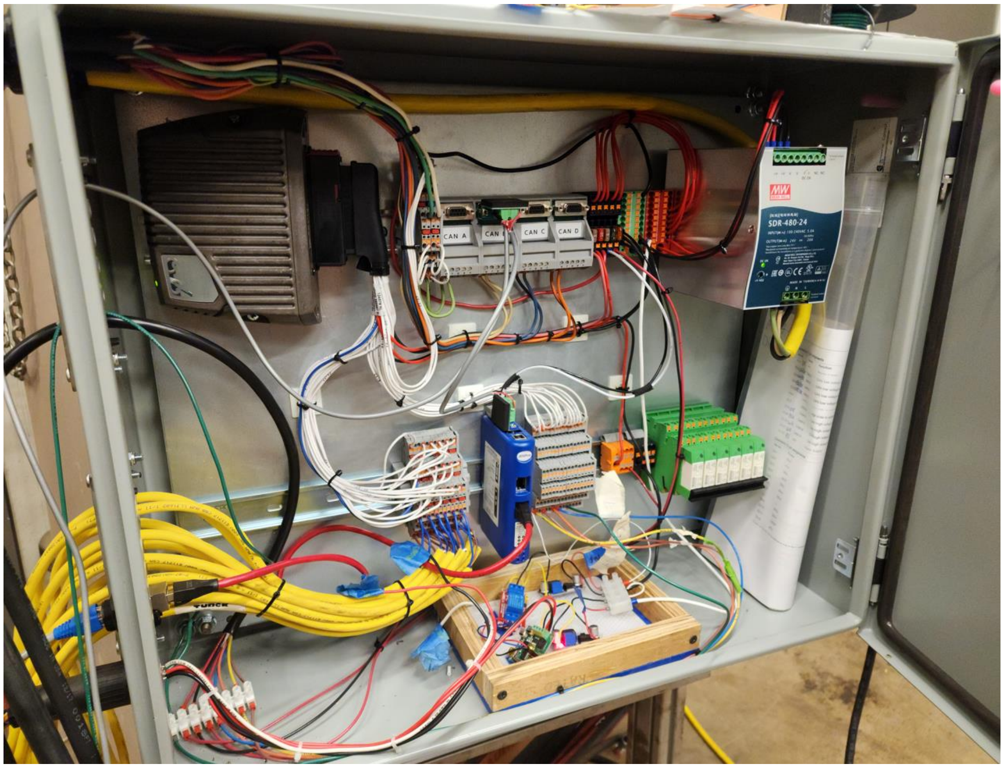


Figure D1: The Internal Component of the PLC.

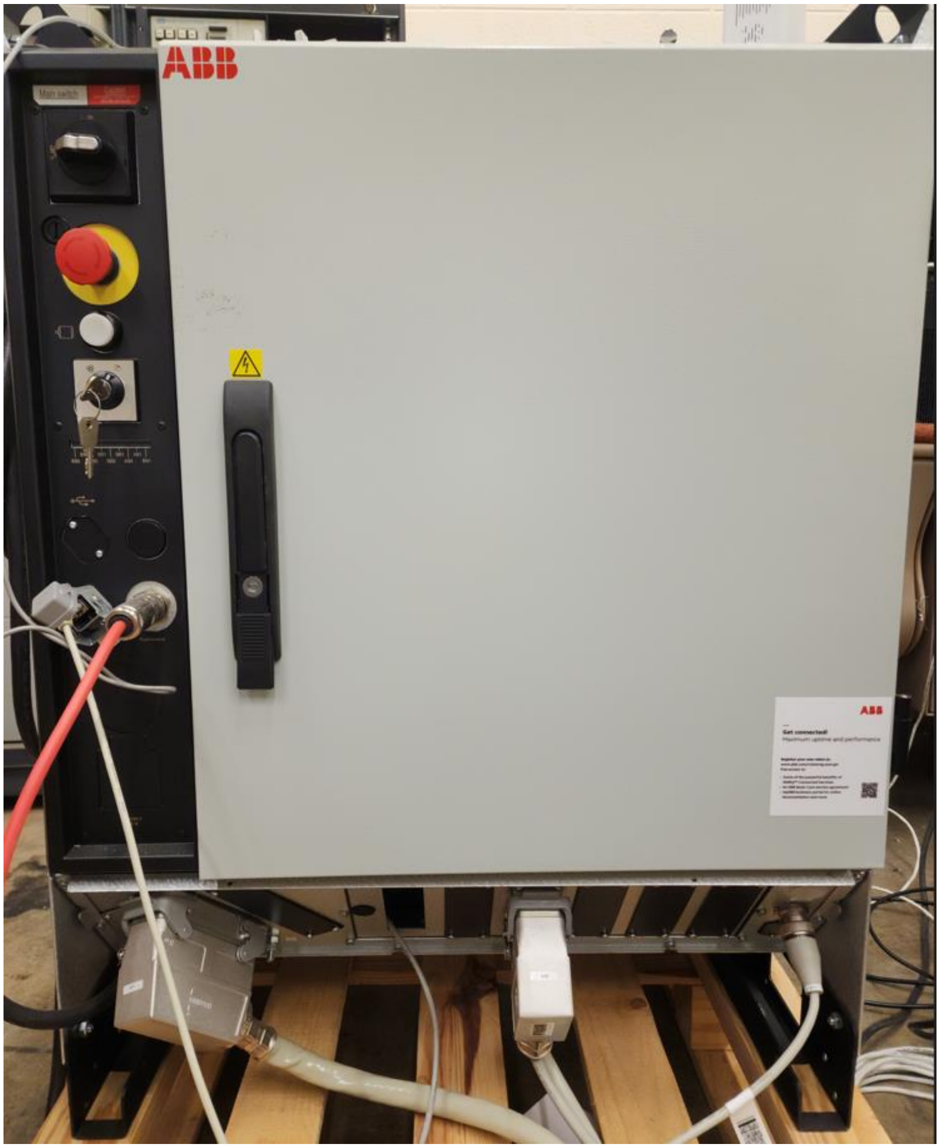


Figure D2: Robot Controller of the ABB IRB 1600 Robotic Arm.

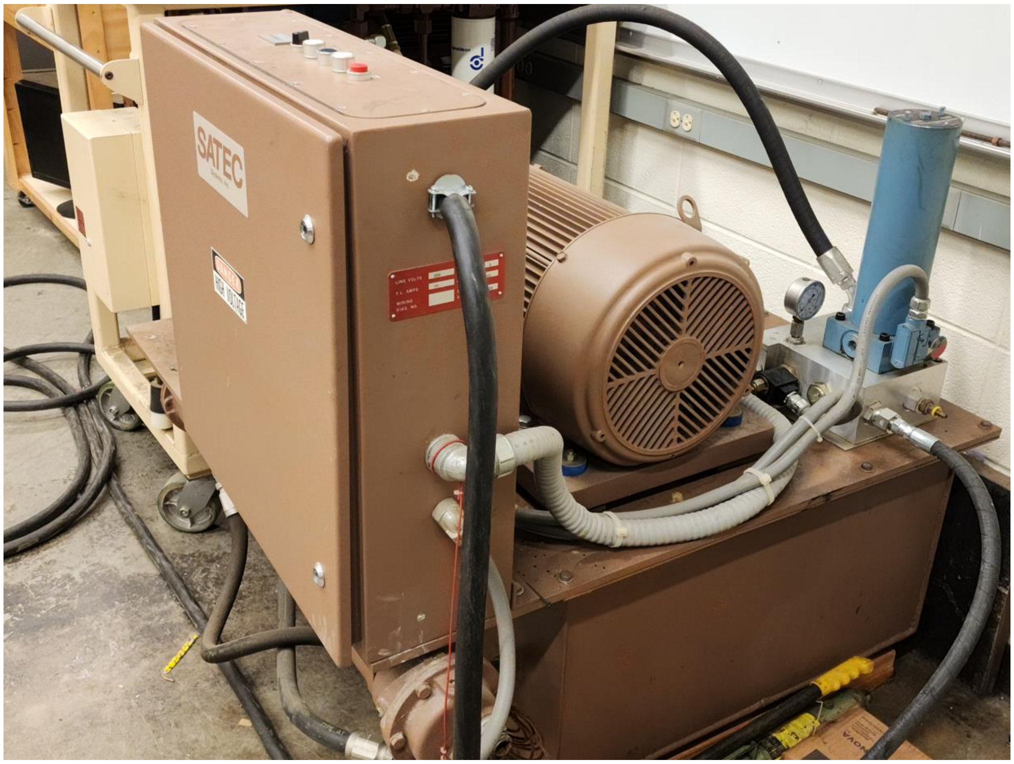


Figure D3:The Hydraulic Pump

Figure D4: Desktop Computer at the Workstation

Appendix E: Tabulated Steps Taken During the Automated Roof Bolting Process.

Table E1: Roof Drilling Steps

S/N	TASKS	TIME (ms)	COMMAND	PARTS
1	Wait for robot to place first Drill Steel 1		300/5	Robot
2	Clamp closes		120	Hydraulic
3	Guide closes		130	-
4	Robot retract to its initial position		310/10	Robot
5	Lift Pod to engage Drill Steel 1		140	Hydraulic
6	Clamp opens		100	-
7	Lift pod to the maximum height +Rotate (CCW)		170	-
8	Clamp closes at maximum height		120	-
9	Pod travels down to engage the wrench +Clamp close		125	-
10	Wrench In		200	Wrench
11	Lift pod to engage the wrench and drill steel 1		140	Hydraulic
12	Clamp opens		100	-
13	Guide opens		110	-
14	Lift pod until the wrench top is above the guide		140	-
15	Clamp closes		120	-
16	Pod travels down to the lowest position		150	Wrench
17	Wrench out		210	Robot
18	Wait for robot to place first Drill Steel 2		320/15	Hydraulic
19	Guide closes		130	
20	Lift Pod to engage drill steel 2		140	
21	Wait for robot to retract		330/20	
22	Lift pod + Rotate (CCW) to couple drill steel 1 and 2		190	
23	Open clamps		100	
24	Lift pod + Rotate (CCW) to the max position		190	
25	Clamp closes		120	
26	Pod travel down to the lowest position + Clamp closes		125	
27	Wrench in		200	
28	Lift pod to engage drill steel 2		140	
29	Clamp opens		100	
30	Guide opens		110	
31	Lift pod to your desire position for the drilling		140	

Table E2: Removal Drill Steels Steps

S/N	TASKS	TIME (ms)	COMMANDS	PARTS
1	Pod travels down to red mark X		140	Hydraulic
2	Clamp closes		120	-
3	Guide closes		130	-
4	Pod travels down to remove the wrench		140	-
5	Wrench out		210	Wrench
6	Lift Pod to engage drill steel 2		140	Hydraulic
7	Clamp Opens		100	-
8	Guide Opens		110	
	Spin (CCW)			
10	Close the guide		130	
11	Pod down to mark 2 + rotate (CW) to disengage drill steel 2		180	-
12	Robot travels to grab drill steel 2		340/25	Robot
13	Robot remove Drill Steel 2		350/30	Robot
14	Wrench in		200	-
15	Clamp closes + Wrench in		145	-
16	Guide opens +Wrench in		135	-
17	Pod travels up to engage drill steel 1+Wrench in		105	Hydraulic
18	Clamp opens +Wrench in		125	
19	Pod travels down to red mark X + Wrench in		155	Hydraulic
20	Clamp closes +Wrench in		145	-
21	Pod travels down to the lowest position +Wrench in		155	Wrench
22	Wrench out		210	-
23	Pod up to meet with drill steel 1		140	-
24	Clamp opens		100	
25	Pod travels to the lowest position		150	Wrench
26	Robot travels to grab drill steel 1		360	Hydraulic
27	Robots remove Drill Steel 1		370	
28	DRS Waiting		470	

Table E3: Insertion of Simulated Pumpable Resin and Bolt Installation

S/N	TASKS	TIME (ms)	COMMANDS	PARTS
1	Robot places J-Lok			
2	J-Lok clamp closes			
3	Robot retracts			
4	J-Lok guide closes			
5	J-Lok pod up			
6	J-Lok clamp closes			
7	J-Lok pod up			
8	J-Lok pod down			
9	Robot grabs J-Lok			
10	J-Lok guide opens			
11	Robot Retracts			
12	Bolt feeder ON			
13	Robot grabs bolt			
14	Bolt alignment closes			
15	Robot pushes the plunger to fix the plate on bolt			
16	Bolt alignment opens			
17	Robot places bolt on Hydraulic Bolter			
18	Bolt clamp closes			
19	Bolt guide closes			
20	Robot retracts to start position			
21	Clamp opens			
22	Lift bolting pod up			
23	Clamp closes bolting			
24	Pod Down			
25	Bolt wrench in			
26	Lift pod up to meet the bolt			
27	Clamp Opens			
28	Guide Opens			
29	Pod Up			
30	Installing Bolt			
31	Pod Down			
31	Bolt feeder OFF			
31	Wrench Out			
32	Magnetic Bolting			

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Education

- Master of Science (MSc) in Mining Engineering at the University of Witwatersrand, Johannesburg, South Africa, December 2019.
- Bachelor of Engineering in Mining Engineering at the Federal University of Technology Akure, Ondo State, Nigeria, November 2012.

Professional Positions

- Graduate Research Assistant, Department of Mining Engineering, University of Kentucky, USA, August 2021-December 2023.
- Production Engineer (Intern), Chorus Energy Limited, Kwale Delta State, Nigeria, January 2020 – April 2020.
- Graduate Research and Teaching Assistant, Department of Mining Engineering, University of Witwatersrand, Johannesburg South Africa, March 2017-December 2019.
- Network Operation Engineer, IHS Africa PLC (Network Operations Center), Federal Capital Territory Abuja, Nigeria. September 2014-February 2017.
- Field Engineer, Golden Peters and Company Limited (Engineering Geological Services), Federal Capital Territory Abuja, Nigeria. September 2013-August 2014.
- Graduate Engineering Trainee, Geocardinal Engineering Services, Federal Capital Territory Abuja, Nigeria. February 2013-July 2013.

Scholastic and Professional Honors

- Recipient of America Society of Safety Professional Foundation Scholarship for 2021-2022.
- Recipient of Syd.S and Felicia F. Peng Ground Control in Mining Scholarship - Society of Mining, Metallurgy and Exploration (SME) December 2022.
- Recipient of Syd.S and Felicia F. Peng Ground Control in Mining Scholarship - Society of Mining, Metallurgy and Exploration (SME) December 2021.

- Postgraduate Merit Award from the University of Witwatersrand (PMA) 2017 – 2019.
- Sibanye - Stillwater Digital Mining Laboratory (DigiMine) Research Assistantship 2017 – 2019.

Professional Publications

- Kolapo, P., Ogunsola, N.O., Munemo, P., Alewi, D., Komolafe, K.**,** Giwa-Bioku, A., (2023). "DFN: An emerging tool for stochastic modelling and geomechanical design**".** *Engineering* 4(1), pp 174-205.

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