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Final Technical Report

Autonomous Underground Mining Systems to Improve Safety - Intelligent Coal Mining

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Chapter 1

Executive Summary

The working face of an underground coal mine is a dynamic work area that exposes miners to numerous occupational hazards, including mobile equipment congestion, shock and vibration, excessive noise, and respirable dust.

The introduction of an autonomous shuttle car system has the potential to significantly reduce the health and safety hazards faced in shuttle car haulage. The project aligns with the Alpha Foundation for the Improvement of Mine Safety and Health's topic area (1) Health and Safety Intervention.

There are multiple benefits related to the development of autonomous shuttle cars. The main benefit is that the shuttle car operator can be located away from the shuttle car, and thus exposures to noise, dust, vibrations, bad ground conditions, etc., can be dramatically reduced. In addition, in an environment characterized by autonomous haulage, the role of the shuttle car operator is both enhanced and transformed as they transition to shuttle car controllers or managers that can be located outside the active mining area between the continuous miner and the feeder-breaker.

Lab-scale prototypes were constructed and deployed in a mock mine under laboratory conditions. The prototypes were equipped with a number of sensors that allowed mapping of the surrounding area as the prototype moves. A data acquisition and data management system were developed that allows for near-simultaneous storage, analysis, calculation, and decision-making from any sensor platform, several platforms were tested. An autonomous logic controller (ALC) was developed and was driven by a command sequence that was subsequently adjusted by the real-time data feed. The lab-scale prototype was successfully tested under lab conditions. The ALC communicated with the lab-scale prototypes via an Arduino connected to a remote-control unit.

In terms of human factors, the organizational challenges involving the introduction of an autonomous shuttle car system to a room-and-pillar coal mining operation were addressed. Work analyses included mapping the general organizational structure, identifying the key work processes and activities, defining roles/responsibilities of different actors (humans and machines) in the system, and ascertaining the values/motivations and cognitive strategies of individual workers. Furthermore, based on input generated from the lab-scale trials as well as worker role analysis, a Human Machine Interface (HMI) unit was developed that has the potential to both control and manage shuttle car operations.

Finally, a full-scale shuttle car was retrofitted for steering and tramming and was fitted with commercial-grade LiDAR units for providing real-time feed of distances and angles to the surrounding structures. The autonomous logic controller as well as the Arduino microcontroller program, were modified to address the challenges of controlling a full-scale shuttle car, especially with respect to latencies. Full-scale shuttle car trials were performed at the West Virginia Training and Conference Center Simulated Mine Laboratory and demonstrated that a shuttle car can be autonomously driven along an entry past multiple crosscuts, and it can also autonomously turn into a crosscut.

Chapter 2

Problem Statement and Objectives

The underground coal mine working section is a dynamic work area that exposes miners to numerous occupational hazards. These hazards include but are not limited to mobile equipment congestion, excessive noise, and respirable dust. The goal of this project is to address these hazards for room-and-pillar coal mine face haulage through supporting the development of an autonomous shuttle car system. The proposed system will enhance and transform the role of the shuttle car operator as well as reduce the risk of all miners at the working section. The intent of this project is not to replace shuttle car operators but rather to complement their expertise, improve their comfort, and ensure their well-being while remaining competitive in a challenging and changing industry. This project involves multiple technical and ergonomic challenges, namely: a) developing an accurate and reliable underground autonomous navigation system and methodology and b) accounting for human factors related to the automation of certain tasks.

The objective of this project is to develop and demonstrate a functional prototype of an autonomous shuttle car system with a specific focus on evaluating the feasibility and impact of such a system on the miners and the underground coal work domain. This effort will require the collaboration of many disciplines to devise an effective and holistic solution. Required competencies and expertise will include mining engineering, advanced systems, machine automation, data science, behavioral analysis, safety and human factors. The results of this project will constitute a significant advancement towards improving the performance and safety of underground coal mines. Other underground mining and industrial operations that implement discrete vehicle haulage or other comparable mobile haulage system are additionally expected to benefit from this project.

2.1 Background Information

Underground room-and-pillar coal mines that utilize shuttle cars for face haulage will be the focus of the proposed project. Although shuttle cars are applied in other underground haulage roles, which are also expected to benefit from this project, the proposed research will target underground room-and-pillar coal mines to constrain the project to a manageable scope. Shuttle cars in the aforementioned context are used to transport run-of-mine coal and rock from the working face to the feeder-breaker. Typically, a single continuous miner section is operated with two or three shuttle cars, which follow a number of pre-determined paths through entries and cross-cuts to complete their travel between the continuous miner and the feeder-breaker.

Shuttle cars are electrically powered through a trailing cable, which not only limits the number of allowable travel paths, but also necessitates frequent relocation of ancillary equipment, such as power centers. As the continuous miner moves from location to location, the shuttle car's travel path changes in both length and direction, which requires the shuttle car operator to constantly adjust to new conditions. The environment in underground room-and-pillar coal mines is inherently challenging and natively presents significant hazards to the shuttle car operator, mobile equipment operators near shuttle car haulage routes, and to miners in proximity to the shuttle cars. Travel ways are also poorly illuminated, which combined with the possible presence of suspended dust and in-roadway ventilation controls create a poor visibility situation. In addition to the working environment, the design of the shuttle car also creates a set of issues.

Shuttle cars are designed for transporting raw coal from one location to another with limited regard for operator comfort. Operator cabs are usually open and positioned on the side of the vehicle. In addition to a poor field-of-vision, operators are also left exposed to dust, spray from the continuous miner, and noise from mining operations without the ability to move away from these hazards. The shuttle car's suspension is designed to function while loaded, which results in significant vertical deflection while traveling unloaded. As a result, the operator is subjected to constant vibration while travelling.

The aforementioned environmental and design factors create many hazards for both the shuttle car operator and personnel working near the shuttle car. These hazards are clearly demonstrated by incidents involving powered haulage vehicles in underground coal mines. Nearly 800 miners have been injured and 16 fatalities have occurred in underground powered haulage incidents involving shuttle cars and scoops from January 2000 to September 2010 (MSHA 2010). Many of these incidents have a common theme, such as being struck by a shuttle car while walking in an entry, being crushed by a shuttle car moving through a ventilation curtain, being entangled in the shuttle car's trailing cable, and being involved in a shuttle car collision (Mine Safety and Health Administration 2010). Even with the advent of proximity detection systems and increased regulation, incidents involving shuttle cars and other related powered haulage vehicles are still prevalent. From 2014 to 2016, approximately 277 injuries and four fatalities have occurred in incidents involving underground powered haulage vehicles, which indicates a continuing issue (MSHA 2014, 2015, 2016).

Automating shuttle car coal face haulage from the continuous miner to the feeder-breaker will remove the operator from the active mining area, thereby reducing exposure to dust, noise, and other hazardous conditions. Although an autonomous shuttle car would not have a human occupant, equipment operators would still be needed to serve in a supervisory capacity. The new responsibilities of the shuttle car operator would include tasks such as adjusting travel paths, manipulating the chain conveyor (if not also automated in the future), and fine tuning other relevant operating parameters. Therefore, the automation of shuttle cars would not displace operators but would enhance their productive capacity, transform their role, and reduce their exposure to risk.

As previously introduced, underground room-and-pillar mines are composed of many independent, interacting components that must function in challenging environmental conditions. Although the proposed project is focused specifically on automating the haulage task of the shuttle car, a number of intervening and interacting factors are still present. The majority of the factors can be grouped into two categories, equipment and human. Equipment factors include but are not limited to interaction with other mobile equipment, physical obstacles, other shuttle cars, etc. Complications derived from these factors include addressing questions of "how will the autonomous shuttle car work with another shuttle car?" and "how will the shuttle car react when another vehicle is unexpectedly encountered?" Although addressing vehicle interactions is expected to bring a level of complication to developing shuttle car autonomous navigation, many of the decision variables can be simply defined, such as "stop" or "wait for input." Major complexities from intervening and interacting factors are expected from the human aspect, which encompasses one of the main thrusts in this research.

Human-factor considerations are always of key importance in the context of automation issues. This includes ways to present relevant information and warnings, how the state of the automation can be made transparent to humans interacting with it as well as more general questions related to how existing work processes and organizational structures are influenced by the introduction of automation. A general overview of key human factors issues in the context of mining automation is given by Horberry et al. (2011). In the present underground mining application, where autonomous shuttle cars are foreseen to operate alongside humans in the mine, the interaction between the human and the machine will be even more critical for ensuring safe and efficient operations.

When introducing automation into a complex workplace, simply replacing the human operator with automated processes is typically not a useful strategy, especially in a complex and constrained working environment such as a coal mine. Rather, the human operator must assume a different role and the automation will have implications for the work domain, as a whole, that must be carefully considered. This may include the need for changed work processes, roles and responsibilities of the workforce and new organizational structures. Thus, a holistic approach is needed that, in addition to technology development, takes into account human-factor issues at all levels, from basic function allocation between the human and the machine to the social organization of the workplace.

Thus, as further described below, a significant effort of the current project will be devoted to developing a thorough understanding the entire work environment in the coal mine, from general organization, work processes, and safety constraints to the roles, competencies, and values/motivations of individual workers. Although the results of this project will have a much broader impact, the scope of this research effort is focused on autonomous navigation of the shuttle car. This analysis will be the basis for deriving functional requirements of the autonomous shuttle cars as well as requirements at the process and organizational levels. This will be critical for successfully integrating the automation into the challenging work environment of the coal mine.

More specifically, key human factors issues to be considered include (but are not limited to):

- Functional task allocation: What tasks (e.g., tramming, docking, loading, unloading etc.) should be automated and which should remain under the control of the operator?

- Identification of new operator tasks: For example, monitoring of the shuttle location and implementing remote-control for specific tasks.

- Interaction design: In what ways should the automated shuttle car be able to interact with its operator and other people it encounters in the mine, for example by enabling input commands, indicating if it is in automated/manual mode and communicating its intended path and destination?

- Implications for the work process: For example, does the automation allow performing different sub-tasks in a way that results in better health and safety practices for the workforce?

- Organizational implications: For example, who should be responsible for the operation of an individual autonomous shuttle car versus monitoring the entire fleet of cars? Who makes decisions at the shuttle/fleet level and how are those decisions communicated? What type of new training curricula are needed, who needs to be trained and how is such training best implemented?

- Employee acceptance: Throughout the process, it is critical that the human subjects involved understand that the project objectives are to enhance and expand the responsibilities of the shuttle car operators, not eliminate them. This acceptance is essential for the human factors components to be successful.

Significant advancements in autonomous mine haulage vehicles have been made in recent history, such as with the development and implementation of surface haul trucks and locomotives (Simonite 2016). These vehicles have the ability to navigate haulage routes as well as to interact (to a degree) with other equipment. Equipment manufacturers, such as Caterpillar, Komatsu and Volvo, have been developing autonomous vehicle technologies for many years, with some equipment already available for implementation (Jamasmie 2010, Jensen 2016, Simonite 2016). Autonomous surface haulage vehicles utilizing GPS navigation and proximity sensors are in fact currently being employed by several mining operations including, but not limited to, Western Australian surface mines operated by Rio Tinto, BHP Billiton, and Fortescue Metals Group (Fischer 2011, Jamasmie 2010, Simonite 2016).

Caterpillar is presently the clear leader in autonomous haulage with a number of trucks being deployed at major operations as well as a fleet being actively demonstrated at Caterpillar's Tucson Proving Grounds in Arizona (Jensen 2016). Although surface haulage automation has advanced meaningfully in recent history, a large part of this success is derived from the ability to access accurate, long-range, line-of-sight tracking technologies such as GPS (Fischer 2011, Jamasmie 2010, Jensen 2016). Thus, precise guidance and tracking of haulage vehicles are facilitated. However, underground room-and-pillar coal mines are GPS-denied environments, in which haulage routes continually change and many wireless technologies cannot function. As such, a separate methodology and a distinct combination of technologies is needed for an underground autonomous vehicle.

Underground mobile vehicle haulage presents a unique challenge that has already received the attention of major equipment manufacturers, such as Caterpillar, Sandvik, and Volvo (Alatalo 2017, Crouch 2016, Evans 2007, Jensen 2016). Caterpillar has already developed a semi-autonomous Load Haul Dump (LHD) vehicle that is in operation at a Newmont mine in Nevada, as well as at other locations around the world. This LHD is capable of autonomously addressing the travel and dump phases of a duty cycle (Jensen 2016). Sandvik has deployed a number of autonomous rubber-tired haulage vehicles at the Pyhäsalmi base metal mine in Finland, the El Teniente copper mine in Chile, and the DeBeers diamond mine in South Africa (Alatalo, 2017). Volvo is close behind with autonomous underground haul trucks being demonstrated in Sweden (Crouch 2016). Although underground haulage vehicles, including coal mining shuttle cars, operate under the similar principle of moving material from one point to another, the challenging nature of the underground environment has required the development of numerous technologies. The largest efforts have concentrated on navigation.

As mentioned, autonomous underground navigation technologies are not new and have been applied with varying degrees of success. Methodologies of note include laser positioning arrays, image processing sensors, RFID beacons, reflective strips, light ropes, and inductive wires (Chi et al. 2012, Crouch 2016, Evans 2007, Makela 2001, Roberts et al. Corke 2002). The majority of the technologies above that enable autonomy rely on the installation of additional infrastructure in the haulage route to guide the vehicle. Vehicle-mounted approaches, namely laser and image sensors, allow the vehicle to understand its relative position within an underground space but not its relative position within a route without some external queue (Chi, et al. 2012, Crouch 2016, Jensen 2016, Roberts et al. 2002). Although the previously introduced operations reflect successful underground mining production-grade implementations of these technologies, the operational environment of a room-and-pillar coal mine is vastly different from these examples.

The automated systems that are currently employed in underground mines require the construction of isolated underground workings to which human access can be controlled and the haulage route is relatively fixed (Alatalo 2017, Evans 2007, Jensen 2016, Makela 2001). Both of these characteristics are not applicable in a room-and-pillar mine, where shuttle car paths continually change. Although externally mounted navigation technologies may be used to address the issue of dynamic routes, the difficulty and expense of installation and maintenance for this purpose preclude comprehensive use in a room-and-pillar setting. Human factors interaction and intervention in this environment, which are prevalent and unavoidable, further challenge autonomous shuttle car application.

Human factors associated with autonomous mining vehicles have undergone some cursory investigation. Horberry et al. (2011) discuss potential human factors issues associated with the introduction of proximity sensing technology in both underground and surface mining, including the role of site management, risk compensation and display design. However, there is a lack of comprehensive research efforts specifically investigating human factors issues related to automated underground mining vehicles. Hence, given these issues, no research initiative to date has attempted to develop a comprehensive autonomous system for a room-and-pillar coal mine shuttle car.

Given the difficulty of the problem space in terms of dynamic navigation and vehicle interactions, this project approached the research in a holistic manner integrating both technical and human factor considerations from the onset. Such an approach was needed because of the complex operational nature of room-and-pillar shuttle car haulage. Available autonomous haulage technologies have likely not transitioned into the room-and-pillar arena because available components would only address one aspect of the problem. The resulting piecewise implementation would be cumbersome and inefficient. For example, underground navigation technologies do exist, but they ignore critical functionality such as sensitive collision avoidance with personnel. If adopted, operational procedures would need to be modified to accommodate the navigation technology.

Moreover, the introduction of automation in this domain needs to be based on careful analysis of work processes. This analysis must also include a strong focus on the new roles of the shuttle operators as well as the design of the interaction between the shuttle car, the operator and other mine personnel. If the humans required to interact with the autonomous shuttle car do not properly understand its operation, or do not perceive it as useful, the deployment of the autonomous shuttle cars is likely to fail (Horberry et al. 2011).

The holistic approach proposed in this project addresses all of the critical functional areas needed to automate shuttle car haulage from technological development to human factor considerations. This comprehensive approach will ensure that modifications to existing practices and job tasks will be focused around unit operations that directly involve the shuttle car, such as controlling the shuttle car, maintaining the shuttle car, etc. As a result, the autonomous system can be adopted with minimal impact to existing tasks executed by complementary roles, such as the roof bolter or the continuous miner. Detailed transition plans and guidance for those areas that will be affected, such as the role or the operator, will also be defined, to further entice industry adoption of the proposed autonomous shuttle car system. This project's holistic approach will ensure the development of not only a comprehensive autonomous shuttle car technology but also an autonomous system that can be synergistically integrated into established room-and-pillar mines.

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Chapter 3

Research Approach

The autonomous shuttle car system developed during the proposed project aims to automate the transfer of coal from the continuous miner to the feeder-breaker in underground room-and-pillar coal mines. Even with this focused scope of research, the intricate nature of room-and-pillar coal face haulage, coupled with unavoidable, varied interactions with personnel, mining equipment, and environmental artifacts by the shuttle car, create numerous challenges. Given these complexities, a holistic approach is employed to comprehensively address the components of the autonomous shuttle-car system. Approaching the autonomous shuttle car in a holistic manner required the development and deployment of a suite of technologies whose roles are to automate coal face haulage, facilitate remote shuttle car management by the new operator role, and enable the shuttle car to safely interact with external elements at the working face.

3.1 Aims and Objectives

At the time this project was started, autonomous underground room-and-pillar haulage has not received significant, targeted research efforts. A comprehensive collection of multi-disciplinary technologies must be holistically integrated to develop the autonomous shuttle car. The following provides an overview of the categories of technologies that are necessary to achieve the proposed holistic system.

- Develop the framework for an accurate and reliable underground navigation system and methodology,
- Evaluate the impact of an autonomous haulage system on the miners and work domain as a whole including changing work processes and organizational structures, and
- Develop and demonstrate a functional prototype of the automated shuttle car haulage system.

More specifically, the research approach was organized to address the following major aims:

- Aim 1: Develop a framework for an accurate and reliable underground navigation system

- Aim 2: Evaluate the impact of an automated haulage system on the miners and work domain as a whole including changing work processes and organizational structures

The list below includes the specific objectives that represent the flow of research and findings.

- Objective 1: Determine the state of the art in vehicle navigation systems
- Objective 2: Analyze the work domain and define human factors requirements
- Objective 3: Develop small scale (lab scale) prototypes, a data acquisition and management system, and a real-time mapping system component
- Objective 4: Develop a Logic Controller and evaluate the performance of the lab-scale prototypes in a lab-scale mine environment
- Objective 5: Develop design proposals for shuttle car integration
- Objective 6: Equip a full-scale shuttle car with sensors and controls for autonomous navigation
- Objective 7: Perform full-scale testing of the autonomous shuttle car

In support of these objectives, a number of focused research components were identified for developing the technology needed to enable and control the autonomous shuttle car. These research components include (but are not limited to) geolocation and tracking, automation logic and controls, human-machine interaction, and task allocation between human and machines.

It should be noted that the above components simply provide a solution for the shuttle car without consideration for processes, policies and procedures that will be impacted by this technology's introduction. In order to address these considerations, a second group of research components were defined to allow a truly holistic approach to the problem. These components encompass both the technological and the human interacting/intervening factors introduced previously, as well as constrain how the technological development of the shuttle car is approached. The additional research components include (but are not limited to) organizational structure, training needs, work processes, coal mine working face, and technological constraints underground.

A graphical representation of these research components is presented in Figure 3.1.

3.2 Project Partners

The Department of Mining Engineering at the University of Kentucky (UK) and the Virginia Center for Coal and Energy Research (VCCER) at Virginia Tech led the effort with respect to the mining aspects of the project. Mining Engineering as a discipline is necessary for the success of the autonomous shuttle car. Knowledge of the mining environment, expertise on the health and safety priorities in a mining operation, tasks involved, mine face logistics, and sources of human labor are all required for this project. UK and VCCER worked with the Virginia Tech Transportation Institute (VTTI) to make shuttle car operations safer and implement a two-way communication between the human and the machine. This communication is fostered by the knowledge "given" to

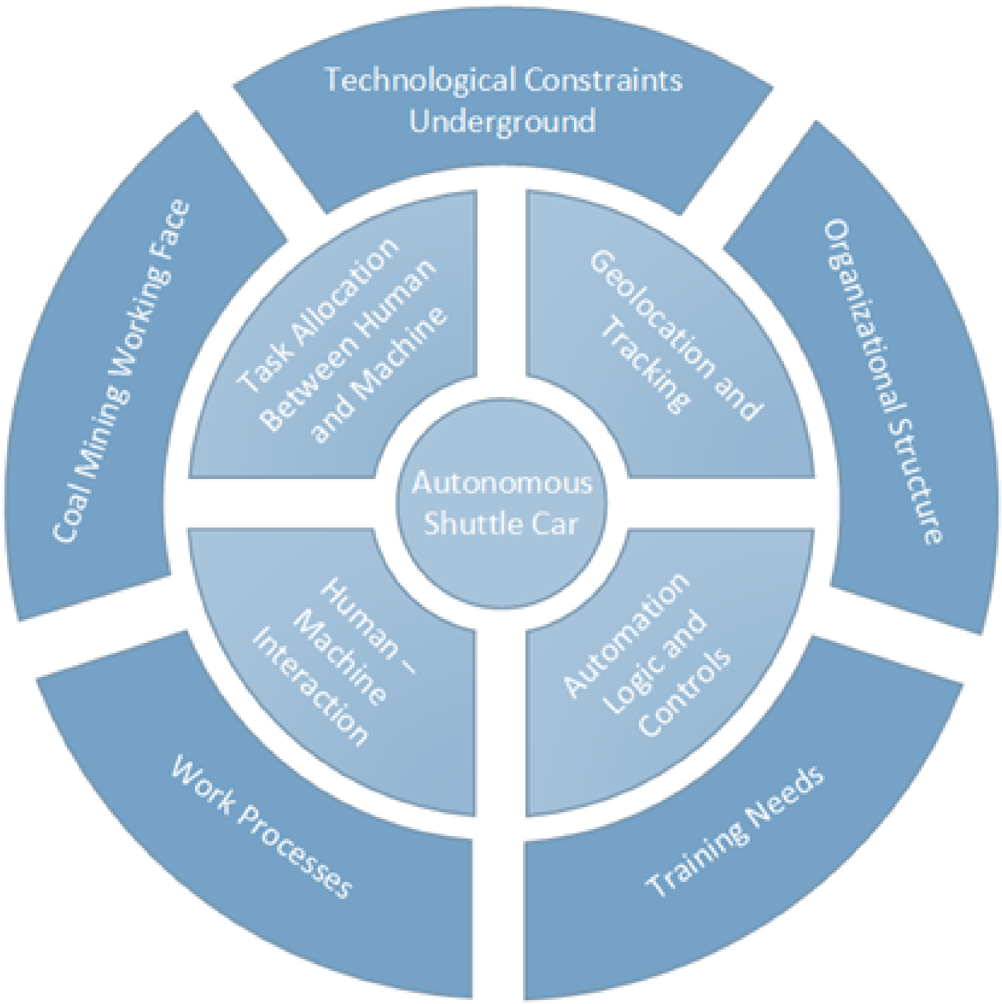

Figure 3.1: Research component diagram for developing the autonomous shuttle car system

it by the mining engineers of the project. This satisfies the implications for the work process and knowledge-rich requirements for an autonomous machine.

The VTTI led the activities related to human factors analysis, requirements, design and evaluation. This work leveraged VTTI's extensive experience in human factors engineering in the road transportation domain, in particular the design and evaluation of onboard vehicle safety and automation functions and the analysis of safety practices and organizational factors in commercial vehicle fleets. VTTI worked in tandem with the UK and the VCCER to identify the critical issues related to human behavior when operating a shuttle car. UK and VCCER worked with VTTI to ensure that constraints and restrictions are satisfied from both approaches: safe mining and autonomous guidance.

Alliance Coal provided access to their mining facilities and links to shuttle car manufacturers. As the project approached the phase where an actual shuttle car would be needed for testing, it became clear that due to supply chain issues, Alliance Coal could not provide access to any of their shuttle cars.

The project team then utilized the Simulated Mine Laboratory available at the West Virginia Training and Conference Center (WVTCC) in Julian, WV for the full-size testing. The 96,000 square foot facility imitates an underground mine with heavy equipment located throughout. The lab includes eight 20-foot entries and seven 20-foot crosscuts in a simulated underground mine with 40-foot and 20-foot-deep mining cuts as well as an operational shuttle car.

Chapter 4

Research Findings and Accomplishments

4.1 Introduction

This chapter includes a brief description of the research findings and accomplishments for each objective, while a full description is given in Appendices. Consequently, each Appendix relates to a different research component and can function as a stand-alone report.

In essence, the following sections address the following research questions:

- Geolocation and tracking, which addresses the challenge of enabling the shuttle car to travel through entries and crosscuts in a GPS-denied environment. This component will also give the shuttle car situational awareness by determining position tracking relative to other underground assets and facilitating proximity detection.
- Automation logic and controls, which addresses the issue of how the shuttle car operator will be replaced with an autonomous control system so that the operator may transition from an active control role to a management role
- Human-machine interaction, which addresses the issue of providing (i) the new managing shuttle car operator with a remote platform that allows for intuitive control of the shuttle car when needed and (ii) presenting the operator with adequate situational awareness about the shuttle car.
- Task allocation between humans and machines, which defines the new role of the shuttle operator as a manager of the autonomous system and determines which specific functional activities should be manual and which should be automatic.

4.2 Objective 1: Determine the State-of-the-Art in Vehicle Navigation Systems

An in-depth study of the literature for autonomous vehicle guidance, navigation systems, and collision avoidance under non-GPS conditions was completed. Existing systems for autonomous vehicle guidance, navigation systems, and collision avoidance were investigated, and systems that do not rely on satellite navigation (GPS, or powerful radio / telemetry signals) were identified. The literature review included over 150 journal papers and book chapters relevant to autonomous vehicles and their application to mining operations.

Promising systems for localization in non-GPS environments were also investigated, which included multiple sensor types and existing industrial proximity detection systems (inertial navigation system, laser, infrared, ultrasound, radio-based) for achieving localization. The literature review indicated that vehicle-mounted beam-forming sensors (ultrasound, infrared, laser), which do not rely on additional infrastructure, optimized localization efficiency, efficacy, and cost. Ideally these sensing technologies should be evaluated in conjunction with existing proximity, tracking and communication systems. This information is detailed in Appendix A.

Off-the-shelf components available for use in autonomous vehicles were identified, and their suitability to underground coal mine face environments was assessed. Numerous components are currently available for autonomous vehicles. Such systems include sensor fusion systems (e.g., NXP's BlueBox system), several proximity detection systems (e.g., the Matrix Design Group/Joy Global's IntelliZone and the Nautilus system, both of which are approved by MSHA for use in underground coal mines), ultrasonic detectors (e.g., TIDA-00151 from Texas Instruments), odometer sensors as well as other sensors (i.e., imaging in the visible or not visible spectrum). The NXP BlueBox system was found to be impractical for use in an underground mining environment. Proximity detection systems were found to be promising. As a result, these systems will be tested exhaustively during the construction of the tethered prototypes. Ultrasonic detectors and odometry sensors were found to be essential for collision avoidance and navigation. This information is detailed in Appendix A.

Real-time mapping of the continuously changing mine face is the most challenging aspect of vehicle automation (because of the high computational cost) and essential for the efficient navigation and localization of the autonomous vehicle, as well as for the monitoring and the managing of the entire mining cycle. The most efficient way for mapping a mine is to deploy the sensors already mounted on the autonomous vehicles and, based on the provided data, to construct and continuously update real-time maps. The most popular technique for mapping is the Simultaneous Localization and Mapping (SLAM) method.

4.3 Objective 2: Analyze the Work Domain and Define Human Factors Requirements

A Cognitive Work Analysis (CWA) study was conducted on-site at the mine with the goal of mapping the general organizational structure, identifying key work processes and activities, the roles/responsibilities of different factors (humans and machines) in the system, and the values/motivations and cognitive strategies of individual workers. This was done by means of interviews, focus groups, and other analysis techniques in the CWA toolbox. The CWA report can be found in Appendix I.

The report also includes the requirements for automation integration. The generated list of requirements for how the automated shuttle car system should function both individually and as a system address human-machine interaction design and functional allocation/re-allocation of tasks currently performed by mine personnel.

It mainly addresses the following:

- Organizational structure: answers the questions of who should be responsible for the operation of the individual autonomous shuttle car and who should be responsible for monitoring the entire fleet of cars? Who makes decisions at the shuttle/fleet level, and how are those decisions communicated? Will additional positions be needed to support the autonomous system?
- Training needs: identifies the skills needed by the shuttle car operator and any supporting roles necessary to operate autonomous technologies and to understand the new integrated process flows; defines the training needed to transition the shuttle car operator to a more supervisory role.
- Work processes: addresses how the automated shuttle car system should function both individually and as a system as well as how established procedures may need to be modified for integrating the autonomous system.
- Coal mine working face: determines how an autonomous shuttle car system can best be integrated into the work domain, taking into account opportunities and constraints at all levels
- Technological constraints underground: defines the physical, technological, and regulatory limitations of the underground room-and-pillar environment so that an autonomous system can be tailored to operate effectively under these conditions

4.4 Objective 3: Develop Small Scale (Lab-Scale) Prototypes, a Data Acquisition and Management System, a Real-Time Mapping System Component

Two lab-scale prototypes were constructed using off-the-shelf components and 3-D printed modules. The second prototype was a slightly improved version of the first prototype. Figure 4.1 shows the first lab-scale prototype while turning inside a scaled mock mine plan. The scaled mock mine was made of plywood and was built in the UK laboratory space. The shuttle car is equipped with four LiDAR units (one at each corner) and ultrasonic units. The sensors are controlled by Raspberry Pis and are powered by several portable battery packs. The lab-scale prototype is powered by a separate battery pack.

Details are included in Appendix C. It should be noted that the prototype construction was very robust and both lab-scale shuttle cars remain fully functional.

In parallel with the lab-scale prototype construction, the data management system (DMS) was developed. The DMS was designed to allow each sensor to work independently and save the collected data to a central database repository. The actual software or hardware used for this is not important as long as the format of each data record as generated by the sensor or the related microcontroller follows the same specification. Details are included in Appendix D.

For example, the lab-scale LiDAR units utilized a Python script running on a Raspberry Pi to collect the data, while the full-scale LiDAR units utilized a Python script running on a laptop.

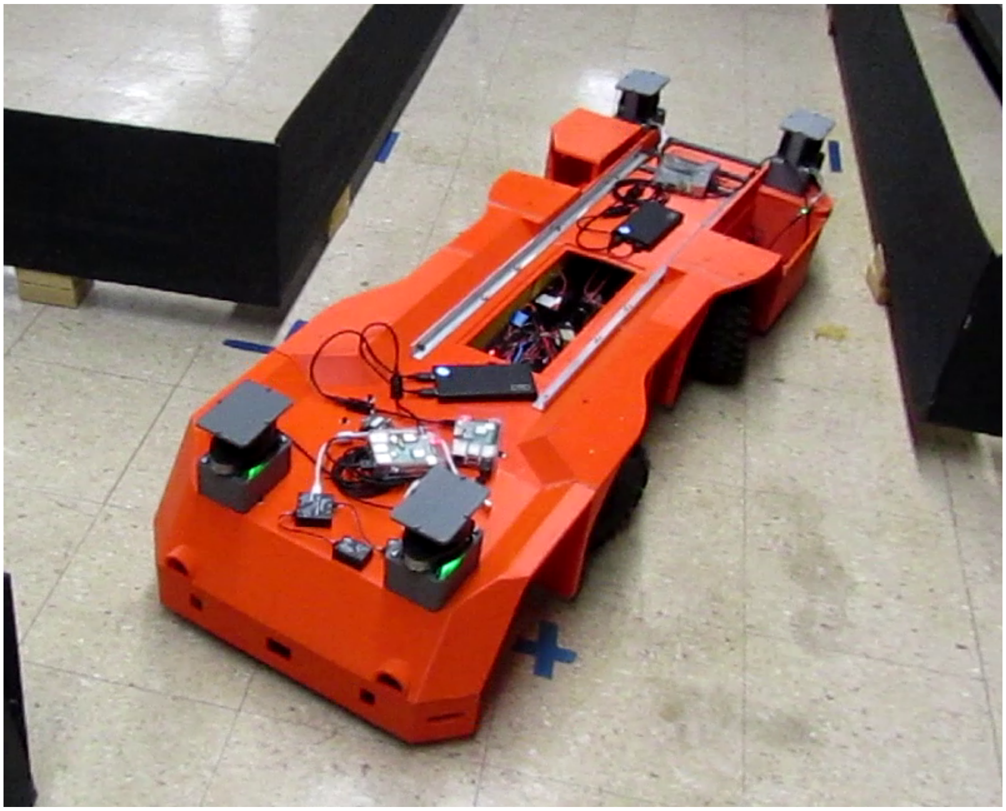

Figure 4.1: Lab-scale prototype

More specifically, for the lab-scale implementation, the data from the onboard sensors were collected through a number of Raspberry Pi 3 Model B+ microcontrollers. These microcontrollers are equipped with a quad-core 64-bit CPU with a frequency of 1.2 GHz and 1GB RAM, as well as wireless LAN connectivity. Each microcontroller is assigned to one LiDAR scanner and two ultrasonic sensors in parallel processes. The collection of data is accomplished through scripts, written in the Python programming language. The microcontrollers are programmed to collect data from the sensors and post the data into the custom MySQL database through a continuous loop.

Once data were stored in the DMS, the logic controller could retrieve the needed data to perform navigation. Initially, it was envisaged that all communications (i.e., sensor to database, database to the logic controller) would be over WiFi, however, to decrease latencies (delays in communication), data were transmitted via wired cables. In summary, the system utilizes simultaneous processes and is divided into three main parts or nodes, as shown in Figure 4.2. See also Figures D.1 to D.3 in Appendix D.

- Data Collection (Onboard sensors): The onboard hardware that is responsible for collecting the sensor data by onboard microcontrollers and for transmitting the data via Wi-Fi to an SQL database.
- Data Management (Servers for data storage): An SQL database server and a Web server that facilitate the storage of the sensor data.

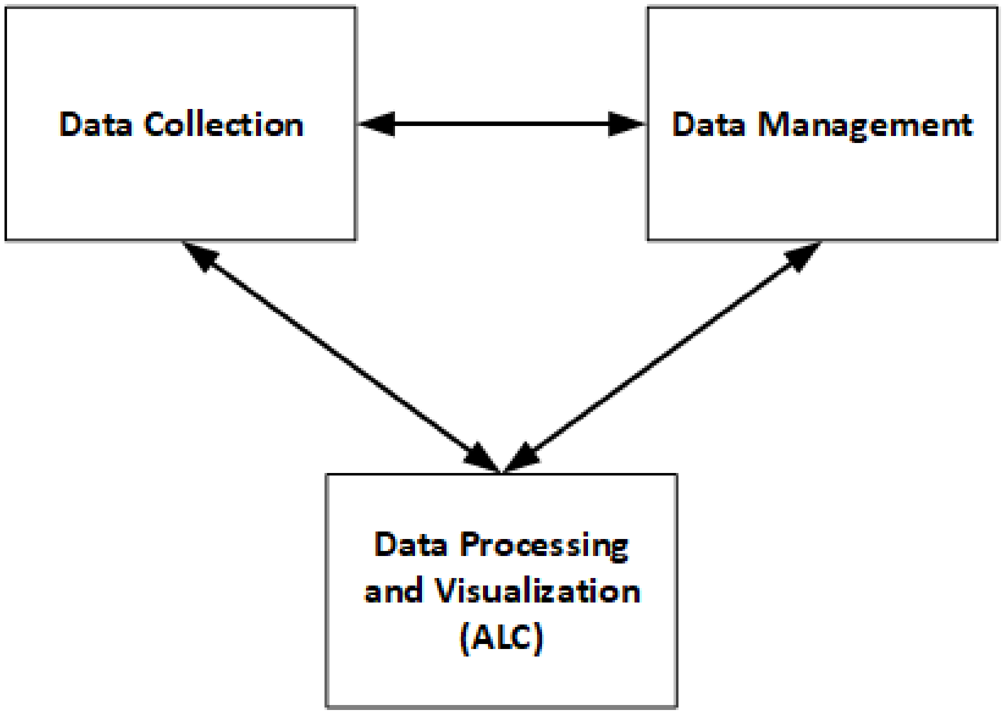

Figure 4.2: Data collection, management and processing

- Data processing and visualization (Autonomous Logic Controller, Mapping Tool, Path Planning Module, etc.): A Windows application for analyzing the data stream and generating the PWM signals that control the movement of the shuttle car in real-time. This part includes the multi-modular interface developed for decision-making and for communication to the shuttle car traction motors and steering servomotors. Human input is also required for setting parameters and assigning missions.

4.5 Objective 4: Develop a Logic Controller and Evaluate the Performance of the Lab-Scale Prototypes in a Lab-Scale Mine Environment

The development of an autonomous logic controller (ALC) started early. The ALC was based on the already-described data acquisition and data management system (see Appendix D) and communicated with the lab-scale prototypes through an Arduino microcontroller and a remote-control unit as described in Appendix C.

A scaled mock mine plan made of plywood was constructed as discussed in section C.3 in Appendix C.

During the course of the project, the ALC underwent many changes and improvements. For example, significant effort was expended into further interpreting the derived maps into useful information and integrating this information into the autonomous driving processes. This signifi-

Figure 4.3: Snapshot of a lab-scale test where the HMI run on a tablet controls the ALC which in turn controls the shuttle car through a remote control unit

cantly improved the reliability and the repetitiveness of the successful trials. Based on this information, the older PID controller algorithms used for correcting the steering angle of the vehicle were replaced with a Stanley Controller process. The latter controlling process allows for better and smoother performance around the corners of pillars.

The ALC was interfaced with the HMI, which was developed in a parallel process and is discussed in Appendix K. Figure 4.3 shows a snapshot of a lab trial whereby the HMI is used to control the ALC (i.e., start the mission). Subsequently the ALC assumes control to navigate the lab-scale shuttle car through its defined mission. Figure 4.4 shows a snapshot of the shuttle car turning at the first crosscut controlled by the ALC. The real-time map is visible on the ALC, and the location of the shuttle car is visible on the HMI, which is running on a tablet (bottom right of the photo). The Arduino that controls tramming and steering on the lab-scale shuttle car is visible on the left of the photo.

A plethora of scenarios were tested in the lab with various mission and path configurations. Four scenarios were tested in the mock mine and detailed data were collected. These scenarios were designed to simulate simple missions and not the actual shuttle car operation during a full shift at an underground coal mine. The scenarios with their respective success rates are listed below:

- Scenario 1: Traverse Along two Consecutive Pillars, with a success rate of 86%.
- Scenario 2: Two Consecutive Turns, with a success rate of 84%.
- Scenario 3: Traverse along two Consecutive Pillars and Turn, with a success rate of 90%.
- Scenario 4: Obstacle on Turn, with a success rate of 100%, i.e., the navigation system identified the obstacle and stopped the shuttle car in all cases.

Figure 4.4: Snapshot of a lab-scale test where the ALC controls the shuttle car. The real-time map is visible on the ALC and the location of the shuttle car is visible on the HMI

Each scenario was run 50 times, half with the prototype moving inby and half with the prototype moving outby (returning along the same route). A detailed account of the evaluation of the performance of the lab-scale prototypes using representative testing scenarios is given in Appendix F.

4.6 Objective 5: Develop Design Proposals for Shuttle Car Integration

The Human Machine Interface (HMI) design proposal contains a number of design plans for shuttle car integration based on human factors interaction. It basically defines how tasks allocated to the shuttle car can be automated, as well as the requirements for each task and how the shuttle car should interact with its operator and other humans surrounding it. For example, these design plans at the system level address changes to work processes or propose completely new work processes, which are enabled by automation, and propose new role assignments and decision structures.

The ALC that controls the navigation of the shuttle car and the HMI (which the supervisors located at the feeder-breaker or the continuous miner have, allow control of the semi-autonomous shuttle car) need to communicate effectively through a framework for information sharing. The HMI should allow selection of the path, initiation/termination of the mission, start/pause/resume actions of the shuttle car movement, and emergency shutdown trigger of the shuttle car. However, because the HMI is designed as a lite application, able to run on a simple, portable tablet, most of this information must be retrieved from the ALC.

The ALC is located on-board the autonomous system, where it has direct access to the sensor data (thus minimizing the workload on the wireless network bandwidth) as well as a power source

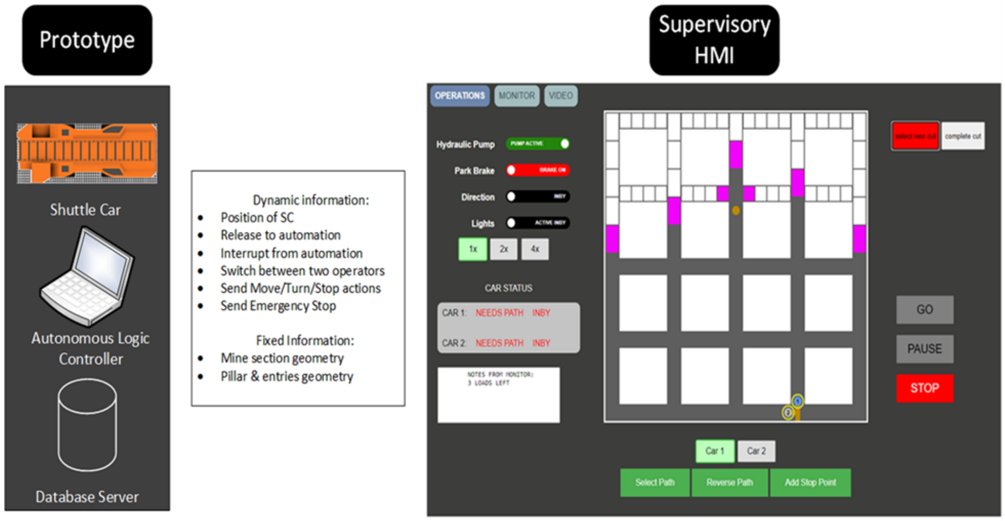

Figure 4.5: ALC and HMI schematic interactions

and memory space that will enable the uninterrupted processing of the collected data and the execution of the decision-making algorithms. In other words, the HMI is merely a display of the basic function of the ALC and a tool for remotely controlling the start/stop function of the ALC, as well as for path selection. The information that needs to be shared can either be low-frequency information, such as mine section geometry, pillar, and entry geometry, etc., or high-frequency, such as control triggers (e.g., the status of the mission, the status of shuttle car movement, emergency stop initiation/clearance) and localization of the shuttle car (Figure 4.5).

Figure 4.6 shows a snapshot of the HMI design running on a tablet. The shuttle car is controlled by the operator at the feeder-breaker.

Details are included in Appendix K.

4.7 Objective 6: Equip a Full-Scale Shuttle Car with Sensors and Controls for Autonomous Navigation

The initial plan was to retrofit an Auxier Welding shuttle car supplied by Alliance Coal - the industry partner in this project. However, due to supply chain issues, this was not feasible and retrofitting and testing were performed at the West Virginia Training and Conference Center (WVTCC) Simulated Mine Laboratory using an older Joy (Komatsu) shuttle car.

Retrofitting of that shuttle car included two modifications:

- Mounting of the Ouster OS1-32 LiDAR scanners on the shuttle car through custom aluminum bases that can grip the thin sides of the shuttle car on the inby/load end or attach through custom magnetic bases to the flat surfaces of the shuttle car chassis on the outby/discharge end.
- Mounting of two servomotors inside the operator's cab that control the tram pedal and the steering lever through tie rod ends as links.

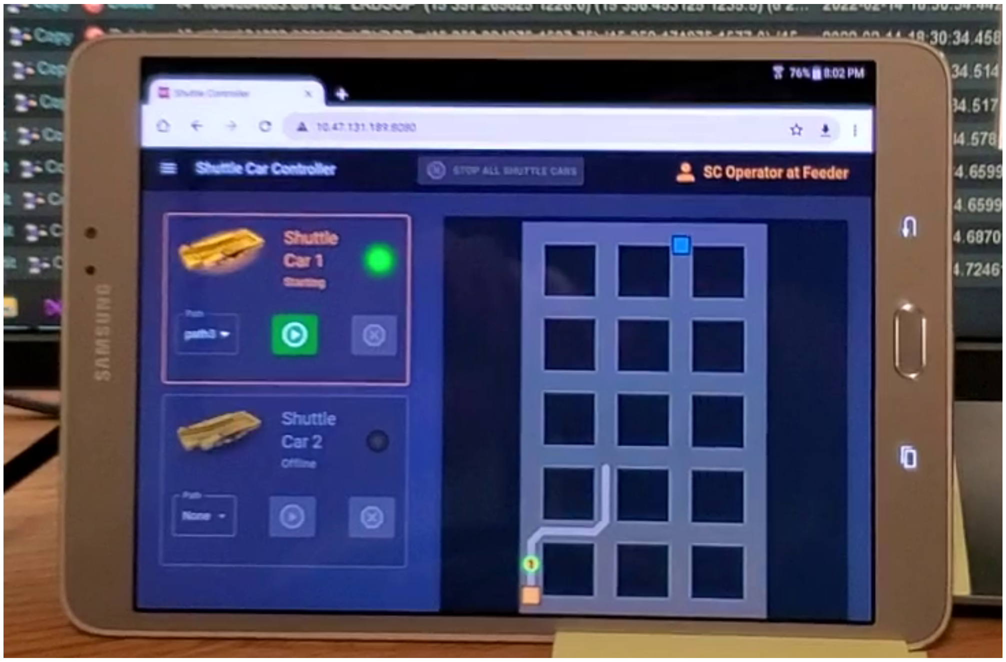

Figure 4.6: The HMI design proposal running on a tablet

More details of the initial plan and of the retrofitting of the Joy (Komatsu) shuttle car at WVTCC are given in Appendix G.

4.8 Objective 7: Perform Full-Scale Testing of the Autonomous Shuttle Car

The Joy (Komatsu) shuttle car available at the West Virginia Training and Conference Center Simulated Mine Laboratory was used for all field trials. In order to evaluate the performance of the lab-scale prototypes, two scenarios were planned and tested in the Simulated Mine Lab, as discussed in the following sections. The scenarios were designed to simulate simple missions and not the actual shuttle car operation during a full shift at an underground coal mine. Each of the two scenarios was tested multiple times over several field-testing days. The pillar lengths (and widths) of the Simulated Mine Lab were (only) 20 ft, which presented another set of challenges when using the autonomous navigation algorithm. It should be noted that early in the process of field testing, it was recognized that the wheels of the shuttle car were not correctly aligned. Although it was identified that one of the shuttle car tie-rods was loose, it was not feasible to remedy the issue in the framework of this project.

The evaluation metric used for both scenarios was simple and only consisted of overall "success" or "failure". It should be noted that failures due to field testing conditions that were not related to data collection, data processing, or the navigation algorithm were not included in the metric. Such conditions include, for example, power outages, extension cable failures (the extension cable powered an uninterrupted power supply (UPS), which was placed on the shuttle car and

Figure 4.7: Full-scale shuttle car traversing along a number of pillars

provided continuous power to the LiDARs, the laptop, and the servo controller box), testing of the servo controllers, calibration of the servo controllers under hydraulic power, etc.

Because of the misaligned wheels, it was easier (and took less time) to steer to the right than to steer to the left. Thus, the navigation algorithm had to be adjusted and tailored to the behavior of this particular shuttle car. Figure 4.7 shows a snapshot of the shuttle car traversing along a number of pillars. The average success rates for tramming on an entry across multiple pillars at low speed was 55%. The average success rate for turning into a crosscut was 50%. More details on the full-scale testing are given in Appendix H.

Chapter 5

Publication Record and Dissemination Efforts

This section presents a complete record of publications and presentations which were generated from this project.

5.1 Technical Papers

1. Androulakis, V., S. Schafrik, J. Sottile and Z. Agioutantis, (2019), Opportunities and Challenges for Autonomous Shuttle Car Operation in Underground Coal Mines, SME Preprint No 19-032, SME Annual Meeting, February 24-27, 2019, Denver, CO

2. Androulakis, V., J. Sottile, S. Schafrik and Z. Agioutantis, (2019), Elements of Autonomous Shuttle Car Operation in Underground Coal Mines, Proceedings, 54th IEEE Industry Applications Society Annual Meeting, Sept 29-Oct 3, 2019, Baltimore, MD

3. Androulakis, V., J. Sottile, S. Schafrik and Z. Agioutantis, (2020), Concepts for Development of Autonomous Coal Mine Shuttle Cars, IEEE Transactions on Industry Applications, Volume 56, Issue 3, May-June 2020, Print ISSN: 0093-9994, Electronic ISSN: 1939-9367, https://dx.doi.org/10.1109/TIA.2020.2972786

4. Androulakis, V., S. Schafrik, J. Sottile and Z. Agioutantis (2021), Navigation System for a Semi-Autonomous Shuttle Car in Underground Room and Pillar Coal Mines Based on 2D LiDAR Scanners, Tunnelling and Underground Space Technology, vol. 117, pp. 104149, 2021, https://doi.org/10.1016/j.tust.2021.104149

5. Androulakis, V., S. Schafrik, J. Sottile and Z. Agioutantis (2021), Data Management System for a Semi-Autonomous Shuttle Car for Underground Room and Pillar Coal Mines, Automation, vol. 2, no. 3, pp. 153-172, 2021, https://doi.org/10.3390/automation2030010

6. Androulakis, V., J. Sottile, Z. Agioutantis and S. Schafrik (2021), Automation Considerations for Underground Shuttle Car Haulage, Proceedings, Future Mining 2021, 6-10 December 2021, AUSIMM

7. Miller A. (2021), Developing and Creating an Operational Controller for Automation Within Mining Operations. In: Ahram T.Z., Falcão C.S. (eds) Advances in Usability, User Experience, Wearable and Assistive Technology. Conference in Applied Human Factors and Ergonomics Conference (AHFE 2021). Lecture Notes in Networks and Systems, vol 275. Springer, Cham., https://doi.org/10.1007/978-3-030-80091-8_52

8. Agioutantis, Z., V. Androulakis, S. Schafrik and J. Sottile, (2023), LiDAR Navigation in Underground Openings, Proceedings, World Tunnel Congress, ITA-AITES (WTC 2023), Conference, May 12-18, Athens, Greece

5.2 Technical Presentations (in Person and Virtual) and Poster Presentations

1. Schafrik, S. (2018), Autonomous Shuttle Car Research, 31st Annual Kentucky Professional Engineers in Mining Seminar September 14, 2018, Lexington, KY (oral presentation)

2. Androulakis, V., S. Schafrik, J. Sottile and Z. Agioutantis (2019), Opportunities and Challenges for Autonomous Shuttle Car Operation in Underground Coal Mines, SME Preprint No 19-032, SME Annual Meeting, February 24-27, 2019, Denver, CO (oral presentation based on full paper)

3. Sottile J., Z. Agioutantis and S. Schafrik, (2019), Intelligent Coal Mining: Automating Shuttle Car Haulage, 2019 Longwall USA Exhibition and Conference, May 20-22, 2019, Pittsburgh, PA (abstract and oral presentation)

4. Sottile J., Z. Agioutantis and S. Schafrik, (2019), The Automation Loop: Sensing and Controlling Underground Equipment, 32nd Annual Kentucky Professional Engineers in Mining Seminar September 6, 2019, Lexington, KY (oral presentation)

5. Androulakis, V., J. Sottile, S. Schafrik and Z. Agioutantis, (2019), Elements of Autonomous Shuttle Car Operation in Underground Coal Mines, 2019 IAS Annual Meeting, Sept 30-Oct 3, 2019, Baltimore, MD (oral presentation based on full paper)

6. Miller A., (2019), Automation and Autonomy, 24th Annual Underground Stone Safety Seminar, December 10-11, 2019, Louisville, KY (oral presentation)

7. Androulakis, V., S. Schafrik, J. Sottile and Z. Agioutantis (2020), Development of a Lab-Scale Autonomous Shuttle Car and Implications for the Full-Scale Autonomous Vehicle, SME Annual Meeting, February 23-26, 2020, Phoenix, AZ (abstract and presentation)

8. Sottile J., Z. Agioutantis and S. Schafrik, (2020), Advances in Automation of Shuttle Cars and Underground Equipment, 33rd Annual Kentucky Professional Engineers in Mining Seminar, September 11, 2020, Lexington, KY (virtual meeting, oral presentation)

9. Androulakis, V., J. Sottile, S. Schafrik, Z. Agioutantis and H. Heady, (2020), Advances in Automation of Shuttle Cars, 4th Annual Commonwealth Computational Summit, October 12-16, 2020, Lexington, KY (virtual poster presentation)

10. Androulakis, V. and Z. Agioutantis (2020), Developing an Autonomous Shuttle Car, 2020 SME/PCMIA Virtual Annual Joint Meeting, December 15, 2020 (virtual meeting, oral presentation)

11. Agioutantis, Z., V. Androulakis, S. Schafrik, and J. Sottile (2021), Challenges in autonomous underground tramming operations, Society of Mining Professors Annual Meeting, Sept 24, 2021, Medellin, Colombia (oral presentation)

12. Androulakis, V., J. Sottile, Z. Agioutantis, S. Schafrik (2021), Automation Considerations for Underground Shuttle Car Haulage, Future Mining 2021, 6-10 December 2021, AUSIMM (oral presentation based on full paper)

13. Androulakis, V., S. Schafrik, J. Sottile and Z. Agioutantis (2022), Developing a Semi-Autonomous Shuttle Car: Performance of a Lab-Scale Prototype, SME Annual Meeting, February 27-March 2, 2022, Salt Lake City, AZ (abstract and oral presentation)

14. Agioutantis Z., J. Sottile and S. Schafrik, (2022), Advances in Automation of Shuttle Cars and Underground Equipment, VA Professional Engineers Seminar, March 31, 2022, Cedar Bluff VA (oral presentation)

15. Agioutantis Z., S. Schafrik, J. Sottile, and V. Androulakis (2022), Underground Shuttle Car Automation, SME/CAS, April 25 - 27, 2022, Lexington, KY (abstract and oral presentation)

16. Androulakis, V., S. Schafrik, J. Sottile and Z. Agioutantis (2022), Developing a Semi-Autonomous Shuttle Car: Performance of a Lab-Scale Prototype, SME Summer MineXchange Conference, July 19, 2022, (virtual meeting, oral presentation)

17. Agioutantis, Z., V. Androulakis, S. Schafrik and J. Sottile (2023), Challenges and Opportunities in the development of autonomous shuttle cars, GRawMat Innovation Cluster, a virtual webinar series, June 29, 2022 (virtual meeting, oral presentation)

18. Schafrik S., (2022), Field Testing of an Autonomous Shuttle Car, SME/PCMIA (Pittsburgh Coal Mining Institute of America), Fall meeting, October 2022 (oral presentation)

19. Sottile, J., A. Rajvanshi, Z. Agioutantis, A. Krasner, V. Androulakis, S. Schafrik, J. Rose, M. Sizintsev, H-P. Chiu (2023), Evaluating the Efficacy of Autonomous Shuttle Cars Tramming and Docking Sensor and Control Packages, SME Annual Meeting, Feb 26 – March 1, 2023, Denver, CO, (abstract and oral presentation)

20. Agioutantis, Z., V. Androulakis, S. Schafrik, J. Sottile (2023), LiDAR Navigation in Underground Openings, Proceedings, World Tunnel Congress, ITA-AITES (WTC 2023), Conference, May 12-18, Athens, Greece (oral presentation based on full paper)

5.3 Dissertations

1. Androulakis, V. (2021), "Development of an Autonomous Navigation System for the Shuttle Car in Underground Room and Pillar Coal Mines", PhD Dissertation, University of Kentucky, UKnowledge.

Chapter 6

Conclusions

The autonomous shuttle car concept that was developed during this project aligns with the Alpha Foundation for the Improvement of Mine Safety and Health topic area "Health and Safety Intervention."

The development of an autonomous shuttle car is a very challenging project as it involves both the development of an accurate and reliable underground navigation system and methodology that allows the shuttle car to travel through entries and crosscuts in a GPS-denied environment, while at the same time avoid collisions with personnel, equipment, physical barriers, and other related items.

Two lab-scale prototypes were constructed and deployed in a mock mine under laboratory conditions. The mock mine simulated relevant room-and-pillar mining conditions.

After testing multiple sensor packages, it was decided to equip the lab-scale prototypes with LiDAR sensor units which provided all of the necessary data for underground navigation and collision avoidance. A custom data acquisition and data management system was built to accommodate the large amount of sensor data that was generated. An autonomous logic controller was developed that provided mission planning, mapping of the surroundings as well as navigation logic to travel in a GPS-denied environment. Data were transmitted over WiFi for the lab-scale prototype as the laptop controlling the lab-scale shuttle car could not be placed on the prototype. The above-mentioned components were optimized through multiple iterations and tested via a number of missions or path navigation scenarios.

The navigation scenarios included tramming between two points in different crosscuts and entries. However, it disregarded any operations related to loading coal from the continuous miner or discharging coal to the feeder-breaker. In other words, it simulated tramming from the continuous miner change-out point to the feeder-breaker.

At the same time, a Human Machine Interface (HMI) was developed that allowed the controlling / managing of shuttle car operations from a tablet. This simulated the controlling device that would be available to the shuttle car supervisor to monitor the progress of autonomous haulage. The displacement of the operator to a remote location required that the implemented HMI technology was able to clearly communicate the state of the shuttle car as if the operator were directly operating the vehicle. Input for the development of this HMI device was based both on the parameters affecting the development of the navigation system as well as parameters and constraints that were developed as part of the cognitive work analysis of shuttle car operations.

A number of challenges were overcome during the development of the lab-scale shuttle car, including the following:

- Design and construct a robust system
- Develop a reliable way to communicate four-wheel steering and tramming commands to the lab-scale shuttle car
- Ensure an appropriate data refresh rate so that the navigation logic can be fed with the latest data
- Minimize latencies pertaining (i) to data transmission and retrieval to/from the database, (ii) car response to issued commands, (iii) frequency of decision making
- Develop a fast mapping routine that could represent the localization of the lab-scale prototype in real time

Based on the design principles developed for the lab-scale prototype, a full-scale shuttle car was retrofitted for steering and tramming and was fitted with commercial-grade LiDAR units for providing a real-time feed of distances and angles to the surrounding structures.

The autonomous logic controller as well as the Arduino microcontroller program were modified to address the challenges of controlling a full-scale shuttle car.

Full-scale shuttle car trials were performed at the West Virginia Training and Conference Center Simulated Mine Laboratory and demonstrated that a shuttle car can be autonomously driven along an entry past multiple crosscuts, and it can also autonomously turn into a crosscut.

A number of challenges were overcome during the retrofitting and testing of a full-scale shuttle car including the following:

- Reduce the latencies related to data acquisition and storage of the LiDAR data. The commercial LiDAR units scan information on up to 32 planes ($\pm$ 16 rows from the horizontal plane)
- Reduce the latencies related to decision-making at each step. Note that the navigation algorithm needs to start checking on the next decision while the current decision is implemented, (imitating the behavior of a human driver).
- Reduce the latencies related to turning the wheels of the full-scale shuttle car. The commands are related to the servo motors, which in turn control the steering and tram pedal. The steering arm, in turn, activates the hydraulics for turning the wheels. In addition, in this particular shuttle car steering arm does not have a symmetric response between the two axles.
- Stop in time without damaging the ribs of the simulated mine
- Turn in very tight spaces without damaging the ribs of the simulated mine

Due to the fact that the full-scale shuttle car was an older model, which was not developed with automation in mind, there was no direct feedback from the steering or the wheels into the navigation algorithm. Thus, navigation only relied on distance measurements between the shuttle car and different points of the mine structures (distance to corners, distance to ribs, distance to obstacles, etc.). A PLC-driven shuttle car with appropriate feedback would be much more straightforward to navigate in a room-and-pillar section.

Chapter 7

Recommendations for Future Work

The development of an autonomous shuttle car would be greatly facilitated through the improvement of a number of supporting technologies, including the following:

- Development of inertial measurement units (IMUs) that are hardened and smoothed by integration with the LiDAR data for the enhancement of determining the distance traveled while moving, can keep track of trajectories (i.e., pitch and roll), and allow for correction in the navigation due to acceleration.

- Increase in the robustness of structure recognition (i.e., pillars, crosscuts, cable, and curtains) is needed to improve the accuracy of the decision-making algorithm as well as to provide a means of error correction. The latter capability is essential to ensuring that technological components responsible for shuttle car interactions, such as proximity detection, are able to react rapidly, accurately, and precisely.

- Fast and reliable data measurements from LiDAR sensors would improve mapping refresh rates. LiDAR technology is evolving rapidly due to demand from the automotive industry. In the last year or so, technology has been developed to have LiDAR on a chip (https://spectrum.ieee.org/lidar-on-a-chip#toggle-gdpr). This technology has no moving parts and generates, emits, and receives light with no external hardware. And its tiny size makes it easy to incorporate into the bodies of any size vehicle. Note that LiDAR is similar to radar, but it operates in the infrared portion of the spectrum, with wavelengths typically between 905 and 1,550 nanometers (compared with a few millimeters for automotive radar). This difference in wavelength gives LiDAR much better spatial resolution because the waves sent out from the sensor can be more tightly focused. Also note that LiDAR excels in precise 3D mapping, while radar is better for long-range detection and adverse weather conditions.

- Incorporation with PLC-Driven shuttle cars, would allow the navigation algorithm to receive feedback on wheel position and trajectory as well as deliver commands in the same means as the human operator allowing cars to be driven either in traditional or autonomous mode without extra apparatus.

- Docking capabilities should be integrated into the autonomous or at least the remote shuttle car operations. At this stage of the development, the shuttle car operator is positioned at the continuous miner and the Monitor is positioned at the feeder/breaker and are (or maybe) required to assist in the loading/unloading efforts. Since close proximity to the loading and unloading activities will expose the operator to some hazards (i.e., dust, noise), removal of the operator from these areas would be beneficial. The docking technology has been developed in other work, and should be tested in conjunction with this project's work.

- The mission planner should be expanded to include options for rectangular pillars and/or cross-cuts at an angle. The ALC will need to be adjusted in terms of decision making to accommodate angled cross-cuts.

- Field trials in a mine. The mine conditions are not as benign as the laboratory conditions or the simulated mine lab conditions. The floor can be uneven, rutted, and wet. Wheel slippage will be more prevalent. Pillar corners may be sloughed, which may create imaging/mapping errors.

Chapter 8

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Below is the global list of references. Appendices and chapters may include subsets of this list.

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Appendix A

State-of-the-Art in Vehicle Navigation Systems

A literature review for autonomous vehicle guidance, navigation systems and collision avoidance under GPS-denied conditions is presented below. References are listed at the end of this Appendix.

A.1 Abbreviations

Table A.1 presents the abbreviations shown in this Appendix.

A.2 Introduction

In recent decades, the construction and utilization of autonomous vehicles have gained great interest in many engineering and scientific applications. Such applications include (but are not limited to) intelligent transportation, agriculture, marine and planetary environment exploration, mining, and disaster reconnaissance and rescue. Common reasons for the necessity of autonomous vehicles are the inability of humans to carry out the desired tasks due to inaccessibility (e.g., marine environments, planetary exploration, confined spaces after the collapse of a building or mine) or the prevalence of hazardous conditions (e.g., nuclear radiation, toxic gases). Other reasons include the necessity of precision and speed that cannot be achieved by a human. In general, automation is employed for repetitive tasks. Such tasks can be executed faster and more precisely by a machine, while the risk for the operators is reduced as they are removed from active and potentially hazardous areas.

However, the construction of robust autonomous vehicles able to carry out the tasks at hand imposes many challenges. The autonomous vehicles, in contrast to the humans, are not good at making decisions. For this reason, the scientific and engineering society has put much effort in the last decades towards the development of efficient and reliable hardware and software that can enable such systems with sufficient environmental perception, robust data processing, and planning and control capabilities. In general, the autonomous/robotic system has to successfully carry out

Table A.1: Abbreviations

Acronym	Definition
AGV	Autonomous Ground Vehicle
AoA	Angle of Arrival
ARS	Autonomous/Robotic System
DoF	Degrees of Freedom
EKF	Extended Kalman Filter
ICP	Iterative Closest Point
IMU	Inertial Measurement Unit
INS	Inertial Navigation System
IR	Infrared
KF	Kalman Filter
LADAR	Laser-Radar Range Sensing
LHD	Load Haul Dump vehicle
LiDAR	Light Detection and Ranging
LoS	Line of sight
PDoA	Phase Difference of Arrival
PF	Particle Filter
RADAR	Radio Detection and Ranging
RFID	Radio Frequency Identification
RSS	Received Signal Strength
RSSI	Received Signal Strength Index
SIFT	Scale Invariant Feature Transformation
SLAM	Simultaneous Localization and Mapping
SURF	Speeded Up Robust Features
TDoA	Time Difference of Arrival
ToA	Time of Arrival
ToF	Time of Flight
UHF	Ultra-High Frequency
UWB	Ultra-Wide Band
US	Ultrasound/Ultrasonic
VO	Visual Odometry

four subtasks: localization and mapping, path planning, navigation (including obstacle avoidance), and process control.

The perception of an autonomous/robotic system of its surroundings as well as its internal state is the first step for any autonomous operation. The system has to acquire reliable and sufficient data, the processing of which can give to it awareness of its external and internal state. A big variety of sensors exploit different physical means are currently available for data acquiring inertial measurement units (IMU), optical sensors which include infrared sensors (IR) and lasers (LiDAR), ultrasound sensors (US), radio-based sensors which include WiFi, RFID and BLE, as well as visual sensors which include cameras in both the visible and non-visible region.

The data acquired by the system has to be processed with a proper method in order to provide the necessary information for the planning and process control step. Common desired outcomes of the data processing are the localization of the system with regard to its surroundings, the mapping of the environment, the obstacle detection and the definition of the system's state.

Because the autonomous vehicle/robot has a sufficient perception of its surroundings, it can proceed and plan a path for reaching its final goal position. To do so, the autonomous vehicle has to traverse the planned path while avoiding the observed obstacles, both static and dynamic, including people, monitor its internal state, i.e., its stability, energy consumption and functionality of its sensors and other hardware and software, and making the right decision to execute the task in hand.

A.3 General Workflow of an Autonomous Navigation System

The construction of a robust autonomous ground vehicle (AGV) able to carry out required tasks is based on an appropriate architecture that will enable it to make decisions, like humans inherently do. The autonomous navigation system (ANS) must be capable of sufficient environmental perception, robust data processing, and planning and control capabilities. In general, an ANS has to successfully perform the following functions: localization and mapping, path planning, navigation and obstacle avoidance, and process control.

The basis of an ANS architecture is the perception module. This module is responsible for the function of perception of the surrounding environment as well as the state of the vehicle. The system acquires this information by using appropriate sensors. Exteroceptive sensors provide information about the surrounding environment, while interoceptive sensors provide information about the internal state of the autonomous vehicle. A wide variety of sensors are currently available for data acquisition. Inertial measurement units and wheel or angle optical encoders are commonly used for internally monitoring the pose, the speed and the direction of movement of an autonomous vehicle. On the other hand, IR, lasers (LiDAR), ultrasound and radio-based (WiFi, RFID and BLE) sensors, as well as cameras (operating in the visible and non-visible spectrum) are used for measuring distances between the vehicle and surrounding static or dynamic objects such as walls, roof, obstacles, humans, etc. This module is also responsible for the preliminary processing of the data collected by the sensors, i.e., filtering, time-labelling, etc.

This information is used as input to the data processing and interpretation module. This module interprets the information into a more appropriate form by implementing the embedded algorithms. This information can then be used for planning, decision-making and process control purposes. Common desired outcomes of the data processing module are the localization of the ANS with respect to its surroundings, the mapping of the environment (when an a priori map is not available), the detection of obstacles and the definition of the system's internal state. Commonly used tools in this module include geometric algorithms, Simultaneous Localization and Mapping (SLAM) logic and image processing procedures.

As an autonomous vehicle acquires a sufficient perception of the surrounding environment and its location within, it can proceed and plan a path for reaching its final goal position. This task is carried out by the planning module.

Subsequently, the navigation and control module is responsible for implementing the planned path. To do so, the ANS has to traverse the planned path while avoiding the observed obstacles, both static and dynamic and continuously monitor the internal state of the autonomous vehicle, i.e., its stability, energy consumption and functionality of its sensors and other hardware and software components. This module includes also the control of all the actuators of the autonomous vehicle (i.e., brake, throttle, turn controls, etc.).

An additional significant component of an ANS is the process control module. This module continuously operates in parallel with all the other modules and is responsible for monitoring that the navigation and control module is working correctly, and that the vehicle does not deviate from the desired planned path. Common practice is that data from some of the vehicles' sensors are used in conjunction with a controller to ensure that the ANS works properly.

A.4 Common Sensors

The first step for any autonomous operation is the ability of the autonomous/robotic system (ARS) to perceive its surroundings and monitor its internal state. The system must acquire sufficient and reliable data, process the data and become aware of its external and internal state. A wide variety of sensors which exploit different physical principles are currently available for data acquisition: odometry sensors which include wheel encoders, magnetic compasses and inclinometers, inertial measurement units (IMUs), optical sensors which include infrared sensors (IR) and lasers (LiDAR), ultrasound sensors (US), radio-based sensors which include RADAR, RFID, WiFi, BLE and ZigBee, as well as visual sensors which include cameras in both the visible and non-visible spectrum.

Commonly, sensors are categorized based on whether the data that they measure describe the internal state of the ARS or its external state relatively to its environment. In the first case, they are referred to as proprioceptive sensors and are commonly used to measure speed, direction and inclination of the ARS. Examples of such sensors are the wheel encoders and the inclinometers. In the second case, they are referred to as exteroceptive sensors and are used to measure mainly distances between the ARS and surrounding static or dynamic objects such as walls, roofs, obstacles, humans. Examples are the IR, LiDAR and US sensors.

A.4.1 Odometry Sensors

The estimation of the AGV's trajectory through integrating the measured speed and direction of its wheels is called odometry. Optical or magnetic encoders measure the number of revolutions of the wheels, and thus the distance covered can be calculated. The direction of the wheel is calculated using two optical signals with predetermined phase difference and grids of transparent and non-transparent areas.

Magnetic compasses can be used to measure the moving direction of the AGV. This is achieved by constantly measuring the direction of the moving system relatively to the Earth's magnetic field.

Finally, inclinometers give useful information regarding the upward or downward movement of the ARS, the steepness of its route or whether it shifts to a side. One technique used by inclinometers is the projection of a LED's light through a water droplet into an oil-filled transparent hemispherical plastic bowl which is attached to the AGV.

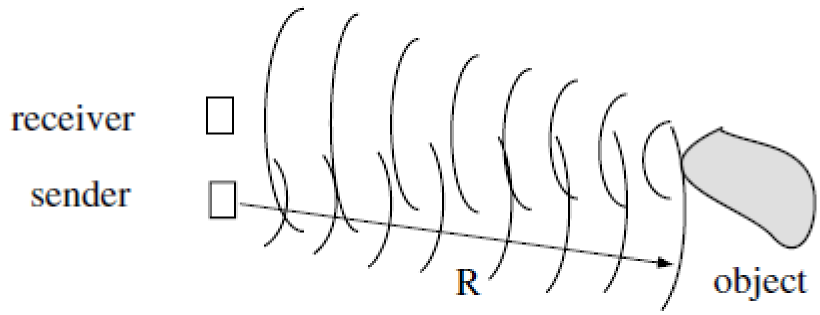


Figure A.1: Principal operation of distance sensor (Burns and Puttkamer, 2009)

A.4.2 Inertial Measurement Units

Inertial measurement units (IMUs) integrate accelerometers and gyroscopes to provide data about the angular rate (i.e., the direction) and the speed of the ARS. Magnetometers can also be integrated. Typically, the IMU contains an accelerometer, a gyroscope and a magnetometer for each axis, measuring the pitch, the roll and the yaw of the AGV. Recent advances in microelectromechanical systems (MEMS) have allowed the integration of all these components into a single, small chip (MEMS IMU).

The usage of IMU and wheel encoders is a robust, lightweight solution with low computational load appropriate for short-term navigation (Rekleitis et al., 2013; Svensson, 2015). However, this dead-reckoning based navigation method suffers from accumulation of error, which rapidly degrades accuracy and leads to significant drift over time. Moreover, IMU and wheel encoders cannot track the true motion of the autonomous vehicle in the cases of uneven or slippery terrain (Bakambu and Polotski, 2007).

A.4.3 Optical Sensors

Optical sensors are commonly used for measuring the distance between the ARS and objects of its surrounding environment. They are considered essential tools for autonomous navigation and collision avoidance, and to a lesser extend for mapping. The most common optical sensors are Infrared (IR) sensors and lasers. The later sensors are usually found in the literature under the term LiDAR, which stands for Light Detection and Ranging.

The operation principle of these time-of-flight (ToF) distance sensors is illustrated in Figure A.1. The transmitter of the sensor sends a signal to the environment. When there is an object in the signal's path, the signal is reflected and is recorded by a receiver. The distance is calculated by measuring the time of flight between the emission of the original signal and the return of the reflected signal.

Infrared (IR) sensors are lightweight and low-cost solutions used mainly for safety and proximity alerts. IR sensors typically can detect nearby obstacles at distances between 5 and 80cm (Berns and Puttkamer, 2009). Another common usage of IR sensors is for localization as they exhibit fast update rate and high accuracy (Koyuncu and Yang, 2010; Oh et al., 2014). On the other hand, their disadvantages include the necessity of line of sight (LOS) with the target object, the high signal attenuation, and the negative effect of the ambient sun light.

LiDAR range finders are very robust sensors, due to their long effective range, accuracy, high resolution and because their operation is independent of the light conditions and airborne dust. The 2D LiDAR range finders (SICK, Hokuyo, etc.) data can provide a very efficient perception of the environment if processed with the appropriate software. Three-dimensional LiDAR scanners can be constructed by mounting a 2D LiDAR on a servo motor to enhance the perception capabilities of an autonomous vehicle. Their main drawback, however, is related to the high computational cost and the memory requirements for the storage and processing of the raw data. Several implementations of LiDAR sensors in autonomous ground vehicles can be found in the literature. As discussed in Nüchter (2008) the Kurt3D robot uses a 2D range finder and performs 6DOF (six degrees of freedom) Simultaneous Localization and Mapping. Lee et al. (2014) present the subterranean robot Cave Crawler, which uses a 2D range finder along with wheel encoders and IMU for band–based, real-time mapping and localization in underground mines. CSIRO developed a platform integrating three LiDAR sensors with an IMU for gathering data, while it is driven at speeds of 20 to 30 km/h. The off-site processing of the data enabled the complete mapping of over 17 km of mine tunnels (Zlot and Bosse, 2014). In Azizi and Tarshizi (2016) a lab-scale haul truck is automated, based on LiDAR sensors and triangulation. The main drawback of LiDARs are their relatively high cost, the high memory requirements for saving the recorder data and the high computational cost they impose to the system for processing the collected data.

A.4.4 Ultrasound Sensors

Ultrasound (US) sensors are also time-of-flight distance sensors. A broad cone of ultrasound waves is created either with oscillating membranes or piezo crystals and the echo signals caused by obstacles are recorded with a receiver.

US sensors can provide reliable localization methods, but their effective range is relatively short (shorter than that of IR sensors). Also, they suffer from high signal attenuation with distance and are affected by noise (Jordaan et al., 2017; Priyantha et al., 2000).

A.4.5 Radio-based Sensors

Radio-based sensors are very popular tools in navigation and localization for autonomous vehicles. Radio Detection and Ranging (RADAR), Radio Frequency Identification (RFID), WiFi, Bluetooth, Bluetooth Low Energy (BLE) and ZigBee are some common sensors in this category. An overview of tracking systems implemented in coal mines can be found in Sunderman and Waynert (2012).

RADAR belongs to the time-of-flight distance sensors. It transmits radio waves in multiple directions and records the reflected waves that are reflected by obstacles. RADAR can detect multiple objects per single transmission, in contrast to other time-of-flight sensors which allow one target detection per transmission. Moreover, the very low attenuation of the radio signals results in higher effective range compared with other sensors. Also, weather conditions (i.e., fog, clouds, snow, rain) that usually block visible light and LiDAR do not affect it. However, RADAR suffers from limited angle resolution, specularity effects and a large footprint (the footprint increases with distance; as the footprint increases angle resolution may increase), all of which add difficulty in interpreting the recorded data (Rasshofer and Gresser, 2005; Reina et al., 2011).

RFID uses radio waves to transmit wirelessly the unique identity and other information of an RFID tag to a dedicated reader. In this way, the position of an object that carries a tag can be determined in relation to the position of a fixed reader, or the position of a moving reader can be determined in relation to the positions of fixed tags. Three types of RFID tags are available: i) passive tags, which transmit their ID signal when triggered by the signal of an RFID reader using the energy of the triggering signal, ii) active tags, which periodically transmit their ID signal independently of the presence of a reader using energy from batteries, and iii) semi-active or battery assisted passive tags, which transmit their ID signal in the presence of a reader using energy from batteries. The distances between the tags and the reader are calculated using the Received Signal Strength Index (RSSI) method along with multilateration or multiangulation. The RFID tags do not require line-of-sight and do not require cables. The effective range of RFID is up to 20m (60ft) for passive RFID tags or up to 100m (300ft) for active RFID tags. The range can be further increased up to 300m (900ft) by using UWB or UHF radio signals and active or semi-active tags. However, the RFID sensors cannot be easily integrated with other sensors, are affected by the presence of metals, and require a dedicated infrastructure.

WiFi is another tool for positioning in indoor or underground areas. The ubiquity of wireless access points makes it a low-cost solution. Commonly used methods for positioning the node of interest are the RSSI method, the fingerprinting method, the Time of Arrival and the Angle of Arrival. The effective range of WiFi sensors is relatively low as it does not exceed 20m (60ft). The disadvantages of these sensors are the lower accuracy compared with RFID and BLE, the requirement of external power supply, the requirement of cables for some nodes of the network, and the fact that signals are affected by the presence of metals.

Bluetooth and Bluetooth Low Energy (BLE) work in a way that is similar to WiFi, with the difference that preinstalled BLE beacons are required. The position of the node of interest can be calculated as in WiFi positioning methods with the RSSI method, the fingerprinting method, the ToA or the TDoA method. BLE sensors consume considerably less power and cost less than original Bluetooth. Hence, it is a low cost and low–energy-consumption solution. However, the effective range of Bluetooth sensors is less than 100m and requires LoS. The main drawbacks of Bluetooth sensors are the high energy loss when solids interfere between the beacon and the receiver, and the noise from radio signals.

One more wireless technology which uses small, low-power digital radios for low data rate and close proximity communication is ZigBee. ZigBee is a technology similar to BLE, which can transmit data with high security through node networks. Like BLE it is characterized by low power consumption, low cost and requires LoS and dedicated infrastructure. Moreover, it is less accurate that other radio sensor and suffers from multiple interferences. However, its most significant advantage compared with BLE is the considerably higher effective range which can reach up to 300m (900ft).

A.4.6 Visual Sensors

The usage of cameras, especially stereo (or depth) cameras can lead to very robust navigation methods, as they provide extensive information about the surroundings of the autonomous vehicle. In general, the algorithms implemented along with visual sensors extract unique features from the images, such as lines, planes or objects. The extracted features are either stored as landmarks and integrated into a map or are temporarily used as reference points for tracking the relative short-term movement of a vehicle in their vicinity.

However, the image processing algorithms required impose a high computational cost and are time consuming. Thus, it is challenging to achieve real-time mapping, navigation and obstacle avoidance based on cameras. Moreover, cameras are strongly affected by the illumination and weather conditions. Low illumination, dust, smoke, rain and snow are common factors that negatively affect visual perception. Nevertheless, in indoor and outdoor urban environments the implementation of cameras has been shown to be effective (Kubelka et al., 2015; Murcott et al., 2011).

In a mining environment where low-lit conditions and dust are prevalent, the usage of cameras in the visible-range is considered impractical. Thermal (infrared) cameras could, however, be useful under specific conditions. As an example, Nagatani et al. (2014) integrate a 2D LiDAR sensor and a thermal camera for developing a 3D thermal mapping method for rescue robots.

Tables A.2 and A.3 summarize the advantages and disadvantages of sensors and beacons.

Table A.2: Advantages and Disadvantages of Different Sensors

Sensors	Advantages	Disadvantages
INS/IMU	• High-update rate • Lightweight	• Accuracy degrades rapidly due to high accumulated errors
Cameras visible	• High accuracy • Low cost	• Affection by light conditions, dust, etc. • High computational cost • High memory requirements
Cameras IR (thermal)	• Detects humans • Not affected by light conditions • Low cost	• High-computational cost • High memory requirements
IR	• High Accuracy • High-update rate • Lightweight • Low cost	• Requires line of sight (LOS) • High signal attenuation • Affected by ambient light
US	• High-update rate • Lightweight • Low cost • Does not require LOS	• High signal attenuation • Affected by humidity and temperature

Continued on next page

Sensors	Advantages	Disadvantages
LiDAR	• High accuracy • High resolution • Not affected by light conditions	• High computational cost • High memory requirements • Relatively high cost
Beacons (RFID, WiFi, BLE, UWB, ZigBee)	• High accuracy	• Requires dedicated infrastructure • Requires a priori knowledge of beacons locations
Fingerprinting	• High accuracy • Existing infrastructure can be used	• Requires time consuming training phase

Table A.3: Advantages and Disadvantages of Different Beacons

Beacons	Advantages	Disadvantages
WiFi	• Few devices required • Existing BLE infrastructure can be used • Low cost • Low energy consumption • Long lasting batteries	• Less accurate than RFID, BLE • Requires external power supply • Signals are affected by metals
Bluetooth/BLE	• High accuracy • Low cost	• High energy loss of signals through solid • Radio interference • Signals are affected by metals
UWB	• High-update rate • Immunity to multipath fading • Does not interfere with other radio frequency systems	• Requires dedicated infrastructure • High cost • Signals are affected by metals
RFID	• Requires dedicated infrastructure • No cables (like WiFi)	• More power consuming (than IR) • Signals are affected by metals • Small coverage (can be improved with UWB RFID or UHF RFID)
ZigBee	• Low power consumption • Low cost	• Low accuracy • Requires dedicated infrastructure • Interference by multiple signals

A.5 Localization/Positioning

One of the principal desired outcomes after processing sensor data is the determination of the position and orientation, also called “pose”, of the AGV. The task of localization/positioning is of great importance for an ARS as it determines the maneuvers necessary for executing the task at hand. The estimation of the vehicle’s pose can be either absolute, i.e., with respect to a global coordination system, or relative, i.e., with respect to a landmark in the local environment.

Many techniques are used for obtaining the pose of an AGV. Such techniques can also be combined for improving the accuracy and avoiding poor decisions (for the vehicle) in the case of sensor malfunctioning or complete failure. The technique chosen in each case strongly depends on the type of sensors on the AGV. Common localization/positioning techniques include odometry, IMUs, geometric methods, feature extraction, landmarks and fingerprinting.

A.5.1 Odometry

The pose of the AGV can be estimated by processing the data measured with wheel odometry sensors, i.e., wheel encoders, magnetic compasses and inclinometers. In theory, by summing the number of revolutions of a vehicle’s wheels, one can derive the traversed distance. The speed of the vehicle can also be estimated by measuring the time each revolution takes. In addition, considering the changes of the direction of the wheels as measured using additional encoders or a magnetic compass, the path of the vehicle can be drawn in a 2D graph. Moreover, in cases where the travelling terrain is uneven and rough, inclinometers provide information about the inclination, and thus the altitude of the vehicle. This allows the 3D representation of the path of the vehicle. Therefore, the location and orientation of the AGV can be determined relative to its initial position.

Wheel odometry is a lightweight method for localization that requires low cost sensors and can be easily implemented. However, in the cases of rough and slippery terrain, the odometry sensors cannot reliably track the changes of position and speed. As a result, wheel odometry fails for long term positioning due to the high accumulation of error over time. In the later cases, it can be used only as a complementary technique under the condition that additional information acquired by more sophisticated and reliable sensors that can track wheel slippage (Berns and Puttkamer, 2009).

A.5.2 IMU

An IMU uses accelerometers and gyroscopes to measure speeds and angular rates in three dimensions. These data allow the determination of pose changes, relative to an initial steady-state pose of the AGV.

Because IMU data are internal, IMUs are immune to wheel slippage errors unlike wheel odometry. However, due the dead-reckoning-based acquisition of data, IMUs suffer from high accumulation of error, which rapidly degrades the accuracy of the estimations. In order to avoid these errors an AGV equipped with an IMU must stop every few meters to allow the internal recalibration of the IMU using the zero velocity of the stopped vehicle. As a result, IMUs, like wheel odometry, are not appropriate for long-term positioning. However, they can be used as complementary sensors when other more sophisticated and reliable sensors provide additional information that enable the internal recalibration of the IMU.

A.5.3 Geometric Methods and Beacon-based Localization

Geometric methods are frequently used for determining the location of the autonomous vehicle. If the distances or angles of the vehicle from at least three known points can be measured, the position of the vehicle can be straightforwardly determined through multilateration or multiangulation, respectively. In practice, the known points are the locations of preinstalled beacons/landmarks. On-board sensors are used to detect and measure the distances between the mobile vehicle and the beacons based on the transmission and receipt of signals between them. Geometric methods such as Time of Arrival (ToA), Time Difference of Arrival (TDoA), Angle of Arrival (AoA), and Phase Difference of Arrival (PDoA) provide the position of the autonomous vehicle relative to the position of the landmarks.

The Received Signal Strength (RSS) or Received Signal Strength Index (RSSI) can also be used for calculating distances based on the equations describing the attenuation of a propagated signal. Subsequently, with the a priori knowledge of the global position of the landmarks, a globally consistent localization of the vehicle can be achieved.

Landmark-based localization methods are characterized by high accuracy due to the unique identities of the deployed beacons. However, their main disadvantage lies in the requirement of needing a dedicated infrastructure and the a priori knowledge of the exact location of the beacons. Moreover, the detection of the beacons from a mobile vehicle is not always successful, which increases location uncertainty. Various technologies can be used to construct beacons, including RFID, Bluetooth and Bluetooth Low Energy (BLE), WiFi, Ultra-Wide Band (UWB) and ZigBee (He et al., 2017).

A.5.4 Feature Extraction

Feature extraction is a common approach for processing the data captured by visual sensors (i.e., cameras) or laser range finders (i.e., LiDAR). Visual Odometry (VO) and 3D Point Clouds are based on this approach. These techniques are common tools for both localization and mapping.

Visual Odometry

Visual Odometry (VO), like wheel odometry, estimates the pose of the AGV by integrating observed changes. In this method, the estimation of vehicle movement is derived by examining the changes between consecutive images taken by onboard cameras. As the AGV moves, the consecutive images depict the same features of the environment, but with a different angle of view and/or from a different distance. Analysis of these differences can give an estimation of the vehicle's motion, and thus provide the vehicle's relative position with respect to its previous position.

Widely used algorithms for extracting salient features from consecutive images are the Scale Invariant Feature Transforms (SIFT) and the Speeded Up Robust Features (SURF).

Compared with wheel odometry, VO exhibits higher accuracy and is not affected by wheel slippage. However, VO requires sufficient illumination of the environment and variation of texture in order to extract the motion. Also, the use of vision cameras results in high-computational and memory requirements, rendering the procedure time-consuming (Fraundorfer and Scaramuzza, 2012; Scaramuzza and Fraundorfer, 2011).

Scale Invariant Feature Transforms (SIFT)

SIFT algorithm uses the difference of Gaussian (DoG) operator to extract features which can be detectable even under changes of viewpoint, illumination and scale. Such features are usually found in highly textured regions of the image. The SIFT feature descriptor is invariant to uniform scaling, orientation, illumination changes, and partially invariant to affine distortion. (Lowe, 1999)

Speeded Up Robust Features (SURF)

The Speeded Up Robust Features (SURF) detector is similar to the SIFT detector, but it is faster and more robust to image transformations (Bay et al., 2006).

3D Point Clouds

A rotating LiDAR measures the distance and the direction of a large number of points, based on where the laser beam hits an object, with respect to the vehicle's coordinate system. Subsequently, these measurements are aligned with the point sets of previous scans and registered to a global reference system, usually by using an Iterative Closest Point (ICP) algorithm. The outcome of this procedure is a dense set of points in 3D space that resemble a cloud. Hence the term 3D point clouds.

These 3D point clouds can be further processed towards extracting salient and easily detectable features, such as lines, planes or distinct objects. After determining features, they can be used for determining the position of the AGV in a similar way as in VO.

A.5.5 Fingerprinting

Fingerprinting is based on the principle that each position has its own signature (or fingerprint) comprised by the multiple signals arriving at that position. These signals can be transmitted by one or multiple beacons of different technologies (RFID, WiFi, Bluetooth or BLE, magnetic, etc.) located in the surrounding environment.

If a database of these signatures is created for a number of locations in the environment of interest, then the position of an AGV can be determined by matching the measured signature with one in the database.

The advantage of this method is the high positioning accuracy and low cost in cases where existing hardware is available. On the other hand, the drawbacks are the time-consuming training and the susceptibility of the fingerprints to noise.

A.5.6 Filters

Several types of filters, such as Kalman Filter (KF), Extended Kalman Filter (EKF) and Particle Filters (PF) , can be used for the localization of an AGV. These filters employ stochastic methods for producing optimal estimations of unobservable state variables of the vehicle based on the known data acquired by the sensors. The integration of data from multiple sensors is also enabled with these filters. Therefore, these filters are a very useful and robust tool for localizing an ARS, as well as for constructing a map of its surrounding environment.

For example, an AGV equipped with an IMU and an RFID reader measures the speed of the vehicle in regular time intervals and a distance from a beacon at a known location. The desired unknown position can be estimated using the data from these two sensors and a previously constructed kinematic model of the AGV.

A significant advantage of these filters is their flexibility and their ability to integrate multisensory data. Their drawbacks, however, include the high computational-cost and high memory requirements.

A.6 Mapping

The process of autonomous mapping of the environment is often within the tasks of an ARS, as an a priori map may not be available. In this case, the autonomous vehicle or robot must use its onboard sensors and appropriate algorithms to build a consistent and accurate global map. Based on this map the vehicle or robot is subsequently called to navigate and plan an efficient path to execute its given tasks. The major difficulty of autonomously constructing a map is imposed by the inaccuracy and uncertainty of the various sensors of the vehicle, as well as the complexity of the mapping problem based on partial information (Berns and Puttkamer, 2009).

A.6.1 Map Types

The most common map types discussed in the literature can be divided into six categories:

- Metrical maps: The world is represented by geometric features and their location in the space. These features can be points, lines, boxes or even unique landmarks.

- Grid maps: The environment is modeled as a 2D or 3D grid. Each cell of the grid is assigned a binary value representing the probability of occupancy (occupancy grid maps). Grid maps are usually constructed based on the raw data of LiDAR scanners. Consecutive scans are assigned to a global map through scan matching, called LiDAR odometry. The relative position of the autonomous vehicle is then estimated from the relative position of consecutive scans. The scan matching process is commonly based on a variant of the Iterative Closest Point (ICP) algorithm. In Zhang and Singh (2017) a Low-drift Odometry and Mapping (LOAM) algorithm is proposed for 3D mapping using an IMU and a laser scanner.

- Feature maps: Features are extracted from the data, labeled and used as a map. In most cases, features are extracted from consecutive frames of vision sensors. Scale Invariant Feature Transformation (SIFT) and Speeded Up Robust Features (SURF) algorithms are commonly used for feature extraction (Fraundorfer and Scaramuzza, 2012). The vehicle is localized based on the relative position of these features after their global assignment.

- Topological maps: The environment is modeled “in the form of compact and connected paths and intersections”(Saeedi et al., 2016). These maps reduce significantly the computational cost and increase the speed of the data processing. Different variations of Voronoi Diagrams are examples of topological maps.

- Semantic maps: Similar to topological maps, semantic maps include paths and places but are enriched with details such as type objects and places.
- Appearance maps: Images are attached to vertices of a graph. Such maps are constructed with vision sensors. The require high computational memory.
- Hybrid maps: Hybrid maps are essentially combinations of two or more of the aforementioned mapping methods.

In Berns and Puttkamer (2009) several approaches for the construction of the above referenced map categories are briefly described. However, the most important and popular method for mapping is the method known as Simultaneous Localization and Mapping.

A.6.2 Simultaneous Localization and Mapping

Simultaneous Localization and Mapping is a process that determines the location of an autonomous vehicle within a map, while constructing this map at the same time. To do so, it uses probabilistic tools for considering spatial as well as measurement uncertainties. SLAM became a very popular approach after its successful application to the DARPA Grand Challenge and the DARPA Urban Challenge by Thrun et al. (2006).

SLAM is usually based on LiDAR scanners (2D or 3D) or vision (stereo or RGB-D cameras). A variety of algorithms, both open-source and commercial, which implement SLAM, are currently available. In general, the core of SLAM is an EKF, which is used to update the unreliable odometry position of the AGV. Consecutive laser scans (or vision images) are aligned and registered to a global 3D point cloud (or a global image). A number of features are extracted from the globally registered data and are re-observed continuously, while the autonomous vehicle is in motion. By inputting the locations of new features in the EKF, the optimal position of the AGV, as well as the optimal position of the landmarks are estimated by minimizing the uncertainty. This procedure is done incrementally; every time the vehicle moves, a new odometry position is estimated, while a number of the old landmarks that can be detected along with a number of newly observed landmarks are added to the EKF.

Depending on the sensors and the algorithms used, different types of maps can be constructed. According to Saeedi et al. (2016), all the types of maps discussed in the previous section, except the metrical maps, are commonly created and/or used with SLAM algorithms.

A.7 Navigation

The function of navigation for an AGV refers to the planning of the vehicle's movement through its surrounding environment based on its estimated position and the built (or an a priori provided) map. Navigation consists of three subfunctions:

1. Global Path Planning: The task of defining a path from the starting point to the goal point based on the position of the AGV and the map of the environment. The global path is defined as a set of subgoal points connecting the start point and the final goal point. This plan must fulfill a number of conditions or constraints. A common condition is to minimize the cost. The subgoal points are usually nodes of a topological graph and the connecting lines are assigned a cost value. The A*algorithm is a common tool for finding the path with the minimum cost.

2. Local Path Planning: In addition to the global path which rules the long-term navigation of the vehicle, a finer sequence of intermediate goal points based on the kinematics of the vehicle is necessary. The local path is planned such that task-specific goals are fulfilled. Driving along a wall, traversing an area for exploration of the environment, and obstacle avoidance are common tasks that are to be considered for local path planning.

3. Path Control: Path control is the implementation of the control of a vehicle's actuators to execute the planned paths. This task utilizes the steering functions along with integrated data from multiple sensors, both proprioceptive and exteroceptive, for monitoring the proper execution of the planned paths.

Common Multi-sensor Modalities

A common framework for robotic perception includes the combination of inertial measurement units (IMU) and odometry sensors (wheel and rotary encoders) with vision (i.e., cameras) or range measurement sensors (LiDAR, infrared, ultrasound). The former sensors provide high-frequency proprioceptive information of the vehicle dynamics, while the later provide low-frequency exteroceptive information about the vehicle's movement relative to its surroundings (Kubelka et al., 2015). Common alternatives for obtaining external information are the landmark based techniques, which utilize radio or optical signals to determine the position of the vehicle relative to beacons (i.e., landmarks) at known positions. These techniques are usually used for localization. Examples are RFID (Zhang et al., 2009; Zhou and Shi, 2009), Bluetooth and BLE (Dickinson et al., 2016; He et al., 2017; Momose et al., 2017), WiFi (Chen et al., 2016; Cypriani et al., 2013; Yang and Shao, 2015) , UWB (Alarifi et al., 2016; Qin et al., 2015; Takeuchi et al., 2015; Zhu and Yi, 2011), IR (Koyuncu and Yang, 2010; Oh et al., 2014) and ZigBee (Chu et al., 2011; Song and Qian, 2016) based positioning. A less common exteroceptive sensing method is the matching of the sensed information with features from an a priori constructed database. This database contains features that are assigned to specific locations. These features can be fingerprints of various signals (Dayekh et al., 2014; Pereira et al., 2012; Wang et al., 2016; Wilfinger et al., 2016; Zhang et al., 2009) or features extracted from images.

Depending on the application, there are some multi-sensor modalities that have gained great popularity in recent years. For urban outdoor and structured indoor environment exploration, the most commonly encountered architecture consists of IMU and vision. The lighting conditions in such environments permit the usage of cameras, despite the presence of limitations due to ambient light or bad lighting angles in many cases. Murcott et al. (2011) point out that the "two main approaches widely used in vision aided navigation are based on visual odometry and visual SLAM, both of which can be supplemented by readings from an INS”. Murcott et al. (2011) also cite Veth and Raquet (2007) for the application of the visual odometry approach by integrating the readings of an INS with a stereoscopic pair of cameras to update the navigation state of the autonomous vehicle, while Davison et al. (2007) apply the visual SLAM approach with a humanoid equipped with a gyro (accelerometer which measures the velocity of the robot) and a monocular camera. Several vision-based techniques can be found in the literature; Milford et al. (2014) refer to a number of techniques which include the following: FAB-MAP (Cummins and Newman, 2011), MonoSLAM (Davison et al., 2007), FrameSLAM (Konolige and Agrawal, 2008), V-GPS (Burschka and Hager, 2004), Mini-SLAM (Andreasson et al., 2007) and SeqSLAM (Milford and Wyeth, 2012). Moreover, applications where only vision is used for navigation and mapping are also examined in the literature (Botterill et al., 2011; Meilland et al., 2015; Santana et al., 2011).

In indoor environments where poor lighting conditions are prevalent (e.g., mining operations, exploration of underground environments, destroyed buildings) the usage of vision is not practical. Instead, LiDAR scanners are commonly used as they do not rely on ambient light and are accurate. LiDAR scanners are used in structured indoor and outdoor environments as well (Fentanes et al., 2011; Hu et al., 2013; Lee et al., 2014; Milstein et al., 2011; Nagatani et al., 2011; Nüchter, 2008; Trulls et al., 2011; Zlot and Bosse, 2014). The combination of cameras and LiDAR sensors is another common approach, which offers improved perception of the surrounding environment. This approach is well established in the literature. Droeschel et al. (2016) integrate 3D laser scanners, stereo camera pairs and ultrasound sensors for enabling unmanned aerial vehicles (UAVs) to navigate and avoid obstacles, while mapping the environment. Kubelka et al. (2015) discuss the development of a search and rescue robot, which uses track encoders, IMU, omnidirectional cameras and laser range finders. Siagian et al. (2014) fuse IMU, wheel encoders, vision and LiDAR to construct an occupancy grid map for a service robot operating in an outdoor urban environment. This approach is also popular for semi-autonomous (i.e., teleoperated) vehicles. This is well demonstrated in robotic competitions like the Multi Autonomous Ground-Robotic International Challenge (MAGIC) held in Adelaide, Australia in 2010 (Boeing et al., 2012; Butzke et al., 2012; Lacaze et al., 2012), and the DARPA Robotic Challenge (DRC) held in 2013 and 2015 (Fallon et al., 2015; Johnson et al., 2015; Lim et al., 2017; McGill et al., 2017; Stentz et al., 2015).

In accessible indoor environments, the additional deployment of beacons provides a robust means for localization and navigation. To this end, RFID tags are commonly used (Azizi and Tarshizi, 2016; Larsson et al., 2006; Lavigne et al., 2010; Zhou and Shi, 2009). This approach can also be utilized in indoor and outdoor environments where pre-existing landmarks (WiFi or Bluetooth network nodes) are available (Chen et al., 2016; Dickinson et al., 2016).

A.8 Existing Applications

Selected applications, from both academia and industry are briefly described below. Their advantages and disadvantages are discussed in order to extract useful information that will help with the current research.

A.8.1 Research Applications

Mobile Robot Kurt3D

The mobile robot Kurt3D is a 6-wheeled skid-steered robot, which is based on a SICK 2D laser range finder (LMS-200). The functionality of the 2D laser range finder is extended to 3D by mounting it on a servomotor. The resulting field of view of the robot is 180^o(h) x 120^o(v). The robot operates in a stop-scan-go fashion. Subsequently, the scans are registered in a 3D point cloud with 6 degrees of freedom Simultaneous Localization and Mapping (6 DoF SLAM) algorithm which uses the Iterative Closest Point (ICP) Method. The algorithm runs in a Pentium-Centrino-1400 with 768 MB RAM and Linux, while an embedded 16-Bit CMOS microcontroller is used to control the motors.

This platform is intended to produce 3D maps of the environment by using only the custom 3D laser range finder. The advantages of this robot include the real time scanning while driving, the use of only one sensor, and the immunity of the laser range scanner to the low-light conditions and airborne dust, both prevalent in the mine environment. On the other hand, the weaknesses of this platform are the high computational cost of the algorithm and the off-site processing of the scans (Nüchter, 2008).

Cave Crawler Platform

The Cave Crawler platform (Field Robotics Center, Carnegie Mellon University), equipped with a SICK 2D laser range finder (LMS-200), is used for real-time localization and mapping in underground mines. (The Cave Crawler platform is also supplied with an Inertial Measurement Unit (IMU) and wheel encoders, but they are not used for this application.)

This platform intends to provide a robust mapping tool, which is superior of the insufficient 2D representations, while simultaneously avoiding the computational expense of the full 3D solution. This is achieved with band-based laser scan sampling. Consecutive bands are extracted from the laser scans of the spinning 2D laser range finder and are registered into a global map using a point-to plane-ICP method. In this way, the non-planar movement of the platform, which is typical in an underground mine is captured sufficiently without employing the time-consuming and computationally expensive 3D solution. Trials at a research coal mine near Pittsburgh demonstrated the feasibility of this platform.

The main advantages of this platform are the immunity of the laser range scanner to the low-light conditions and the dust in the mine, the lower computational cost and time requirements compared to the 3D solution (as only bands are extracted from the scans) and the real time scans.

However, errors in x and y position occur due to the limitations of using 2-D data (Lee et al., 2014).

RFID Assisted Underground Mine Mapping

A mapping tool, applicable to underground mining which combines odometry, laser range scanners and RFID beacons has also been demonstrated. Globally consistent occupancy grid maps are generated offline with data collected by a custom-modified electric vehicle. This vehicle is equipped with drive-shaft and steering encoders, a scanning laser range finder and a passive RFID reader.

The localization and mapping algorithm is comprised of two steps: 1) estimation of the pose by integrating encoder measurements with an open-loop method, and 2) closing the loop by aligning consecutive laser range scans. The RFID measurements are used in the second step for robust and accurate loop-closing.

The advantages of this platform are the low cost of RFID landmarks and the ability of the vehicle to move relatively fast while gathering the necessary data. On the other hand, the optimal number and placement of the RFID tags is not easily defined, and the mapping process is completed offline(Lavigne and Marshall, 2012; Lavigne et al., 2010).

LiDAR Triangulation Navigation

A lab scale dump truck equipped with a LiDAR sensor is used in combination with reflective beacons placed on a priori known positions, to demonstrate the feasibility of autonomous underground navigation. The signal intensity (strength) of the reflected laser beams are filtered to obtain the stronger ones that correspond to the reflective beacons. These high-intensity signals are used to localize the vehicle relative to the a priori known positions of the beacons with triangulation. A PID controller is employed to ensure the truck follows the desired path.

The advantages of this platform include the robustness of LiDAR in underground mine environments and the low computational cost of the triangulation algorithm. The disadvantage is that additional infrastructure, i.e., reflective beacons are required, as well as the knowledge of the exact positions of the beacons (Azizi and Tarshizi, 2016).

MIT Race Car

An autonomous small-scale race car has been constructed by an MIT research team, which is able to navigate in relatively high speeds. It fuses data from a 2D Lidar, an RGB-D camera and an IMU. The data processing is done on-board by an NVIDIA Jetson TX2 CPU (RACECAR: A Powerful Platform for Robotics Research and Teaching, 2015). The Hokuyo 2D Lidar has a scanning angle of 240^o with 0.36^o resolution, and it detects objects within a range of 20 to 5600 mm, with a sampling rate of 10 Hz. The Intel RealSense ZR-300 RGB-D camera provides images with up to 1080 pixels resolution with a sample rate of 30 Hz. The IMU combines accelerometers, gyroscopes and magnetometers, and outputs absolute orientation with a rate of 50 Hz.

Figure A.2 shows the MIT race car with the mounted components highlighted, while Figure A.3 shows each component individually.

A.8.2 Commercial Applications

Volvo FMX Underground

Volvo tested a self-driving truck at the underground Boliden mine in Kristineberg, Sweden in 2016. The fully autonomous truck was developed in partnership with Saab-owned tech consultancy Combitech.

The sensors for mapping the surroundings and for navigation used by the truck include GPS (for surface operation), Radar and LiDAR. The autonomous truck is able to map the tunnels of the

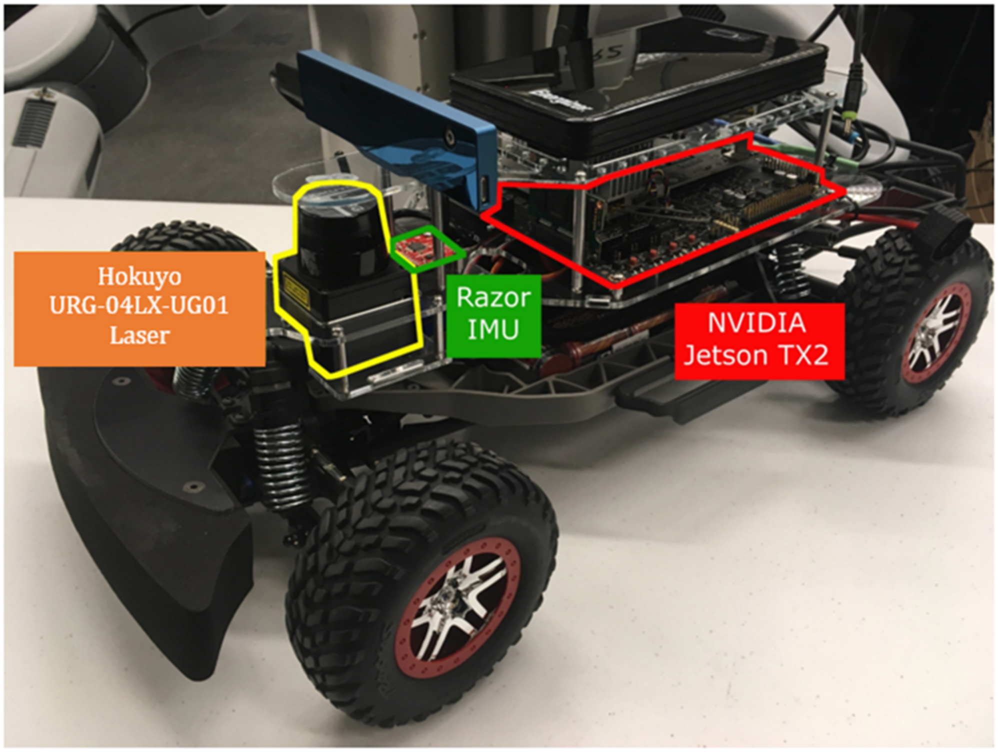


Figure A.2: MIT race car with highlighted components

mine and (based on this map), the truck can plan an optimum path and traverse it. If an obstacle is detected the truck stops and contacts the control center.

The sensors are located in such way that every point in the surroundings is scanned by two or three sensors simultaneously (use of redundancy for safety reasons) (Robarts, 2016). A video clip demonstrating this test is available at https://www.youtube.com/watch?v=JwhyoUyJNoY.

Caterpillar MINEGEM System

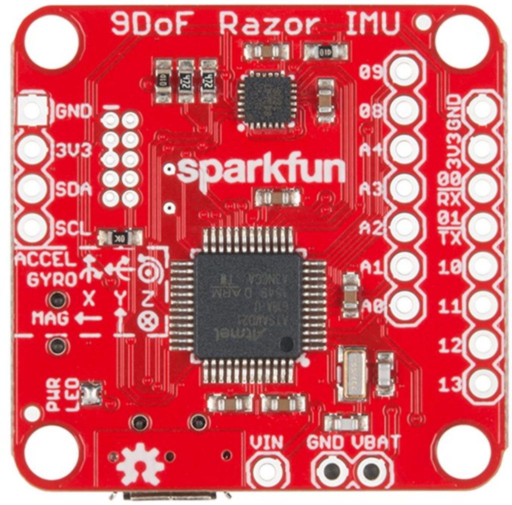
The MINEGEM Automation System was developed by Caterpillar and Lateral Dynamics as an attachment to LHDs. The system can either operate in a fully autonomous mode for executing a full operational cycle, i.e., tramming, dumping and navigation, or can be piloted remotely by an operator from a control room (usually located at the surface).

The autonomous vehicles use on-board scanners and radio-based technology for navigating in the mine. The hardware used for the trials include LoS aerials, a radio and repeater network, security gateways and a leaky-feeder cable. The setup of this equipment does not require much time and can also be easily uninstalled and reinstalled at other locations.

The system scans the sidewalls with a LADAR and identifies their profiles by comparing the scanned data with an existing database of the mine walls. In addition to the sensor data and vehicle movement, the operator can monitor in his console the status of the vehicle and its engine, as well as its health status.

The MINEGEM system has successfully completed a 12-month trial at the Malmberget mine

(a) https://devblogs.nvidia.com/parallelforall/jetson-tx2-delivers-twice-intelligence-edge



(b) https://www.sparkfun.com/products/14001

(c) https://www.robotshop.com/en/hokuyo-urg-04lx-ug01-scanning-laser-rangefinder.html

(d) https://click.intel.com/intelr-realsensetm-development-kit-featuring-the-zr300.html

Figure A.3: MIT race car components

using the Cat R2900G sXTRA LHD (Caterpillar, 2018).

Hitachi Autonomous Haulage System

Wenco International Mining Systems, Ltd., acquired by Hitachi Construction Machinery (HCM) in 2009, and its parent, Hitachi, have developed an autonomous haulage system (AHS) for surface mine dump trucks. The system is being developed at three sites: Japan, Canada, and Australia. The system uses the Global Navigation Satellite System (GNSS) for localization, and millimeter-wave radar and LiDAR for obstacle detection.

A unique aspect of the HCM system is the use of permission control. Permission control divides the truck routes into sections and permits only one truck at a time to drive in each section. This approach reduces the demands on the communication system by reducing the frequency at which the truck must communicate with the central control system. Hitachi estimates that this approach will increase the number of vehicles that can be controlled autonomously by a factor of 1.7 (compared with a system having the same communication scheme but not using permission control).

The AHS is being implemented on the Hitachi EH-3 Series dump truck, which has a very comprehensive vehicle stability control (VSC) system that provides increased driving stability compared with previous truck models. Because the VSC controls many functions of the EH-3 trucks, the autonomous haulage system can be integrated into existing trucks with an interface consisting of only steering and acceleration inputs. This simplifies the task, and reduces the cost, of switching from an operator-controlled fleet to an autonomously controlled fleet (Hamada and Saito, 2018).

The prototype system being developed in Australia is at the Stanwell Corporation Meandu coal mine located approximately 100 km inland from Brisbane. The test site has one loading area and three dumping areas (over-edge dumping, paddock dumping, and crusher dumping). The project was announced in 2014 and three driverless trucks have been tested at Meandu over the last year (Creagh, 2018).

A.9 Off-the-shelf Components Available for Use in Autonomous Vehicles

A.9.1 BlueBox System

The NXP BlueBox System is a hardware component capable of integrating radar, cameras and LiDAR (Figure A.4). It consists of two powerful processors that can process the data of these sensors in real-time and control the car's behavior by making the correct decisions. The BlueBox is a promising tool for automotive applications and can be a robust and reliable basis for developing self-driving cars (Figure A.5).

A.9.2 NXP BlueBox: Automated Drive Kit

The NXP BlueBox System is available as part of the NXP Automated Drive Kit. The Automated Drive Kit is a development platform for autonomous cars. The kit includes:

- Computing: NXP BlueBox 2.0 – BLBX2-DB
- Vision: NXP S32V234 vision processor, Truly MIPI CSI2 Camera and option of Neusoft front vision application software
- LiDAR and Radar sensors
- Positioning kit

Figure A.4: NXP BlueBox System

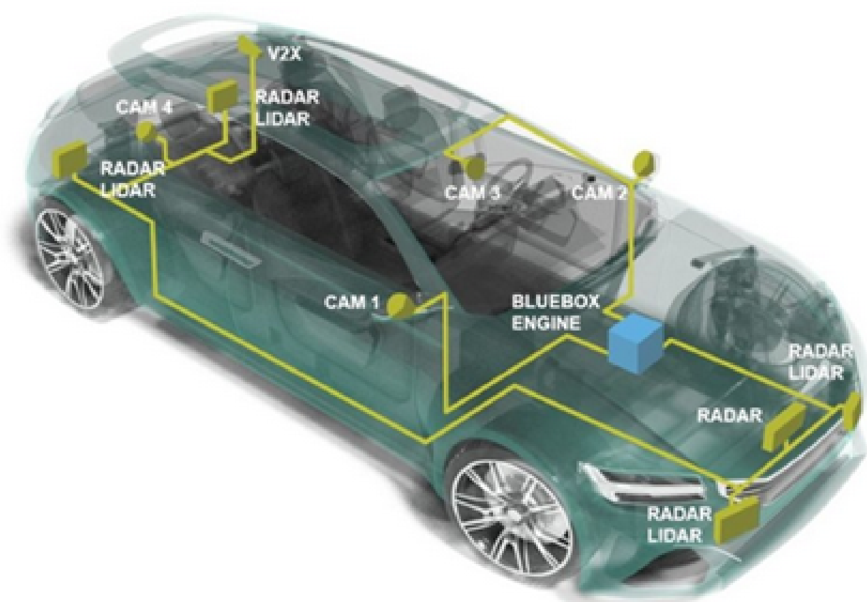


Figure A.5: Schematic of BlueBox System application in autonomous driving

Figure A.6: IntelliZone system for a Continuous Miner

- Leading O/S
- Middleware: ROS (Robot Operating System)
- Optional: LiDAR Object Processing modular software

At the time this review was completed, the cost of the NXP BlueBox Automated Drive Kit was US $3500.00 excluding taxes.

A.9.3 IntelliZone® Proximity Detection

The MATRIX IntelliZone® system is an MSHA-approved proximity system for use in underground coal mines. The system uses wearable devices to warn workers when they are close to potentially dangerous zones around working equipment. Moreover, it is able to slow down or completely shut down the working equipment depending on the distance of the worker and the equipment. The IntelliZone® system can also be implemented for other equipment for avoiding collision between working machinery.

Typically, two operational awareness zones are used, the Warning zone and the Shutdown zone (Figure A.6). When a worker or a piece of machinery enters the Warning zone, the wearable locator initiates visible and audible alerts (Figure A.7), and the equipment may be slowed down. On the other hand, when a worker or other machine enters the Shutdown zone, the equipment is immediately de-energized. These zones are customizable for different machines and applications. For example, the zones can be expanded for mobile machinery depending on their speed or can be configured for different states of a machine. Also, the system is not hampered by ventilation curtains.

Figure A.7: Miner locator (cell-phone sized)

Figure A.8: Nautilus MF4 Antenna - Dimensions: 6.2in x 3.5in x 1.4in (157mm x 89mm x 36mm). Weight: 2.25lb (1.02kg)

A.9.4 Nautilus TC5 Buddy System

The Nautilus System is also an MSHA approved proximity system for use in underground coal mines. The system consists of two components: the Nautilus TC5 Buddy – MF4 Magnetic Field Antenna (Figure A.8), and the Nautilus TC5 Buddy – Proximity Detection Device (Figure A.9).

One or more MF4 Magnetic Field Antennas, mounted on a vehicle, generate a magnetic field around it. The operator's unit with its three built-in field detectors detects and measures the strength

Figure A.9: Nautilus Proximity Detection Device

of this field and warns the operator when the strength exceeds a threshold or halts the vehicle if the distance is too small. The advantage of this system is that it does not require line of sight between the operator's unit and the antenna. Moreover, two tiny MF4 Antennas can generate a field that provides coverage for very large and complex mining equipment, such as continuous miners.

A.9.5 HazardAvert® Proximity Detection

The STRATA HazardAvert® Proximity Detection system is an electromagnetic-based proximity detection system designed for underground coal mines. All the system's components are enclosed in explosion proof enclosures. The system generates electromagnetic zones around machinery and alarm when a worker enters these zones. The system has the following components (Figure A.10):

- Generators: Installed onto machinery, generate two electromagnetic zones, 'WARNING' zone and 'HAZARD' zone, which can cover the entire machine or part of it. More than one can be installed onto a piece of equipment for configuring coverage and shaping.
- Controller Box: Monitors the system's status and the interaction between multiple generators and controls the slowing or stopping of the machinery.
- Display tracking POD: Mounted on the machinery, contains the LEDs used for alerting of triggered alarms. It also logs and stores all activity.
- Personal Alarm Device (PAD): Detect and measure the distance of the miner from the machine and warn them when they enter warning and hazard zones.

Figure A.10: HazardAvert system components

A.9.6 TIDA-00151

The Texas Instruments TIDA-00151 is an interface for automotive ultrasonic sensors (Figure A.10). According to the manufacturer, it provides all signal conditioning and processing for the transducer echo signals and for calculating the distance between the transducer and objects. The MCU, program memory and LIN allow for full configurability for the specific application. It can be used for multiple applications such as ultrasonic park assist, blind-spot detection and park distance warning.

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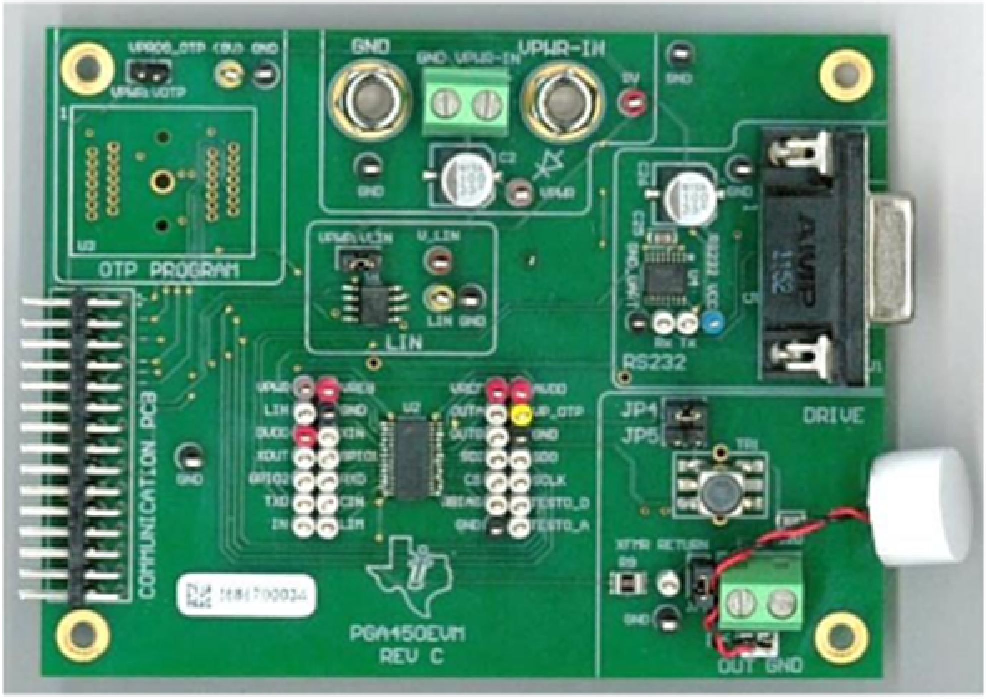

Figure A.11: TIDA-00151

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Appendix B

Review of Existing HMI Solutions in Autonomous Mining Vehicles

This appendix details the material developed with respect to existing Human Machine Interface (HMI) solutions in autonomous mining vehicles. More specifically, a number of cases of HMI usage in automated mining found in the literature are briefly described.

B.1 Case Study 1: Underground Loader Automation at CMOC Northparkes, Australia

B.1.1 Overview

This case study summarizes the successful implementation of automated underground loaders at the CMOC Northparkes block caving mine in New South Wales, Australia. Various methods of teleoperation and automation have been tested at this operation since 1998 and the Sandvik Automine system was implemented in 2010 and it is currently in use. This solution locates operators in a control room on the surface who load ore at specified draw points using manual teleoperated controls. The loader then travels autonomously to the run-of-mine ore bin to dump the material, and then to the next selected draw point where the operator manually loads ore again. The primary human-machine interface consists of several screens in the surface control room and controls for the manual operations. Audio from the loader is also available should the operator choose. The various types of information and warning alarms provided by the system were customized according to operator feedback and were designed to provide necessary alerts that were not overwhelming or a nuisance (Horberry et al., 2018; Schunnesson et al., 2009).

B.1.2 Operator-Vehicle Interface

Operators in this study were typically monitoring three loaders and responsible for:

- Loading ore using manual teleoperation
- Planning the sequence of draw points

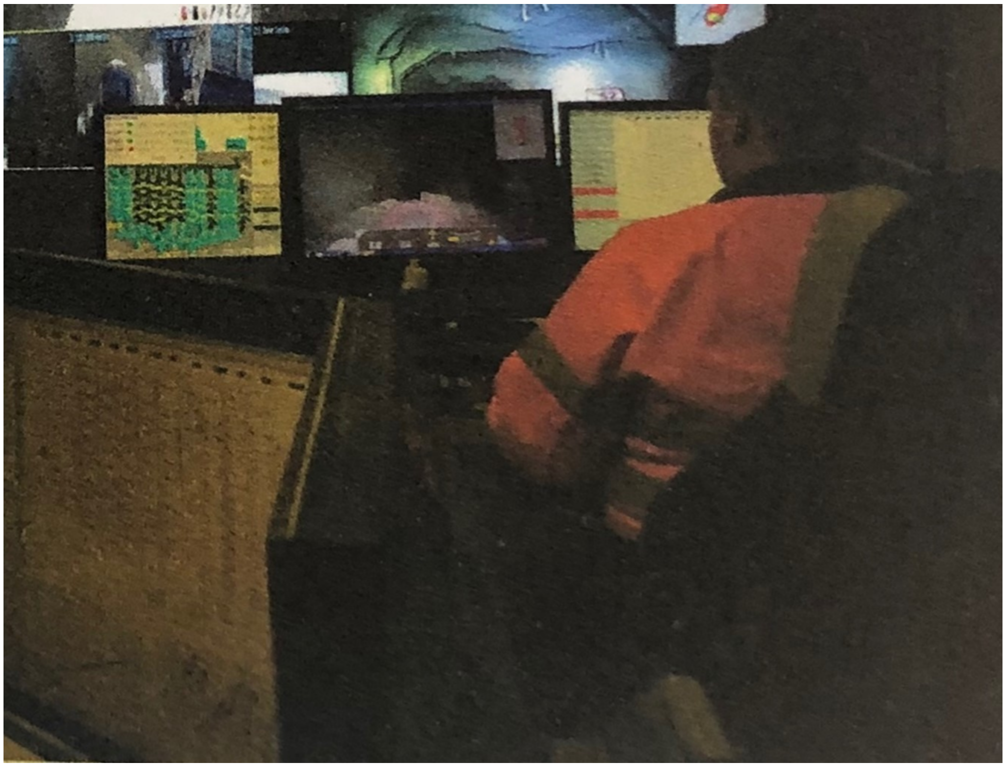

Figure B.1: Multi-screen operator interface

- Monitoring of the overall system status
- Responding to other events such as breakdowns and deteriorating conditions

The operator interface consists of a station with three screens, keyboard and mouse, and a setup that mimics the joystick and pedal controls found in the manual loaders. Radio audio from the loader is also available if the operator chooses. Figure B.1 and Figure B.2 detail the screen interfaces and work station controls.

From Figure B.1 it can be seen that the workstation has three displays of information. The rightmost screen displays the Autonomous Control System, which provides information and control over the overall system. The leftmost screen displays the Mission Control system that allows the operator to monitor the location of each loader, select a loader for manual control, and choose which draw points a loader will autonomously travel to. The screen in the middle provides a video feed, switchable from front and rear views, from the selected loader to be used for the manual teleoperated loading, as well as general monitoring of the machine. A small "teleoperation assist" window also provides an indication of the location of the selected loader relative to its surroundings, which are scanned via lasers. Additionally, this assist window provides feedback from sensors that indicate wheel slip and the proximity of walls for collision avoidance. Changes in color of the relevant portions of the loader schematic in the assist window are used to signal to operators when wheel-slip occurs, or the loader begins to approach a wall.

Figure B.2 displays the manual controls available to the operator at the workstation. A standard keyboard and mouse control the three-screen display, and a joystick-pedal setup that mimics the

Figure B.2: Operator workstation controls

controls found on the loader is used for the manual loading operations. This control setup can also be used to manually control the machines during their autonomous traveling should an emergency condition arise.

B.1.3 Human-Machine Interaction

While this segment of the operation limits the exposure of humans to the loader while it is operating autonomously, the existing proximity detection equipment utilized in many mining operations will still work in concert with the automation equipment to prevent the loader from colliding with other equipment or people in the area. Additionally, the video feedback screen can be utilized to visually confirm that any humans in the vicinity of the machine are clear of the area after in-person inspections or maintenance. In addition, manual override controls can be activated to ensure that an operator on the surface can work with personnel underground via radio should the need arise.

B.1.4 Operator-Operator Interaction

In this case, the operator workstations are all in the same room on the surface and communication between them is rather straightforward. Typically, each operator is responsible for three loaders, although four is possible. However, responsibility for four loaders was deemed to be overly fatiguing at a cognitive level. The system also allows for more flexibility that is largely at the discretion of the crew. Each operator could elect to be assigned to three loaders and be solely responsible for their own small fleet, or the group could choose to allow all loaders to be controlled by any of the operators on shift at any point in time. The Automine system accommodates both of these strategies and also allows different crews to communicate in a manner that is more customized to their preferences. Comparisons between the productivity of each method can also be made in order to fine-tune operator strategies and identify other behavioral or technical aspects that can be used to boost productivity or improve the system.

B.2 Case Study 2: Interface Design for Haul Truck Proximity Advisory Systems

B.2.1 Overview

This case study summarizes the implementation of a proximity advisory interface in surface haul trucks to help improve collision avoidance and situational awareness when visibility and line of sight are impaired. While this situation is not a direct parallel to the automation of underground shuttle cars, the system interfaces used in this case do provide valuable insights into viable options for presenting information about the surroundings of a vehicle to a remote operator. The advisory system tests included two different interfaces: an LED ring and a schematic display. Information was presented on a tablet to the operator about the proximity, location, and movement of various nearby vehicles. Audio cues were also combined with the visual proximity information. The goal of the study was to test the effectiveness of the LED ring and the schematic display compared with a control setting where no advisory system was in place, to improve collision avoidance skills, braking times, and speed. Overall, the schematic layout of the proximity advisory interface yielded the best results, while the ring schematic showed improvement over the control setting in only a few areas. Simulation drivers also noted that alerts for vehicles not at risk of a collision were undesirable and unproductive (Horberry et al., 2018).

B.2.2 Operator-Vehicle Interface

The interface of the proximity advisory system tested in this case was a Samsung tablet connected through a dedicated wireless network. The tablet displayed various visual information about the identity, location, and proximity of other vehicles in the area, as well as cues or changes that reflect the movement of the other vehicles. Additional auditory information was also provided in the form of tones that varied in pitch and frequency based on the proximity of other vehicles.

The two types of interfaces tested in the case were the “ring” interface and the “schematic” interface as shown in Figure B.3 and Figure B.4.

The ring interface shown in Figure B.3 consists of a ring of simulated LEDs that will illuminate to indicate the direction of approach and distance range of another vehicle in proximity to the operator vehicle. When the tablet initially detects another vehicle, a yellow LED illuminates to reveal its location and distance between 100m to 150m away, accompanied by a low-pitch alert tone. When the vehicle approached within 100m, the LED would change to red and a higher-pitched tone would sound. As the vehicle approached within 80m, the red LED would begin to

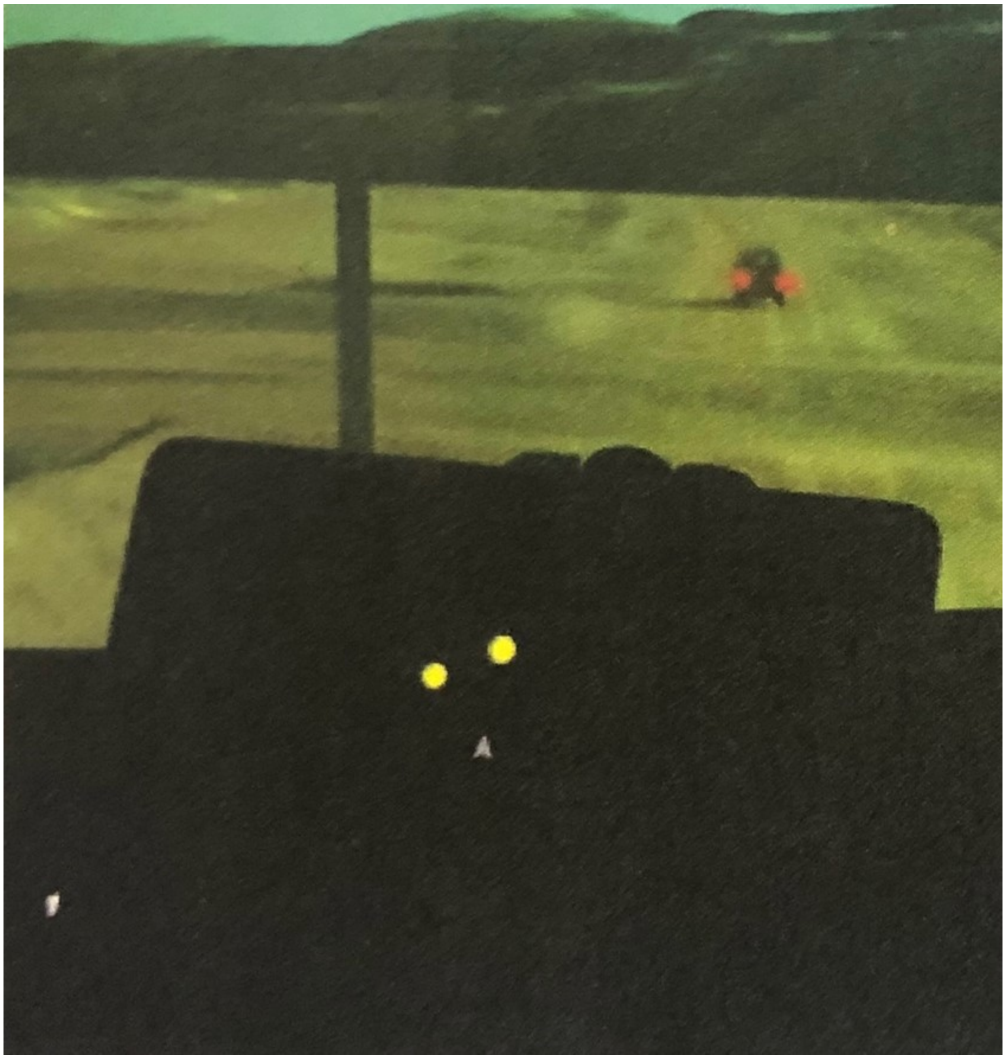

Figure B.3: Ring display interface

flash, and a progressively higher tone would sound.

The schematic interface shown in Figure B.4 utilized the same audio cues as the ring interface, but the screen provided a continuously updated display of the locations of other vehicles and additional information about the relative velocity of approaching vehicles and the type of vehicle, either light duty or haul truck, via different schematic symbols. At the conclusion of the study, participants strongly preferred this method of proximity advising and the results for time to collision awareness and speed further supported its superiority over the control and ring interface scenarios.

B.2.3 Human-Machine Interaction and Operator-Operator Interaction

While this case is not directly applicable to the interaction between other humans and an automated machine or between operators monitoring autonomous equipment, the interfaces in the case show viable methods of displaying relevant information. The schematic tablet interface can facilitate

Figure B.4: Schematic display interface

easier interaction with an automated machine due to the user-friendly nature of a tablet interface. The portability of the tablet can also improve the ease of monitoring the equipment while it is moving through a mine and will allow for clear and quick communication between operators due to the simple but effective information that is displayed.

B.2.4 Operator Concerns

Several concerns were expressed by participants in this case with regards to the proximity advisory system as a whole. The main concerns were related to the relevance of information and the effects of false alarms. Participants expressed strong feelings against alerts to vehicles that posed no collision risk, stating that they would become a nuisance and were counterproductive. It is critical to ensure that operators are not overloaded with too much information at one time and also that the amount of unnecessary information is minimized. If too many false alarms or non-risk alerts require the operator's attention, they would be increasingly likely to ignore these alarms and make potentially serious mistakes. An optimal proximity advisory system would only alert the operator when attention to the interface is required and would display information in a clear and accurate manner that would allow the operator to quickly understand the situation and adjust the machine as needed.

B.3 Case Study 3: Komatsu FrontRunner Automated Haulage System

B.3.1 Overview

Komatsu Mining Corp. has been a leader in pioneering automated haulage in the mining industry. The Komatsu Automated Haulage System (AHS) began testing in 1990 and presently manages approximately 130 trucks across the globe for Rio Tinto, Codelco, and Suncor Energy. The system also recently celebrated 10 years of autonomous success, with zero safety incidents in the system's existence. The system uses a combination of sensors, lasers, mine maps, GPS, Wi-Fi, and gyroscopes for positioning, navigation and managing interactions among the machines. The system is composed of Komatsu's FrontRunner software controlling the autonomous decisions of the trucks, while the Dispatch program acts alongside FrontRunner to assign load/dump points and monitor truck locations to aid in collision avoidance. This system is readily available from the factory for new trucks but is also available in a retrofit kit that can also be modified for other brands to allow for interoperability between new and old trucks of varying makes and models (Gleason, 2018; Grayson, 2018). Key features of the system include:

- Auto Interaction: communication capabilities between autonomous machines
- Manual Vehicle Interaction: communication capabilities with manned vehicles
- Collision Detection System (CDS): a safety envelope warns of potential collisions
- Obstacle Detection System (ODS): units in the front and back stop the truck if needed
- Emergency Stop Button (ESB): included on all machines to stop all autonomous trucks

B.3.2 Operator-Vehicle Interface

The central control room that serves as the hub for all trucks controlled by the FrontRunner system consists of a multitude of monitors and TV screens that show the various windows included with the FrontRunner and Dispatch software, along with any other relevant mapping or planning software. This main control room is where trucks are assigned various jobs, and the locations of trucks on the mine site are displayed. This is where operators will interact with the vehicles most frequently. A common setup of a central control room is shown in Figure B.5.

An additional interface that accompanies the Komatsu AHS is a modular display that is mounted in every vehicle at an AHS equipped mine. An example is shown in Figure B.6.

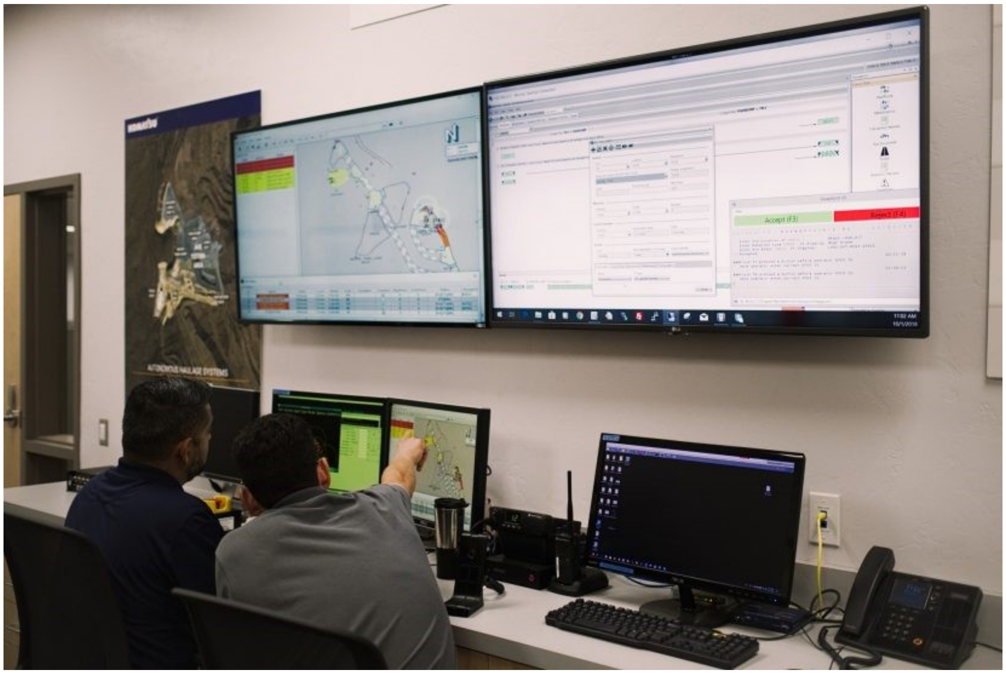

Figure B.5: AHS Central Control room

Figure B.6: Modular AHS display

This modular display is essentially a tablet that shows much of the information visible to operators in the Central Control room. A mapped outline of the site is displayed and color-coded paths show where FrontRunner is driving the autonomous trucks. Each machine's safety envelope is also displayed as a bubble, which allows operators to conveniently monitor machine proximity in the area. Several controls for an autonomous truck, such as releasing or suspending a truck from its assignment and starting and stopping the engine are also available.

B.3.3 Human-Machine Interaction

Given that the Komatsu AHS was designed for surface haul trucks, the FrontRunner system was designed to minimize contact and proximity to manned vehicles or personnel. The decisions that the software makes use feedback from the locations of all manned vehicles, in addition to the other AHS equipped trucks, and prioritizes routes that avoid manned vehicles. Also, the CDS and ODS systems are in place to ensure that collisions do not occur when autonomous vehicles are in closer proximity to humans. Komatsu also requires extensive training of personnel who will be required to work with and around autonomous vehicles to reduce the likelihood of an accident. It is also recommended to post appropriate signage to note areas where autonomous machines are operating so that all mine site workers are aware. The Modular display can also be used by non-operators to ensure safe conditions near the autonomous trucks.

B.3.4 Operator-Operator Interaction

The Komatsu AHS system was specifically designed for surface applications, so traditional methods of communication, whether it be radio, internet, or even cell phones, are the primary methods of communication between operators in the Central Control room and the rest of the site. Few operators are required, however, as a well-trained controller can typically manage close to 30 trucks once all of their loading assignments have been distributed. Strong partnership and extensive communication are required for the best results with this system, and Komatsu offers 24/7 support for any software and hardware issues that may arise. Strong on-site support is critical as operations become larger and more complex.

B.4 Case Study 4: Epiroc Scooptram Automation Regular

B.4.1 Overview

Epiroc has recently released the "Automation Regular" automation package for their Scooptram underground loaders. The automation package consists of cameras, sensors, safety equipment, and a control station setup that allows for easy installation on the existing loaders and integration into the mine. The package offers convenient switching between automatic operation and manual remote control as the situation dictates. Epiroc cites advantages in terms of safety and productivity where mining can continue when safety risks would normally prohibit personnel from working, such as during ventilation after blasting, and during shift changes. The package is designed specifically for Epiroc Scooptram loaders, and the control stations can be located in mobile units underground or in

Figure B.7: Epiroc mobile automation control station

fixed stations on the surface. The software package can be programmed with a given route for the machine to traverse and also has safety provisions for collision avoidance and proximity detection based on the work zone of the machine (Epiroc, 2018; Fiscor, 2018).

B.4.2 Operator-Vehicle Interface

The human-machine interface in this system consists of an operator station that is equipped with several small displays and an operator seat with remote controls that mimic the actual controls on the Scooptram loader. The station can either be located underground in a mobile vehicle or can be fixed in a space on the surface. Figure B.7 and Figure B.8 show the operator control station setup and the display information available to the operator.

It can be seen from Figure B.7 that the mobile control station consists of a pair of screens positioned in front of an operator setup that mimics the joystick controls of the physical loader. This allows for monitoring the machine while it is in automatic mode and for quick switching to manual controls in case of emergencies or other situations that require human interaction. A similar setup, with monitors and a control pad, is available for use on the surface or in a fixed location if the option is desired. Figure B.8 displays the information provided to the operator who is monitoring the machine. A map of the area with the location and orientation of the loader and a camera feed from the machine are the prominent windows on the display. Additional information about the machine, such as the boom angle, various degrees of tilt, and engine/payload information is also shown. An additional screen contains a window detailing the selected loader and options for selecting route information. These screens also show warnings about collisions or other obstructions in the intended workspace.

Figure B.8: Scooptram automation regular display interface

B.4.3 Human-Machine Interaction

One of the key safety features of this package is the inclusion of a set of "safety gates" that are easily mounted to the ribs of the mine in the working area of the loader. The operator would be responsible for the setup and arming of these barriers prior to beginning work with the equipment, in either manual or automatic modes. These gates function in a manner similar to motion sensors. If movement is detected within the gates, the automated loader will shut down until it is verified that the obstruction, be it another machine or a person, is clear from the area. Figure B.9 and Figure B.10 illustrate the safety gate equipment.

Figure B.9 shows the hardware associated with the safety gate setup. A control box is mounted on the rib of the mine and is connected to the interface of the control station. This control box must be armed prior to running the loader once the gate sensors, shown on the left, are also in place. Strategic placement of these gates would be required to ensure proper use of this system. Figure B.10 shows the activation of the safety system when a machine crosses through the safety barrier while the loader is in motion. This would shut down the automatic loader and allow for manual control in order to allow equipment or personnel to pass safely. The safety barrier system would then have to be reset in order for the operation to continue. In areas without safety gates, the system would have to rely upon traditional proximity detection methods, cameras, and the vigilance of the operator in order to avoid collisions or other accidents.

B.4.4 Operator-Operator Interaction

In this case, each loader has its own control station setup, since allowing for control of multiple loaders at one station is not an available option. In order to interact, operators have to rely upon traditional communication methods, such as radio. Alternatively, multiple control stations would

Figure B.9: Safety barrier equipment

have to be located in the same area, such as a designated location on each loading level of a stoping operation for example. The simplistic design of the displays facilitates general communication. In addition, activation of the safety gates during a shift change also allows the operators to update the new shift on conditions in the mine and the status of the system.

B.5 Case Study 5: CAT MineStar: Command, LHD Automation

B.5.1 Overview

The Command branch of the CAT MineStar software system, built upon the MINEGEM predecessor, is similar in design to that of the Komatsu AHS, but CAT has also developed the Command software to be used in underground conditions. The software was initially proven in several Australian mines and is now used primarily with LHD machines around the world. The Command software works within the CAT MineStar system and uses a combination of onboard computers, lasers, sensors, wireless networks and operator control stations to enable multiple levels of manual and automated control. The system offers basic teleoperated remote control, where the remotely located operator has complete control of the machine, and also a Co-Pilot mode, where the operator monitors the LHDs location on a mine map and has controls available to provide additional input to the machine if necessary. The autopilot mode allows the machine to tram, dump, and return to the

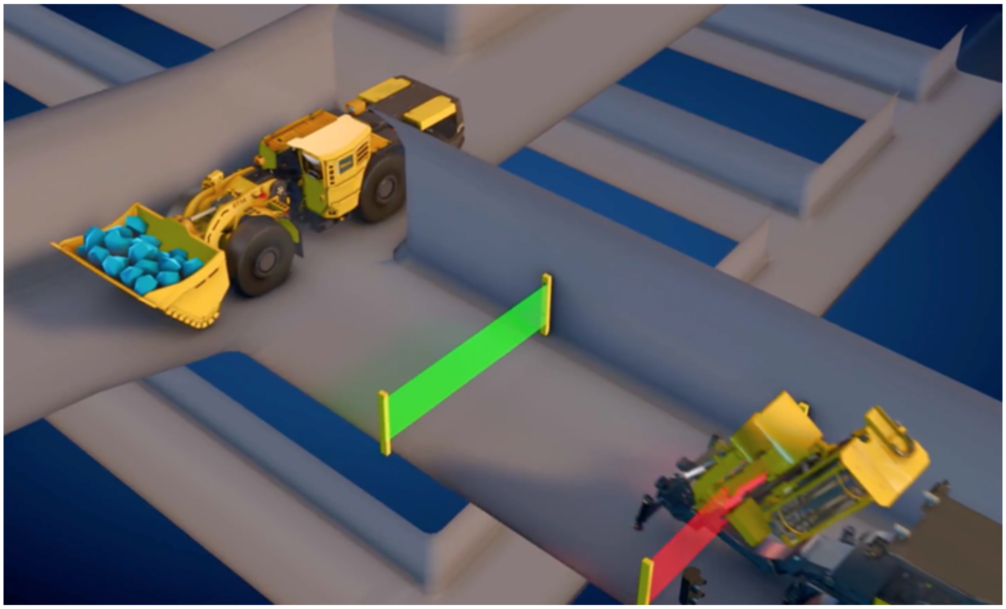

Figure B.10: Simulation detailing safety barrier functionality

dig face autonomously for the operator to control the loading process. The newest LHD units now feature AutoDig technology which allows for fully autonomous operation. Multiple safety features are also present within MineStar, such as proximity awareness, personnel detection, and collision avoidance offerings. The command systems capabilities are also designed to be scalable and will integrate with equipment fleets of varying brands (Sprouls, 2018).

B.5.2 Operator-Vehicle Interface

The primary interface between the operator and the autonomous loader is through the MineStar system with the CAT Command feature. This software is typically displayed on multiple screens at a control station that also contains an ergonomic seat with joystick controls for manual teleoperation. Figure B.11 shows an example of a typical control station.

It can be seen from Figure B.11 that the control station uses computer monitors to display various forms of information such as camera feeds, vehicle telemetry, and the location and orientation of the machine in the mine environment according to a mine plan. The mine plan is one of the key sources of information for navigation and must be updated regularly to ensure accuracy. This interface setup is the most common for the use of this technology. The control stations, while often located underground, may be installed on the surface, if the required wireless infrastructure is available.

Figure B.12 offers a more detailed view of the format and types of information available to the operator, who may be remotely operating the machine or simply monitoring progress. This particular screen shows detailed information about the active mining face, which is updated through the MineStar software as mining occurs, as well as various vehicle telemetries and options for the various modes of the Command software. Front and rear camera feeds supplement the digital landscape. Additional screens show a larger scale layout of the mine site so the locations of other

Figure B.11: CAT MineStar and CAT Command control station

personnel and equipment can also be tracked.

B.5.3 Human-Machine Interaction

The CAT Command system is designed to allow for remote teleoperation as a minimum, so interactions with other humans in the working area is minimized by design. Additionally, the Command system contains an Area Isolation System that further reduces hazards in the machine's work space. This system draws on proximity devices and location information from MineStar that relates to other equipment and personnel to ensure that the machine will cease operation when equipment/personnel are present or moving through the working area of the machine when it is being controlled with Command. The equipment can then resume production once the Isolation Area is clear of people or equipment. Visual confirmation through the camera feeds also helps ensure the area is safe to continue operation.

B.5.4 Operator-Operator Interaction

In this case, operator-operator interactions would primarily occur over traditional channels, such as Internet or radio, as the control stations would be located in safer areas away from the actual machines. A single operator is also capable of controlling or monitoring several machines at once, so communication with other operators in the same area would be primarily for coordination among the needs of the mine fleet. The remote location of the control station improves the quality of this communication. Additionally, shift changes occur much more efficiently, as operators simply swap

Figure B.12: Detailed view of information available to the operator

out at the control station and can easily discuss operational details and conditions without having to stop the machines. Confusion due to excessive noise is also avoided.

B.6 References

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Appendix C

Laboratory Scale Shuttle Car and Navigation Systems

C.1 Lab Scale Shuttle Car

The laboratory-scale shuttle car model was designed and constructed to take advantage of available consumer off-the-shelf (COTS) components, while preserving tramming, steering, and relevant dimensional aspects of a production shuttle car. Based on the needs of the project and available components, the team decided that the prototype should be constructed at a one-sixth scale. Each aspect of the laboratory-scale prototype is briefly described below.

C.1.1 Prototype Chassis and Frame

The chassis and frame were designed to take advantage of a four-wheel drive, four-wheel steering, remotely controlled (RC) truck available for RC vehicle hobbyists. Specifically, the team wanted to use the axles, steering components, and gearbox of the RC vehicle. Therefore, the chassis and frame consisted of the RC vehicle axles, the RC vehicle steering components, and two rails fabricated to connect the axles together and support the body. The length of the axles was ideal for 1/6-th scale; the length of the rails was determined to provide the proper wheelbase. In addition, the RC vehicle selected had a gear-case gear ratio of 1:25 and an axle gear ratio of 1:2.55, providing a total speed reduction of 63.75. This was ideal for the low speeds required by this application (corresponding to full-scale speeds of zero to six miles per hour).

The frame consisted of two pieces of angle aluminum that were cut to length and bolted to the axles. A component enclosure was constructed between the rails for housing the batteries, motor controller, etc. Two spacers were 3-D printed and mounted above the frame to provide the necessary clearance for attaching the body. Figure C.1 shows the assembled frame and chassis.

C.1.2 Traction Motors and Controller

Tramming is accomplished through motor-on-axle design. The traction motors selected were 24 V brushless dc (BLDC) planetary gear motors (model LRPX32-090V24-000-X003) manufactured by

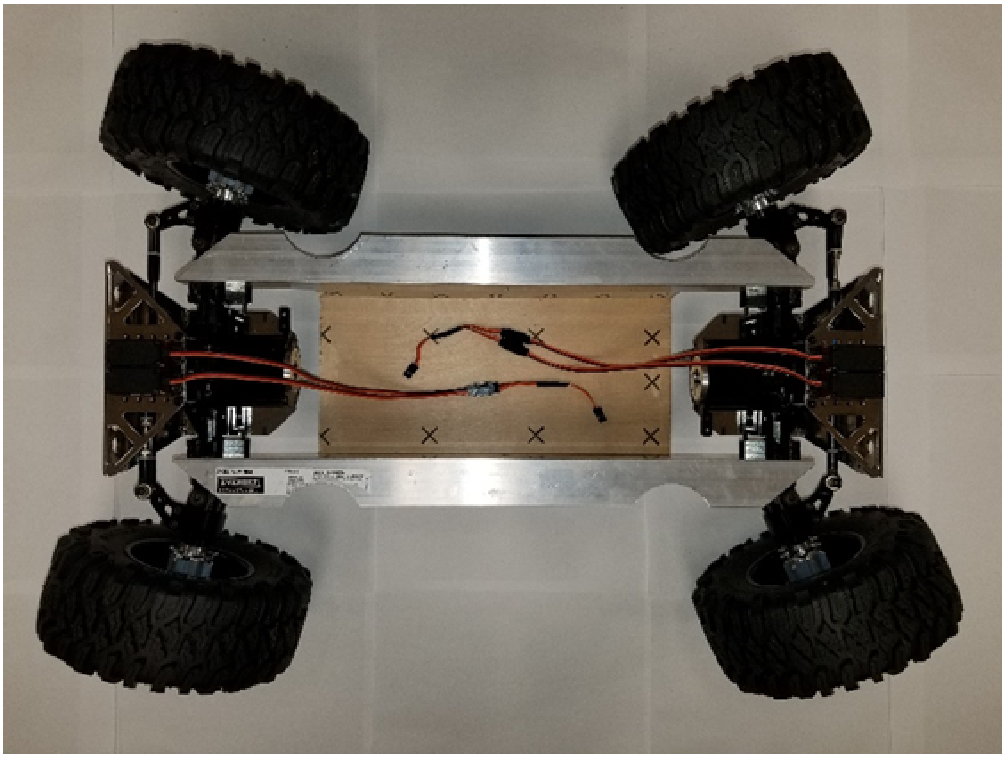


Figure C.1: Plan view of prototype frame and axles

ElectroCraft. The motor continuous running speed is 8000 rpm. The planetary gear included with this motor provides an additional speed reduction of 3.21, making the continuous running speed of the motor shaft 2489 rpm. With the 63.75 speed reduction from the gearbox and axles, the wheel speed at rated continuous operation is 39 rpm. This provides a linear speed of up to 415 mm/s (approximately 3.4 seconds to travel the length of the scale model). Table C.1 provides traction motor speed, torque, and current specifications at continuous and peak operation.

Table C.1: Traction motor specifications (LRPX32-090V24-000-X003)

	Continuous Running				Peak Operation			
Voltage (V)	Current (A)	Motor Torque (Nm)	RPM	Linear Speed (mm/s)	Current (A)	Motor Torque (Nm)	RPM	Linear Speed (mm/s)
24	4.6	0.16	2489	415	17.7	0.62	498	83

The traction motors are controlled by a Roboteq SBL2360, 60V, 2x20A (dual) BLDC Motor Controller (controller and motors shown in Figure C.2). The controller was chosen primarily because of its wide range of operating modes available, including pulse (RC radio) mode. The controller also permits hall sensor or synchronous serial interface (SSI) rotary shaft encoder signals. This controller can supply two, 12-60 V BLDC motors continuously at 20 A, which exceeds the peak operating current and voltage rating of the traction motors selected. The controller and traction motors are supplied by a 22.2 V, 5.0 Ah, lithium polymer (LiPo) battery.

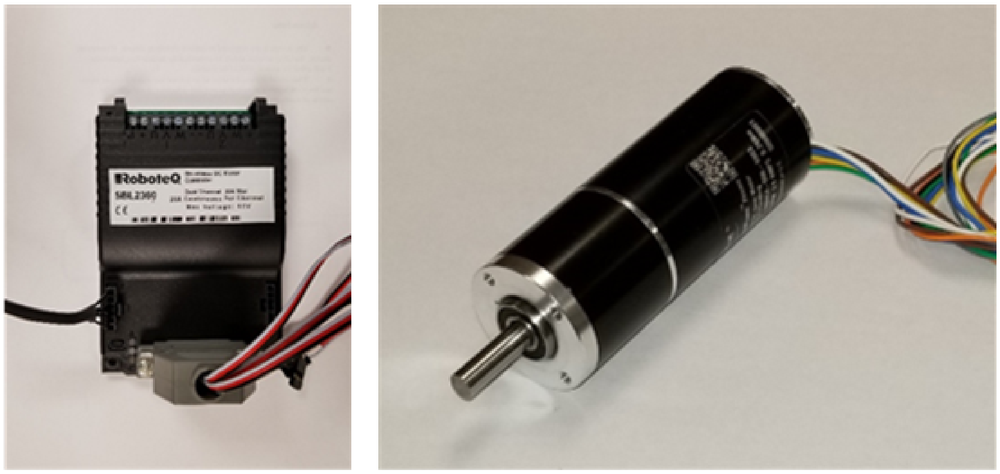


Figure C.2: Traction motor controller and motor

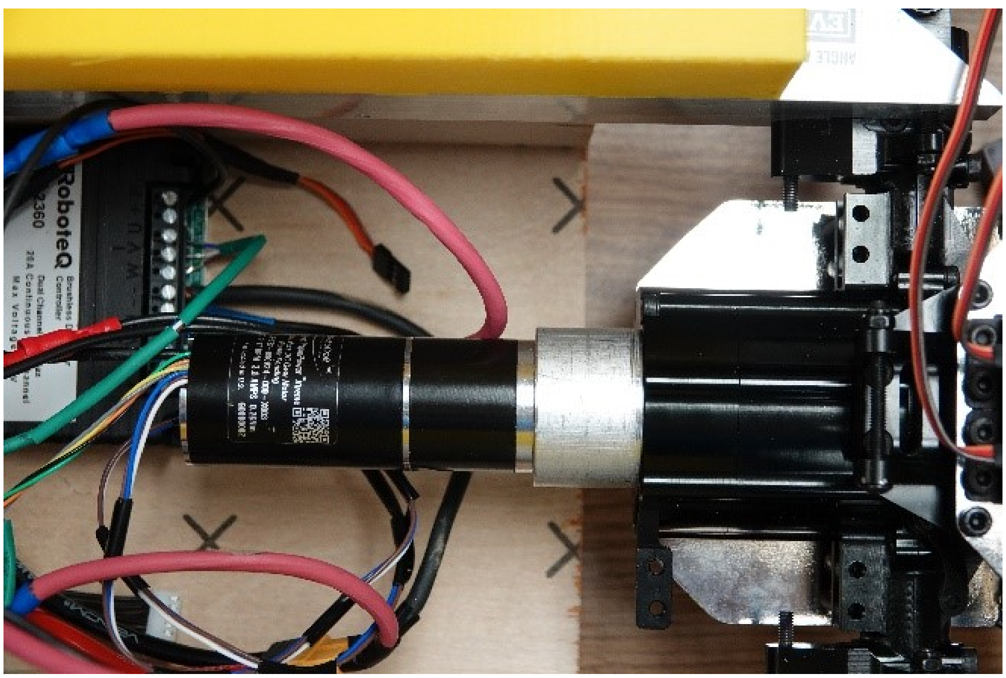


Figure C.3: Traction motor mounted to gear case

Because these motors have a 6.00 mm shaft diameter and the gear case requires an input from a 5.00 mm shaft, the traction motors had to be modified to couple properly to the gear case. This modification consisted of the design and construction of a collar and motor mount that would reduce the shaft diameter to 5.00 mm. Figure C.3 shows one of the traction motors and coupler mounted to the prototype gear case.

The motor controller was integrated into the laboratory-scale model and tested for proper operation using Hall sensors for detecting rotor position and speed. There were no issues with motors or controller during the project. Figure C.4 shows the traction motors and controller mounted in

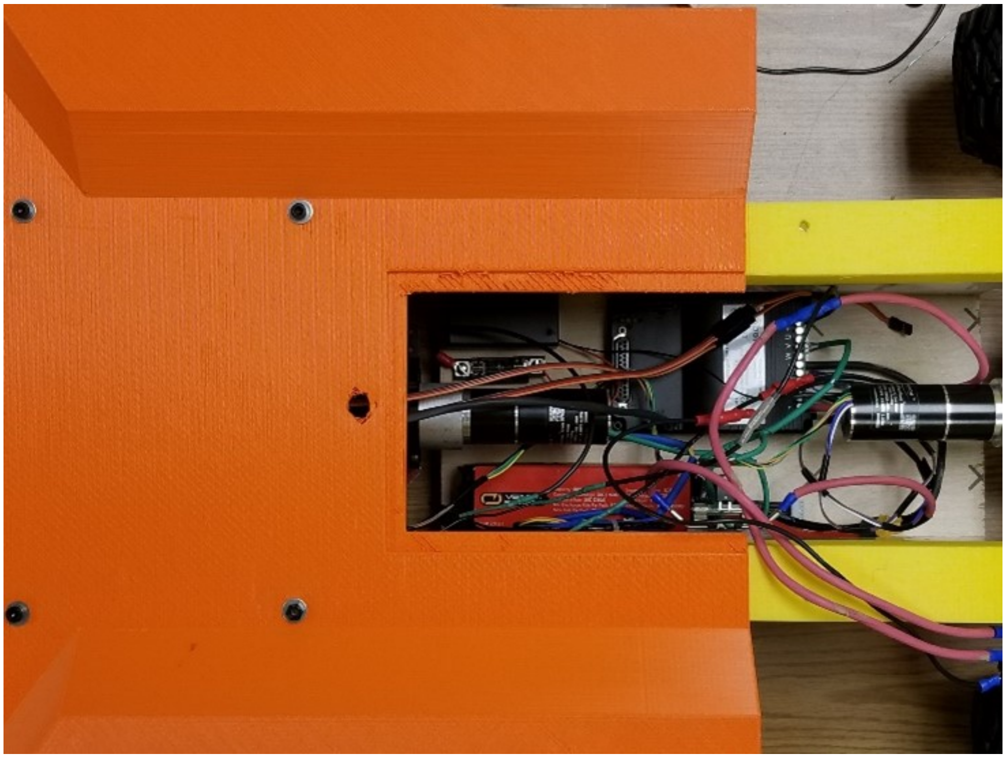


Figure C.4: Traction motors, controller, and battery

the electronics enclosure of the scale model. (Note that a portion of the shuttle car body, discussed in a subsequent section, is also shown in this figure.)

C.1.3 Steering

Steering is accomplished by four Savox SAVSC1256TG servo motors, with two servos mounted above each axle. Each servo develops a torque of 1.96 N·m, which provides a steering torque of nearly four Newton·meters per axle. Figure C.5 shows the steering servos mounted above one of the prototype axles. The steering servo motors operate on five volts with standard pulse-width-modulation (PWM) used for servo position control.

C.1.4 Prototype Body

A .step file of a Joy 10SC32B provided by Komatsu Mining Corp. was used to establish the relevant dimensional ratios and details for the laboratory-scale prototype body. Figure C.6 shows an image of the shuttle car developed from the .step file. Note that the image does not include the operator's platform/deck and cable reel. These items were not included in the file because their location depends on whether the shuttle car is configured as a standard or off-standard vehicle. Consequently, the dimensions of the cable reel assembly and operator's platform were obtained from a separate 2D drawing file provided by Komatsu and incorporated into the prototype body design. For both prototypes constructed, the model preserves the important features of the shuttle

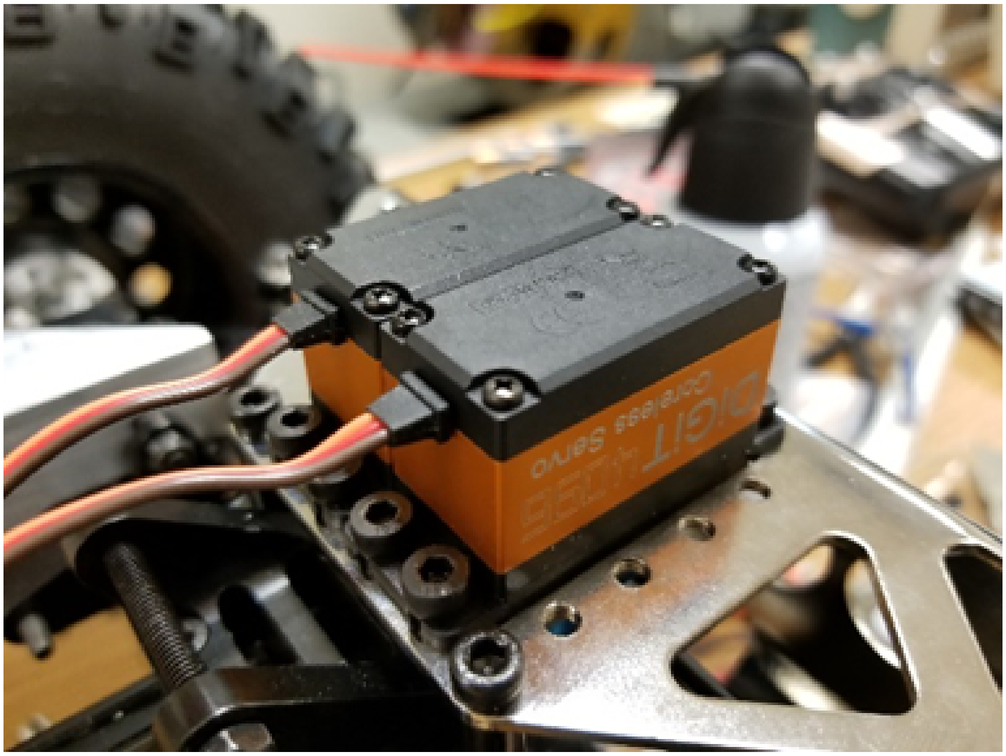


Figure C.5: Steering servo motors

car, while simplifying some of the details of the body to facilitate 3D printing of the different parts. Figure C.7 and Figure C.8 show the cross section and plan view this shuttle car.

Table C.2 shows the dimensions of a 10SC32B shuttle car compared with the prototype. In all cases, except for the tire size, the prototype is approximately a one-sixth scale model of the 10SC32B. Slightly smaller wheels and tires were preferred; however, none could be found that were compatible with the axles. The larger wheels and tires caused no issues during testing. Figure C.9 shows an image of the 3-D model of the body.

Table C.2: Dimensions of prototype shuttle car compared with Joy 10SC32B

Parameter	Joy 10SC-32B	Prototype 1	Scale Factor
Length	9080 mm	1448 mm	0.16
Width	3404 mm	500 mm	0.15
Wheelbase	2900 mm	480 mm	0.17
Tire diameter	740 mm	200 mm	0.27

Several options were considered for constructing the prototype body, including fabrication from metal panels, fabrication from plastic panels, and 3-D printing. After considering the advantages and disadvantages of each option, the team decided to 3-D print the shuttle car body.

The three-dimensional model (Figure C.9) was used to produce .stl files to 3-D print the body. Because the scale model is approximately 1450mm x 500mm, it was impossible to print the entire body in one part. Therefore, the body was divided into four major parts, plus 10 additional

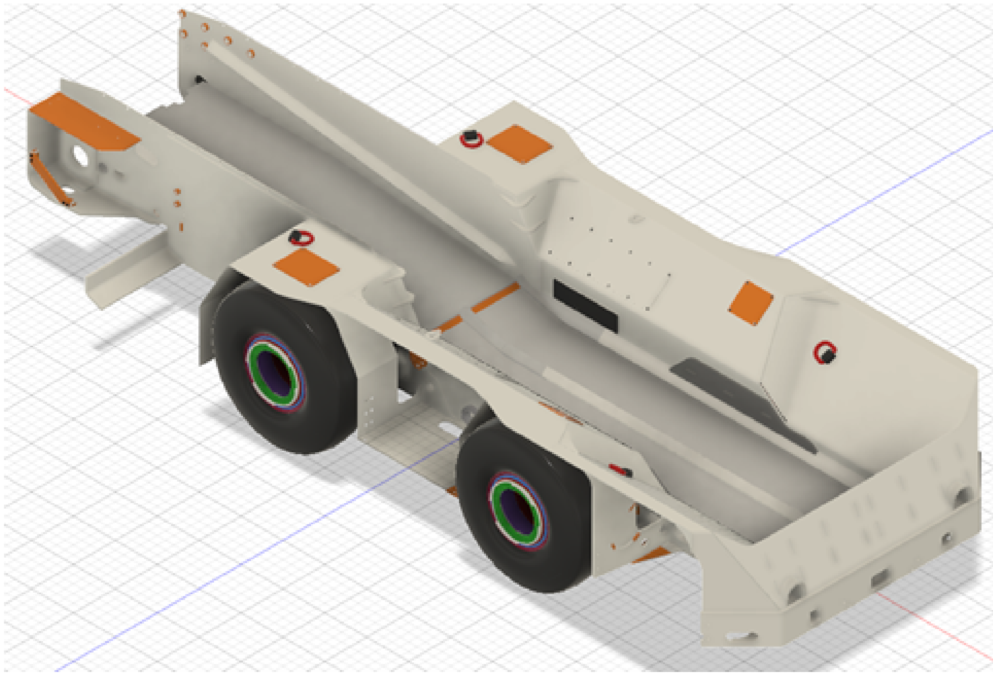


Figure C.6: Image of Joy 10SC32B shuttle car from the 3-D STEP file provided by Komatsu

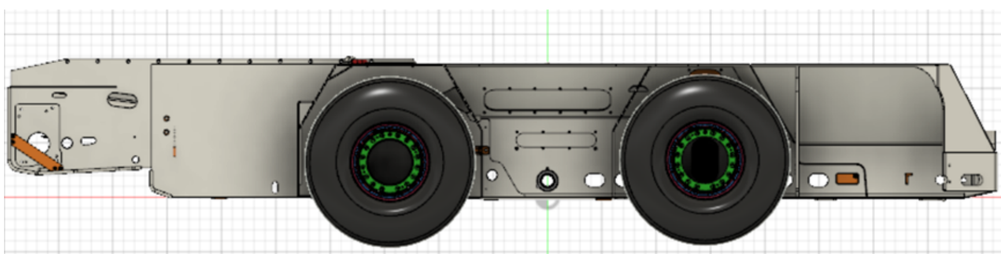


Figure C.7: Joy 10SC32B cross section

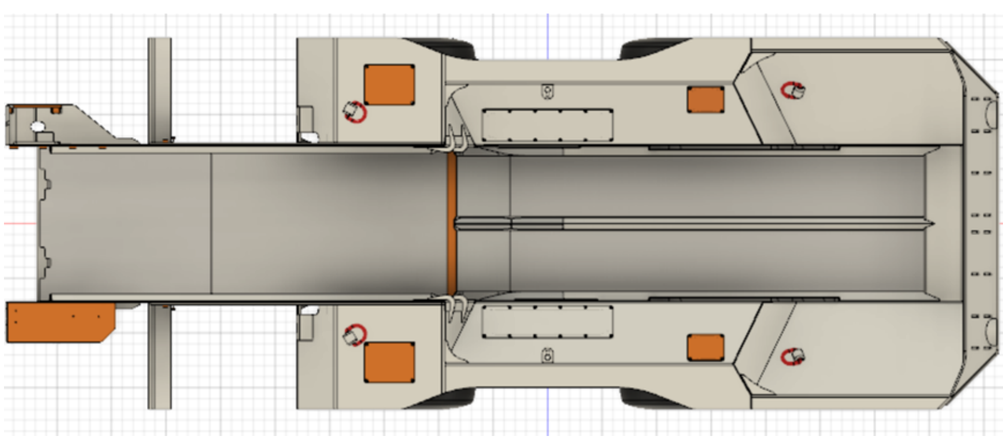


Figure C.8: Joy 10SC32B plan view

Figure C.9: Image of three-dimensional model used for construction of scale model

components that were cemented/bolted together. Parts were printed primarily on a Gigabot 3+ 3D printer, which has a 24x24 (in.) print bed, wide enough to print the full width of each body part. A Makerbot Replicator Z18, with a 12x12 (in.) print bed, was also used for printing smaller parts.

Figure C.10 shows drawings of the four main body parts. These parts were designed to be attached to the frame by being bolted to the spacers mounted on top of the frame shown in Figure C.11. Drawings of the remaining 10 parts are shown in Figure C.12. Figure C.13 and Figure C.14 show the completed prototype shuttle car from different angles.

Figure C.15 shows an exploded view of all shuttle-car body parts of the second prototype (off-standard) before assembly. After all parts were printed, they were cemented together, and the entire assembly was reinforced by adding two angle-aluminum rails to the underside of the assembly. Figure C.16 shows the underside of the body after assembly.

C.1.5 Performance

Throughout the design and construction phase of the prototypes, the goal was to develop models with physical dimensions and operating characteristics similar to that of a full-scale shuttle car. This includes (1) four-wheel drive, (2) opposite-direction, four-wheel steering, (3) length-to-width and wheelbase-to-width ratios close to that of a typical shuttle car, (4) a body that is a scaled replica of a typical shuttle car, and (5) traction motors with high-torque at low speed. By doing this, the problems associated with maneuvering a large shuttle car within relatively small entries and crosscuts are preserved, making the concepts developed for the small-scale prototype scalable to the full-size shuttle car. The final design, as summarized in Table C.3, achieved this goal.

The traction motors and controller installed in the first prototype exceeded performance expectations; they are very robust and there were no issues with them. Consequently, the motors and controller of the second prototype were identical. Table C.4 provides a summary of the traction motors' relevant specifications. Table C.5 shows a few of the relevant specifications of the motor controller.

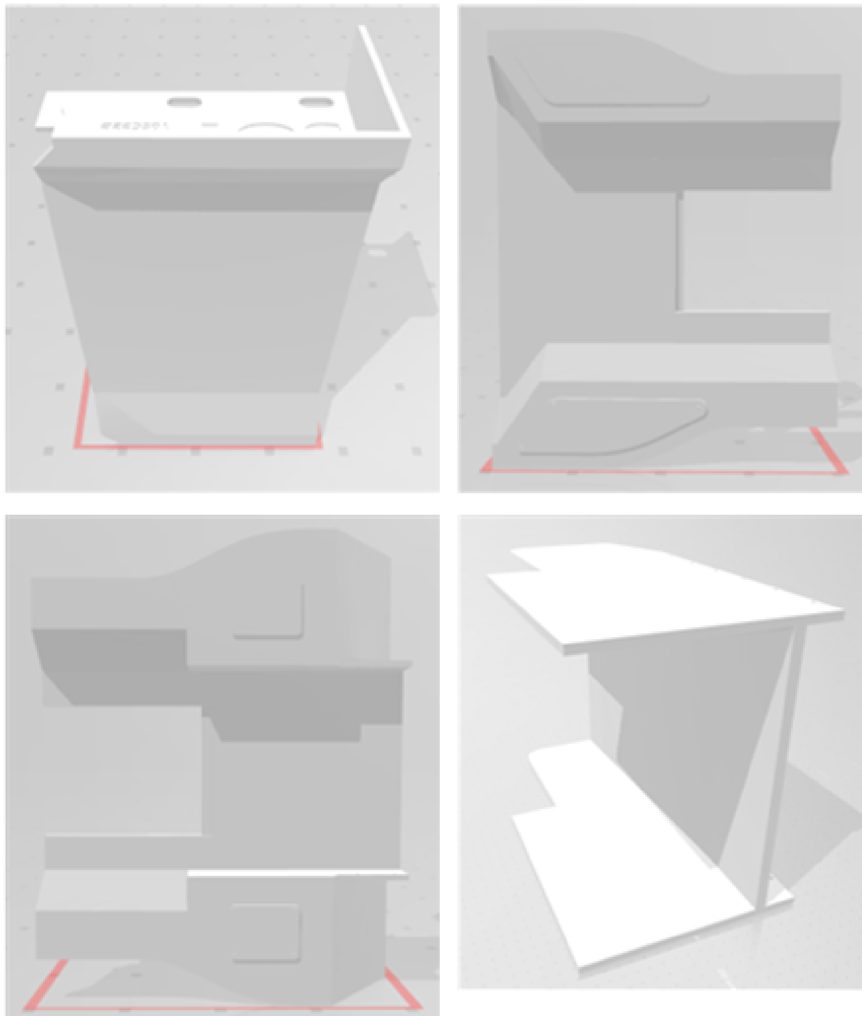


Figure C.10: Four main body parts of scale model

Figure C.11: Scale model chassis and frame rails for mounting model body

Table C.3: Specifications of prototype shuttle cars

Parameter	Specification
Length	1448 mm
Width	500 mm
Wheelbase	480 mm
Tire Diameter	200 mm
Frame	38 mm angle aluminum 500 mm (length)
Steering Servo Model	Savox SAVSC1256TG
Gear-case gear ratio	25:1
Axle gear ratio	2.55:1
Prototype calculated linear speed	415 mm/s (based on motor continuous rating)
Prototype measured linear speed	390 mm/s (tramming on horizontal)
Prototype turning radius	1.2 m outside (approximate)

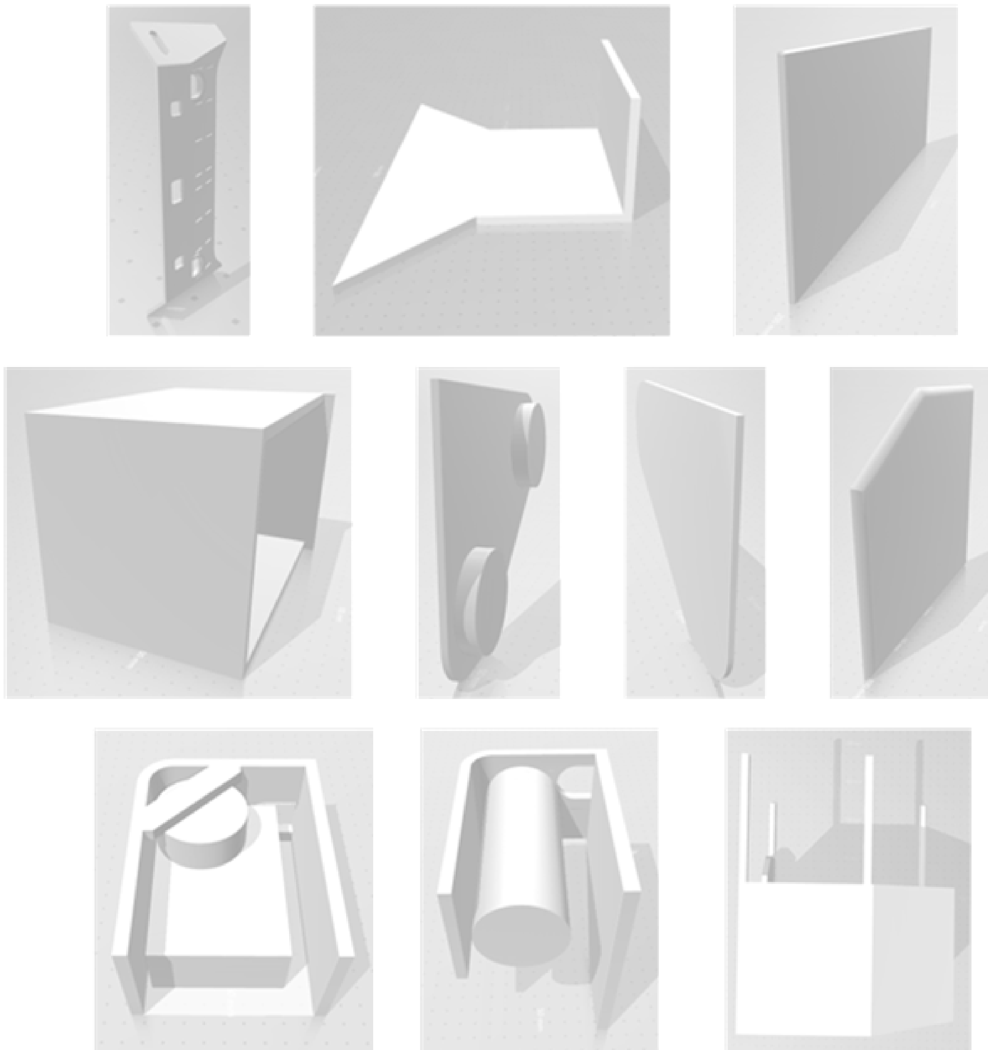
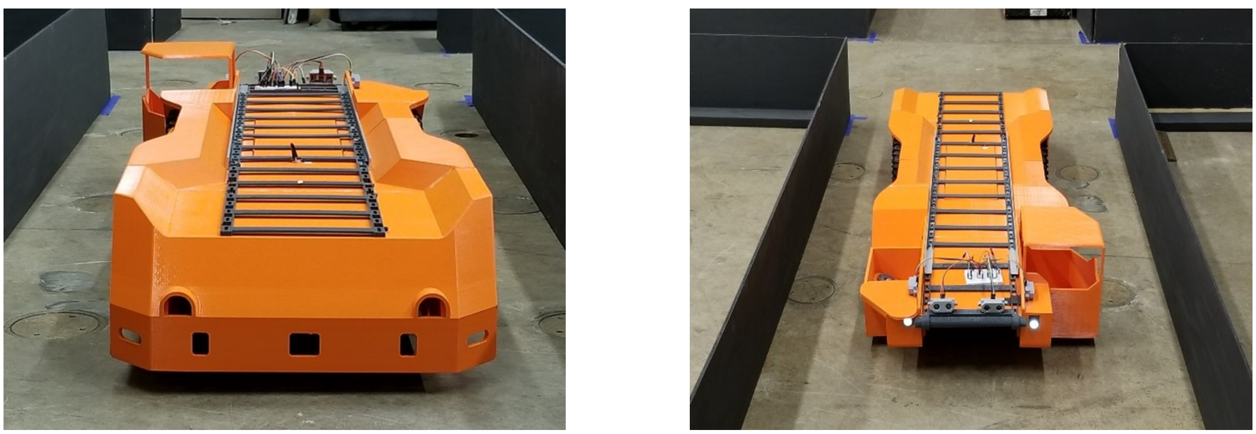


Figure C.12: Smaller components of lab-scale shuttle car body

Table C.4: Summary of prototype traction motor specifications

Manufacturer and Model	ElectroCraft LRPX32-090V24-000-X003
Motor type	Brushless dc
Voltage	24 V
Current	Continuous running: 2.1 A Peak: 11.8 A
Speed	Continuous running: 2489 rpm Peak: 498 rpm
Torque	Continuous running: 0.15 Nm Peak: 0.81 Nm
Gearbox	One stage with 3.21: 1 speed reduction

Figure C.13: Completed 1:6 scale prototype shuttle car



(a) Loading-end of prototype

(b) Discharge-end of prototype

Figure C.14: Loading and discharge-end of prototype shuttle car

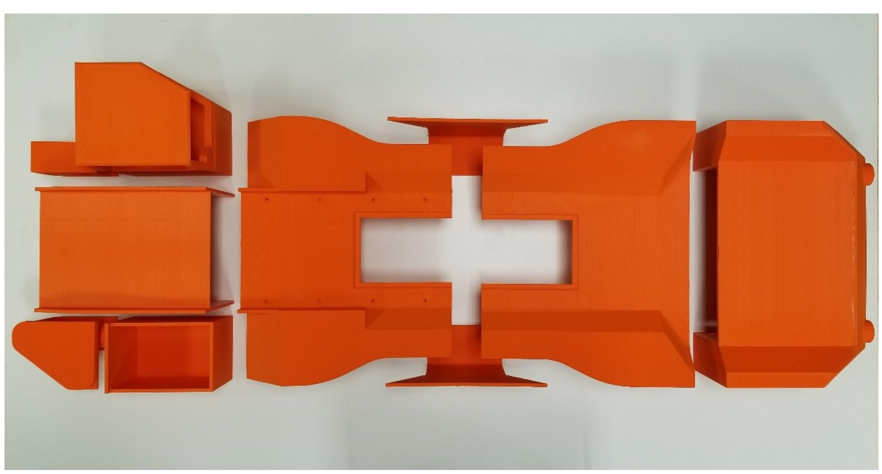


Figure C.15: Exploded view of 3D-printed body parts of second prototype

Figure C.16: View of underside of second prototype shuttle car

Table C.5: Traction motor controller specifications

Manufacturer and model	Roboteq SBL 2360 60V 2x20A BLDC motor controller
Voltage rating	10-60 V
Current rating	Up to 30 A per channel (20 A continuous) Up to 60 A, with channels paralleled
Control modes	Open or closed loop speed mode, position mode, torque mode
Command modes	USB, serial, 0-5 V analog, pulse (RC)

Figure C.17: Initial layout of the sensors on the 1:6 scale shuttle car prototype

C.2 Lab-Scale Shuttle Car Instrumentation

The initial design was to instrument the lab-scale prototype using four LiDAR units and number of ultrasonic sensors positioned around the perimeter of the car. The prototype was equipped with 4 LiDAR units (gray boxes) which were placed above the wheels (see Figure C.17.

The 2D LiDAR scanner used for the lab-scale shuttle car prototype was the RPLiDAR A1M8 scanner developed by SLAMTEC, which is a low-cost 360^o laser scanner with a 12-meter range. Table C.6 summarizes its performance specifications. The point data collected can produce a map of the surrounding environment. A housing assembly was designed, and 3-D printed to facilitate mounting the sensor on the lab-scale shuttle car.

Table C.6: RPLiDAR A1M8 performance specifications (Shanghai Slamtec Co., 2021)

Measurement Range	0.15 to 12 m
Angular Range	0 to 360 degrees
Measurement Resolution	<1% of actual distance
Angular Resolution	$\leq$ 1 degree
Time for single measurement	0.5 ms
Measurement Frequency	$\geq$ 4000 Hz
Scan Frequency	5 to 10 Hz (typical 5.5 Hz)

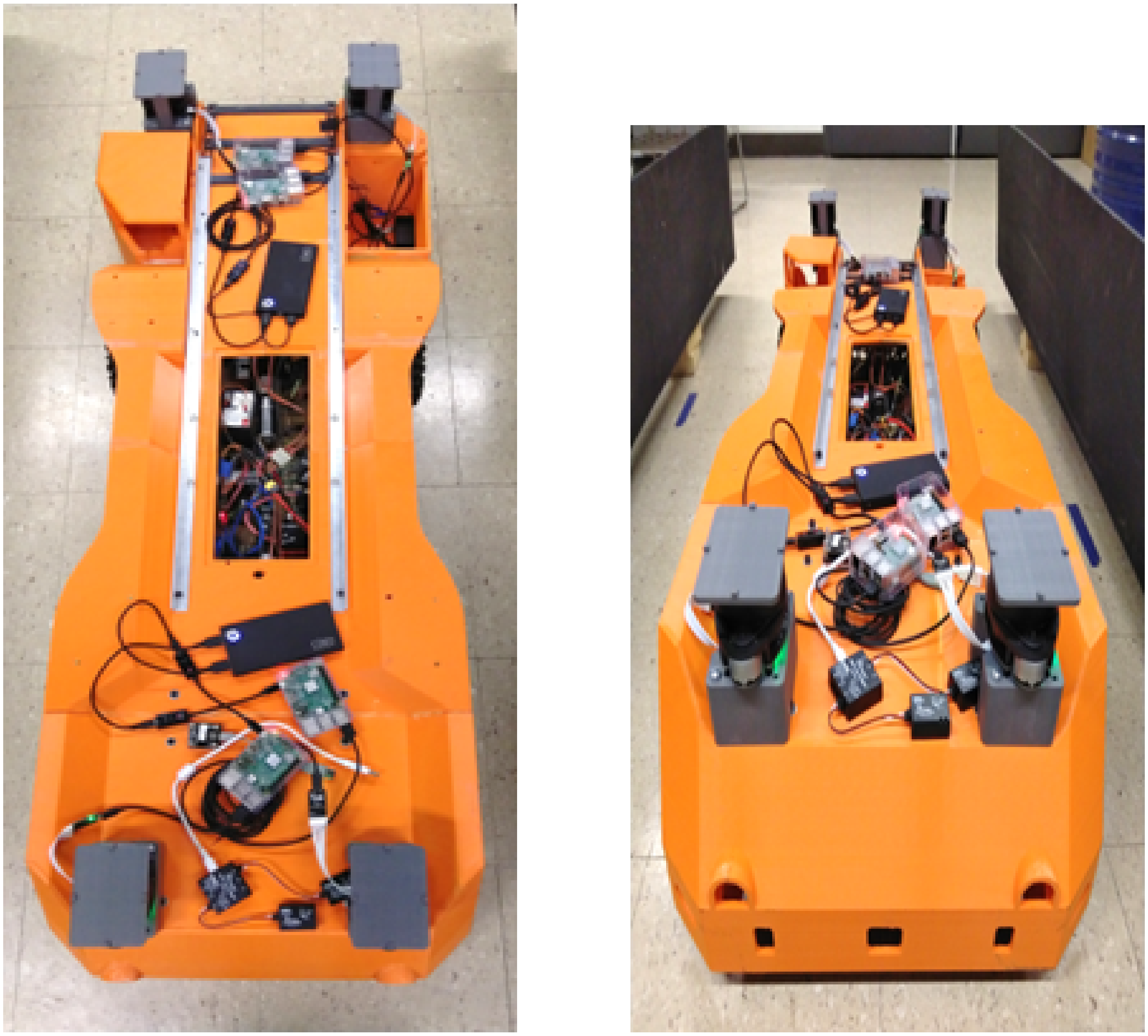
Based on feedback from the navigation algorithm it was decided to modify the initial design and relocate the LiDAR scanners and the ultrasonic sensors. This modification was deemed necessary to improve the “visibility” of the LiDAR scanners when the vehicle approaches an intersection (see Figure C.18). Consequently, the relocation of the ultrasonics sensors was necessary because of the rearrangement of the LiDAR scanners. Also, new (higher performance) ultrasonic sensors replaced the older units. Their replacement was decided based on the relatively low quality and performance of the current units. Note that the number of the LiDAR scanners ensures sufficient redundancy, with the added advantage of higher resolution when compared with the ultrasonic sensors.

The ultrasonic sensor used was the Sonar Phidget DST1200_0 sensor (Phidgets, 2023). This device was selected because of its relatively low cost and convenience of use. The DST1200_0 has an ultrasonic transmitter that transmits a series of eight pulses that are reflected back to the DST1200_0 receiver. The elapsed time between sending and receiving the signal is used to determine distance to the reflected surface. The sensor has a range of 40.0 mm to 10.0 m and has a maximum working current of 5.6 mA. Testing with the DST1200_0 has shown that it has sufficient accuracy to determine the prototype distance to the simulated coal ribs when the shuttle car is positioned approximately parallel to the rib, e.g., within $\pm 30^o$, and the sensor is mounted perpendicular to the direction of travel. Figure C.19 shows the DST1200_0 ultrasonic sensor, and Table C.7 lists its specifications. The DST1200_0 comes with an enclosure to facilitate mounting the sensor on the lab-scale shuttle cars.

Table C.7: Sonar Phidget DST1200_0 ultrasonic sensor specifications (Phidgets, 2023)

Dimensions (with enclosure)	75.3(L)x31.8(W)x21.7(H) mm
Operating Temperature	-40 to 85 ^{o}C
Operating Frequency	1 to 10 Hz
Minimum range	40 mm
Maximum range	10 m

Figure C.20 shows four Phidget ultrasonic sensors which were mounted on the discharge-end of the prototype shuttle car.



(a) Top view - note the custom LiDAR housing

(b) Perspective view

Figure C.18: Lab-scale prototype with reconfigured arrangement of sensors

The ultrasonic sensors do have the advantage over the LiDAR scanners in detecting obstacles at small distances and provide an additional and independent layer of proximity detection. An additional modification (Figure C.18) was the reduction of the size of the driver's cab. This was deemed necessary because the asymmetrical nature of the prototype's outline caused by the driver's cab imposes additional complexities to the navigation algorithms. The initial size of the driver's cab was designed based on drawings of a Joy 10SC-32B shuttle car provided by Komatsu Mining Corp. However, in this specific model, the driver's cab (which is located at discharge-end of the vehicle) extends outwards more than any other part of the shuttle car on the operator's side. This is not true for all the shuttle car models that are used commercially. As an example, the Auxier Welding model, which was planned to be the test vehicle for the full-size tests, is a center-drive

Figure C.19: Sonar Phidget DST1200_0 ultrasonic sensor for distance measurement (Phidgets, 2023)

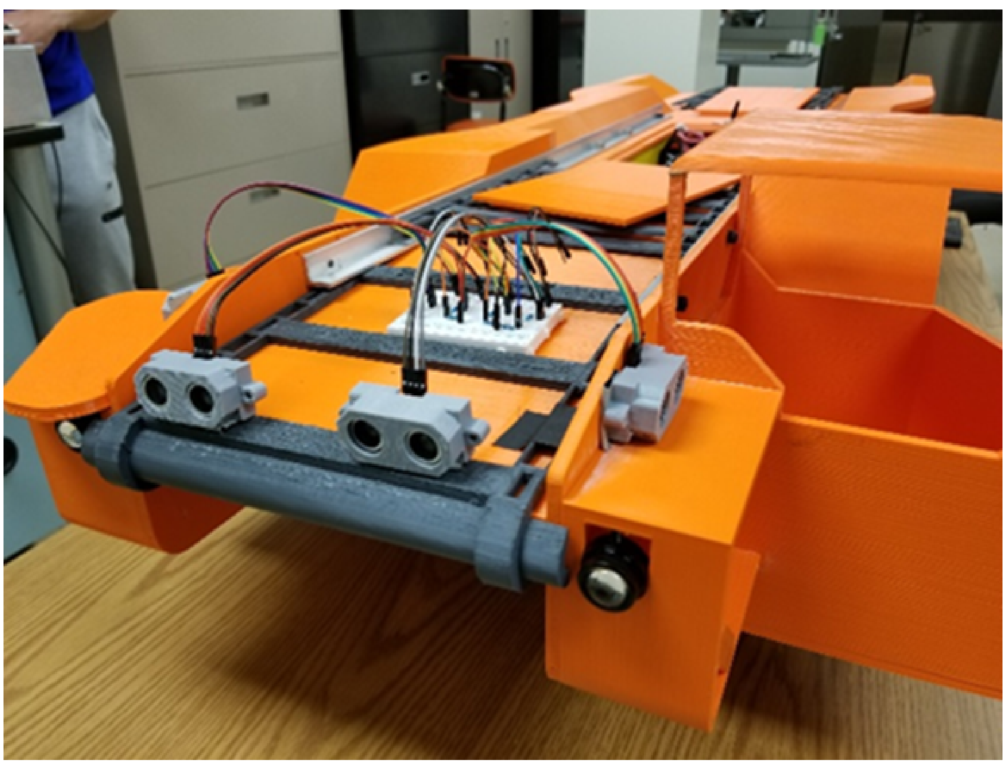


Figure C.20: Ultrasonic sensors mounted on discharge-end of lab-scale shuttle car

design and has a more symmetric outline (see Figure G.1 in Appendix G).

Thus, the reduction in the size of the operator's cab would not affect the validity and the performance of the developed navigation system when implemented on the retrofitted full-scale shuttle car.

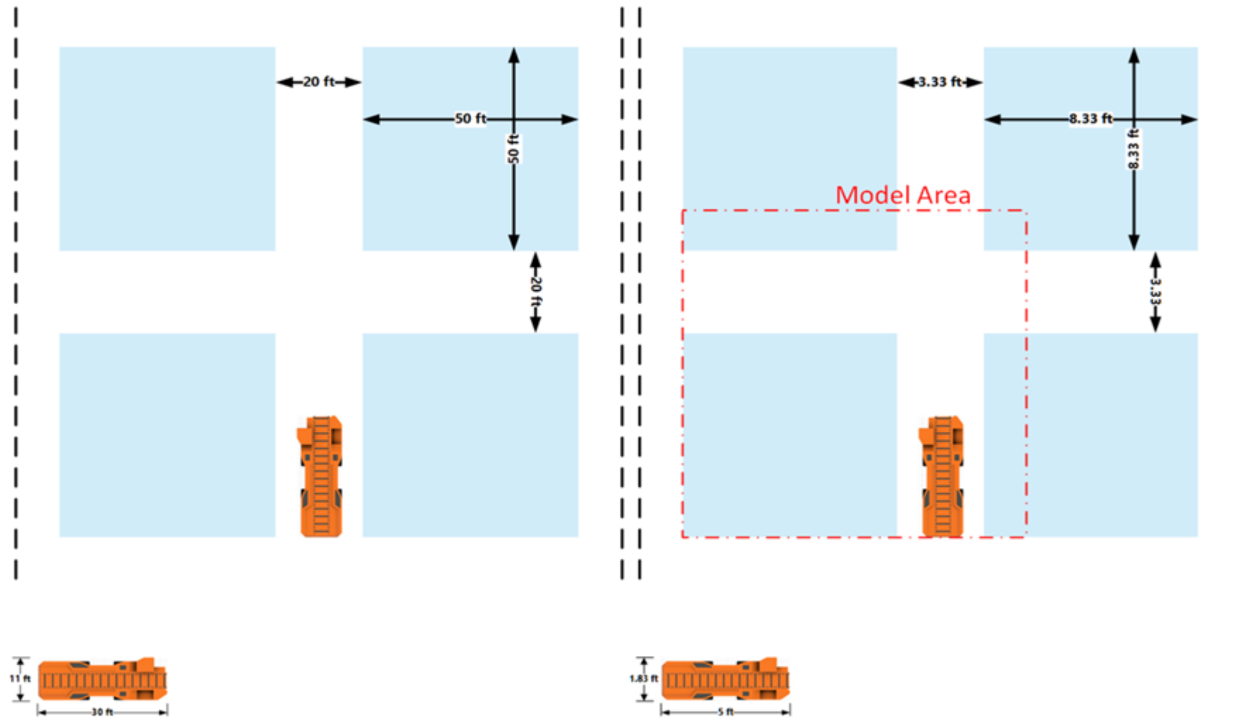


Figure C.21: Illustration and dimensions for the actual (left) and the scaled (right) mine with 90 degrees angled crosscuts.

C.3 Testing Area

A scaled mock mine plan made of plywood was built in the UK laboratory space. The mock mine plan corresponds to a room-and-pillar operation with 90-degree crosscuts, and simulates 50 by 50 ft pillars and 20 ft wide entries. In comparison, the actual dimensions of the shuttle car that is modelled in this project are 30 ft in length and 11 ft in width.

The lab scaled mock pillars are 8.33 by 8.33 ft, while the entries and the crosscuts are 3.33 ft wide. This plan corresponds to a 1:6 scale which matches the scale of the lab-scale shuttle car. The dimensions of the actual and scaled mine plan as shown in Figure C.21.

Figure C.22 shows different snapshots of the a shuttle car moving through a room-and-pillar section.

Figure C.23 shows the mock room-and-pillar section which was constructed to test the lab-scale prototypes.

C.4 Development of Initial Navigation Systems

In addition to the one-sixth scale prototype with emphasis on replicating important dimension and tramming aspects (i.e., motors, suspension, chassis, etc.), two small vehicles were also developed simultaneously to test different sensor functionalities. These small cars (NVS01 and NVS02), or testing platforms, were used for testing autonomous navigation systems. These systems are briefly

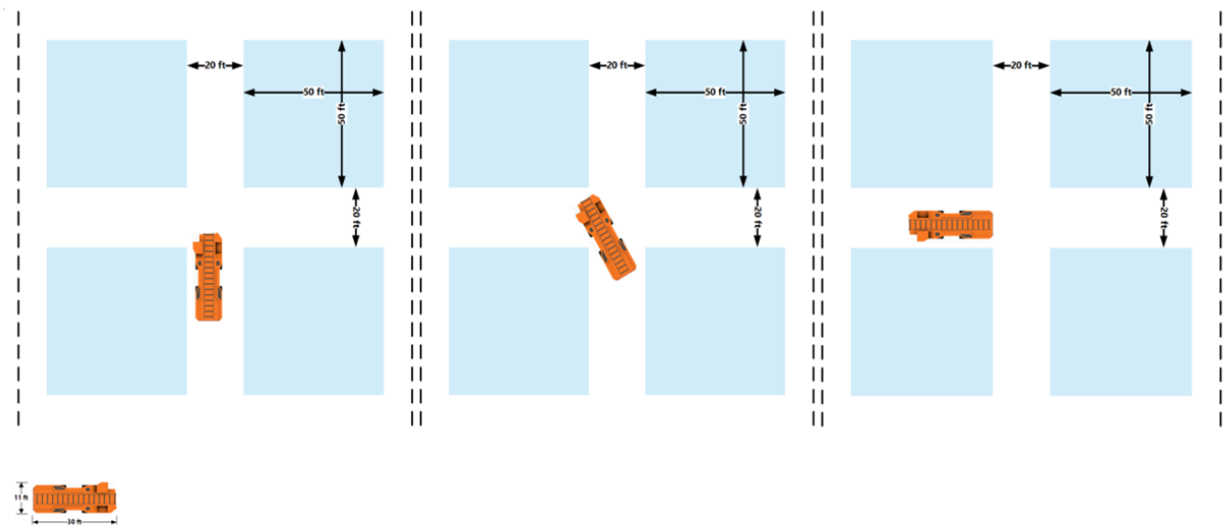


Figure C.22: Different snapshots of the shuttle car route in a mine with 90 degrees angled crosscuts.

described below. The navigation algorithm and system that were implemented both for the lab-scale and full-size shuttle cars are discussed in Appendix E.

C.4.1 Navigation System 1 (NVS01)

Materials

The development of the NVS01 is based on a consumer-grade chassis equipped with several sensor modules and a microcontroller. The chassis is a skid-steer, 4-wheel drive chassis. Each wheel is powered by a DC motor with the motors of the same side connected in parallel, and thus move at the same speed in the same direction. Although the actual shuttle car is not skid-steered, this type of steering for the NVS01 system was used for simplicity. From a practical point of view, the type of steering does not affect the perception and navigation system of the small scale autonomous vehicles, because the software that controls the motors can be easily modified by changing a few lines of code to integrate it with the lab-scale prototype.

The motors of the NVS01 system are controlled with an Adafruit Motor Shield v2.3 which can move the motors at various speeds and in both directions. The microcontroller is an Elegoo UNO R3 microcontroller which executes the script that controls all the sensors and the motor shield. An Adafruit SD Card Shield was used for logging the sensors data. The card communicates with the microcontroller via the I2C protocol.

Several HC-SR04 ultrasonic sensors were mounted on the small scale car for measuring distances to walls and other obstacles, while an inertial measurement module (HiLetgo MPU9250/6500 9-Axis 9DOF) was used for measuring the orientation and the acceleration of the vehicle. Finally, two 12V batteries were used to supply the microcontroller board and the motor shield (see Figures C.24 to C.27).

Figure C.23: Mock mine used to testing the lab-scale prototypes

Results

The above-described system was not always capable of avoiding obstacles, even in simple scenarios. Though the system was able to drive in a straight line and turn if it was programmed to do so, it would not always stop if an obstacle (e.g., a wall) was detected ahead in its path, nor would it always turn away from a wall as intended if the distance measured from the side ultrasonic sensors was below a threshold.

The setbacks encountered in this first attempt can be attributed to technical issues and could be overcome by using more reliable components and developing more sophisticated software, if this vehicle were to be the lab-scale platform used. In addition, another challenging issue encountered was the incompatibility between the SD card shield and the inertial measurement unit. Despite both working when connected to the microcontroller individually, they could not communicate with the microcontroller when they were both connected at the same time. This is because both of these modules use common pins of the microcontroller to communicate with it to send or receive data.

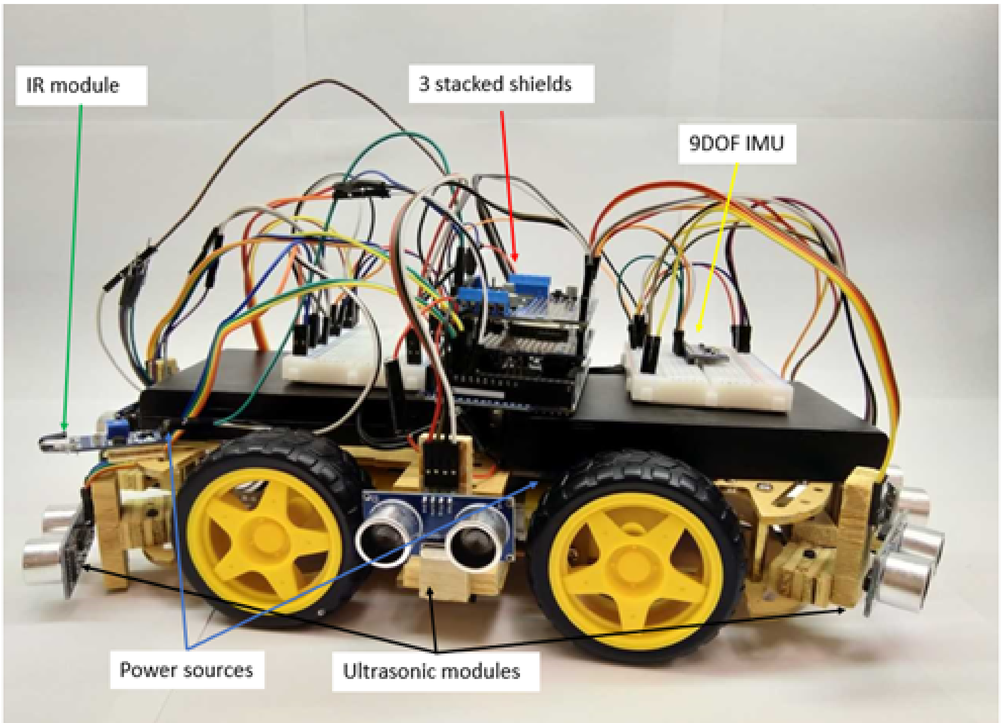


Figure C.24: Side view of the NVS01

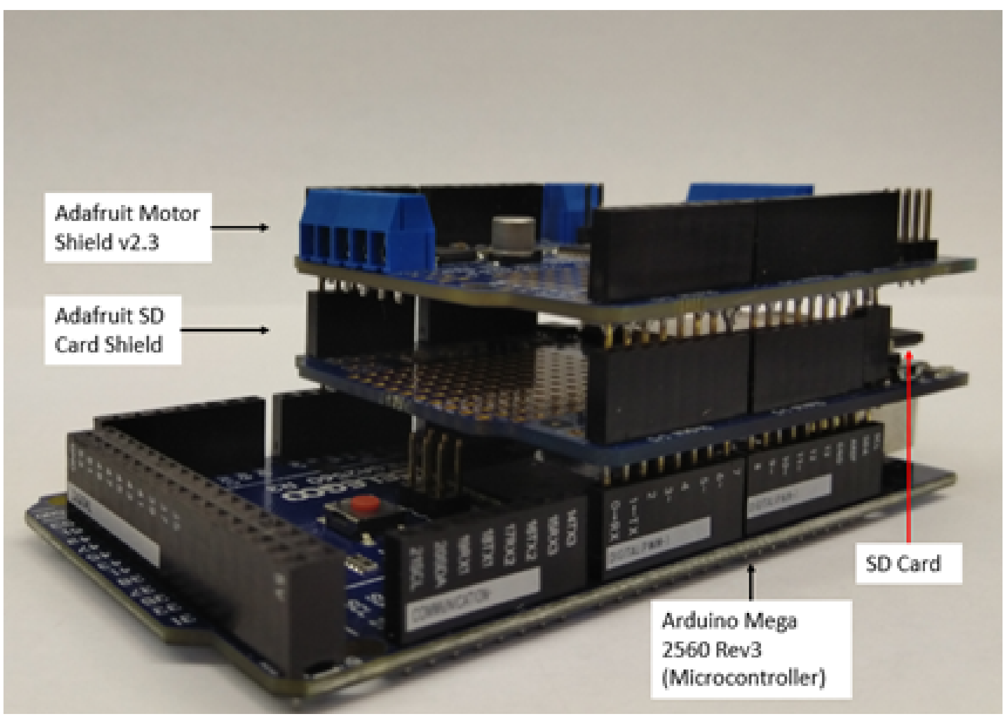


Figure C.25: Detail of the stacked shields of the NVS01

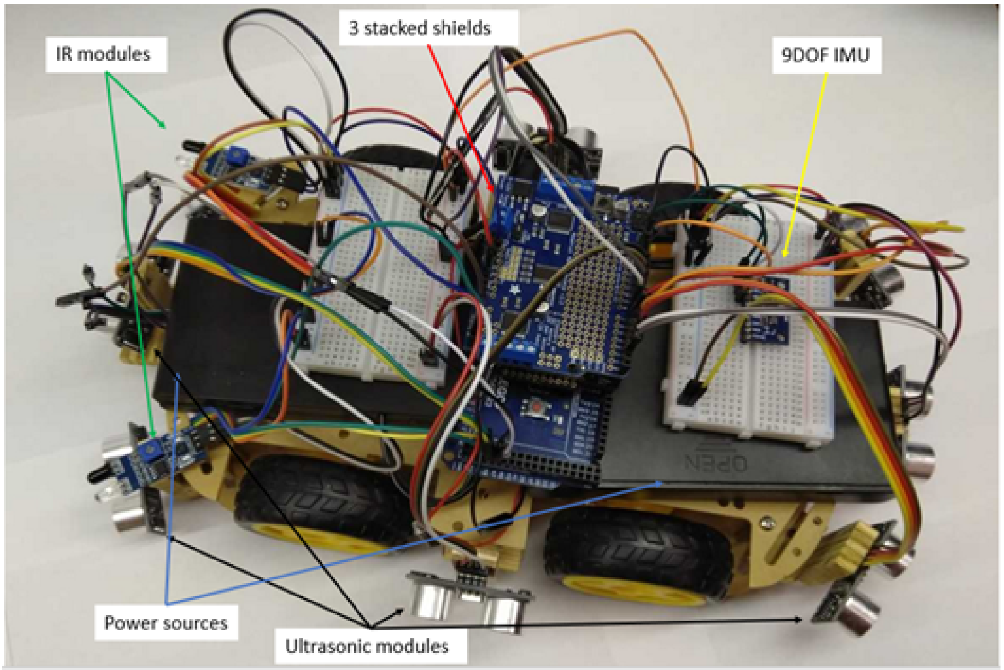


Figure C.26: Top view of the NVS01

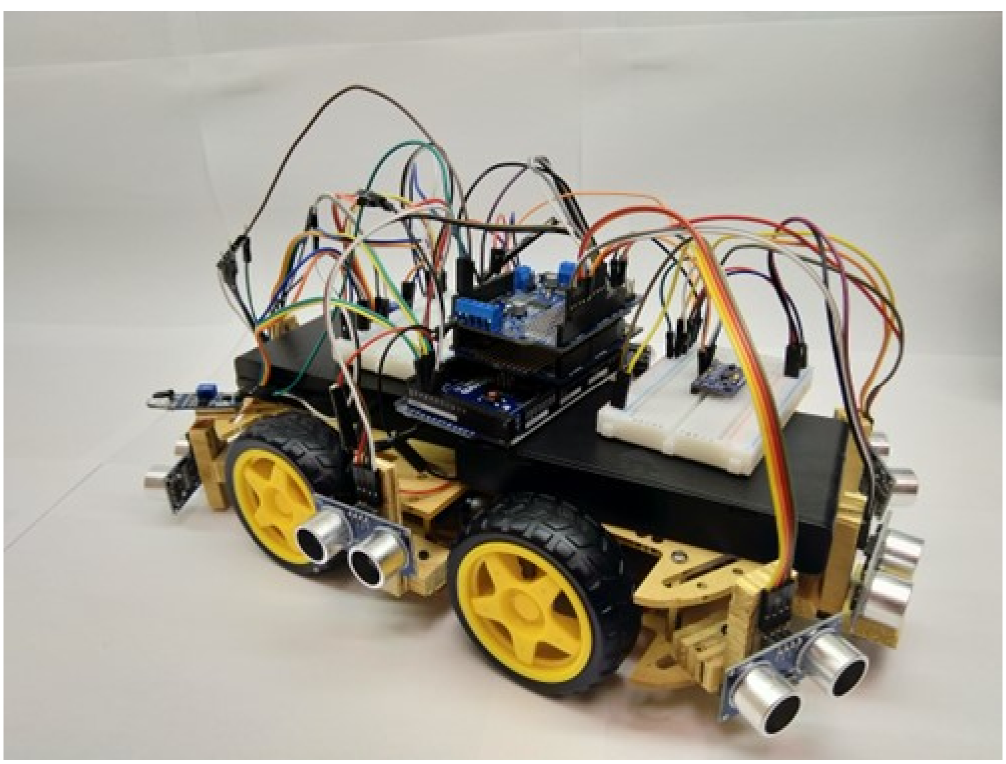


Figure C.27: View of the NVS01 from an angle

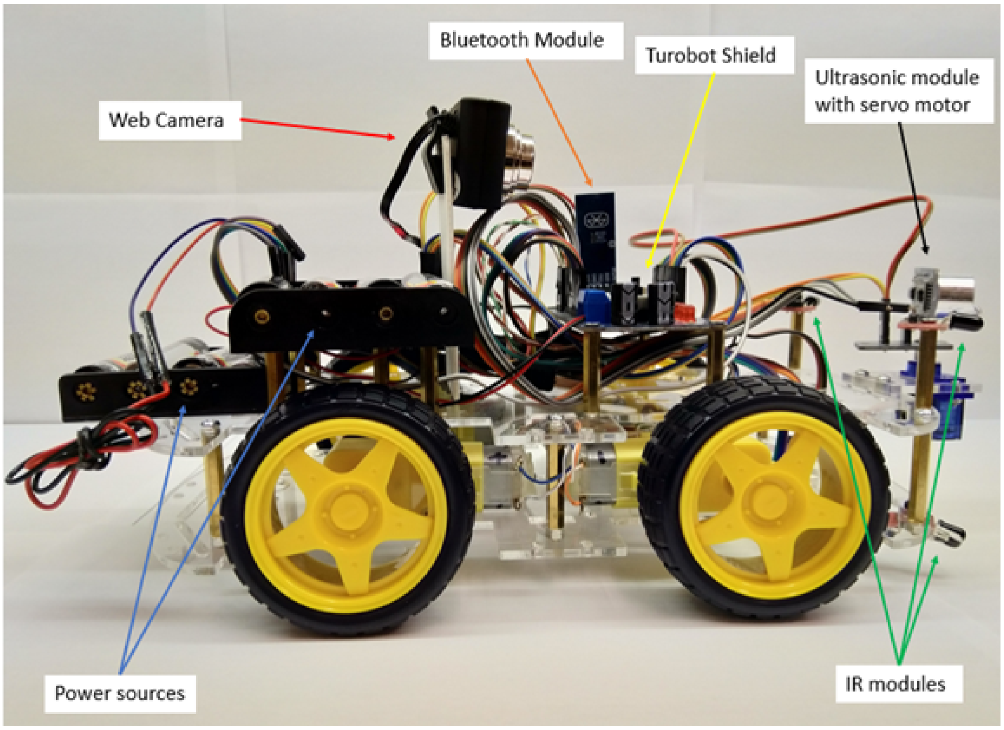


Figure C.28: Side view of the NVS02

C.4.2 Navigation System 2 (NVS02)

Materials

The development of NVS02 was also based on a consumer-grade chassis equipped with several sensor modules and a microcontroller. This vehicle was similar to NVS01 in chassis, but with with different controllers and sensors.

Each wheel is powered by a continuous servo motor allowing for 4-wheel drive. As with NVS01, NVS02 also used skid steering for simplicity. (These devices were used for perception and navigation, not steering control.) The motors of the NVS02 system are controlled with a Turobot Motor Shield v2.3 which can move the motors independently at various speeds and in both directions. The microcontroller is an Elegoo UNO R3 microcontroller which executes the script that controls all sensors and the motor shield. The card communicates with the microcontroller via the I2C protocol and with a direction command via Bluetooth.

An HC-SR04 ultrasonic sensor is mounted on a swivel for measuring distances to walls and other obstacles in conjunction with Infrared Reflection detection modules for path finding and following. An inertial measurement module (HiLetgo MPU9250/6500 9-Axis 9DOF) was used for measuring the orientation and acceleration. The HC-SR04 can be replaced by a VL53L0X Time-of-Flight Sensor. A web camera could also be added to this system to relay images. (see Figures C.28 to C.30).

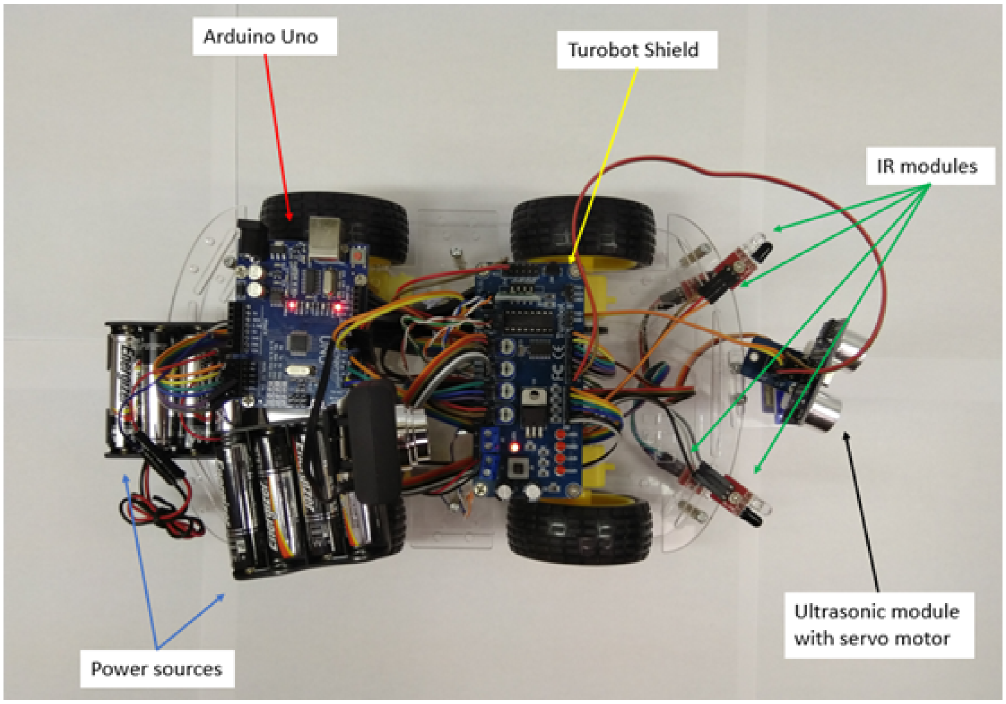


Figure C.29: Top view of the NVS02

Results

This system performed well at avoiding obstacles it encountered, but also required that a lane marker be available to find its way back to the intended path. In the case of a straight path with an obstacle to the right, the system would move to the left until it passed the obstacle, but the lane marker was requied for it to return to the intended path. This result was not ideal for working in small areas such as a table top, but it did demonstrate that directional helpers made from reflective material could be utilized for the full-scale shuttle car. Image processing results were disappointing and required a computer to be attached to the Arduino Uno. A combination of these sensors with logic from Simulink was also explored.

C.5 Simulink

This section includes some information regarding the Simulink® platform that was initially considered to be used for the development of the navigation systems. MATLAB contains a number of capabilities for image recognition, data modelling, and signal analysis that are potentially helpful for the sensor fusion that was employed in this project. There is a well-defined interface from MATLAB to embedded controllers that are useful in practice and in prototyping, such as Arduinos and Raspberry Pis. Implementing these useful and time-saving features that are built into MATLAB on the embedded systems previously required that a computer be interfaced to the controller, because the controllers require a particular programming language and compilation. Simulink is the bridge between the mathematical power of the MATLAB language and the embedded controller that can

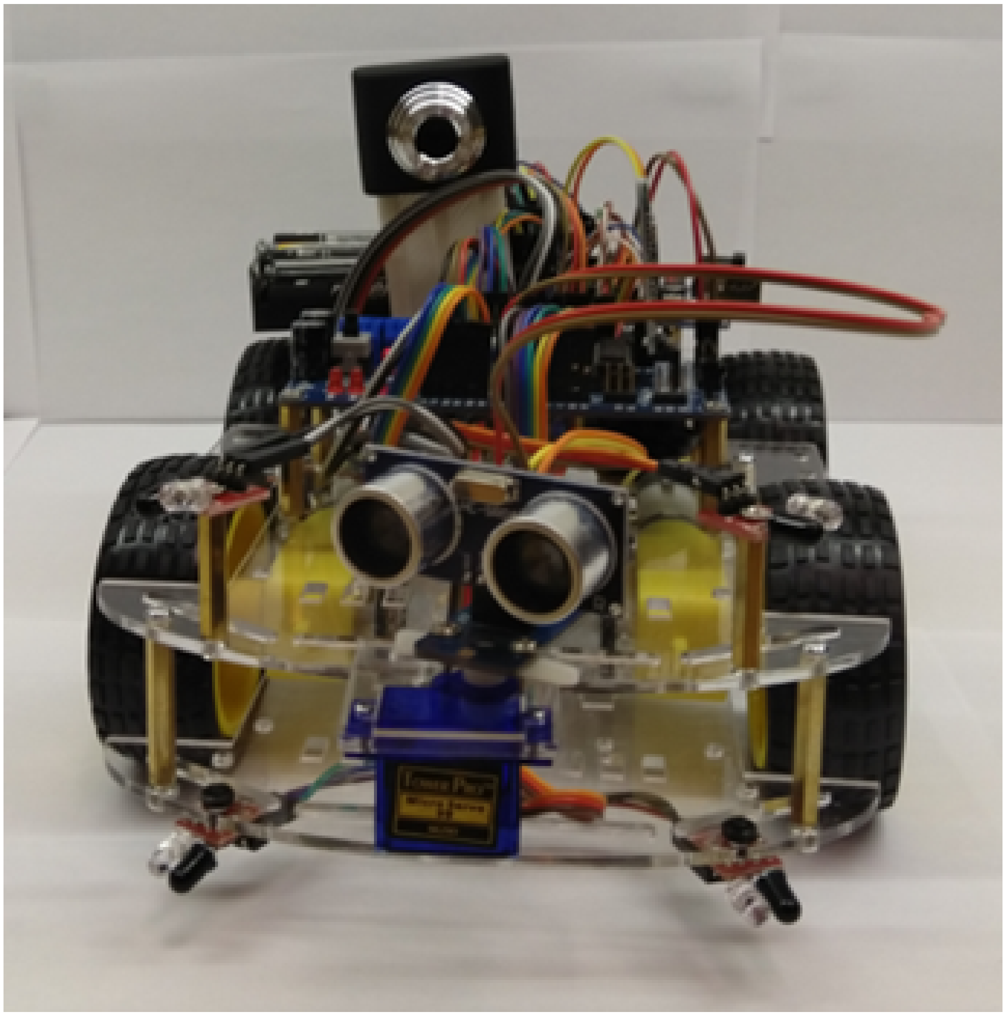


Figure C.30: Front view of the NVS02

interface directly with the real world.

The Simulink programming method uses a collection of visual blocks arranged to process signals and change states, similar to ladder logic programming. However, the visual blocks are programmed with the power of the MATLAB language and toolboxes. It was designed for embedded systems and is able to run the program on the embedded system while connected to a computer for debugging purposes, or run natively on the embedded system without a computer connected. This allows for rapid prototyping of sensors connected to embedded systems that are also able to process data from sensors, including cameras, to control real-world components such as servos and relays. One such example is the Arduino Engineering Kit, photos of which can be seen in Figures C.31 to C.33. Although the testing activities with NVS01 and NVS02 systems and Simulink were limited, a great deal of useful information was derived from the tests, e.g., limitations of ultrasonic sensors and issues with interfacing various sensing and control components with the microcontroller.

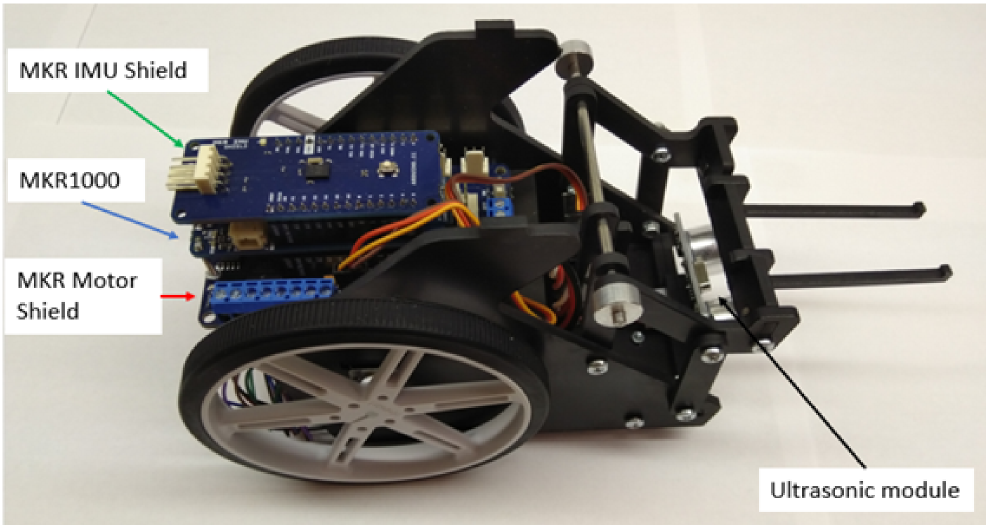


Figure C.31: Side view of the forklift

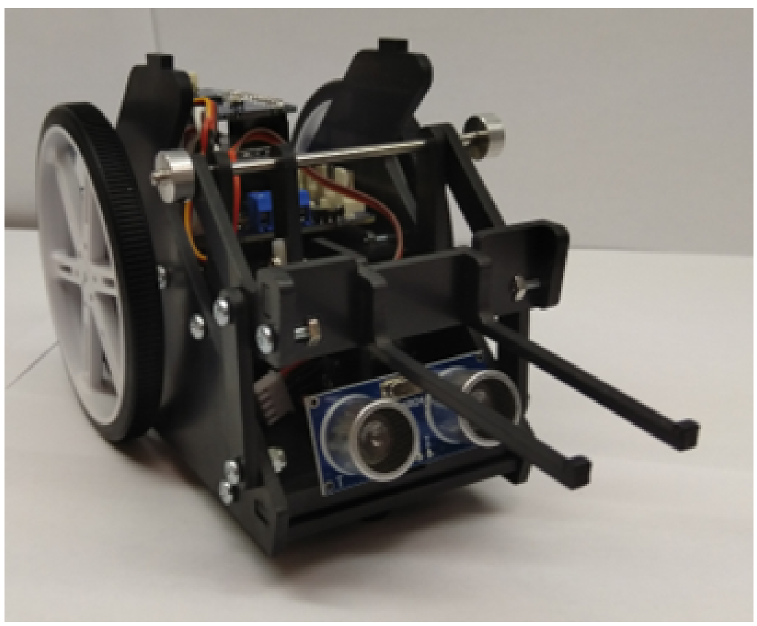


Figure C.32: Front view of the forklift

C.6 References

1. Shanghai Slamtec Co. (2021), "RPLIDAR A1", available online at: https://www.slamtec.com/en/Lidar/A1S (accessed on January 18, 2021)

2. Phidgets Inc. Sonar Phidget. Available online: https://www.phidgets.com/?&prodid=973 (accessed on August 31, 2023).

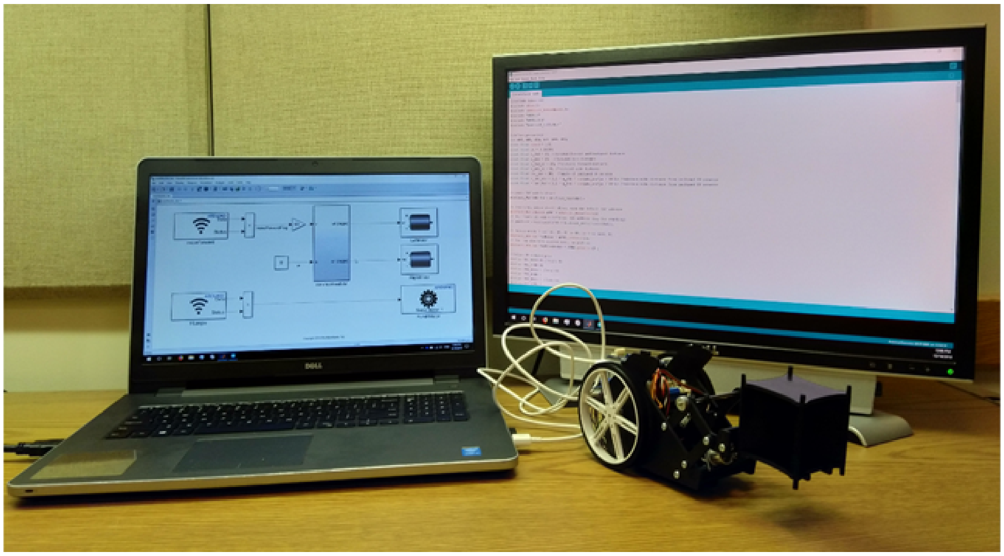


Figure C.33: Connect forklift with Arduino IDE and Simulink

Appendix D

Data Management System and Mapping Tool for the Autonomous Shuttle Car Lab-scale Prototypes

D.1 Introduction

This appendix describes the Data Acquisition and Management System developed for the autonomous shuttle car lab-scale models. A generalized data flow for the Data Acquisition and Management System is presented, followed by a detailed description of the Navigation System. The two major subcomponents of the Management System, the Website Visualization and the Decision Agent are described in detail.

Table D.1 presents the abbreviations shown in this Appendix.

Table D.1: Abbreviations

Acronym	Definition
AHS	Automated Haulage System
CDS	Collision Detection System
HMI	Human-Machine Interface
ESB	Emergency Stop Button
LED	Light Emitting Diode
LHD	Load Haul Dump vehicle
ODS	Obstacle Detection System
RF	Radio Frequency
RFID	Radio-frequency identification

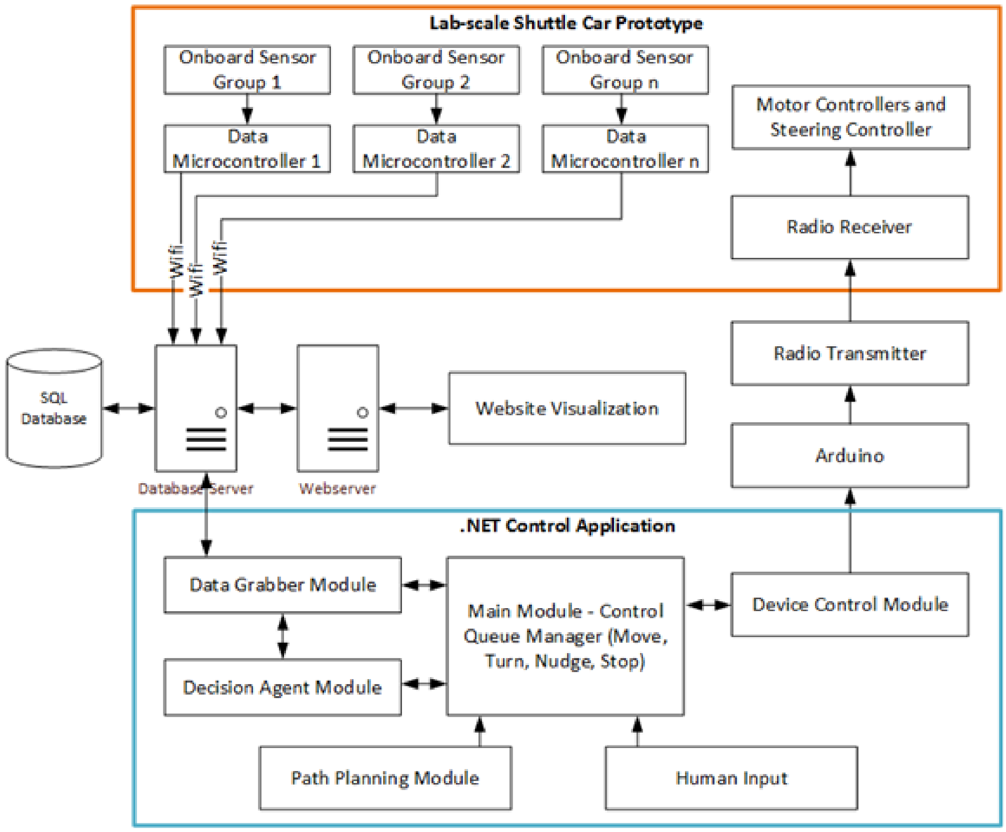


Figure D.1: Data and information flowchart for the shuttle car lab-scale prototype

D.2 Data Acquisition and Management System

D.2.1 Flowchart of Data Collection and Management System

The flowchart shown in Figure D.1 is a representation of the flow of sensor data between the lab-scale shuttle car prototype and the data management module as well as information flow between the Main Control application and the lab-scale prototype. The data management module supplies the .NET control application with information needed to generate and transmit commands to the shuttle car to achieve autonomous navigation of the vehicle. The setup of the sensors and information flow is modular, allowing multiple sensors and processing programs to run in parallel to each other so that operation may persist even if all sensors are not active and sensors can be added or subtracted at will.

The process starts with commands from the Human Input or the Path Planning Module. Multiple groups of onboard sensors collect information about the pose (position and orientation) and speed of the shuttle car which is processed by onboard microcontrollers and sent via Wi-Fi to the database server. More complex information, such as calculations or a map generated from LiDAR data, can also be sent to the database server. This data stream provides information for three purposes: (1) viewing the data through the visualization website (primarily for operator use), (2) processing by the decision agent module, and (3) archiving via a database.

The blue box includes all the modules that comprise the .NET Control Application, which is responsible for controlling the vehicle. The path planning module is responsible for generating the overall path for the shuttle car, i.e., move forward for x feet, turn right, move forward for y feet, turn left, etc. Once a plan is generated, the command queue is loaded with all the necessary commands for following the specific path. More details on the navigation system are given in the next section.

The decision agent module uses a set of rules to analyze the data received and generate a decision for the shuttle car in the form of a command such as nudge left or right, stop, etc. Such commands are sent to the queue manager and modify the predetermined plan specified by the path planner. If the vehicle is not moving and therefore, there is no change in the data collected, the decision agent will not issue any commands.

The human is always in control of the command queue. Once a command is sent to the shuttle car the queue manager will be ready to execute the next command, but will also seek the "advice" of the decision agent. This loop will continue to execute until a stop operation is executed in the control queue.

Once a command is finalized in the control queue (following potential input from the decision agent and or human input), the queue manager will transmit the command via a serial port to an Arduino that converts the signal to be accepted by the radio frequency (RF) communication setup. The RF signal is then transmitted to an RF receiver onboard the shuttle car. Once received, the command is transferred to the motor and steering controllers on the prototype that executes the command.

Every single command sent to the shuttle car follows the logic described above. The control queue can be easily preloaded with all the commands necessary to execute multiple trips between the miner and the feeder-breaker.

The flowchart shown in Figure D.2 represents the proposed data and information flow for the system on a PLC-driven full-scale shuttle car. The overall layout of the system is similar to the prototype configuration, with some notable modifications.

The most significant change is the use of the shuttle car PLC system, in place of the respective .NET module, which is used to communicate the commands of the control queue and decision agent modules to the shuttle car. The PLC system will be a more robust means of communication and will also facilitate human input to the network as needed. The other notable modification would be the implementation of an advanced (but secondary) decision agent that will be able to send more complex information back into the database. This advanced agent would perform functions that require additional processing time and output more complex results, while the primary decision agent is constantly sending simpler commands to the control queue. This additional processing capability will allow for better decisions to be made and can greatly improve the performance of the navigation. In order to facilitate communication and decision-making speed, some of the server components will be hosted on the shuttle car itself to reduce communication latency.

The rest of the system remains largely the same; however, several more subgroups of onboard sensors will be present to improve the accuracy and safety of the vehicle's movements. As with the prototype, Wi-Fi will be utilized to facilitate communication between onboard hardware and the external data processing systems.

Due to supply chain issues, the PLC-driven shuttle car was not available for testing. As a result, the data and information flowchart was modified to accommodate a conventional shuttle

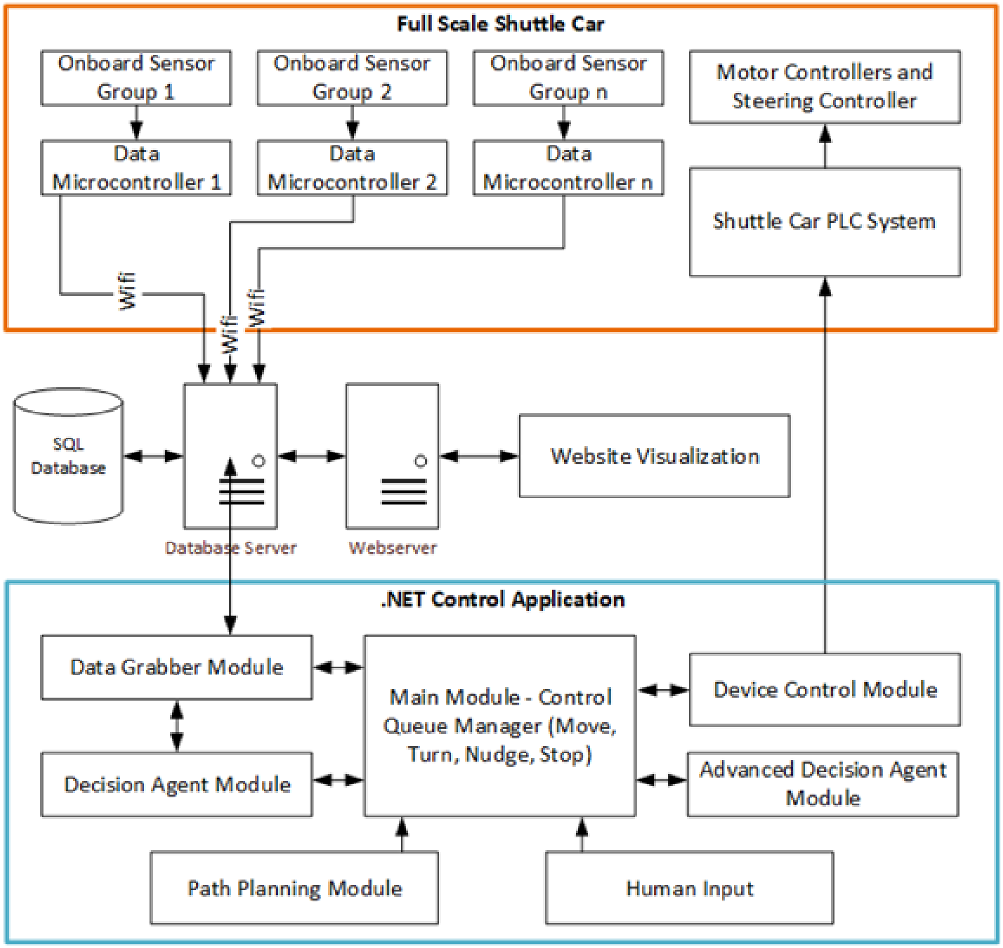


Figure D.2: Proposed data and information flowchart for a PLC-driven full-scale shuttle car

car as shown in Figure D.3. An Arduino unit was employed to communicate with the actuators that were installed in the shuttle car. Communication between the laptop and the Arduino unit was initially done using a serial port but was later upgraded to a CAN-bus interface to eliminate some of the latency issues (the serial port is a slow connection).

D.3 Database Schema

An SQL database schema was developed to handle the data collected from the onboard sensors. The SQL database is populated in real-time by data received from the sensor microcontrollers. The database server accepts asynchronously the SQL post requests that include the collected data. At the same time, the database server responds to data requests from the data processing and visualization node as well as the webserver used for visualization of the collected data (see Figure D.3).

The time needed to post the collected data to the database includes the time for the microcontroller to connect to the database over the available network protocol as well as the time to post each measurement to the SQL database. Thus, the update rate for the different data streams is de-

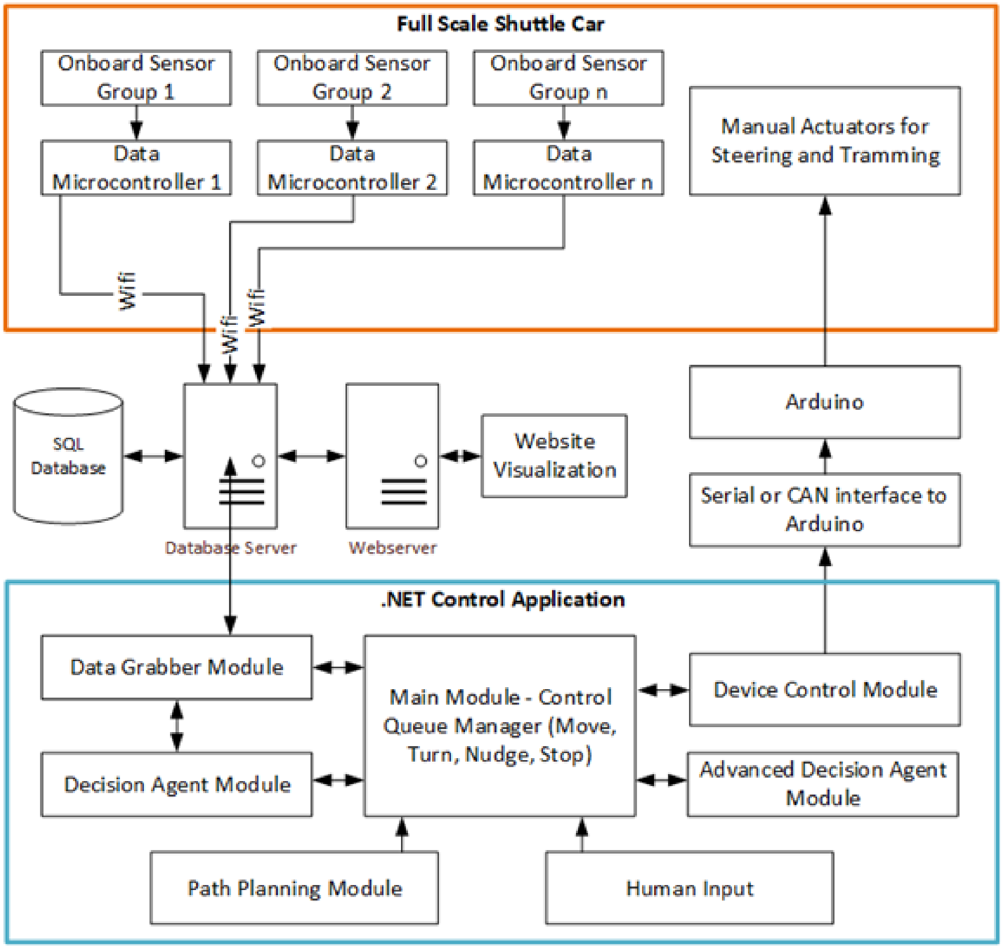


Figure D.3: Proposed data and information flowchart for a conventional full-scale shuttle car

termined by three main factors: (i) the maximum update rate of the sensors, (ii) the number of scans performed per data collection cycle, and (iii) the time needed to post the data to the SQL database.

For example, Table D.2 summarizes the effective update rates for the lab-scale LiDAR sensors as calculated by the data collection microcontrollers. The average effective update rate from the four lab-scale LiDAR scanners is about 135 ms or 7.40 Hz.

Table D.3 depicts an example of data stored in the SQL database as collected from the onboard sensors. Each sensor is designated by a specific name so that the front-end routines that process and visualize the data can easily retrieve the respective sensor data. Sensor names are 6-8 characters long, and each character pair is used to denote specific information about the sensor. The first pair denotes the type of sensor, US for ultrasonic or LR for the LiDAR scanner; the second pair denotes the longitudinal position of the sensor on the prototype, DS for discharge end or LD for loading end; the third pair denotes the lateral position of the sensor on the prototype, OP for operator side or OF for off-side; and the fourth a pair is used for denoting the pointing direction of the point sensors (only the ultrasonic sensors need this descriptor), OP for operator side, OF for off-side, IB for inby direction or OB for outby direction. Moving inby corresponds to movement towards the active face, while moving outby corresponds to movement away from the face. The data collected

Table D.2: Effective update rates of onboard sensors (calculated by the data collection microcontrollers

Sensor	Longitudinal Position	Transverse Position	Update Rate (Hz)	Update Rate (RPM)	Update Rate (ms)
LRLDOP	Loading End	Operator side	7.19	431.44	139.07
LRLDOF	Loading End	Opposite/Off side	7.82	469.23	127.87
LRDSOP	Discharge End	Operator side	7.44	446.13	134.49
LRDSOF	Discharge End	Opposite/Off side	7.14	428.11	140.15

from the 2D LiDAR units are stored as a series of arrays that contain three numbers, namely [signal quality, angle, and distance]. As shown in rows 1 and 15 of Table D.3, each such triplet is registered in the SQL database using a comma to separate the three values and is enclosed in parentheses.

Measurements by the LiDAR scanners are formatted into an array of triplets in the form of [signal quality, angle, distance], while measurements by the ultrasonic sensors include only a value for distance. Each measurement sequence is paired with the designated name of each sensor as will be discussed in the following section. The data packet for each sensor type varies in length, which does not vary significantly between different measurement cycles.

Whenever the server receives a record, the time that record is created (current timestamp) is also recorded through an event triggered by the record insertion process. These times can be used to calculate another effective update rate for each sensor. Note that this update rate is the rate the database receives a new record from a specific sensor, as opposed to the effective update rate described previously which corresponds to the rate the microcontroller sends out a new record to the database. These two effective update rates are different because of latencies in sending and/or recording data. The average update rate for the LiDAR scanners is about 136 ms, which corresponds to an update frequency of 7.35 Hz, while the average update rate of the ultrasonic sensors is about 101 ms or 9.94 Hz.

The maximum sensor update rate is determined by its specifications. In some cases, the user can select any update rate less or equal to the maximum rate. In general, more advanced sensors have higher update rates. The maximum update rate of the ultrasonic sensors used in this project is 10 Hz or 100 ms per measurement, while the maximum update range of each of the LiDAR scanners is 10 Hz or 100 ms per full scan. However, the measured update rates of the 2D LiDAR scanners are lower than the maximum reported in the specifications. The operating frequency of the 2D LiDAR scanners is between the range of 5 to 10 Hz per scan, with the typical frequency reported by SLAMTEC to be 5.5 Hz (under the condition that the LiDAR scanner retrieves 360 range measurements per scan). However, the average update rate measured in the laboratory by units controlled through the Raspberry Pi 3 B+ microcontrollers is between 7-8 Hz per scan. Because of the higher frequency compared with the typical operating frequency, the number of range measurements collected during one scan is less than 360. The average observed value is 160-175 measurements per scan. Despite the fact that the decreased number of measurements reduces the

Table D.3: Stored data in SQL database

ID	Timestamp(UNIX)	Sensor	Value	Datetime
1	1614368508.95632	LRLDOP	(11, 351.234375, 8191.25) (12, 352.5, 8666.0) (10, 356…	2021-02-26 19:41:48.956
2	1614368509.03309	SLDOPIB	90	2021-02-26 19:41:49.033
3	1614368509.09603	USDSOFOB	4530	2021-02-26 19:41:49.096
4	1614368509.13392	USLDOFIB	120	2021-02-26 19:41:49.134
5	1614368509.14794	USDSOPOB	70	2021-02-26 19:41:49.148
6	1614368509.23482	USLDOPIB	90	2021-02-26 19:41:49.235
7	1614368509.33016	USDSOFOB	4530	2021-02-26 19:41:49.330
8	1614368509.38359	USLDOFIB	120	2021-02-26 19:41:49.384
9	1614368509.41965	USDSOPOB	70	2021-02-26 19:41:49.420
10	1614368509.42756	USLDOPIB	100	2021-02-26 19:41:49.428
11	1614368509.57966	USDSOFOB	4530	2021-02-26 19:41:49.580
12	1614368509.64074	USLDOPIB	100	2021-02-26 19:41:49.641
13	1614368509.63843	USDSOPOB	70	2021-02-26 19:41:49.638
14	1614368509.64557	USLDOFIB	120	2021-02-26 19:41:49.646
15	1614368509.82314	LRLDOF	(12, 350.796875, 7930.25) (14, 352.046875, 8602.0) (12,…	2021-02-26 19:41:49.823
16	1614368509.83725	USLDOPIB	90	2021-02-26 19:41:49.837
17	1614368509.88475	USLDOFIB	120	2021-02-26 19:41:49.885
18	1614368509.95217	USDSOPOB	70	2021-02-26 19:41:49.952
19	1614368509.95389	USDSOFOB	4530	2021-02-26 19:41:49.954
20	1614368510.03386	USLDOPIB	90	2021-02-26 19:41:50.034

resolution of the maps created, the information provided is sufficient for the navigation algorithms and the decision-making processes.

D.4 Sensor Data Visualization Website

Data from the various sensors on the shuttle car prototype, including ultrasonic sensors, IMUs, and 2D LiDAR scanners, are processed with onboard microcontrollers and transmitted via Wi-Fi to a separate database. Data from the sensor packages can then be easily managed and used for further processing. A website has also been developed that provides visualizations of the raw sensor data recorded as it is retrieved from the database. The home page to the online visualization interface is shown in Figure D.4. It depicts the top view of a shuttle car with its various parts labeled with the official terminology. At the bottom of the home page the user can access the main menu of the interface in the form of links (blue underlined labels). The description of the functionality and the features of each option of this menu is detailed below.

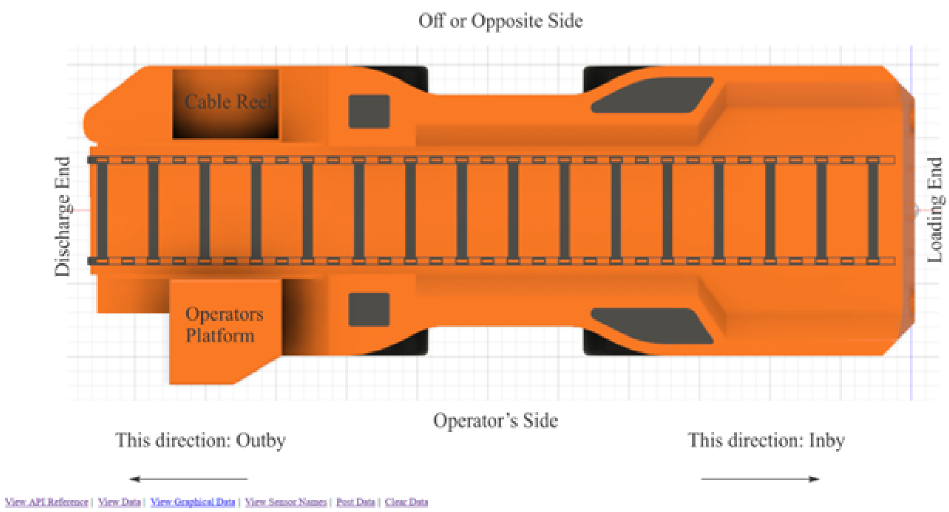


Figure D.4: Home webpage to the online visualization interface

D.4.1 View API Reference

The first option of the main menu leads to an Application Programming Interface (API) Reference page of the Visualization Website. A portion of this webpage is presented in Figure D.5 and Figure D.6.

The API Reference web page summarizes the available data. Data available through the web server belong to two groups (a) raw data uploaded from the onboard microcontrollers and (b) calculated data that correspond to raw measurements. More specifically, the API Reference web page explains the function of the postdata.php and also lists and describes several scripts that can be used for retrieving various sensor data as needed. As shown in Figure D.5 and Figure D.6, the page is divided in 'sections', and each 'section' explains the data that is available and can be retrieved as well as the format options that can be used for formatting result strings. Finally, the web page provides specific examples of how to do so. The scripts provided include functions for:

1. posting data from one or multiple sensors – see sections 'Post Sensor Value (postdata.php)' or 'Post Multiple Sensor Values (postarray.php)',
2. retrieving the list of all currently posted sensor names – see section 'Get Sensor Names (getsensors.php)',
3. retrieving the last time or all recorded times for a specified sensor – see sections 'Get Last Sensor Time (getlasttime.php)' or 'Get Sensor Times (getsensortimes.php)',
4. returning the last value or last n values that a particular sensor has recorded – see sections 'Get the Last Sensor Value (getlast.php)' or 'Get multiple sensor last values (getlastsensors.php)', and
5. returning the last recorded LiDAR sensor value, as an array available in Cartesian or polar coordinates – see section 'Get the Last LiDAR Sensor Value (JSON Array) (getlastrpi.php)'.

The provided scripts further enhance the functionality of the webpage and are particularly useful when troubleshooting and isolating problems that may occur with the multitude of sensors used on the vehicle.

View Data

The View Data label links to a raw data display in the form of plain text, as illustrated in Figure D.7. The raw data are displayed as they are recorded in the database. The plain text display enables copying the raw data to a .txt file so that they can be used by external software. The raw data stream is recorded in the format ‘time, sensor, value’ where ‘time’ corresponds to the timestamp of each measurement collected in Unix time, ‘sensor’ reflects the name of the sensor for which a measurement was collected, and ‘value’ corresponds to the actual measurement. Each line of the plain text file corresponds to a single reading from a particular sensor in the active sensor packages. Note that most sensors output one value per reading, except the LiDAR sensor, which outputs an array of values for each time instant. Moreover, in the case of the LiDAR sensor, each value of the array is enclosed in parentheses and consists of an array of three numbers, namely the quality of measurement, angle in degrees, and distance in millimeters.

This stream can be queried for anomalies or other concerns and can also be supplied with preset values for various sensors or thresholds via the HTTP GET and POST methods. The data stream will continue to populate when the prototype is in operation, however, the displayed data stream can be cleared at any time or converted to a text file for convenient copying to external programs.

Sensor Data labeling convention

In order to differentiate the different sensor data uploaded in the data stream, the team uses a consistent labeling convention of 6-8 characters. All characters are capital letters. The first two letters define the type of sensor and are:

1. US for ultrasonic sensor measurements,
2. LR for LiDAR data,
3. IM for IMU data,
4. RF for RFID data.

The next four letters define the position of the sensor on the shuttle car prototype where the first two letters refer to the position along the length of the car, and the other two refer to the position along the width of the car, i.e., two pairs of letters are used to define the longitudinal position of the sensors, and two pairs to define the transverse position. The former two pairs include DS which means that the sensor is located on the discharge end of the prototype, and LD which means that the sensor is located on the loading end of the prototype. The latter two pairs include OP which means that the sensor is located on the operator-side of the prototype, and OF which means that the sensor is located on the off-side of the prototype. In some cases where four sensors of the same type are located on the centerline of the shuttle car, the following label convention is used: DSDS, MDDS, MDLD and LDLD (where MD stands for ‘middle’).

The first and the last quadruples denote that the sensor is on the discharge- and loading- end, respectively. MDDS means that the sensor is located between the middle and the discharge end of the shuttle car, whereas MDLD means that the sensor is located between the middle and the loading end of the car. Finally, some sensor data need an additional pair of letters that discriminates the measurements of two similar type sensors located on the same part of the shuttle car. For instance, two ultrasonic sensors are mounted at the discharge-end and on the operator side of the shuttle car but point in different directions. One points to the rib on the operator-side of the shuttle car, and one points to the outby direction. In the first case, the last pair of letters is OP, while in the second case, it is OB. Similarly, for the ultrasonic sensor on the loading end, pointing to the inby direction, the last pair of letters is IB. Moreover, the IMU readings need a fourth pair of letters, like the ultrasonic data. However, in this case, the pairs are used to differentiate whether the reading is taken by the accelerometer or the gyroscope, and the axis to which the reading corresponds. Therefore, the pairs AX, AY, AZ are used for the acceleration readings, and the pairs RX, RY, AZ for the angular velocity.

View Graphical Data

The View Graphical Data webpage, as shown in Figure D.8 and Figure D.9, displays a shuttle car model, including a visualization of the various sensor locations on the model and provides information from proximity-based sensors. The view in Figure D.8 specifically shows data from eight ultrasonic sensors, located on the discharge and loading ends of the vehicle. These sensors show the distance, in centimeters, between the sensor and the nearest object. Additionally, the model shows the RFID sensor readings located close to the loading end, and the average IMU readings which are located in various places on the vehicle.

Figure D.9 depicts the part of the webpage below the illustration of the shuttle car and the mounted sensors, where a map as obtained by the LiDAR data is included. The interactive option of defining the refresh time interval for this map is also available. Additionally, the option to enable/disable vocal reading of the proximity sensors, as well as the speed of the reading are offered through this page. These last two elements are useful for troubleshooting and testing purposes.

View Sensor Names

This option of the main menu retrieves the names of all currently posted sensor data in plain text format (see Figure D.10). This simple option is useful for viewing and copying the sensor names that have at least one recording in the database while troubleshooting or testing the prototypes.

Post Data

The Post Data web page provides a tool for the user to manually and online issue POST or GET HTTP requests to the database. As shown in Figure D.11, the webpage provides the necessary textboxes for defining both GET and POST queries, as well as a button to clear the data file recorded by the View Data function (see section D.4.1) without deleting the records in the database. Below the interactive panels for the queries, the webpage also shows the raw data stream in the same format as the one used in the View Data webpage (see section D.4.1).

API Reference

Post Sensor Value (postdata.php)

The **web page** http://10.33.70.246/postdata.php serves three purposes: 1. Example for how data can be accepted by GET and POST 2. Manual Data Entry via GET or POST and 3. Processes incoming data by GET or POST. This web page is the gateway to the data in the API.

example

http://10.33.70.7/postdata.php

Array data should be posted with the POST method and in the ($value_1$ $value_2$ ... $value_n$) ($value_1$ $value_2$ ... $value_n$)$_n$ ... format. Commas(,) should never be used as the delimiter. By including the 'rms' value with the form (any informaiton in this is acceptable) and 'rmshistory' value, then a root mean square value will be calculated for this sensor. This will appear as a new sensor named sensor name + RMS, with the RMS value using the last number of values as indicated by the 'rmshistory' value, if less than the requested number of historical values are available, then less will be used. The RMS does not take time difference between the readings into account, so if a very old value is in the 'rmshistory', then it will be used.

Post Multiple Sensor Values (postarray.php)

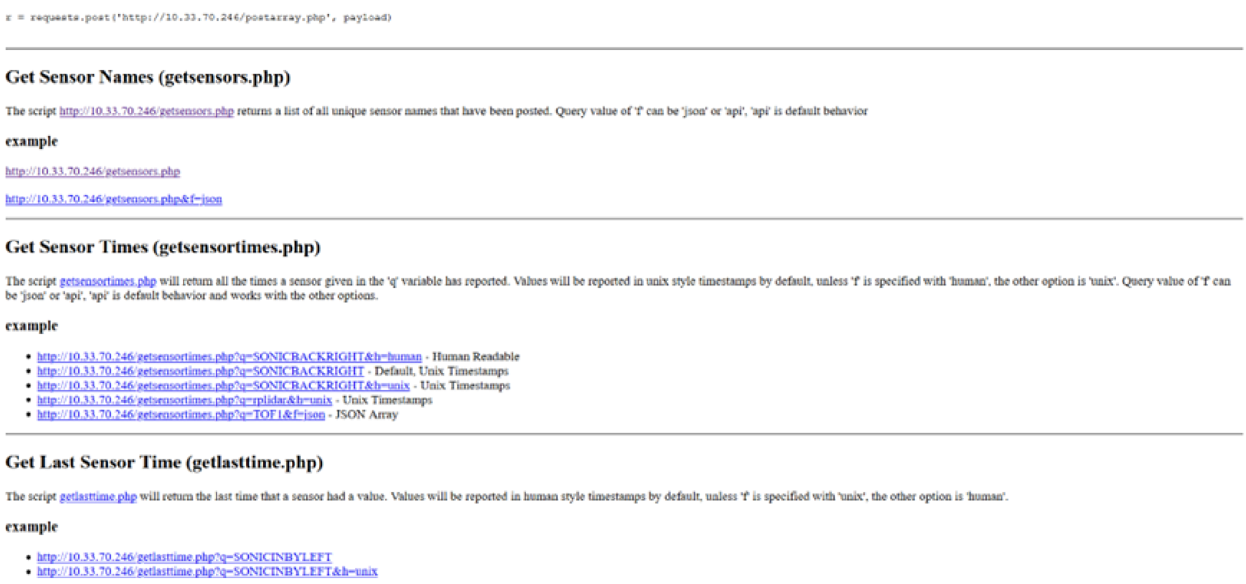
The **web page** http://10.33.70.246/postarray.php will post an HTML array to the data stream. This accepts two HTML arrays in an HTML POST named "sensors" and "values". Both must be of the same length. All the values will be posted to the data stream individually with the same time stamp.

example

Python Code:
```
import requests;

payload = {
'sensors[0]': 'sensor 1',
'values[0]': -12.1,
'sensors[1]': 'sensor 2',
'values[1]': -12.2,
'sensors[2]': 'sensor 3',
'values[2]': -12.3,
'sensors[3]': 'sensor 4',
'values[3]': -12.4,
'sensors[4]': 'sensor 5',
'values[4]': -12.5,
'sensors[5]': 'sensor 6',
'values[5]': -12.6
}
r = requests.post('http://10.33.70.246/postarray.php', payload)
```

Figure D.5: API Reference webpage (1/2)



```
r = requests.post('http://10.33.70.246/postarray.php', payload)
```

Get Sensor Names (getsensors.php)

The script http://10.33.70.246/getsensors.php returns a list of all unique sensor names that have been posted. Query value of 'f' can be 'json' or 'api', 'api' is default behavior

example

http://10.33.70.246/getsensors.php

http://10.33.70.246/getsensors.php&f=json

Get Sensor Times (getsensortimes.php)

The script getsensortimes.php will return all the times a sensor given in the 'q' variable has reported. Values will be reported in unix style timestamps by default, unless 'f' is specified with 'human', the other option is 'unix'. Query value of 'f' can be 'json' or 'api', 'api' is default behavior and works with the other options.

example

- http://10.33.70.246/getsensortimes.php?q=SONICBACKRIGHT&h=human - Human Readable
- http://10.33.70.246/getsensortimes.php?q=SONICBACKRIGHT - Default, Unix Timestamps
- http://10.33.70.246/getsensortimes.php?q=SONICBACKRIGHT&h=unix - Unix Timestamps
- http://10.33.70.246/getsensortimes.php?q=rplidar&h=unix - Unix Timestamps
- http://10.33.70.246/getsensortimes.php?q=TOF1&f=json - JSON Array

Get Last Sensor Time (getlasttime.php)

The script getlasttime.php will return the last time that a sensor had a value. Values will be reported in human style timestamps by default, unless 'f' is specified with 'unix', the other option is 'human'.

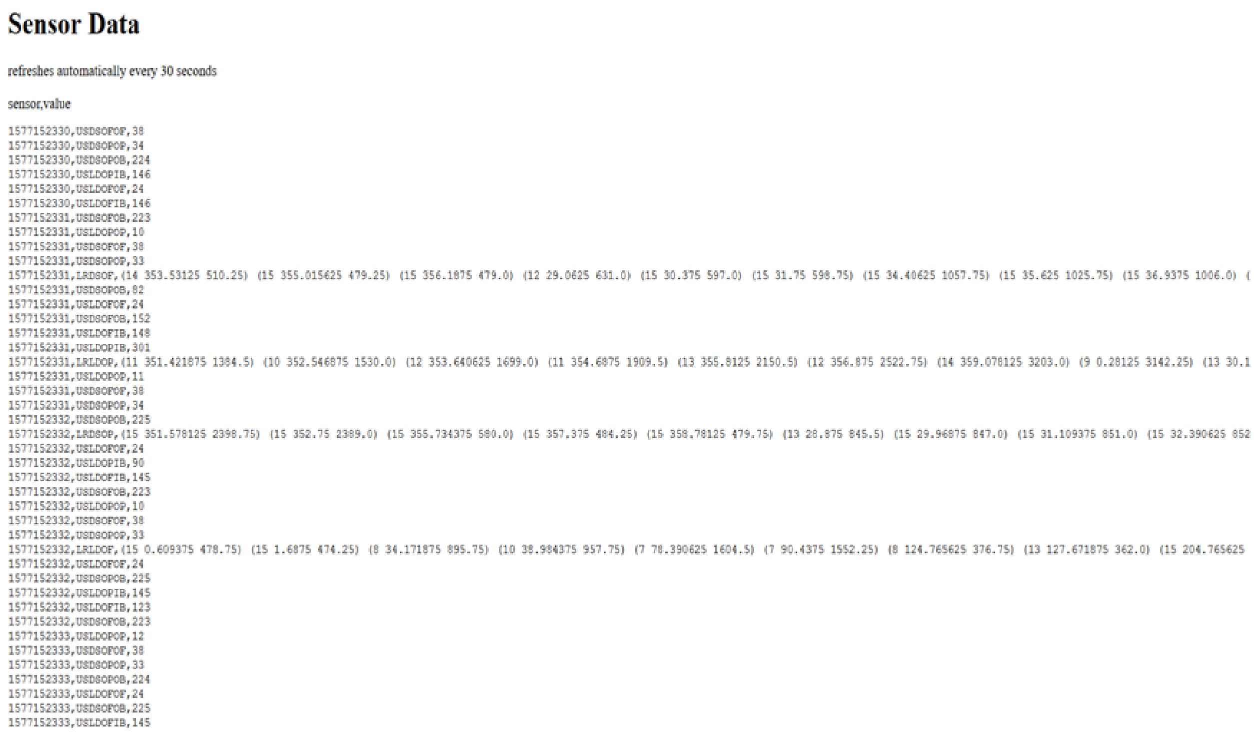
example

- http://10.33.70.246/getlasttime.php?q=SONICINBYLEFT
- http://10.33.70.246/getlasttime.php?q=SONICINBYLEFT&h=unix

Figure D.6: API Reference webpage (2/2)

Clear Data

The Clear Data option simply clears the data file recorded by the View Data function (see section D.4.1) without deleting the records in the database.



Sensor Data

refreshes automatically every 30 seconds

sensor,value

```
1577152330,USDSOFOF,38
1577152330,USDSOPOP,34
1577152330,USDSOPOB,224
1577152330,USLDOPIB,146
1577152330,USLDOFOF,24
1577152330,USLDOFIB,146
1577152331,USDSOFOB,223
1577152331,USLDOPOP,10
1577152331,USDSOFOF,38
1577152331,USDSOPOP,33
1577152331,LRDSOF,(14 353.53125 510.25) (15 355.015625 479.25) (15 356.1875 479.0) (12 29.0625 631.0) (15 30.375 597.0) (15 31.75 598.75) (15 34.40625 1057.75) (15 35.625 1025.75) (15 36.9375 1006.0) (
1577152331,USDSOPOB,82
1577152331,USLDOFOF,24
1577152331,USDSOFOB,152
1577152331,USLDOFIB,148
1577152331,USLDOPIB,301
1577152331,LRLDOP,(11 351.421875 1384.5) (10 352.546875 1530.0) (12 353.640625 1699.0) (11 354.6875 1909.5) (13 355.8125 2150.5) (12 356.875 2522.75) (14 359.078125 3203.0) (9 0.28125 3142.25) (13 30.1
1577152331,USLDOPOP,11
1577152331,USDSOFOF,38
1577152331,USDSOPOP,34
1577152332,USDSOPOB,225
1577152332,LRDSOP,(15 351.578125 2398.75) (15 352.75 2389.0) (15 355.734375 580.0) (15 357.375 484.25) (15 358.78125 479.75) (13 28.875 845.5) (15 29.96875 847.0) (15 31.109375 851.0) (15 32.390625 852
1577152332,USLDOFOF,24
1577152332,USLDOPIB,90
1577152332,USLDOFIB,145
1577152332,USDSOFOB,223
1577152332,USLDOPOP,10
1577152332,USDSOFOF,38
1577152332,USDSOPOP,33
1577152332,LRLDOF,(15 0.609375 478.75) (15 1.6875 474.25) (8 34.171875 895.75) (10 38.984375 957.75) (7 78.390625 1604.5) (7 90.4375 1552.25) (8 124.765625 376.75) (13 127.671875 362.0) (15 204.765625
1577152332,USLDOFOF,24
1577152332,USDSOPOB,225
1577152332,USLDOPIB,145
1577152332,USLDOFIB,123
1577152332,USDSOFOB,223
1577152333,USLDOPOP,12
1577152333,USDSOFOF,38
1577152333,USDSOPOP,33
1577152333,USDSOPOB,224
1577152333,USLDOFOF,24
1577152333,USDSOFOB,225
1577152333,USLDOFIB,145
```

Figure D.7: View Data webpage

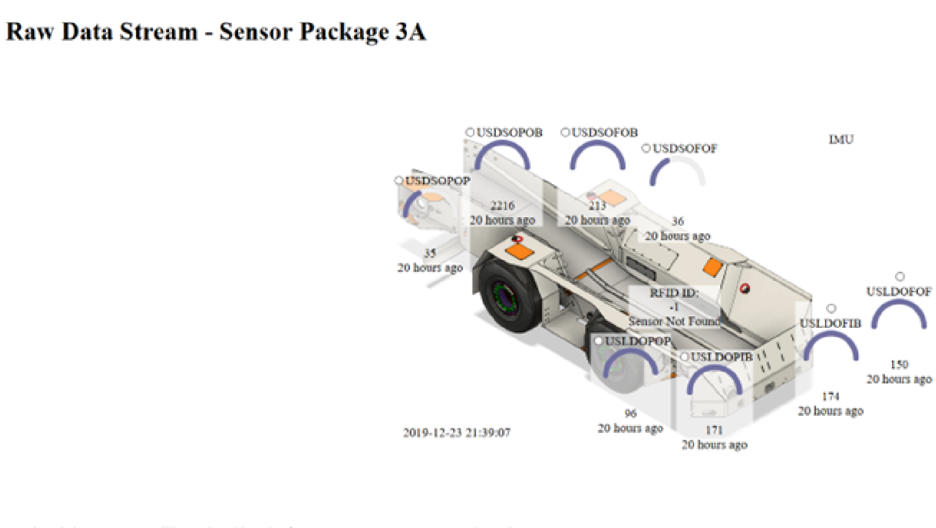


Figure D.8: View Graphical Data webpage (1/2)

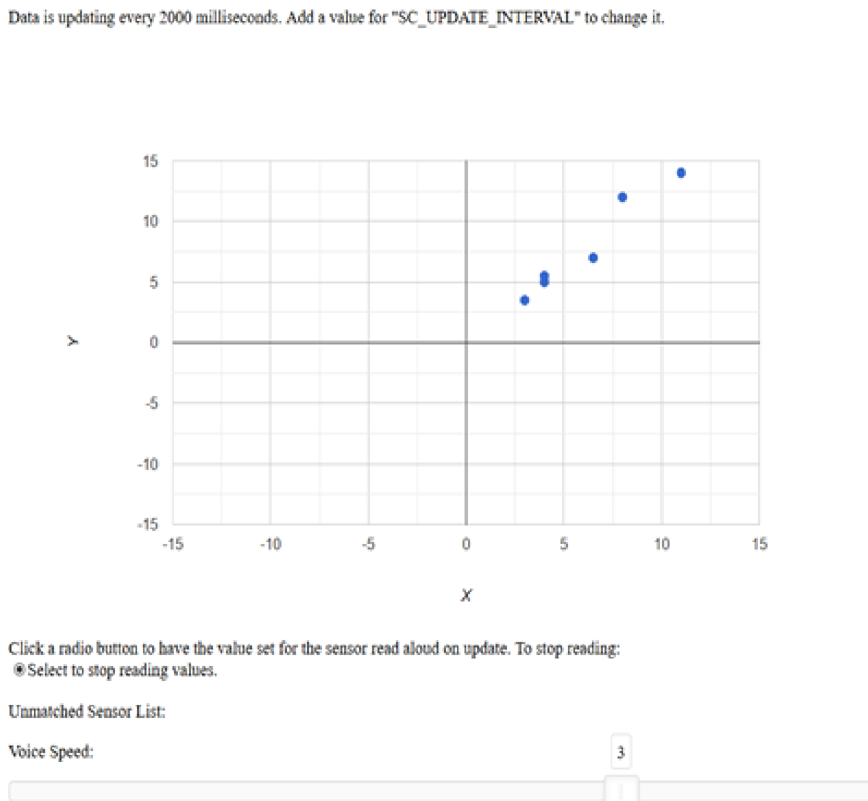


Figure D.9: View Graphical Data webpage (2/2)

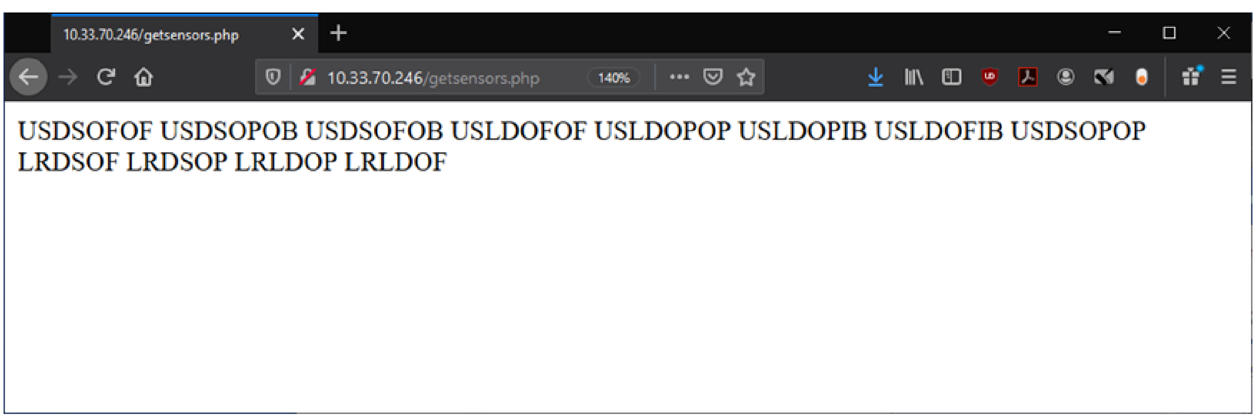


Figure D.10: View Sensor Names webpage

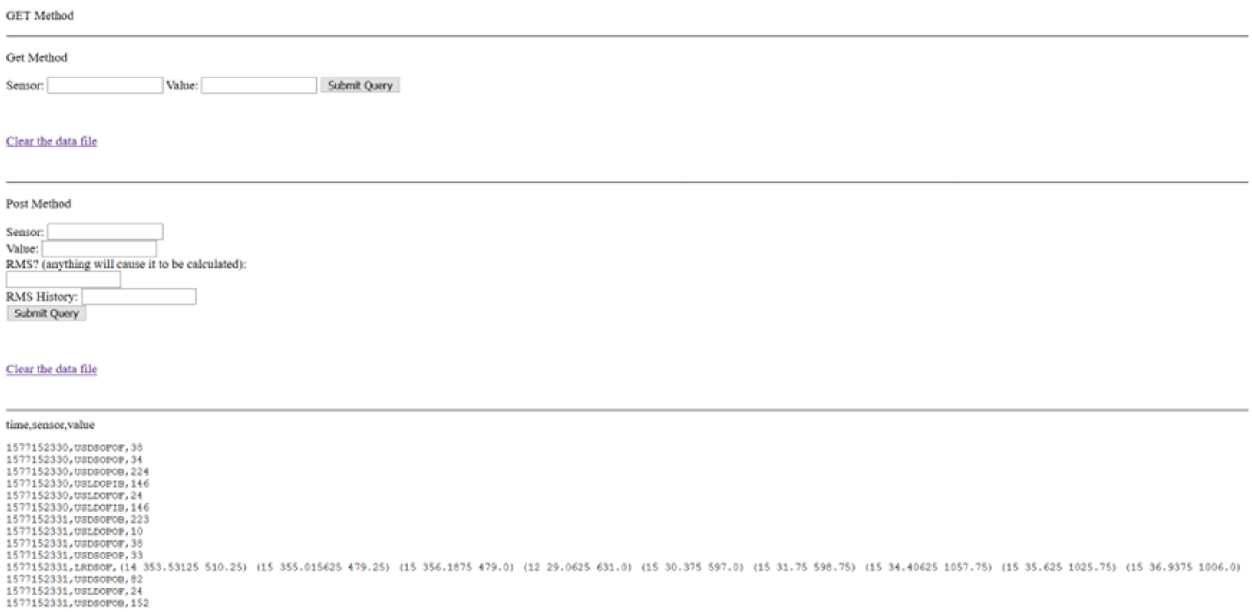


Figure D.11: Post Data webpage

D.5 Control Module

D.5.1 Overview

The flow of information begins with sensors collecting raw data that are sent to the database server and ends with the shuttle car executing a command. The decision agent is an embedded module that analyzes the data stream and generates commands which correct the autonomous motion of the shuttle car. These commands consist of maneuvers or actions such as moving inby or outby, turning, nudging to one side, and stopping. The decision agent uses a set of rules in order to add or subtract blocks from a predefined control queue so that an action can be executed safely.

A GUI, detailing the control queue and allowing other options for human input, has been developed based on the .NET framework. The main application window (GUI) is shown in Figure D.12 and Figure D.13. The decision agent module will continually use information from the database server to process these rules, analyzing data only from the sensors that it needs for a given rule or maneuver. The rules can be related to various sensor thresholds, timeouts, and other characteristics that control how the shuttle car operates in a given environment. Additionally, these rules can either be programmed into the decision agent module or sent through the data stream to allow for easier tuning during operation. The control queue and data logging also provide the benefit of being able to pinpoint a specific command and rule that caused an error to occur in the vehicle's operation, so that adjustments can be made more quickly.

D.5.2 Control Module GUI

Figure D.12 and Figure D.13 show the main window of the Control GUI. The interface details the control queue on the far-left side and the rest of the form includes channel controls for the RF controller that operates the motors and steering on the prototype, as well as several options in the movement panel that can be manually inserted in the control queue. Several switches also allow for changes to the tramming speed of the shuttle car and switching between human and agent queueing settings. The main features of the main window of the Control Module are briefly described below.

D.5.3 Connection Panel and Control Queue Box

The left side of the GUI shows a connection menu, used to initiate and verify connection with the on-board Arduino, and the 'Command Queue' Box. The 'Command Queue' Box will populate with the commands created by the decision agent module and/or a human if they choose to be manually supplied via the movement panel. The ongoing list of commands can be viewed until cleared. The 'Play' and 'Pause' buttons of this menu control the execution of commands within the queue. Last, the 'Save' and 'Load' buttons, along with the textbox below them, are used to save the current commands' list as a .txt file with the name specified in the textbox, or to load the specified .txt file.

D.5.4 Driving Mode Panel

The 'Agent' and 'Human' buttons define whether the execution of the commands in the Control Queue will be executed with or without the supervision of the decision agent module, respectively.

Figure D.12: Main window of the Control Module

In the first case, the commands inputted in the queue are analyzed one by one by the decision agent module before their execution. If the decision agent detects the necessity of error-controlling commands, these commands are inserted into the queue and executed prior to the command under analysis. The error-controlling commands that the agent outputs are either commands that correct the movement angle if the agent predicts a collision between the shuttle car and the ribs of the tunnel, nudging commands if the agent detects a passable obstacle, or stopping commands if the agent detects an unpassable obstacle in the path of the shuttle car. Figure D.14 shows the execution of the Command Queue added in Figure D.13 while the 'Agent' option is selected as driving mode. The error-controlling commands issued by the decision agent can be seen in the 'History Box' preceding every command of the initial Queue. The latest command issued by the decision agent is at the top of the 'History Box' list. In the cases where the driving mode is set as 'Human' the initial Command Queue is executed without any other commands being inserted. An example of this case is shown in Figure D.15.

Figure D.13: Main window of the Control Module with commands added in the Command Queue

D.5.5 Movement Panel

Ordinarily, the Movement Panel, located at the bottom of the GUI, is only used when a human is adding commands to the control queue to operate the shuttle car. It can be seen that turning left or right, setting inby and outby movement, and zeroing options can be added at the user's discretion. The turning and moving forward or reverse commands can be added in single revolution increments (default), as well as in multiple increments by editing the value of the "Steps" option. Moreover, the moving forward or reverse command require the 'Mode' option to be specified. The drop-down menu next to the label 'Mode' includes two options:

1. the 'Centered' option (default), which means that the vehicle will move along the centerline between the two ribs, and
2. the 'RibFollow' option, which means that the vehicle will move along a user-specified distance from a user-specified rib side.

The distance is defined through the 'Target' value, while the rib side is defined from the 'Rib Side' drop-down menu, which includes the 'Of_side' option for following the off-side rib, and the

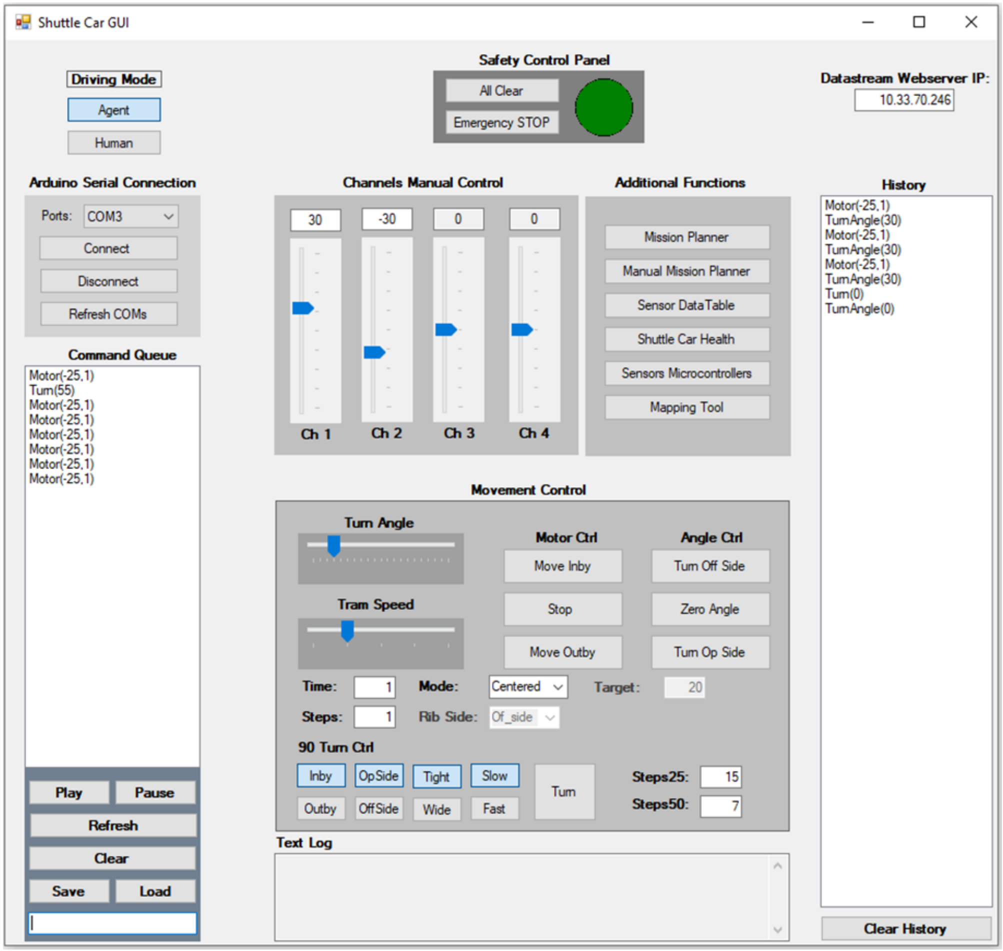


Figure D.14: Execution of Command Queue in "Agent" driving mode

'Op_side' option for following the operator-side rib. The bottom rows of buttons of the main window control the 90 degrees turning of the lab-scale models by defining the direction of movement ('Inby' or 'Outby'), the side to turn ('Op_side' or 'Of_side'), the tightness of the turn ('Tight' or 'Wide') and the speed of the turn ('Slow' or 'Fast'). For the slow turning the speed of the motors applied corresponds to the 25% of the motors' maximum speed while for the fast turning, it corresponds to the 50% of the maximum speed. Speeds more than 50% for turning are prohibited for safety reasons, as the sensors need additional time to detect obstacles within the turning tunnel where the visibility is low while turning. The values of the 'Steps25' and 'Steps50' textboxes define how many motor revolutions are required for the models to perform a 90-degree turn with 25% and 50% speed, respectively, and are necessary only when a human operator inputs the Control Queue.

Angle and Speed Controls

The two options to the right of the Movement Panel are Turn Angle Control and Tram Speed Control. While simply designed, these options allow an operator to customize the angle of turning commands in degrees and the speed, as a percent of the maximum, at which the car will tram as

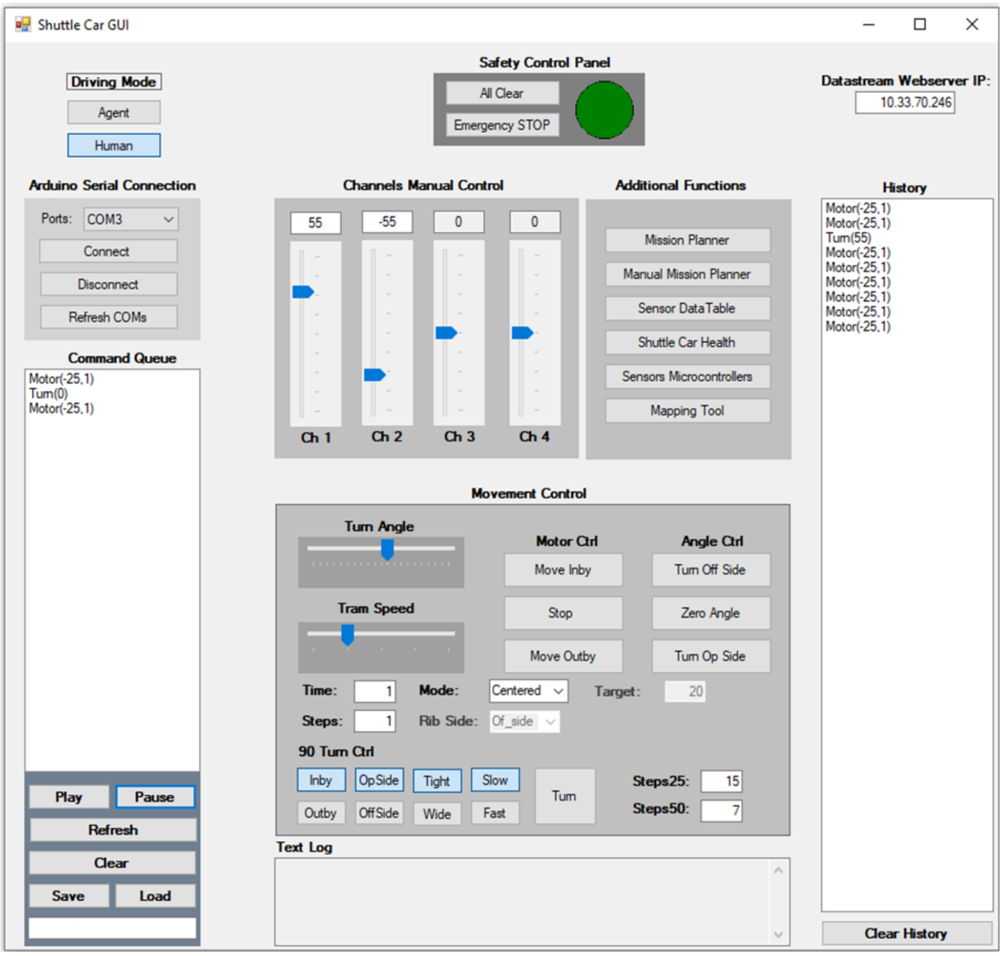


Figure D.15: Execution of Command Queue in “Human” driving mode

dictated by the appropriate commands in the Movement Panel. Adjustments using these controls will take effect during autonomous or human control.

Channel Slider Control Panel

Above the Movement Panel is the Channel Slider Control Panel. This panel is designed to mimic the dual-joystick configuration of the RF controller used to control the motor controllers and steering servos on the prototype. The four-channel setup uses two channels (1 and 2) to control the turning angle and two channels to control motor direction and speed (3 and 6). One channel from each pair is assigned to the inby axle (1 and 3) and the other to the outby axle (2 and 6). During autonomous operation, the current settings for each channel will be displayed, and these channels can be manually adjusted during human operation. The values on the sliders represent percentages of the maximum speed or turn angle that the prototype can achieve. By default, the value of channel 2 is equal to the negative value of channel 1, in order to accommodate opposite-direction four-wheel steering, and the value of channel 3 is equal to the value of channel 6, except they are differently specified.

Emergency Stop Panel and Queue Control

At the top of the GUI, the toggle between Human and Agent is present, as well as the Emergency Stop Panel. The Emergency Stop Panel can be used to immediately stop the vehicle's operation in an emergency situation, and then resume operation when the area is clear. When the EMG STOP button is selected, commands to zero the speed and turn angles are sent to the shuttle car, the status LED will change to red, and the rest of the commands in the queue are discarded. The emergency stop scenario can only be cleared if the "ALL CLEAR" button is pressed.

The toggle switch is used to dictate if commands are added to the top or bottom of the queue. If the dial is switched to Agent, commands will enter the top of the queue, which is more suited to interpretation by the computer. When Hum is selected, commands will enter the bottom of the queue, which is more suited for human interpretation. The GUI cannot be used if this dial is set to Off.

Additional Functions

The panel named 'Additional Functions' contains buttons, each one of which opens a new form. These forms are used for controlling significant aspects of the navigation system and monitoring the sensors data flow by visualizing significant information. This information will be critical for the operator at the remote-control room. The functions that are controlled through this panel include:

1. an autonomous mission planner,
2. a manual mission planner,
3. a sensor data flow monitoring tool,
4. a tool monitoring the status of the sensors,
5. an interface for manual interaction with the on-board microcontrollers that control the sensors and collect the data, and
6. a real-time mapping tool.

Mission Planner

The Mission Planner form can be seen in Figure D.16. By defining a few parameters through this window, the application computes the optimum path around the pillars for a given mission. The parameters that need to be defined include the geometric parameters of the mine (pillar, panel and entry dimensions), driving parameters (max allowable speed, minimum allowable distance from the ribs, minimum distance from obstacles along the path, and vehicle's dimensions), initial and final (x,y)-coordinates, the values of the gains for the proportional-integral-derivative controller, the accessibility costs of the edges that create the graph of the panel that is used in the computation of the optimum path, and the sensors that will control the turning triggering. When the parameters are defined, the optimum path is calculated by pressing the 'Compute Optimum Path' button. A graph will appear in a new window, for example, in Figure D.17, illustrating the panel along with

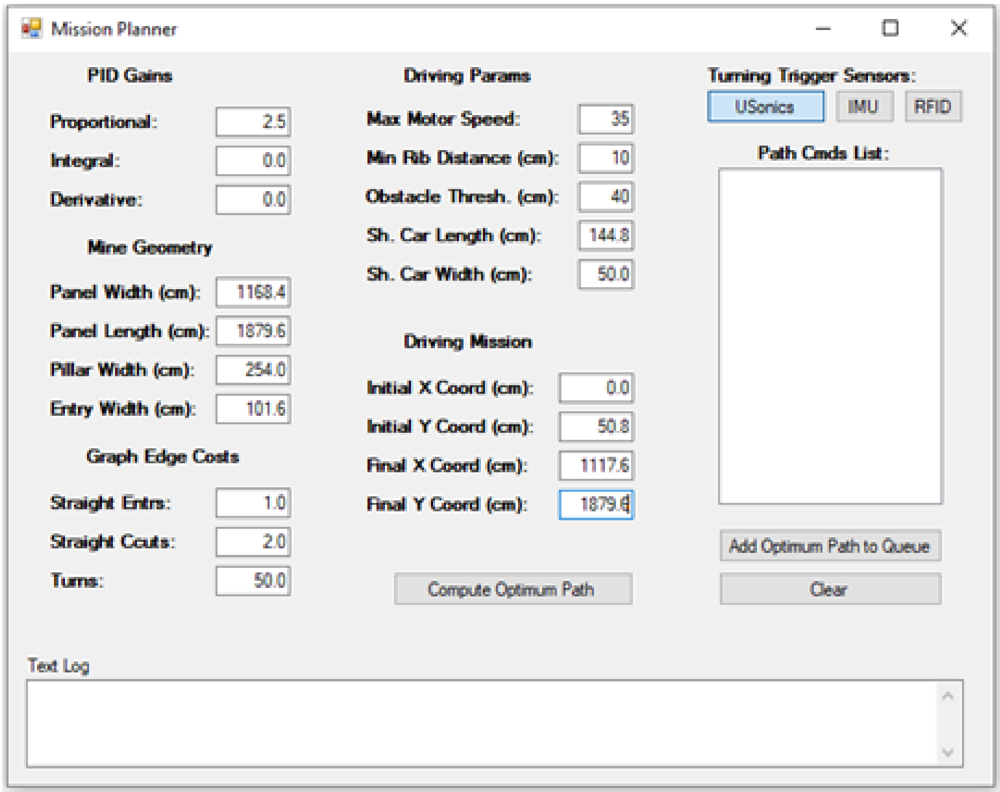


Figure D.16: Mission planner form

the computed optimum path. The computed optimum path is used to calculate a command queue which can be loaded into the Control Queue of the main window by pressing the ‘Add Path to Queue’ button (see Figure D.18).

Manual Mission Planner

The Manual Mission Planner form, shown in Figure D.19, is a tool for the operator to add a path manually in the Control Queue. The parameters on the left side of the form are similar to the ones of the autonomous mission planner and need to be specified only once per mission. These parameters include the PID gains, the pillar and entry widths, and driving parameters like the max allowable speed, the minimum allowable distance from the ribs, the minimum allowable distance from obstacles along the path, and the vehicle’s dimensions. After specifying these parameters, the path is added incrementally by breaking it down into a sequence of ‘path commands’. A path command has the form of: Move Inby or Outby for ‘Distance to Traverse’ and Turn ‘Turn Direction’. The parameters ‘Distance to Traverse’ and ‘Turn Direction’ have to be specified by the operator for every path command. The ‘Turn Direction’ parameter has three available options: ‘Op_side’ denoting a turn to the operator side of the shuttle car, ‘Of_side’ denoting a turn to the off side of the shuttle car, and ‘No_turn’ for the cases where the remaining path does not require a turn. Additional parameters have to be specified for each path command, including the sensors that control and trigger the turning operation, the traversal mode followed for the straight-line parts of the path, and the

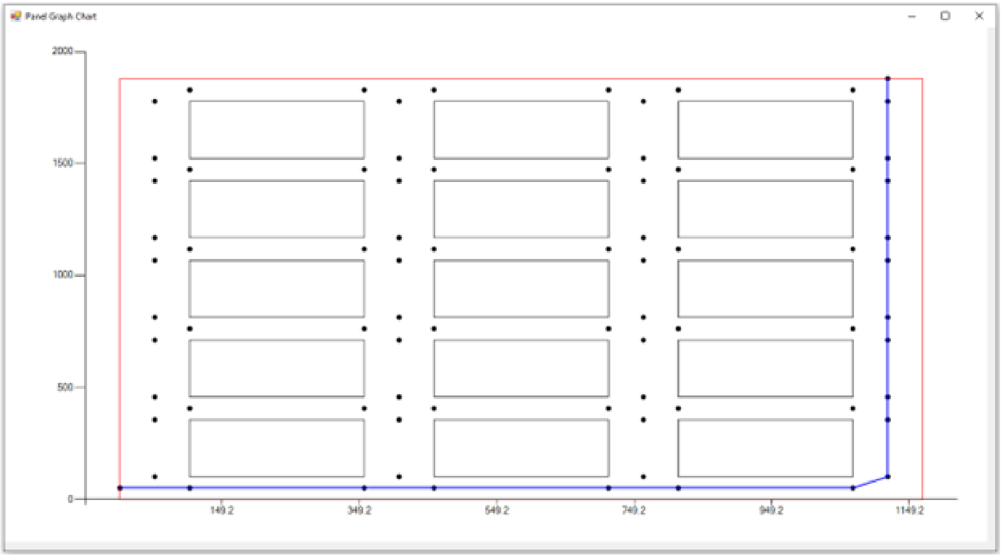


Figure D.17: Optimum path output schematic

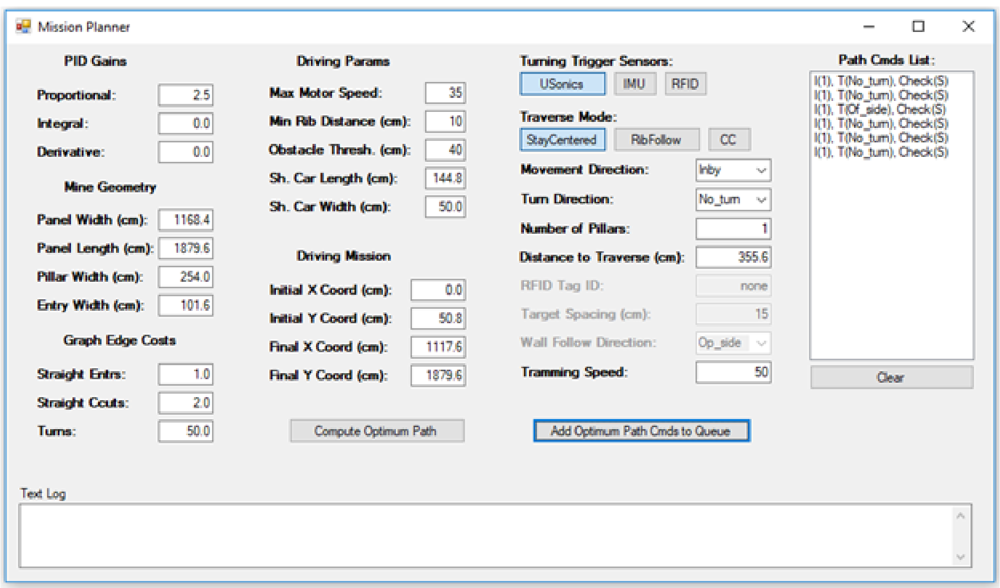


Figure D.18: Insertion of optimum path into the Commands Queue

tramming speed.

Sensor Data

The Sensor Data form is used for real-time visualization of the data obtained by a user-specified sensor type. As shown in Figure D.20 the user can choose the sensor type to be 'Ultrasonics', 'IMUs', 'Encoders', 'LiDAR', or 'RFID'. Additionally, the user can specify the refresh rate of the sensor data table. The main purpose of this tool is for the operator to be able to easily check if the sensors are working properly. More specifically, the operator can see if a sensor is functional

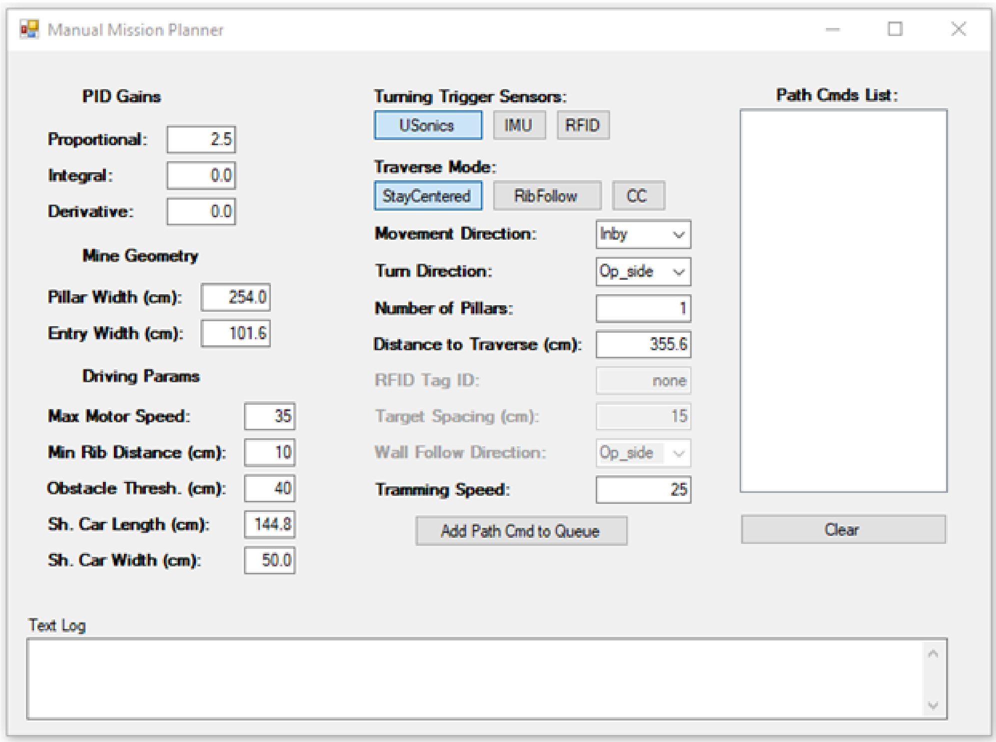


Figure D.19: Manual mission planner form

by checking the color of the table's cells, as illustrated in Figure D.21. If invalid values or no values have been collected from the data stream for a sensor, the cell outputs the dummy value of '-1' and is colored red. Moreover, the operator can check the values of the collected data of one sensor to see whether the values change or remain the same over a long time period. If such a case is encountered while the shuttle car is not stopped, this would mean that despite the sensors appearing to be functional, it is malfunctioning.

Shuttle Car Health

The Shuttle Car Health form, shown in Figure D.22, is a tool for monitoring the health status of all the sensors in a more concise and efficient way than the one provided by the Sensor Data form. The user only needs to specify the refresh rate, and green/red 'LEDs' appear next to every sensor's label that indicate their status.

Sensor Microcontrollers

The Sensor Microcontrollers form, shown in Figure D.23, is an interface that facilitates the manual interaction of the user with the on-board microcontrollers (in this case Raspberry Pi's) which collect the data from the connected sensors. This tool is useful for troubleshooting and testing purposes, as well as for adding new sensors in the sensor suite of the shuttle car. The interface connects to the specified microcontrollers through an SSH connection using the 'Putty.exe' Windows software.

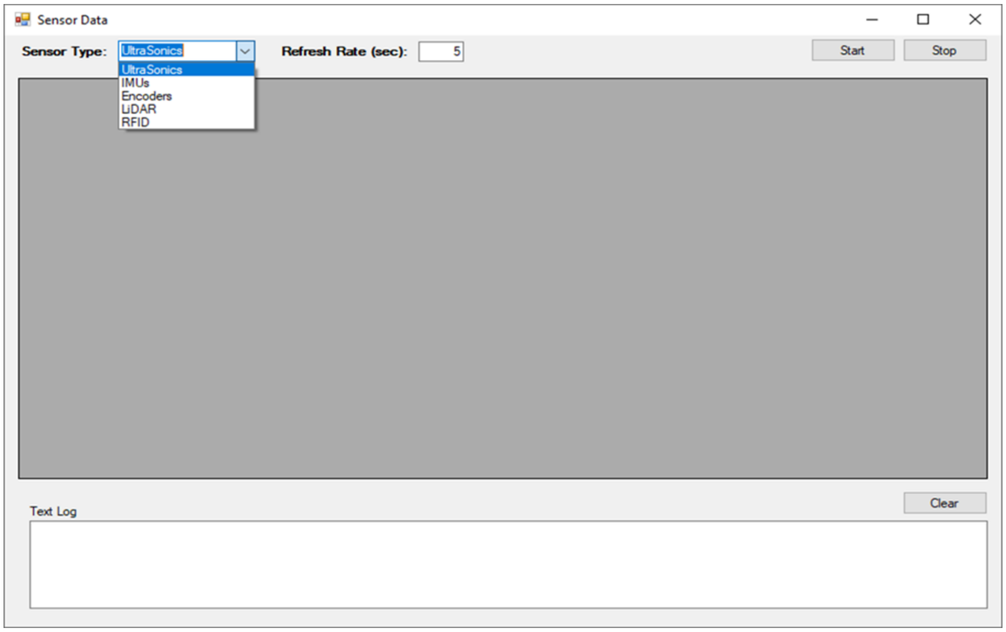


Figure D.20: Sensor data form

Let it be noted that this specific tool is designed for the lab-scaled prototypes and probably will not be necessary for the real-scale shuttle cars.

Mapping Tool

The Mapping Tool form, shown in Figure D.24, is used to visualize the data collected from the four LiDAR units in real time. This provides a real-time map of the current surroundings of the vehicle up to a distance of 12m (39.4ft) (the range of the LiDAR units). The user can specify the refresh rate and the range of the size of the map (the map is always square). The latter parameter gives the user the ability to zoom in and out and observe points of interest in a better way.

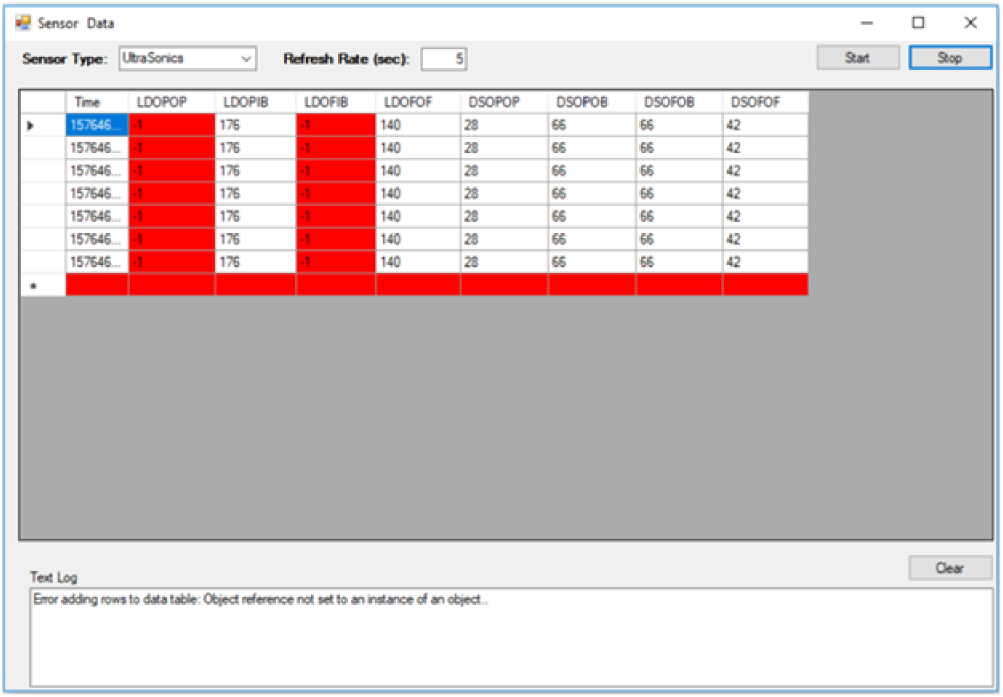


Figure D.21: Visualization of ultrasonic sensors measurements in the Sensor Data form

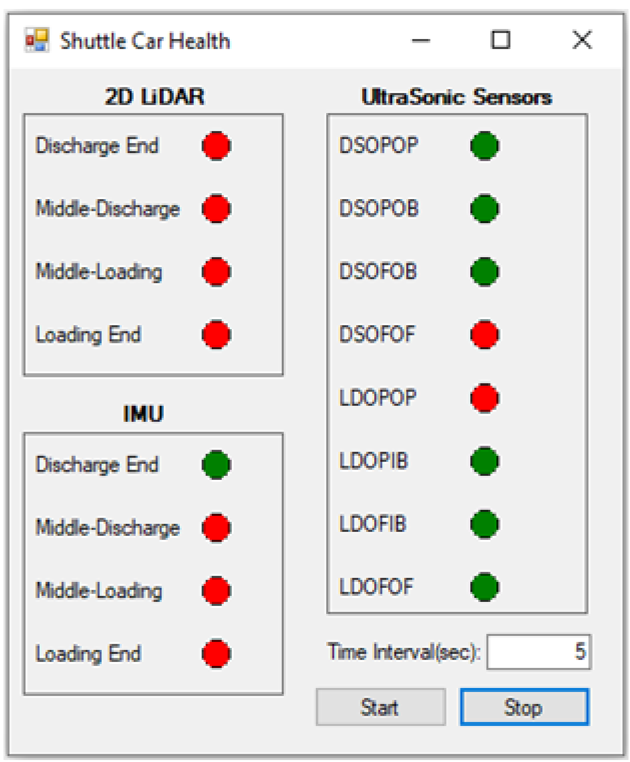


Figure D.22: Shuttle car health form

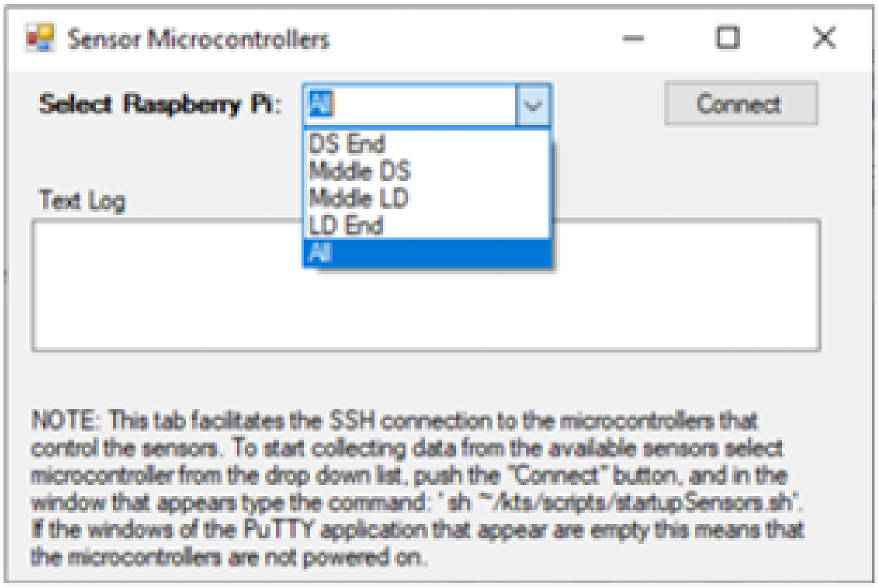


Figure D.23: Sensor microcontroller interface

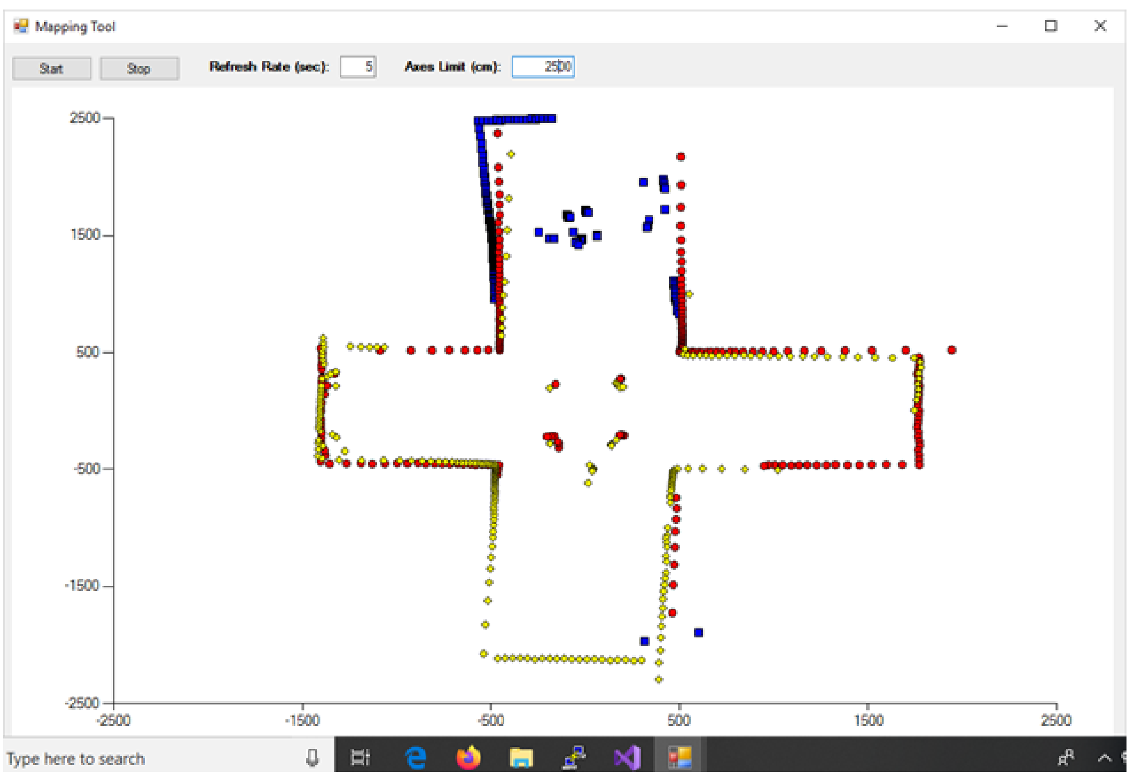


Figure D.24: Mapping tool form

Appendix E

Navigation Algorithms

This appendix includes flowcharts of significant parts of the developed navigation and mapping algorithms (which are part of the ALC) along with a brief description of each flowchart.

E.1 Development of the Navigation System

E.1.1 Overview

The goal of the navigation system is to move the shuttle car from the feeder to the miner by a known and predefined route which will be determined and set up by the shuttle car's supervisor.

The navigation system uses sets of pre-defined commands which are adjusted as necessary by information from the sensor package on the vehicle. There is regularity in the paths that the shuttle car is expected to travel between the fixed feeder-breaker and the miner that is moving places. The vehicle is tethered by its power line and is not free to go by any path other than the one that is prescribed by the vehicle's supervisor. Unlike robots moving in a factory or LHDs traveling to established draw points, the paths to the miner are always relative to the power and feeder but are otherwise moving forward in the mine.

The shuttle car can move forward, backward, turn left and right and apply the brakes. For autonomous operations, these movements are broken into very short commands to the motors that complete a movement, but only for a short time and distance. The simplest example is moving forward 1/4 wheel turn (Motor 0.25). This command alone will engage the motors for the time it takes to move the wheels forward 1/4 turn, which also equates to a known distance of travel at a known time. If the path the shuttle car must travel is only direct to the miner by driving forward, and then backward to return, the path can be divided by 1/4 wheel rotation distances. In this example case, if the miner can be expected to be 10 wheel rotations from the feeder-breaker then the command queue to the miner is 40 1/4 wheel rotation commands.

This set of pre-defined commands, which dictate the major movements of the vehicle, can be pre-loaded into the command queue. Without obstacles or variations in the real environment, this command queue would allow the shuttle car to operate without knowledge of the environment. Thus, these paths can be pre-planned and pre-loaded into the control software.

The motor controller is capable of sending power to a motor for a period of time. During this time, the decision agent can check the sensors and the command queue and adjust the queue according to the information that is collected.

In the 40 1/4 wheel rotation queue example, it is possible that the shuttle car will not be able to drive perfectly straight forward and backward. A side facing distance sensor could measure a distance which is below a threshold. When a 1/4 wheel rotation command is being executed, the decision agent could insert into the queue a command that will turn the shuttle car slightly, keep the next 1/4 wheel rotation command and then another command to straighten the wheels after the 1/4 wheel rotation, as well as a small wheel rotation command to account for the additional distance of travel. If there are any errors in measurements, and the vehicle deviates from its path, the decision agent can act again with additional corrective commands.

The decision agent follows different logic depending on the activity. For instance, while traveling in the forward direction, there is no need to check the rear sensors for obstacles. While turning, the threshold to the walls has to be adjusted down to allow the machine room to maneuver. In all cases, the queues allow for adjustment movements to keep the shuttle car on the path between the destinations.

There are several advantages to this navigation strategy. It allows the shuttle car's supervisor to load pre-defined paths and queues and adjust them according to their knowledge of the path the shuttle car is about to take. In addition, while the car is in motion, a motor controller can be solely occupied controlling the motor, while the control module, which includes the decision agent and the queue manager, can be working with the most recent data from the database completely independently. Should a communication issue arise, the shuttle car will have no new command and will stop because it has no new command. There is an auditable trail of where a command to move arose. This allows scenarios to be built in simulation without the need for the car to be running.

E.1.2 Localization

As discussed in Appendix A, multiple localization techniques are currently available (e.g., inertial navigation system, laser, infrared, ultrasound, radio-based). Some of them need only onboard mounted units, while others need communication or other infrastructure mounted on several locations in the working environment. In the latter techniques existing device networks can be used. However, the literature review indicated that vehicle-mounted beam-forming sensors (ultrasound, infrared, laser), which do not rely on additional infrastructure, deliver optimized localization efficiency, efficacy, and cost. Such sensors can be easily integrated to provide robust mapping and proximity detection. Integration with existing proximity detection systems already being used in the mining industry is possible.

In the scope of this project, the shuttle car is guided by a simplified relative localization with respect to the entry-crosscut corner at which the shuttle car needs to turn. The simplified layout, as well as the a priori knowledge of a room-and-pillar mine layout, helps avoid a more sophisticated and computationally costly approach. As a result, a reliable navigation system was developed that works in real time.

Additionally, the objective is to be able to accomplish multiple zones of localization quality, unlike GPS-based and other autonomous systems. In places where the car will interact with other machines, or be near humans, the localization will need to be on the scale of sub-inches (blue

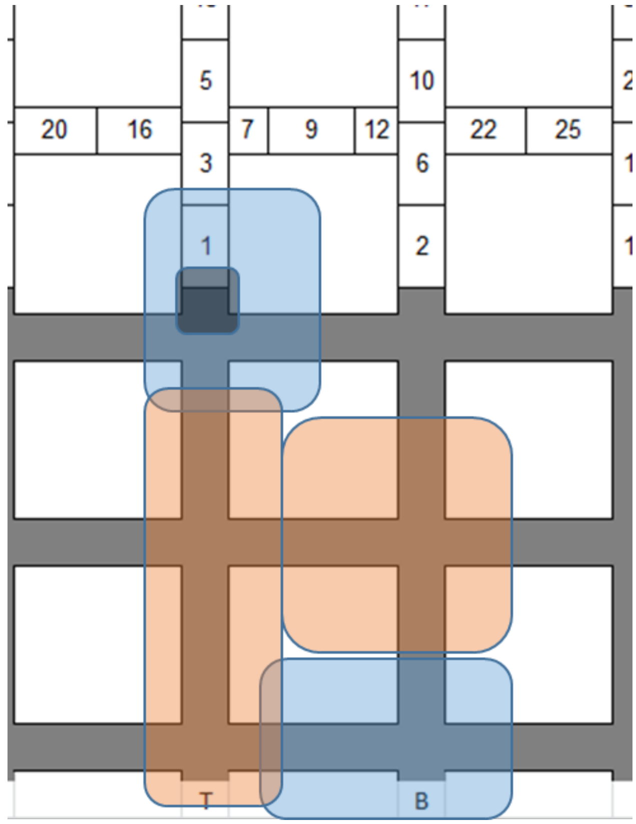


Figure E.1: High and low localization quality areas in a mine

regions in Figure E.1), while in places where the car is tramming, localization needs to be in the order of several inches to a foot (orange regions of Figure E.1). This means that there is flexibility to allow small errors to accumulate and thus simplify the error control routines when the shuttle car navigates through the areas of low localization quality. These accumulated errors do not practically affect navigation through these areas, while it is easy to correct when approaching an area of high localization quality by using additional data which can be collected from the radio emitters carried by the humans or mounted on other vehicles.

E.2 Main Navigation Process

Figure E.2 depicts a high-level decision tree of the navigation algorithm developed. Figure E.3 shows the motor commands and Figure E.4 depicts the detailed decision tree.

E.2.1 Commands Queue

The navigation process requires firstly the creation of a mission for the shuttle car to be executed. In its essence, every mission is the abstract path from point A (feeder-breaker) to point B (continuous miner) within a panel. These missions can be created through the custom developed navigation HMI. The human supervisor can create this mission, either manually, by using the 'Manual Mission

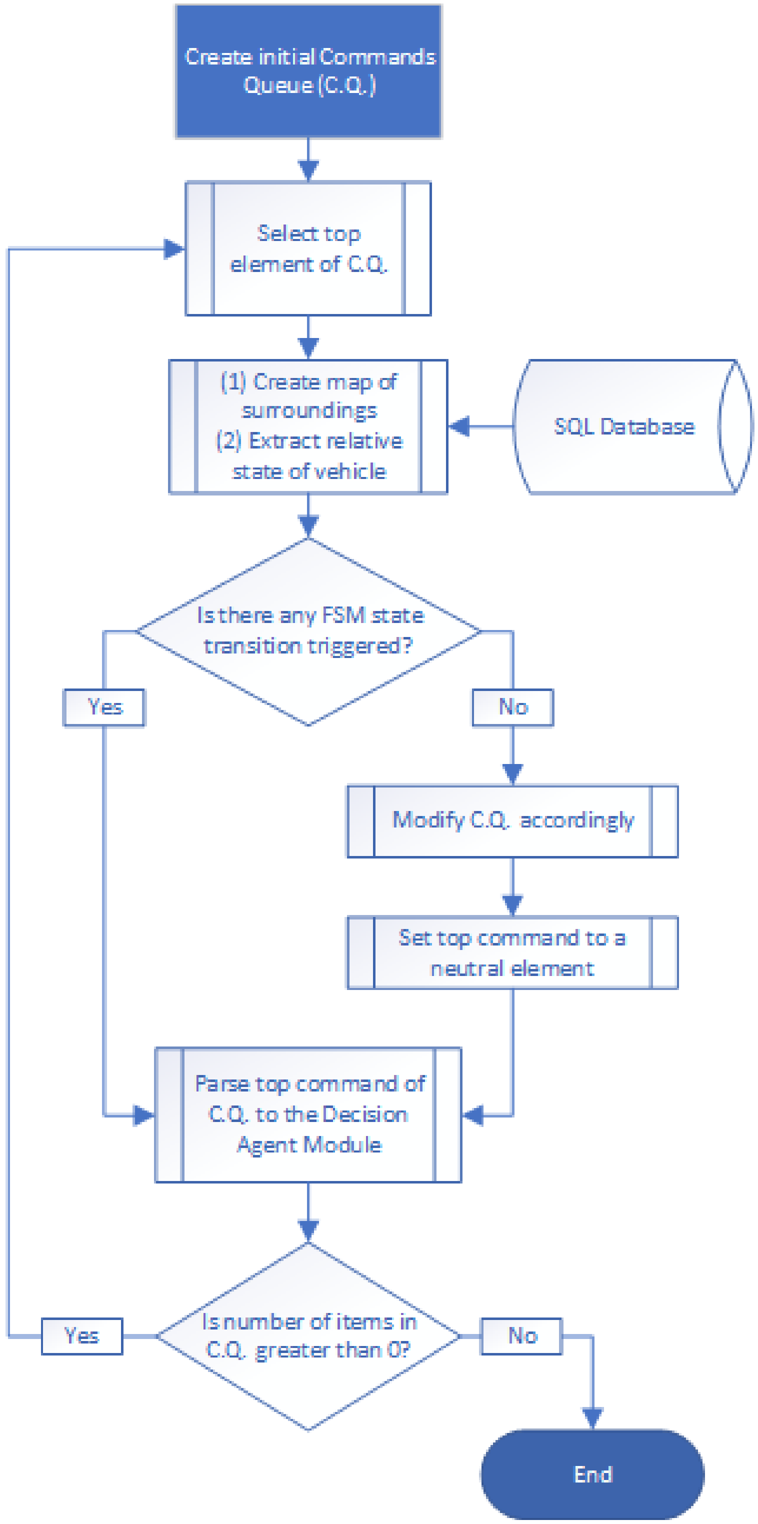


Figure E.2: High-level flowchart of decision tree for shuttle car navigation

```
public class MotorCommand
{

 string str            //used for displaying command into a list box
 int id                //if 1 it is a move forward/backwards command,
                         else if 2 it is a turn command
 int value             //percentage of max motors RPM; sets the speed
                         (if id is 1) or turning angle (if id is 2)
                         of command
 int time              //time in millisecond that the command is to
                         be transmitted to the onboard radio receiver
 string mode           //traverse mode:
                         "Centered" for traversing along an entry/
                         crosscut in the middle of the ribs,
                         "CenteredCC" for passing by a crosscut in the
                          middle of the ribs ahead of the crosscut,
                         "WallFollow" for traversing along an entry/
                         crosscut at a specified distance from a
                         specified rib,
                         "WallFollowCC" for passing by a crosscut
                         at a specified distance from a specified rib
                         ahead of the crosscut,
                         "Arbitrary" for following the predefined
                         command from the commands queue without any
                         corrective actions
 string moveDir        //direction of movement; "Inby" or "Outby"
 double moveDist       //distance to traverse navigating along an entry/
                         crosscut before turning; used with IMU sensors
 double nPillars       //number of pillars to pass by before turning
 string turnDir        //direction to turn after traversing the
                         'moveDist' or 'nPillars'; options are:
                         "Of_side", "Op_side" or "No_turn"
 int targetDist        //target spacing from rib; used when 'mode' is
                         "WallFollow" or "WallFollowCC"
 string wallDir        //side of rib to follow; uused when 'mode' is
                         "WallFollow" or "WallFollowCC"; options are:
                         "Of_side", "Op_side"
 bool turnCheckIMU     //if true the IMU sensors data are to be checked
                         for permitting/triggering a turn
 bool turnCheckUS      //if true the Ultrasonic & LiDAR sensors data are
                         to be checked for permitting/triggering a turn
 bool turnCheckRFID    //if true the RFID sensors data are
                         to be checked for permitting/triggering a turn
 bool turnCheckBuffer //used for making sure that the turn triggers
                         will never be activated
 int nMotorCmds        //number of consecutive commands that have the
                         same 'mode' parameter

}
```

Figure E.3: Motor Command options

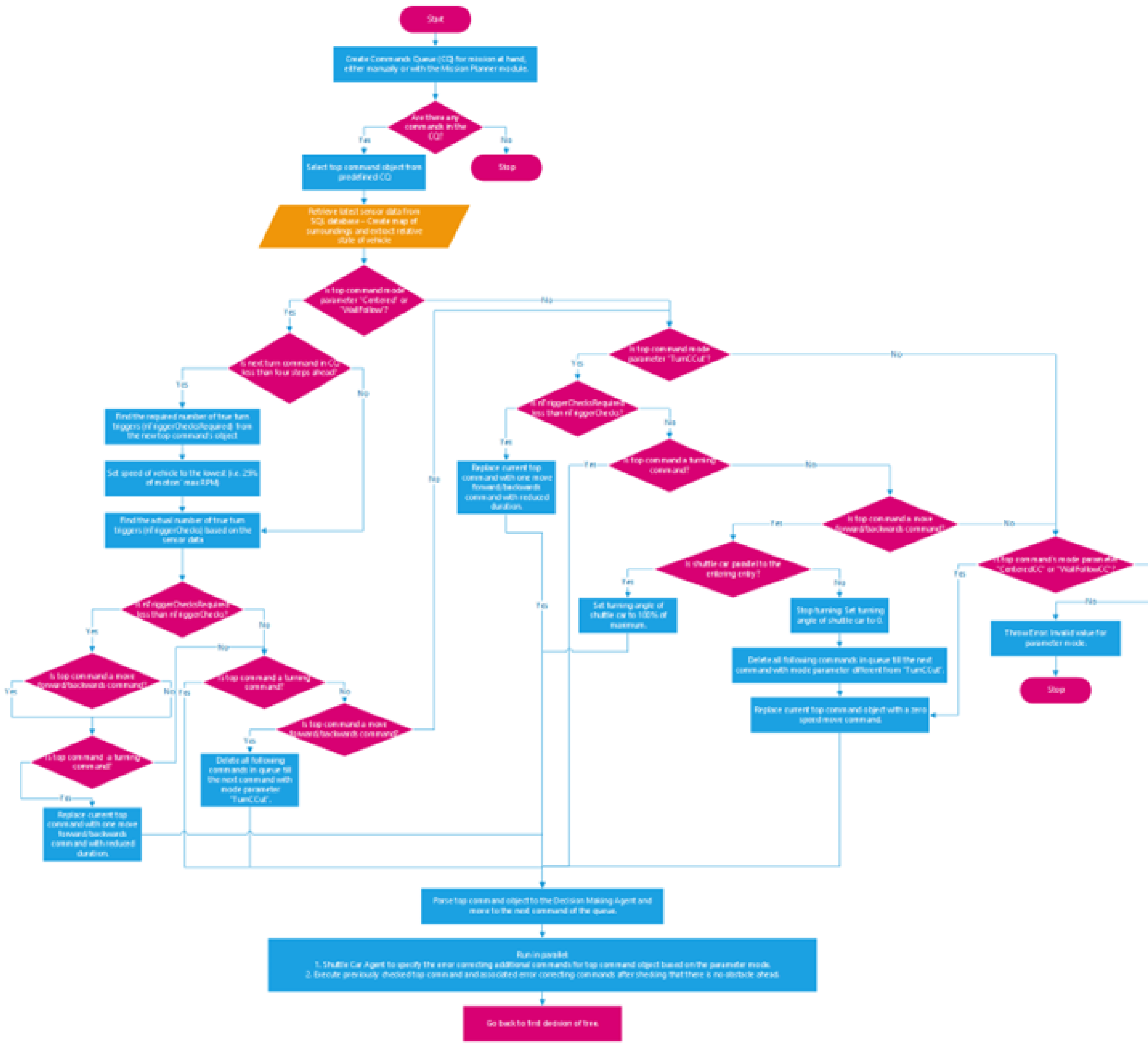


Figure E.4: Detailed flowchart of decision tree for shuttle car navigation

Planner' feature of the GUI, or autonomously, by using the 'Mission Planner' feature of the GUI. The output of both features is a sequence of low-level commands, which control the operation of the tramming and servo motors. These commands can be one of three types:

1. Move inby/outby with specified speed,
2. Stop (it is basically the first type with zero speed), and
3. Turn wheels with specified angle.

The number of moving commands is defined by the geometry of pillars and entries/crosscuts and the actual speed of the shuttle car. These parameters can be specified through the GUI. The combination of these three types of commands (called commands queue) allows the user to predefine the sequence of commands that will enable the lab-scale shuttle car to execute the mission at hand. This commands queue, however, is created with the assumption that the shuttle car has to accomplish its given mission in ideal conditions (e.g., no wheel slippage, no drifts, no obstacles in the entries or crosscuts). The decision tree in Figure E.4 controls the execution of the sequence of commands (created in the first step) that would ideally permit the shuttle car to accomplish its given mission.

E.2.2 Finite-State Machine Modelling

In order to model the behavior of the shuttle car, we implement a deterministic finite-state machine (FSM). The inherent simplicity of the room-and-pillar pattern allows for an abstract determination of a finite number of possible low-level scenarios that a shuttle car can encounter while traversing in a panel. The shuttle car can encounter exactly one state at any given time. Based on the information derived through the interpretation of the acquired sensor data, the FSM can transition from one state to another or remain in the same state. A transition occurs when defined safety thresholds are exceeded, or transition triggers are activated. Each state is associated with a different set of functions (of the data interpretation module of the GUI) that extract the desired information (may be different for different states) from the collected data, and consequently with different thresholds and triggers. A difference between the developed FSM with the common approaches is that the initial state of the shuttle car at any given moment is defined by the current command of the predefined queue instead of being defined only once at the beginning of its operations. Moreover, a transition from a state A to a state B occurs if and only if, the commands in the predefined queue that follow the currently executed state A commands belong to state B.

Every command of the queue is an object that contains several parameters (Figure E.3) which characterize it and define how this command should be checked against the latest sensor data and executed. The most important parameter is the ‘mode’ of the command, which defines the traversing mode of that specific command. There are three possible traversing modes for a moving inby/outby command:

1. “Centered” for following the centerline of the entry/crosscut while traversing it,
2. “WallFollow” for traversing the entry while staying at a given distance from one of the ribs,
3. “CenteredCC” for following the centerline of the entry/crosscut ahead while passing an intersection,

There is only one mode for a turning command:

1. “TurnCCut” for turning in a crosscut/entry.

Additionally, a neutral mode, “Agent”, is attributed to both moving and turning commands, when the decision-making agent issues corrective actions based on the collected data. These modes consist of the states of the finite-state machine (FSM), which is deployed for modeling the behavior of the shuttle car.

E.2.3 State Transitions

The room-and-pillar pattern dictates that all missions given to the shuttle car are combinations of two pairs of abstract commands: (1) move inby/outby for the length of one pillar and turn, or (2) move inby/outby for the length of one pillar and pass the intersection. This limits the number of valid transitions between states. Moreover, this allows us to define, along with the commands queue, an additional queue of the consecutive states that the shuttle car needs to transition through in order to accomplish a mission. This 'modes queue' is used in the different functions of the decision-making agent.

In the case of the first pair of abstract commands, whether the shuttle car can turn at a given moment (i.e., transition from the mode "WallFollow" or "Centered" to the mode "TurnCCut") is specified based on different combinations of the current command's mode and the position of the shuttle car. This is achieved by defining the number of positive checks, "nTriggerChecks". This number is defined based on the position of the shuttle car relative to the ribs and the corners ahead.

If this parameter corresponds with the number of the required positive checks as defined from the command parameters, then the current command is sent to the execution module. Otherwise, adjusting actions are initiated in order to transition to a different state (i.e., to remove the next commands in the queue that belong to the older state) or add corrective commands into the queue under the neutral "Agent" state which sends this command directly for execution. For example, if the current command indicates that the shuttle car must turn, but the sensor data indicate that the shuttle car is not at the right position to turn, then the adjusting action is to add one command that will move forward the shuttle car and then check again whether it can turn. In the reverse situation, where the command indicates to move forward while the shuttle car has reached the turn that it must take, the corrective action is to 'jump' to the next turn command in the queue (and delete the move forward commands that precede it).

In the case of the first pair of abstract commands, the transition from the mode "CenteredCC" to the mode "WallFollow" or "Centered", and vice versa, is specified by the same principle.

Finally, the transition from the mode "TurnCCut" to the mode "WallFollow" or "Centered" is defined based on the relative orientation of the shuttle car with respect to the ribs of the entering entry/crosscut. If the shuttle car is positioned parallel or almost parallel with the ribs, then the transition is triggered.

E.2.4 High-level Flowchart Decision Tree

At a higher level, the decision tree of the developed navigation system (shown in Figure E.2) is as follows: The algorithm starts with the creation of the called commands queue of the given mission. Each command of the queue is consecutively examined by the decision-making agent module of the GUI and its parameters (Figure E.3) are compared to the latest updated sensor data (retrieved from the MySQL database). After specifying the next command to be executed, the current command is being sent to the execution agent. This agent will specify the turning angle of the command and send the corresponding signal to the radio receiver onboard the prototype. At the same time (parallel programming) that the shuttle car moves (executing the latest specified command) the next command of the queue is being analyzed through the previously mentioned procedure. The processing stops when the queue is empty or unresolvable errors occur within the algorithm.

E.3 Mapping Tool

This section includes a detailed description of the Mapping Tool (which is part of the ALC) and the feature extraction process that is used to help the autonomous shuttle car navigate around the pillars of an underground mine.

E.3.1 Overview

The correct perception of the vehicle's surroundings is a fundamental function of an autonomous vehicle. The perception module of the developed software is responsible for collecting and processing the continuously acquired sensor data. The data collected by the various sensor modalities need to be interpreted into proper information that can be input into the navigation algorithms and the decision-making agent.

In the developed navigation system, the primary sensor modality that provides most of the information about the vehicle's surroundings is the system of the four 2D LiDAR scanners. In order to extract the necessary information from the collected data, a Mapping Tool (MT) has been embedded into the GUI.

The core of the MT functionality is a RANSAC-like line-fitting algorithm. This algorithm extracts linear segments from the LiDAR scans to model the ribs of the entries/crosscuts and localize the shuttle car prototype with respect to the ribs. Consequently, the linear segments are used to define the corners of the intersections in the vicinity of the vehicle. Finally, an additional function determines the distance of the closest obstacle (if any) between the adjacent ribs for proximity safety purposes.

This algorithm allows for precise control of the sequence of commands that control turning and enables collision avoidance with respect to the ribs due to delayed or improper turning. In order to achieve sufficient performance of the turning function, the exact position of the corner (between the entry and crosscut around which the shuttle car needs to turn) needs to be determined. Using the linear segments that model the ribs of the entries/crosscuts, it is relatively straightforward to define the position of the corners of interest.

E.3.2 Feature Extraction

The 2D LiDAR scanner data contain raw information that need to be interpreted into a set of parameters that are appropriate for the navigation algorithms. The first step for that includes the extraction of two types of features from the scans: i) linear segments (to model ribs of entries/crosscuts), and significant points (to model the corners of the intersections between entries/crosscuts).

E.3.3 Multiple RANSAC Algorithm

The multi-line fitting algorithm that is used to extract the linear segments from the 2D LiDAR data collected by the 2D LiDAR scanners is based on the widely used algorithm called Random Sampling Consensus (RANSAC) as developed by Fischer and Bolles (1981). This algorithm tries to fit a model (in this case, a linear model) to a set of data, which can contain outliers, by iteratively fitting this model in a randomly selected subset of the data until it finds the best-fit model.

For the mapping tool, it was decided to develop a custom algorithm, which is based on the RANSAC algorithm. This was because the RANSAC algorithm starts by randomly choosing subsets of data. This characteristic leads to increased execution times and often to poor results. Moreover, the original RANSAC algorithm is able to fit only one model to the whole data set. For these reasons, a different approach was developed that takes advantage of the fact that the collected data comes in a particular order due to the revolving scanners. The final implementation consists of four steps:

- Divide 2D data into smaller subsets that contain adjacent data points,
- Apply the RANSAC algorithm to every subset specified in the first step to find the equation of the line that models the subset,
- Convert lines to linear segments, i.e., find the start point and the end point from the inliers of the subsets, and
- Merge subsets that overlap or belong to the same line (in reality) in order to obtain more precise models of the ribs.

E.3.4 Detection of Intersection(s)

The LiDAR data are used to develop a model that represents entries/crosscuts ribs. The next step is to define the corners of the pillars based on the model equations. However, this is a complex task as not all ribs are visible during a particular scan (see Figures E.5 – E.8). As a result, three different ways are used to define the corners of an intersection based on the linear segments that model the ribs:

- Endpoints of closest linear segments,
- Intersections between linear segments, and
- Symmetry of intersection corners

Initially, an estimation of possible locations of the corners is derived from the endpoints of a number of linear segments that are closest to the vehicle. Subsequently, the intersections of linear segments with significantly different slopes are calculated and cross-correlated to the initial estimations in order to determine if they are new estimations of corners or better estimations of the initial corners. A final step ensures that the symmetry of the four (4) corners of an intersection, as it is imposed by the room-and-pillar pattern, is satisfied. This step checks the symmetry of the four (4) closest corners, as defined in the previous two steps, and takes actions to satisfy this symmetry if needed.

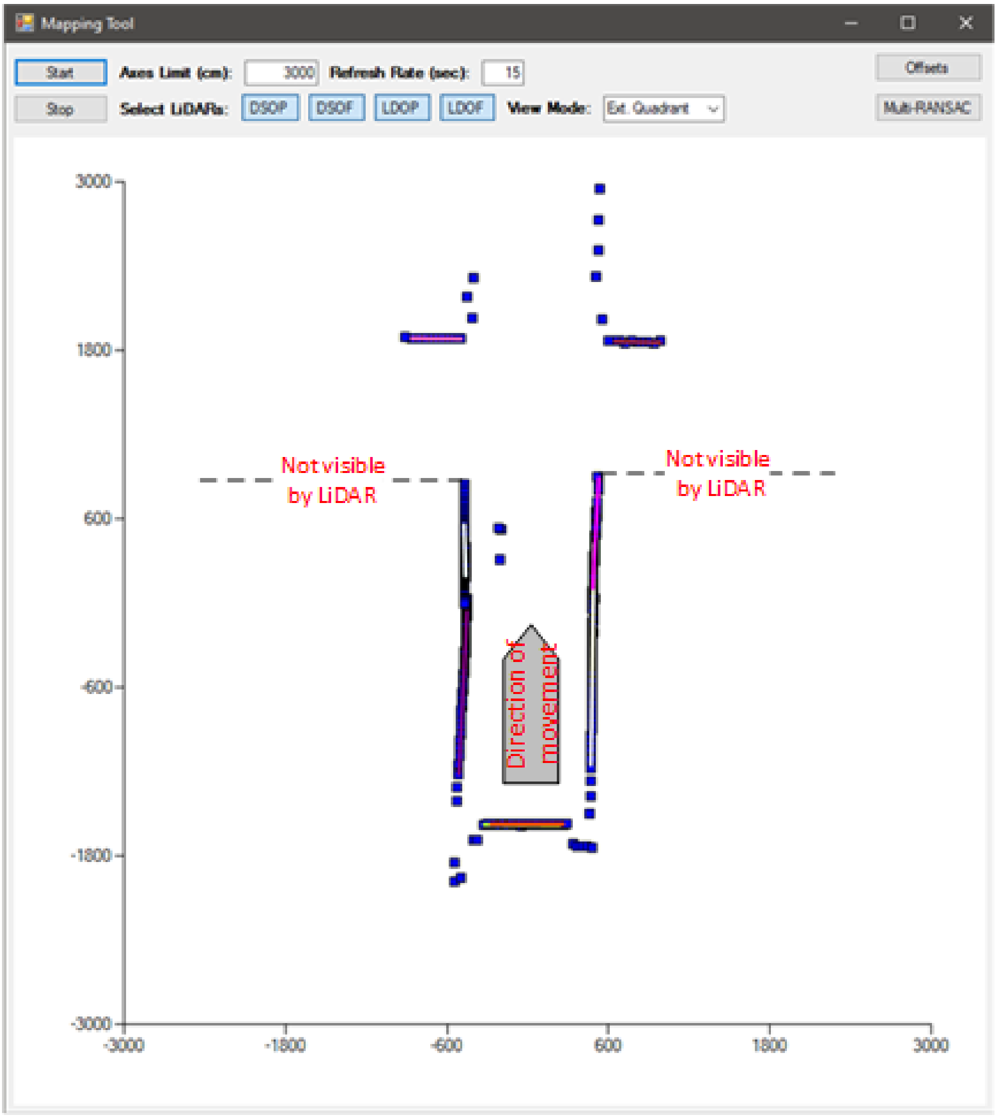


Figure E.5: Intersection map using data from four LiDAR units and linear segments fitted with the RANSAC algorithm (older version of MT)-the grey objects with the red lettered labels are manually added for explanatory purposes

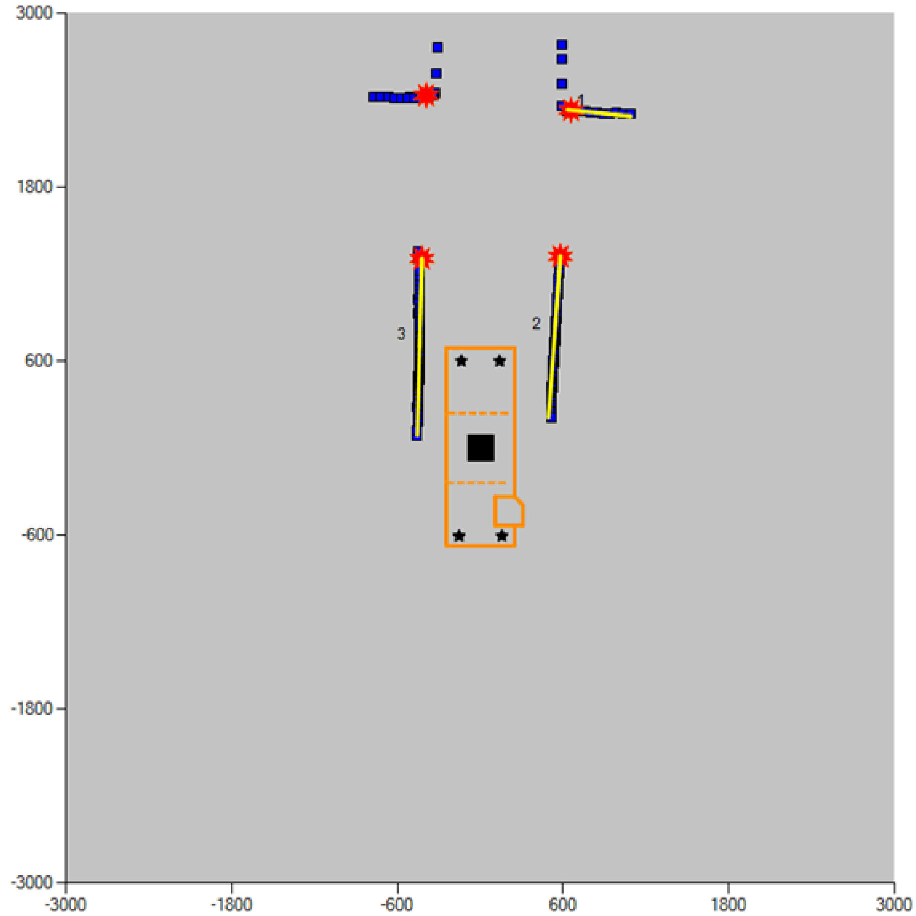


Figure E.6: Map derived by the 2 LiDAR units on the Inby part of the shuttle car, while moving Inby (i.e., towards the positive y-axis). Linear segments fitted with the custom multi-RANSAC algorithm. Red stars denote the corners identified as the most significant corners by the algorithm.

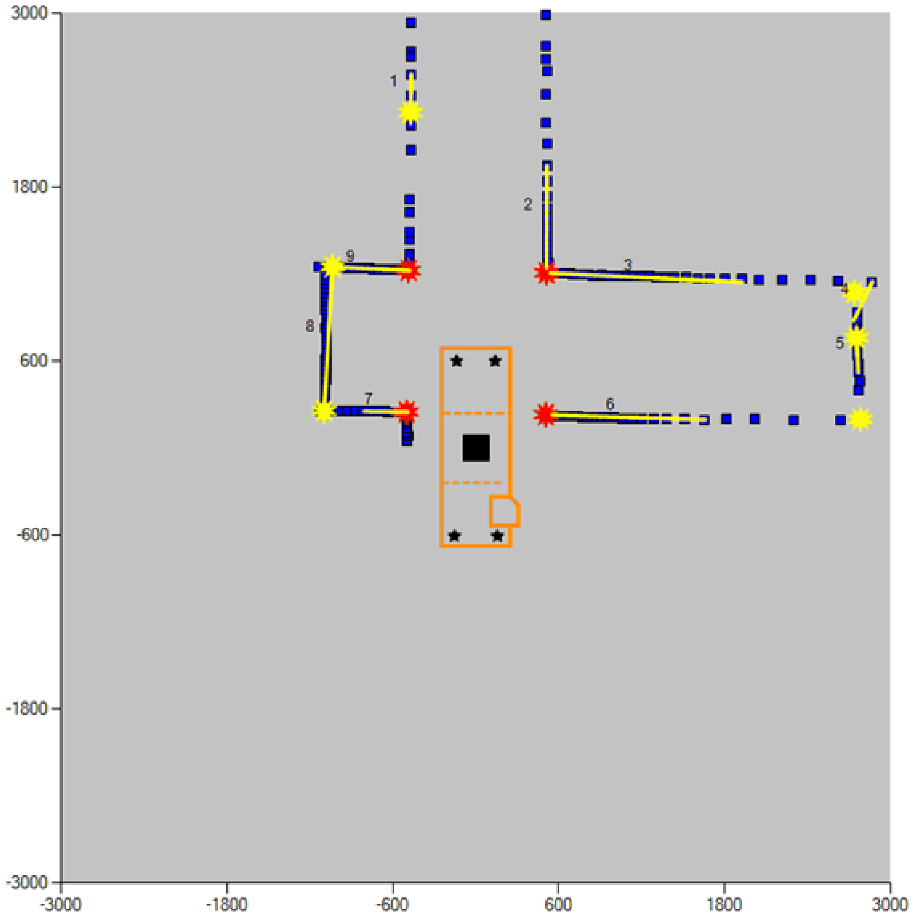


Figure E.7: Intersection map derived by the 2 LiDAR units on the Inby part of the shuttle car, while moving Inby (i.e., towards the positive y-axis). Linear segments fitted with the custom multi-RANSAC algorithm. Red stars denote the corners identified as the most significant corners by the algorithm, while yellow stars denote the remaining corners.

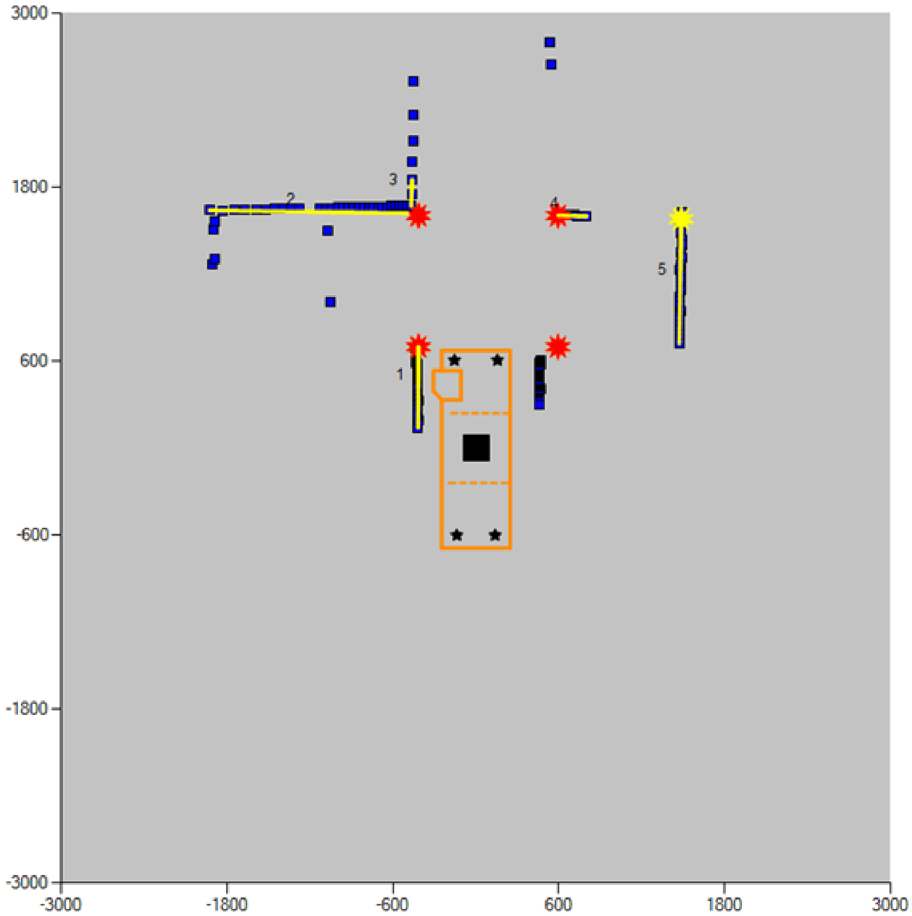


Figure E.8: Intersection map derived by the 2 LiDAR units on the Outby part of the shuttle car, while moving Outby (i.e., towards the positive y-axis). Linear segments fitted with the custom multi-RANSAC algorithm. Red stars denote the corners identified as the most significant corners by the algorithm, while yellow stars denote the remaining corners.

E.3.5 Conversion of Mapping Information to Navigation Parameters

The information derived from the maps must be compressed into a few appropriate and meaningful parameters that can be used by the various modules of the software package that comprise the developed navigation system. This compression takes place within the MT. As a result, the final output of the MT consists of the following three (3) parameters:

- Orientation of the shuttle car
- Deviation of the shuttle car from the centerline
- Distance of the nearest obstacle ahead (towards the direction of movement)

E.3.6 Orientation

The orientation angle of the shuttle car is calculated with regard to the operator side rib of the currently traversed entry/crosscut in a counterclockwise direction (starting from the rib) or with regard to the off-side rib of the currently traversed entry/crosscut in a clockwise direction (starting from the rib). Both reference points yield equivalent estimations due to symmetry (see Figure E.9).

The orientation angle is a crucial parameter for navigating between pillars without colliding with the ribs. The orientation is used in the lateral controller (see Section E.4) for calculating the steering angle of the vehicle while tramming between pillars or passing through intersections.

E.3.7 Deviation from Centerline

A second parameter that is used by the lateral controller for calculating the correction of the steering angle of the vehicle while tramming between pillars (but not while passing through crosscuts) is the distance of the middle of the front axle (reference point) from the centerline of the entry/crosscut. The coordinates of the reference point are always known and fixed since the coordinate frame used in the MT is fixed to the shuttle car (relative coordinate frame). Therefore, any point that belongs to the shuttle car has the same coordinates in every scan. As a result, it is straightforward to calculate the distance of the reference point from the operator side or off-side rib (which are identified by the feature extraction process).

E.3.8 Nearest Obstacle Ahead

The final parameter that is used to stop the shuttle car if an obstacle lies on its course and is closer than a specified threshold (user defined through the GUI) is the parameter that stores the distance of the closest obstacle ahead (towards the direction of movement). This parameter is not defined directly by the MT, like the other two parameters; it is defined based on the values of the orientation. Specifically, the orientation angle estimated from the MT is used to obtain a range of angles (around 180^o) for the LiDAR scanners, which 'looks' between the ribs (see Figure E.10 and E.11). The LiDAR scanners are mounted on the prototype in such a way that the direction of movement is always between 90^o and 270^o, independently of whether the prototype moves 'Inby' or 'Outby'. By examining the measurements of the LiDAR scanners within this range, the minimum distance that corresponds to the nearest obstacle ahead can be determined.

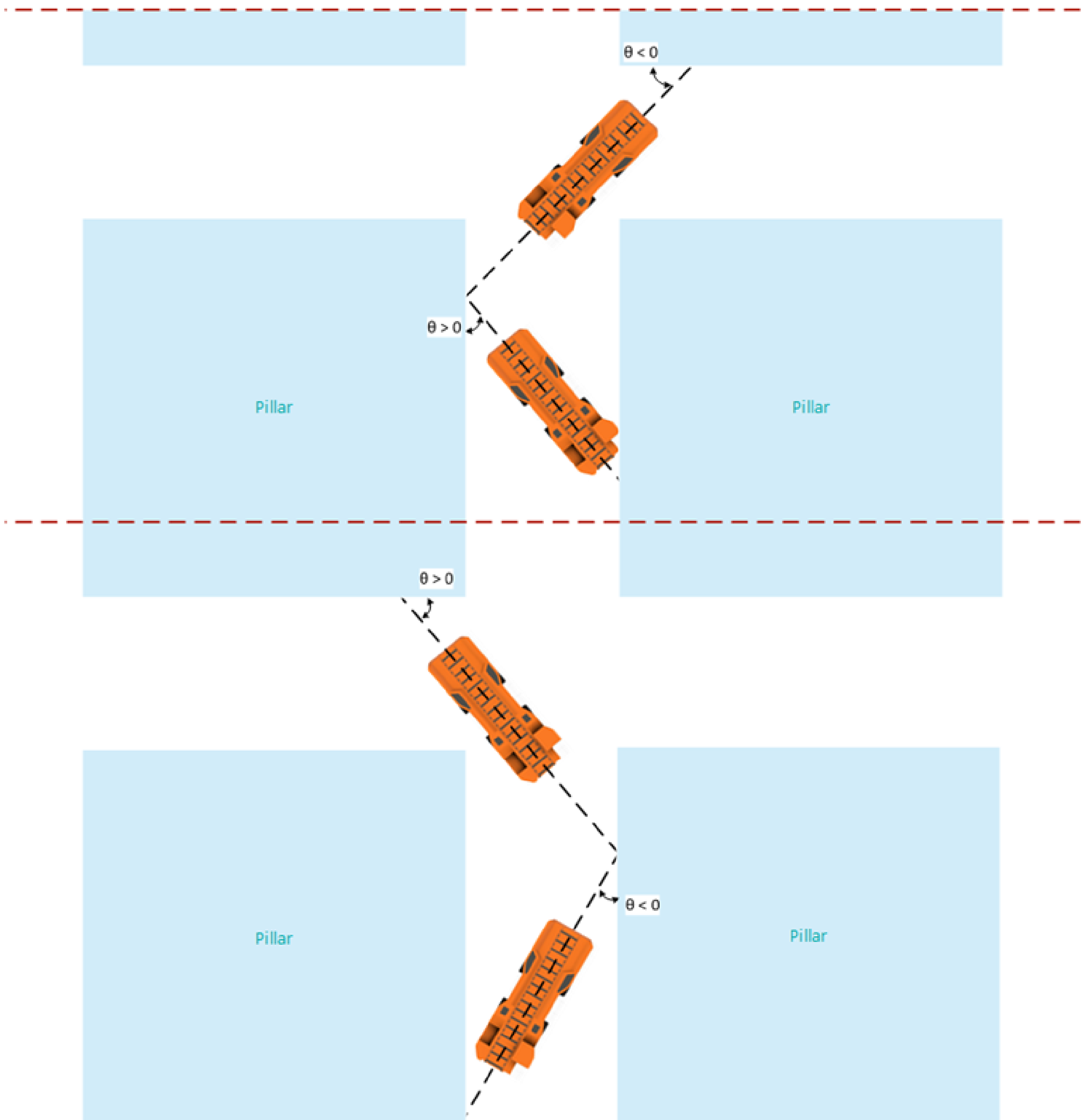


Figure E.9: Relative calculation of orientation angle

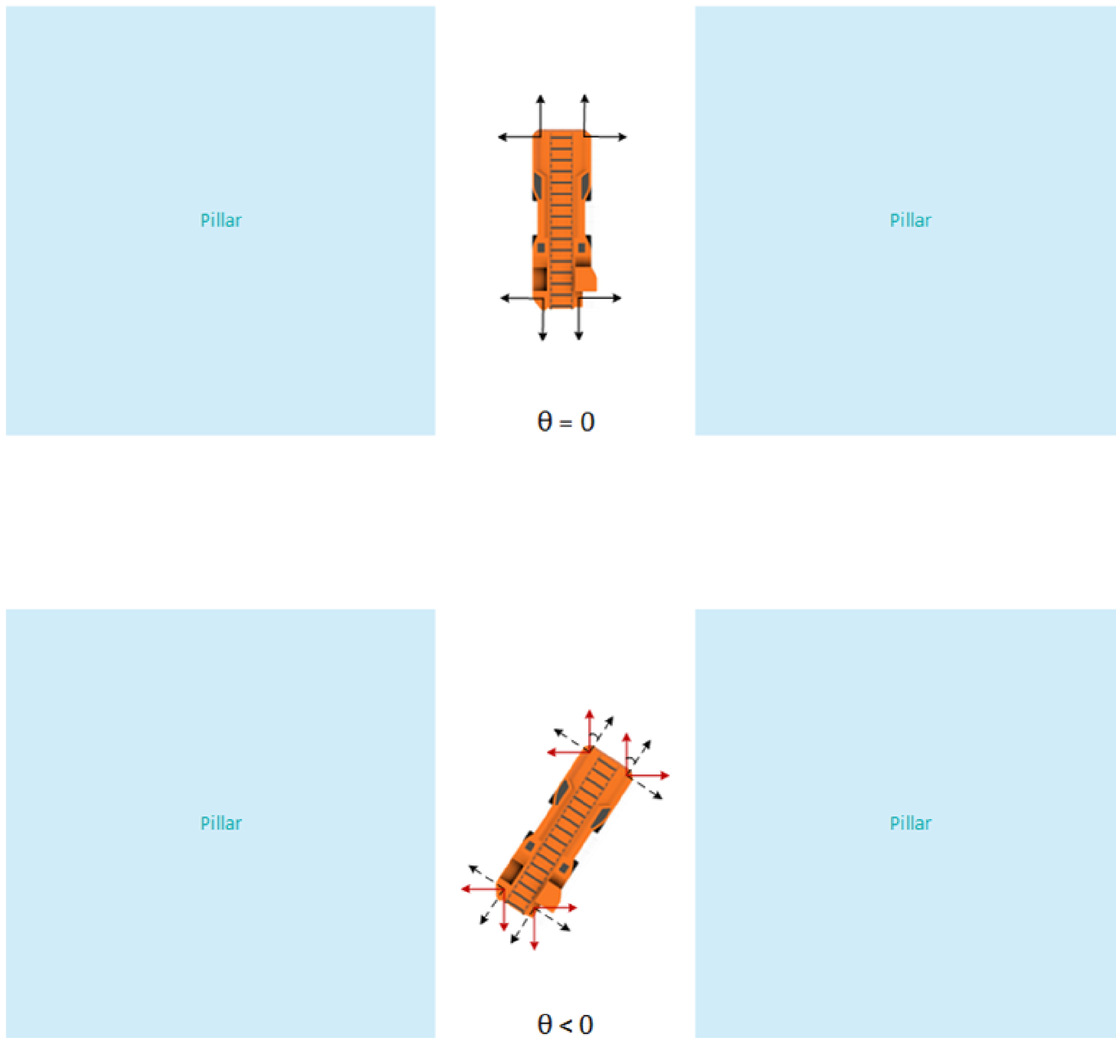


Figure E.10: Correction of range of angles for nearest obstacle ahead detection

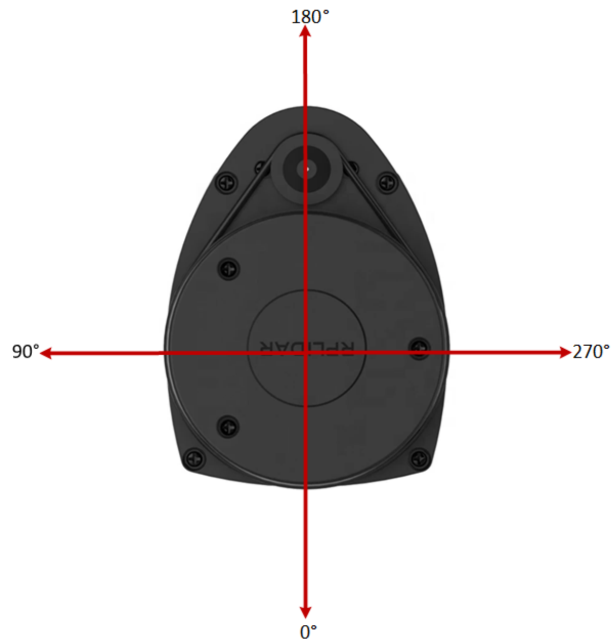


Figure E.11: Coordinate frame with respect to each 2D LiDAR scanner. The LiDAR scanners are mounted on the shuttle car in such a way that the direction of the movement is always between 90^o and 270^o (https://www.slamtec.com/en/Lidar/A1)

E.3.9 Improvements

Selected improvements were made to the mapping tool that enable the shuttle car prototype to correctly recognize and navigate around pillar corners that have a curvilinear circumference (in contrast to the assumption of perfectly rectangular pillars that was adopted previously). A slightly modified RANSAC sub-function is used in order to fit circles to the 2D point-cloud collected through the LiDAR sensors. Figure E.12 and Figure E.13 show two examples of the fitted linear segments and circles that model the pillars' corners while moving straight forward and turning on the corner, respectively.

Figure E.12: Map derived by the 2 LiDAR units on the Inby part of the shuttle car, while moving inby (i.e., towards the positive y-axis). Linear segments fitted with the custom multi-RANSAC algorithm. Circles (modeling the pillar corners) fitted with multi-RANSAC algorithm Red stars denote the corners identified as the most significant

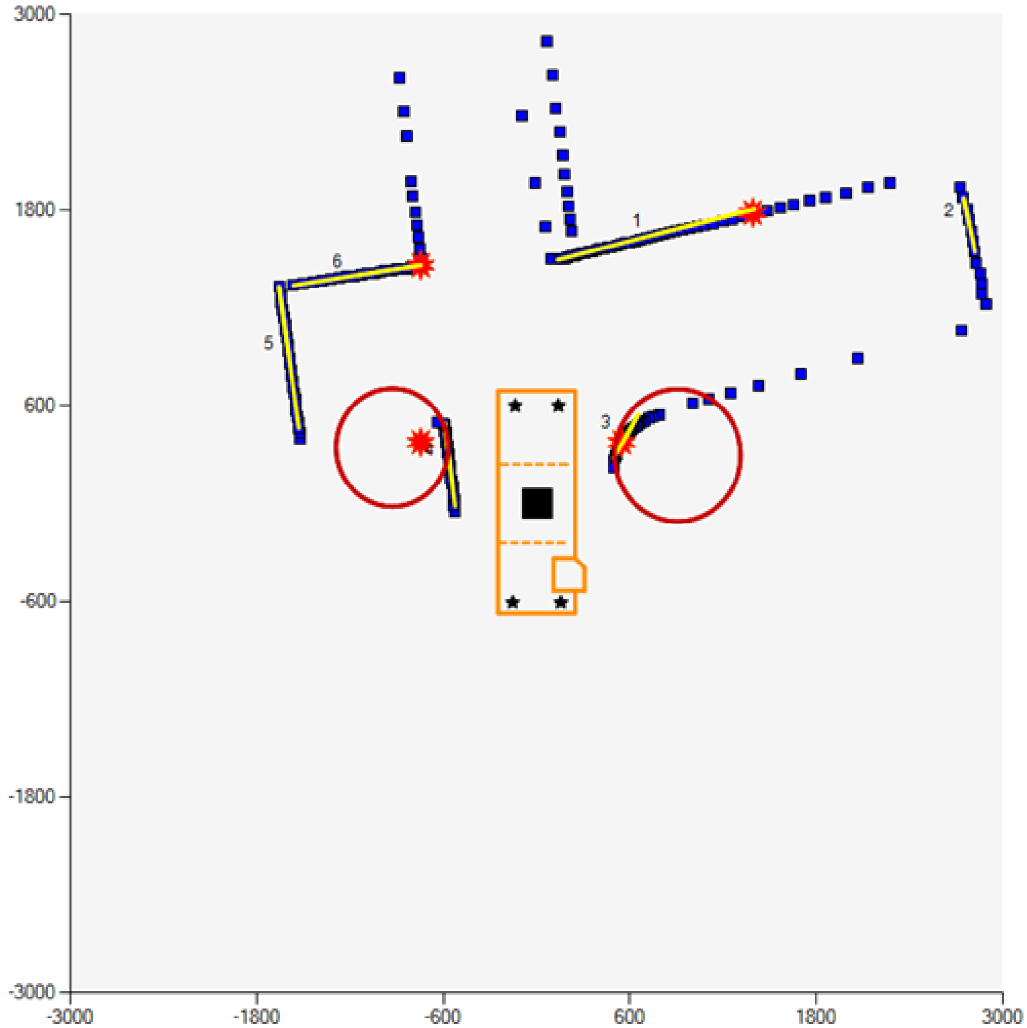


Figure E.13: Map derived by the 2 LiDAR units on the inby part of the shuttle car, while turning. Linear segments fitted with the custom multi-RANSAC algorithm. Circles (modelling the pillar corners) fitted with multi-RANSAC algorithm. Red stars denote the corners identified as the most significant.

E.4 Lateral Control of Autonomous Vehicle

This section describes the controller used for correcting the steering angle of the autonomous shuttle car based on the deviations from the desired path as these are defined through the mapping tool. The developed algorithm is part of additional work done under Task 3.4 to enhance the reliability and accuracy of the lateral control process.

E.4.1 Overview of the Stanley Controller

The Stanley Controller is a non-linear lateral controller for autonomous vehicles for tracking a desired trajectory in real-time. It was implemented for the first time on 'Stanley', the Stanford Racing Team's entry in the DARPA Grand Challenge 2005, which won the challenge after successfully traversing 132 miles over desert terrain in the Mojave Desert. The generic equation that describes the Stanley controller is given below:

$$\delta(t) = \psi(t) + tan^{(-1)}\,(ke(t)/(k_s + v_f(t))), \quad \delta(t) \in [\delta_{min}, \delta_{max}] \tag{E.1}$$

where:
δ(t) = Steering angle,
ψ = Heading error,
$e(t)$ = Cross-track error,
$v_f(t)$ = Velocity of vehicle,
k = Proportional constant, and
k_s = Softening constant.

This equation can be intuitively explained by three principles (see Figure E.14):

- Eliminate the heading error (represented by the 1st term of the equation),
- Eliminate the cross-track error, i.e., the distance between the closest point on the desired path with the front axle of the vehicle (2nd term of equation). The proportional constant, k, defines the contribution of that error in the corrective steering angle, while the softening constant, k_s, ensures a non-zero denominator, and
- Bound the steering angle with respect to the maximum and minimum allowable values.

E.4.2 Implementation for the Autonomous Shuttle Car

The implementation of the above-described lateral controller for the shuttle car traversing between two pillars is depicted in Figure E.15. The prototypes under development receive a value between the range [-100, 100] for the steering angle. The positive values turn the vehicle towards the off-side direction, and the negative values turn it towards the operator side. Therefore, the cross-track error is assigned a sign depending on the relative position of the vehicle with regard to the centerline of the entry/crosscut. If the middle point of the front axle lies on the right side of the centerline, the error is a positive value and will turn the vehicle towards the left (or off-side). Conversely, if the

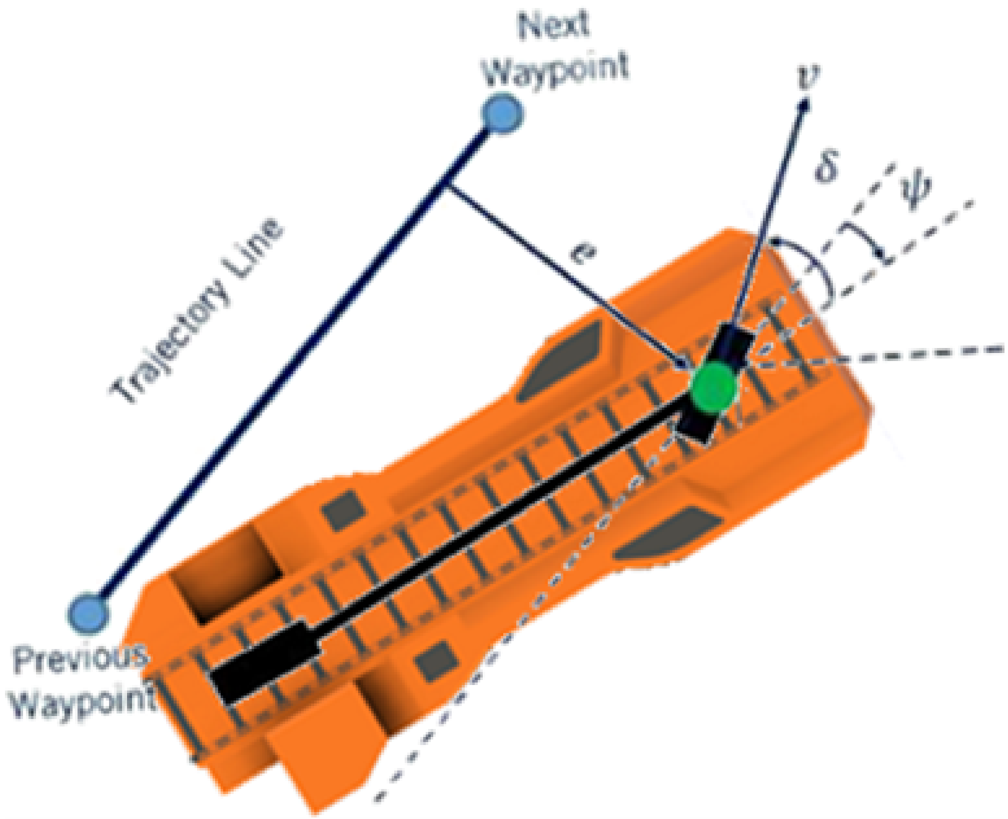


Figure E.14: Stanley geometric relationship

middle point of the front axle lies on the left side of the centerline, the error is a negative value and will turn the vehicle towards the right (or operator side).

However, in the cases where the shuttle car passes through an intersection, a modification needs to be applied. This is because the cross-track errors measured by the sensors, while the shuttle car is in the intersection are invalid numbers with no actual physical meaning. The modification applied in that case is that the second term of the Stanley controller is zeroed out, and only the orientation angle is taken into account for calculating the corrected steering angle.

Finally, the steering angle while turning into an entry/crosscut is set to the maximum value without utilizing the controller, since the confined space calls for sharp turns when the detected corner is within a threshold range.

E.5 Latency Considerations for the Lab-scale Prototypes

The multiple functionalities of the lab-scale shuttle car prototype, which are governed by the tiered software stack inherently exhibits latencies. These latencies occur not only between the data management node and the other two nodes, but also within the multi-modular data processing and visualization node. The magnitude of these latencies is also critically affected by the integrated hardware.

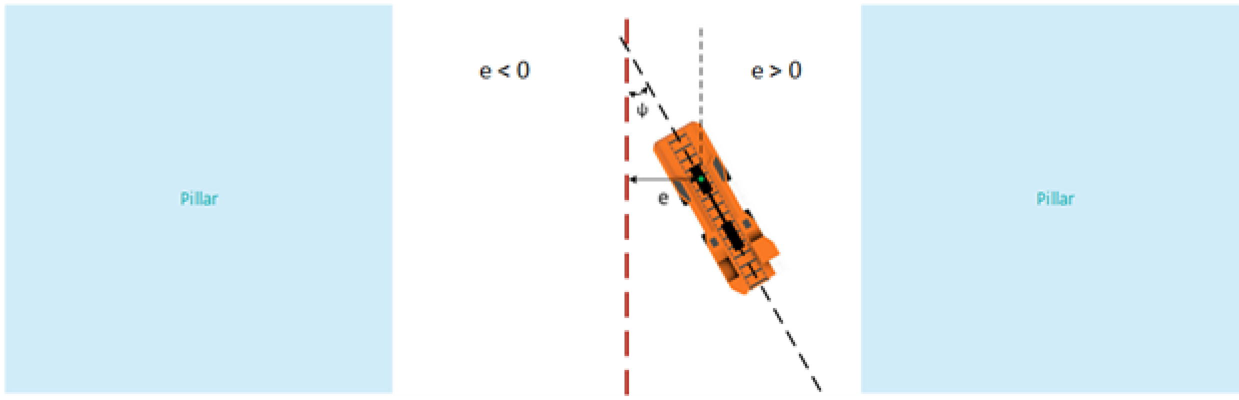


Figure E.15: Stanley controller implementation for shuttle car navigation

Sensors and microcontrollers with higher speed and processing power would naturally lead to shorter latencies. Alternatively, the software developed must compensate for the hardware. The most common approach is to employ parallel processing techniques. Such techniques have been implemented on both the microcontroller side (collection of data) and the front-end interface side (processing and visualization of data).

The process for making a single decision for the next movement of the shuttle car involves the following steps:

1. Communicate with the SQL server and collect the latest updated sensors data,
2. Create a map of the immediate surroundings,
3. Employ the agent to make a decision for the next movement, and
4. Send the proper signal to the shuttle car actuators to execute this decision.

Thus, the fastest processes are the process of acquiring the latest sensor data from the SQL database and the decision-making process based on the mapping output. The duration of the former process is longer than the time needed to simply acquire the data from the SQL database since it includes some preprocessing for the acquired data, as well. The creation of the immediate surroundings map requires about one fourth of the total time. Finally, the execution of the latest decision takes up to 58% of the total time. Note, however, that the signals sent to the prototype's actuators are programmed to be sent for 500 ms. However, each decision-making process starts at the same time as the fourth step of the previous decision.

In other words, the interface starts processing the latest data for the next decision (i.e., data-grabbing, mapping, decision-making) while the shuttle car executes the latest decision. Therefore, these 500 ms are part of the average execution time but do not hinder the process due to the concurrent programming techniques implemented. This compensates for part of the total latencies and subsequently allows for uninterrupted movement of the prototype. The data processing and visualization module is able to retrieve and process the latest data and make a decision for the next movement of the shuttle car prototype in less than 900 ms.

Appendix F

Performance Evaluation of the Lab-scale Prototypes in a Lab-scale Mine Environment

F.1 Introduction

In order to evaluate the performance of the lab-scale prototypes, four scenarios were planned and tested in the mock mine as discussed in the following sections. The scenarios were designed to simulate simple missions and not the actual shuttle car operation during a full shift at an underground coal mine.

Each of the four scenarios was tested 50 consecutive times, half with the prototype moving inby and half with the prototype moving outby (returning along the same route). Considering the pattern of the room-and-pillar mining method, the typical routes that a shuttle car needs to follow between the feeder-breaker and the continuous miner are essentially a combination of these simple scenarios. Despite the simplicity of these scenarios and the relatively small number of trials, every time a scenario is executed, a map needs to be created and the decision-making agent must be utilized for every time step in each scenario (decision cycle). Therefore, the number of decision cycles is sufficient for extracting representative evaluation metrics for the performance of the prototype navigation system.

The evaluation metrics calculated for each scenario are:

- the success rate of the scenario's trials (i.e., the percentage of a successful completion of the conducted trials),
- the average execution time of the trials,
- the average lateral error of the trials (i.e., the average of the deviations from the ideal route as estimated and used by the lateral controller of the prototype), and
- the average error as a percentage of the total distance of the ideal route. The actual trajectories of the prototype during the trials were not able to be recorded (as is common in similar applications) due to the fact that the proposed system does not estimate a global position of the

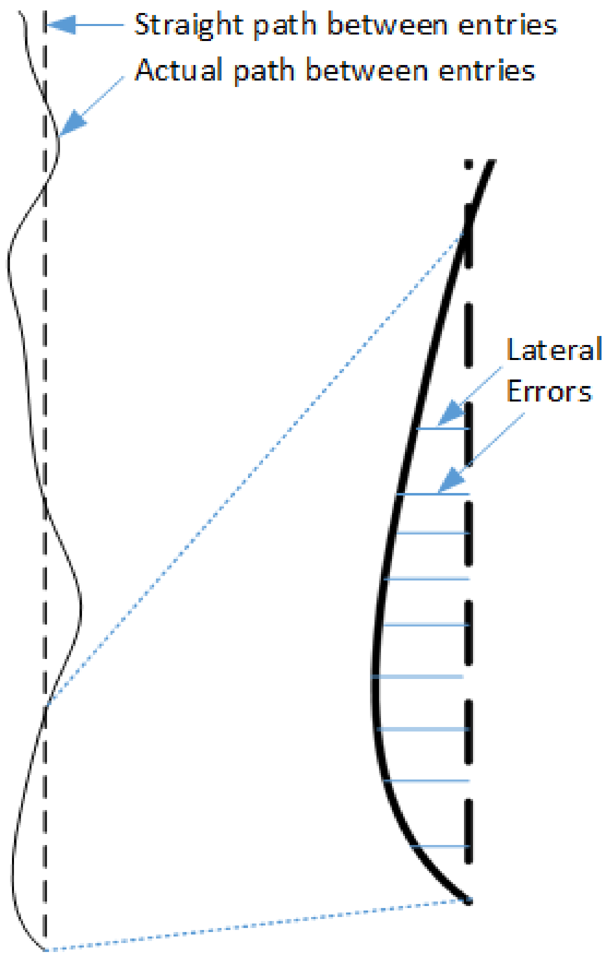


Figure F.1: Definition of lateral error (Figure not to scale)

prototype, as well as the unavailability of a sufficiently accurate sensor (order of centimeters is needed) that can keep track of the trajectory.

A description of each test is provided along with the related performance metrics below.

The lateral error is the sum of the (absolute) deviations from the centerline between entries for straight segments at each decision point. For example, in Figure F.1 10 decision points are shown in the detail view (on the right). The Total Lateral Error is the sum of these deviations for each trial. The Average Total Lateral Error is the average total error for all 50 trials in each scenario. The Average Lateral Error at each decision point is the quotient of the Average Total Lateral Error and the Average Time to complete the trial. This is an approximate value, as there is about 1 decision per second. However, this only applies to each straight segment, as lateral errors are not tracked during turns.

F.2 Scenario 1: Traverse Along two Consecutive Pillars

The first scenario required the shuttle car to travel along an entry for a total distance of two pillar lengths and a crosscut. The shuttle car needs also to stop successfully before an obstacle at the end of the route. Figure F.2 depicts the ideal path for this scenario, while Table F.1 shows the performance metrics for 50 trials. The shuttle car achieved a success rate of 86% for this scenario with an average execution time of 68.8 sec. The average lateral controller error is 138.0 mm, which corresponds to 3% of the total length of the ideal route.

The unsuccessful runs occurred due to two reasons: (i) the lateral controller failed (three times out of 50 trials) to keep the prototype along the centerline of the entry, whereby the prototype veered too close to the ribs and stopped, and (ii) the mapping algorithm failed (four times out of 50 trials) to detect the intersection and correctly transition the prototype to the correct state of the FSM, resulting in the prototype stopping in the middle of the intersection.

Table F.1: Performance metrics for Scenario 1: Traverse along two consecutive pillars

#	Direction	Traverse 1st pillar	Cross Inter-section	Traverse 2nd pillar	Stop at obsta-cle	Success / Failure	Time (sec)
Trial 1	Inby	✓	✓	✓	✓	S	69.3
Trial 1	Outby	✓	✓	✓	✓	S	70.2
Trial 2	Inby	✓	✓	✓	✓	S	71.7
Trial 2	Outby	✓	✓	✓	✓	S	69.2

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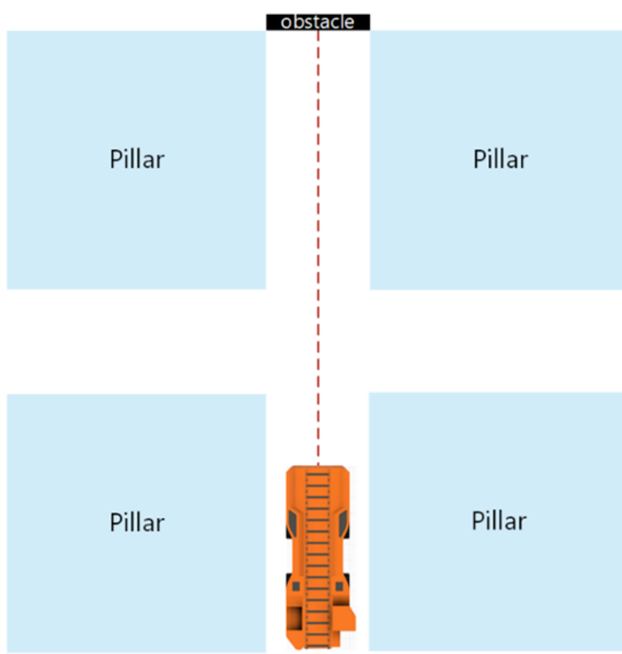

Figure F.2: Ideal path for Scenario 1: Traverse along two consecutive pillars (Figure not to scale)

#	Direction	Traverse 1st pillar	Cross Inter-section	Traverse 2nd pillar	Stop at obsta-cle	Success / Failure	Time (sec)
Trial 3	Inby	✓	✓	✓	✓	S	68.9
Trial 3	Outby	✓	✓	✓	✓	S	70.8
Trial 4	Inby	✓	✓	✓	✓	S	70.8
Trial 4	Outby	✓	✓	✓	✓	S	70.9
Trial 5	Inby	✓	×	-	-	F	-
Trial 5	Outby	✓	✓	✓	✓	S	67.0
Trial 6	Inby	✓	✓	✓	✓	S	67.5
Trial 6	Outby	✓	✓	✓	✓	S	67.0
Trial 7	Inby	✓	✓	✓	✓	S	69.6
Trial 7	Outby	✓	✓	✓	✓	S	67.9
Trial 8	Inby	✓	✓	✓	✓	S	70.2
Trial 8	Outby	✓	✓	✓	✓	S	69.2
Trial 9	Inby	✓	✓	✓	✓	S	69.7
Trial 9	Outby	✓	✓	✓	✓	S	65.9
Trial 10	Inby	✓	×	-	-	F	-
Trial 10	Outby	✓	✓	✓	✓	S	70.8
Trial 11	Inby	✓	✓	✓	✓	S	68.1
Trial 11	Outby	✓	✓	✓	✓	S	67.1
Trial 12	Inby	✓	✓	✓	✓	S	69.1
Trial 12	Outby	✓	✓	✓	✓	S	66.5
Trial 13	Inby	✓	✓	✓	✓	S	68.7
Trial 13	Outby	✓	✓	✓	✓	S	68.2
Trial 14	Inby	✓	×	-	-	F	-
Trial 14	Outby	✓	✓	×	-	F	-
Trial 15	Inby	✓	✓	✓	✓	S	68.5
Trial 15	Outby	✓	✓	✓	✓	S	71.5
Trial 16	Inby	✓	✓	✓	✓	S	69.2
Trial 16	Outby	✓	✓	✓	✓	S	67.0
Trial 17	Inby	✓	✓	✓	✓	S	69.6
Trial 17	Outby	✓	✓	✓	✓	S	69.5
Trial 18	Inby	✓	✓	✓	✓	S	67.7
Trial 18	Outby	✓	✓	✓	✓	S	66.5
Trial 19	Inby	×	-	-	-	F	-
Trial 19	Outby	✓	✓	✓	✓	S	66.3
Trial 20	Inby	✓	✓	✓	✓	S	68.4
Trial 20	Outby	✓	✓	✓	✓	S	68.3
Trial 21	Inby	✓	✓	✓	✓	S	67.7
Trial 21	Outby	✓	✓	✓	✓	S	68.3
Trial 22	Inby	×	-	-	-	F	-

Continued on next page

#	Direction	Traverse 1st pillar	Cross Intersection	Traverse 2nd pillar	Stop at obstacle	Success / Failure	Time (sec)
Trial 22	Outby	✓	✓	✓	✓	S	68.8
Trial 23	Inby	✓	✓	✓	✓	S	71.1
Trial 23	Outby	✓	×	-	-	F	-
Trial 24	Inby	✓	✓	✓	✓	S	68.8
Trial 24	Outby	✓	✓	✓	✓	S	68.3
Trial 25	Inby	✓	✓	✓	✓	S	71.0
Trial 25	Outby	✓	✓	✓	✓	S	68.9
						Total Route Distance (mm):	4,500
						Average Total Lateral Error (mm):	138.0
						Average Total Lateral Error (%):	3%
						Average Lateral Error at each Decision Point (mm):	0.80
						Average Time (sec):	171.8
						Success Rate:	86%

F.3 Scenario 2: Two Consecutive Turns

The second scenario required the shuttle car to make two consecutive turns and successfully stop before an obstacle at the end of the route. Figure F.3 depicts the ideal path for this scenario, while Table F.2 shows the performance metrics of the 50 trials. The shuttle car achieved a success rate of 84% for this scenario with an average execution time of 108.7 sec. The average lateral controller error is 526.1 mm, which corresponds to 7% of the total length of the ideal route.

The unsuccessful runs occurred because of two reasons: i) the mapping algorithm failed (four times out of 50 trials) to detect the intersection and correctly transition the prototype to the correct state of the FSM for executing a turn, resulting in the prototype either passing the intersection or stopping in the middle of the intersection, and ii) the sensors failed (four times out of 50 trials) to timely detect the obstacle at the end of the route and stop before it, resulting in the prototype colliding with the obstacle.

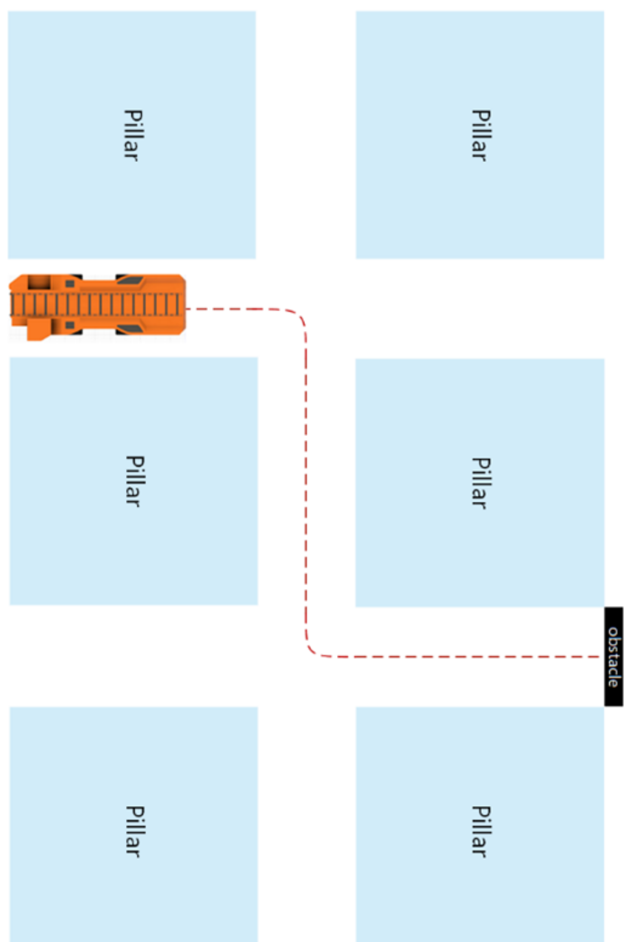

Figure F.3: Ideal path for Scenario 2: Two consecutive turns (Figure not to scale)

Table F.2: Performance metrics for Scenario 2: Two consecutive turns

#	Direction	Traverse 1st pillar	1st Turn	Traverse 2nd pillar	2nd Turn	Stop at obstacle	Success / Failure	Time (sec)
Trial 1	Inby	✓	✓	✓	✓	✓	S	112.4
Trial 1	Outby	✓	✓	✓	✓	✓	S	114.1
Trial 2	Inby	✓	✓	✓	✓	×	F	-
Trial 2	Outby	✓	×	-	-	-	F	-
Trial 3	Inby	✓	✓	✓	✓	✓	S	108.9
Trial 3	Outby	✓	✓	✓	✓	✓	S	114.5
Trial 4	Inby	✓	✓	✓	✓	✓	S	105.1
Trial 4	Outby	✓	✓	✓	✓	✓	S	109.8
Trial 5	Inby	✓	✓	✓	✓	✓	S	109.5
Trial 5	Outby	✓	✓	✓	✓	✓	S	109.5
Trial 6	Inby	✓	✓	✓	✓	✓	S	104.2
Trial 6	Outby	✓	✓	✓	✓	✓	S	110.0
Trial 7	Inby	✓	✓	✓	✓	✓	S	103.3
Trial 7	Outby	✓	✓	✓	✓	✓	S	111.2
Trial 8	Inby	✓	✓	✓	✓	✓	S	107.3
Trial 8	Outby	✓	✓	✓	×	-	F	-
Trial 9	Inby	✓	✓	✓	✓	✓	S	108.9
Trial 9	Outby	✓	✓	✓	✓	✓	S	121.1
Trial 10	Inby	✓	✓	✓	✓	✓	S	106.1
Trial 10	Outby	✓	✓	✓	✓	✓	S	107.8
Trial 11	Inby	✓	✓	✓	✓	✓	S	111.4
Trial 11	Outby	✓	✓	✓	✓	✓	S	112.5
Trial 12	Inby	✓	✓	✓	✓	✓	S	106.2
Trial 12	Outby	✓	✓	✓	✓	✓	S	115.4
Trial 13	Inby	✓	✓	✓	✓	✓	S	111.2
Trial 13	Outby	✓	✓	✓	✓	✓	S	113.5
Trial 14	Inby	✓	✓	✓	✓	✓	S	108.5
Trial 14	Outby	✓	✓	✓	✓	✓	S	109.7
Trial 15	Inby	✓	✓	✓	×	-	F	-
Trial 15	Outby	✓	✓	✓	✓	✓	S	104.4
Trial 16	Inby	✓	✓	✓	✓	✓	S	113.1
Trial 16	Outby	✓	✓	✓	✓	✓	S	114.4
Trial 17	Inby	✓	✓	✓	✓	✓	S	106.1
Trial 17	Outby	✓	✓	✓	✓	✓	S	108.2
Trial 18	Inby	✓	✓	✓	✓	✓	S	102.6
Trial 18	Outby	✓	✓	✓	✓	✓	S	104.8
Trial 19	Inby	✓	✓	✓	✓	✓	S	108.8

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#	Direction	Traverse 1st pillar	1st Turn	Traverse 2nd pillar	2nd Turn	Stop at obstacle	Success / Failure	Time (sec)
Trial 19	Outby	✓	✓	✓	✓	✓	S	104.6
Trial 20	Inby	✓	✓	✓	✓	×	F	-
Trial 20	Outby	✓	✓	✓	✓	✓	S	108.7
Trial 21	Inby	✓	✓	✓	✓	✓	S	101.7
Trial 21	Outby	✓	✓	✓	✓	✓	S	109.6
Trial 22	Inby	✓	✓	✓	×	-	F	-
Trial 22	Outby	✓	✓	✓	✓	✓	S	104.4
Trial 23	Inby	✓	✓	✓	✓	✓	S	109.1
Trial 23	Outby	✓	✓	✓	✓	×	F	-
Trial 24	Inby	✓	✓	✓	✓	✓	S	101.4
Trial 24	Outby	✓	✓	✓	✓	✓	S	105.0
Trial 25	Inby	✓	✓	✓	✓	×	F	-
Trial 25	Outby	✓	✓	✓	✓	✓	S	108.2
							Total Route Distance (mm):	8,000
							Average Total Lateral Error (mm):	526.1
							Average Total Lateral Error (%):	7%
							Average Lateral Error at each Decision Point (mm):	4.87
							Average Time (sec):	108.7
							Success Rate:	84%

F.4 Scenario 3: Traverse along two Consecutive Pillars and Turn

The third scenario required the shuttle car to tram straight through a crosscut (i.e., traverse along two consecutive pillars), take one turn and successfully stop before an obstacle at the end of the route. Figure F.4 depicts the ideal path for this scenario, while Table F.3 shows the performance metrics of the 50 trials. The shuttle car achieved a success rate of 90% for this scenario with an average execution time of 106.0 sec. The average lateral controller error is 514.7 mm, which corresponds to 6% of the total length of the ideal route.

The failures experienced for this scenario occurred because the mapping algorithm failed (five times out of 50 trials) to detect the intersection and correctly transition the prototype to the correct state of the FSM for turning into the intersection or passing the intersection, resulting in the prototype either passing the intersection or stopping in the middle of the intersection.

Table F.3: Performance metrics for Scenario 3: Traverse along two consecutive pillars and turn

#	Direction	Traverse 1st pillar	1st Turn	Traverse 2nd pillar	2nd Turn	Stop at obstacle	Success / Failure	Time (sec)
Trial 1	Inby	✓	✓	✓	✓	✓	S	115.5
Trial 1	Outby	✓	✓	✓	✓	✓	S	108.4

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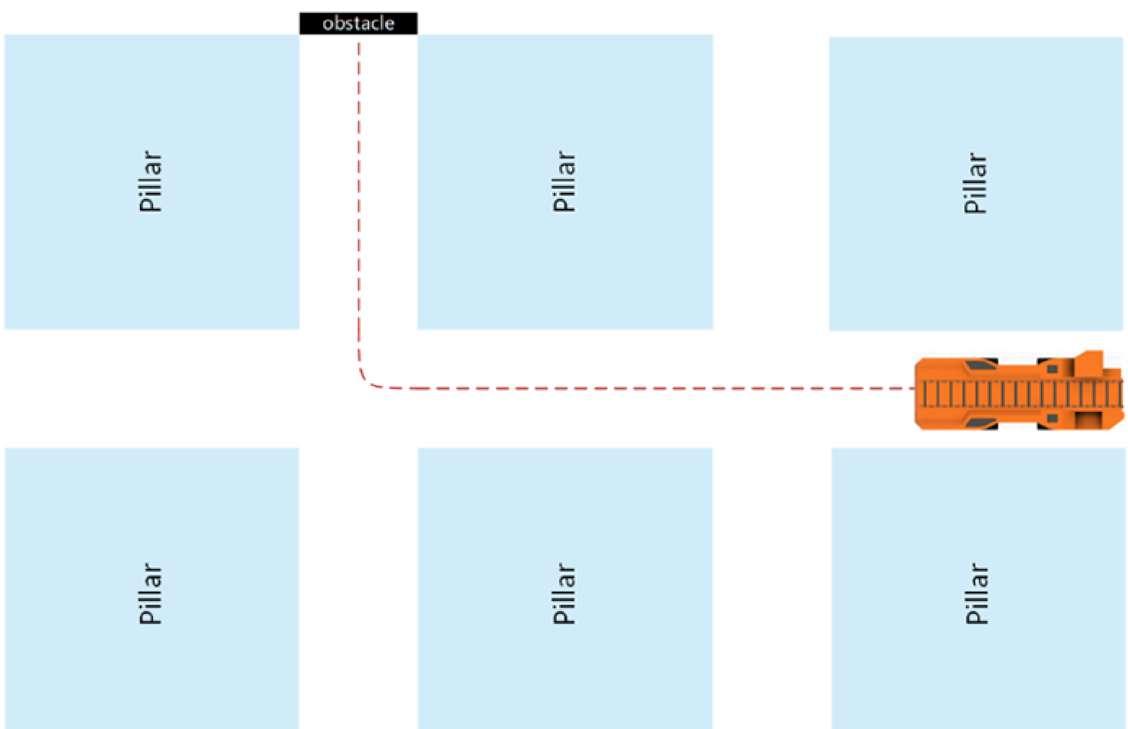

Figure F.4: Ideal path for Scenario 3: Traverse along two consecutive pillars and turn (Figure not to scale)

#	Direction	Traverse 1st pillar	1st Turn	Traverse 2nd pillar	2nd Turn	Stop at obstacle	Success / Failure	Time (sec)
Trial 2	Inby	✓	✓	✓	×	-	F	-
Trial 2	Outby	✓	✓	✓	✓	✓	S	111.8
Trial 3	Inby	✓	✓	✓	✓	✓	S	110.1
Trial 3	Outby	✓	✓	✓	✓	✓	S	97.1
Trial 4	Inby	✓	✓	✓	✓	✓	S	105.7
Trial 4	Outby	✓	✓	✓	✓	✓	S	105.0
Trial 5	Inby	✓	✓	✓	×	-	F	-
Trial 5	Outby	✓	✓	✓	✓	✓	S	107.9
Trial 6	Inby	✓	✓	✓	✓	✓	S	101.2
Trial 6	Outby	✓	✓	✓	✓	✓	S	109.3
Trial 7	Inby	✓	✓	✓	✓	✓	S	105.3
Trial 7	Outby	✓	✓	✓	✓	✓	S	100.9
Trial 8	Inby	✓	✓	✓	✓	✓	S	111.8
Trial 8	Outby	✓	✓	✓	✓	✓	S	107.5
Trial 9	Inby	✓	✓	✓	×	-	F	-
Trial 9	Outby	✓	✓	✓	✓	✓	S	103.2
Trial 10	Inby	✓	✓	✓	✓	✓	S	108.6
Trial 10	Outby	✓	✓	✓	×	-	F	-
Trial 11	Inby	✓	✓	✓	✓	✓	S	108.1
Trial 11	Outby	✓	✓	✓	✓	✓	S	97.2
Trial 12	Inby	✓	✓	✓	✓	✓	S	102.0
Trial 12	Outby	✓	✓	✓	✓	✓	S	101.1
Trial 13	Inby	✓	✓	✓	✓	✓	S	110.2
Trial 13	Outby	✓	✓	✓	✓	✓	S	106.1
Trial 14	Inby	✓	✓	✓	✓	✓	S	116.8
Trial 14	Outby	✓	✓	✓	✓	✓	S	109.5
Trial 15	Inby	✓	✓	✓	✓	✓	S	108.0
Trial 15	Outby	✓	✓	✓	✓	✓	S	97.2
Trial 16	Inby	✓	✓	✓	✓	✓	S	104.4
Trial 16	Outby	✓	✓	✓	✓	✓	S	106.6
Trial 17	Inby	✓	✓	✓	✓	✓	S	106.1
Trial 17	Outby	✓	✓	✓	✓	✓	S	104.9
Trial 18	Inby	✓	✓	✓	✓	✓	S	108.4
Trial 18	Outby	✓	✓	✓	✓	✓	S	100.6
Trial 19	Inby	✓	×	-	-	-	F	-
Trial 19	Outby	✓	✓	✓	✓	✓	S	106.4
Trial 20	Inby	✓	✓	✓	✓	✓	S	108.5
Trial 20	Outby	✓	✓	✓	✓	✓	S	97.1
Trial 21	Inby	✓	✓	✓	✓	✓	S	105.3

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#	Direction	Traverse 1st pillar	1st Turn	Traverse 2nd pillar	2nd Turn	Stop at obstacle	Success / Failure	Time (sec)
Trial 21	Outby	✓	✓	✓	✓	✓	S	109.3
Trial 22	Inby	✓	✓	✓	✓	✓	S	108.1
Trial 22	Outby	✓	✓	✓	✓	✓	S	108.9
Trial 23	Inby	✓	✓	✓	✓	✓	S	107.6
Trial 23	Outby	✓	✓	✓	✓	✓	S	95.6
Trial 24	Inby	✓	✓	✓	✓	✓	S	105.8
Trial 24	Outby	✓	✓	✓	✓	✓	S	100.7
Trial 25	Inby	✓	✓	✓	✓	✓	S	108.2
Trial 25	Outby	✓	✓	✓	✓	✓	S	112.0
							Total Route Distance (mm):	8,000
							Average Total Lateral Error (mm):	514.7
							Average Total Lateral Error (%):	6%
							Average Lateral Error at each Decision Point (mm):	4.86
							Average Time (sec):	106.0
							Success Rate:	90%

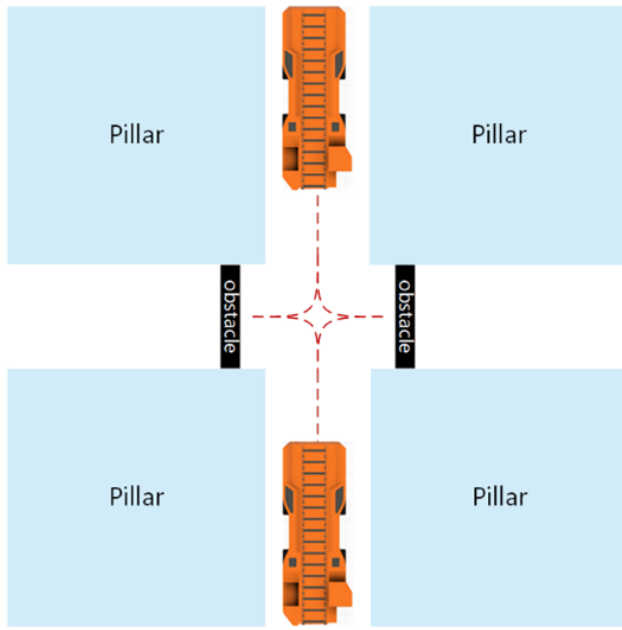

Figure F.5: Ideal path for Scenario 4: Obstacle in Turn (Figure not to scale)

F.5 Scenario 4: Obstacle in Turn

The fourth scenario required the shuttle car to traverse along one pillar, start turning at the first crosscut, but while turning, it should detect and stop before an obstacle located close to the corner of the intersection. Figure F.5 depicts the ideal path for this scenario, while Table F.4 shows the performance metrics of the 50 trials conducted. The shuttle car achieved a success rate of 100% for this scenario.

Table F.4: Performance metrics for Scenario 4: Obstacle on Turn (Operator-side turn means that the shuttle car prototype turns towards the side that the operator cab is located on the shuttle car, while off-side turn means that the shuttle car prototype turns towards the opposite side than that the operator cab is located on the shuttle car.)

#	Direction	Turn Direction	Traverse 1st pillar	Start Turning	Stop at obstacle	Success / Failure
Trial 1	Inby	Operator	✓	✓	✓	S
Trial 1	Outby	Operator	✓	✓	✓	S
Trial 2	Inby	Operator	✓	✓	✓	S
Trial 2	Outby	Operator	✓	✓	✓	S
Trial 3	Inby	Off	✓	✓	✓	S
Trial 3	Outby	Off	✓	✓	✓	S
Trial 4	Inby	Off	✓	✓	✓	S
Trial 4	Outby	Off	✓	✓	✓	S
Trial 5	Inby	Operator	✓	✓	✓	S

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#	Direction	Turn Direction	Traverse 1st pillar	Start Turning	Stop at obstacle	Success / Failure
Trial 5	Outby	Operator	✓	✓	✓	S
Trial 6	Inby	Operator	✓	✓	✓	S
Trial 6	Outby	Operator	✓	✓	✓	S
Trial 7	Inby	Off	✓	✓	✓	S
Trial 7	Outby	Off	✓	✓	✓	S
Trial 8	Inby	Off	✓	✓	✓	S
Trial 8	Outby	Off	✓	✓	✓	S
Trial 9	Inby	Operator	✓	✓	✓	S
Trial 9	Outby	Operator	✓	✓	✓	S
Trial 10	Inby	Operator	✓	✓	✓	S
Trial 10	Outby	Operator	✓	✓	✓	S
Trial 11	Inby	Off	✓	✓	✓	S
Trial 11	Outby	Off	✓	✓	✓	S
Trial 12	Inby	Off	✓	✓	✓	S
Trial 12	Outby	Off	✓	✓	✓	S
Trial 13	Inby	Operator	✓	✓	✓	S
Trial 13	Outby	Operator	✓	✓	✓	S
Trial 14	Inby	Operator	✓	✓	✓	S
Trial 14	Outby	Operator	✓	✓	✓	S
Trial 15	Inby	Off	✓	✓	✓	S
Trial 15	Outby	Off	✓	✓	✓	S
Trial 16	Inby	Off	✓	✓	✓	S
Trial 16	Outby	Off	✓	✓	✓	S
Trial 17	Inby	Operator	✓	✓	✓	S
Trial 17	Outby	Operator	✓	✓	✓	S
Trial 18	Inby	Operator	✓	✓	✓	S
Trial 18	Outby	Operator	✓	✓	✓	S
Trial 19	Inby	Off	✓	✓	✓	S
Trial 19	Outby	Off	✓	✓	✓	S
Trial 20	Inby	Off	✓	✓	✓	S
Trial 20	Outby	Off	✓	✓	✓	S
Trial 21	Inby	Operator	✓	✓	✓	S
Trial 21	Outby	Operator	✓	✓	✓	S
Trial 22	Inby	Operator	✓	✓	✓	S
Trial 22	Outby	Operator	✓	✓	✓	S
Trial 23	Inby	Off	✓	✓	✓	S
Trial 23	Outby	Off	✓	✓	✓	S
Trial 24	Inby	Off	✓	✓	✓	S
Trial 24	Outby	Off	✓	✓	✓	S
Trial 25	Inby	Operator	✓	✓	✓	S

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#	Direction	Turn Direction	Traverse 1st pillar	Start Turning	Stop at obstacle	Success / Failure
Trial 25	Outby	Operator	✓	✓	✓	S
					Success Rate:	100%

F.6 Discussion

The proposed navigation system, which is specifically tailored for the room-and-pillar mining environment, uses the point clouds of a total of four LiDAR scanning units (where only two of them are used at a time, depending on which direction the vehicle is moving) to acquire an instant map of the prototype's surroundings in order to decide whether the predefined sequence of commands is safe to be executed. Point clouds are evaluated only at the current vehicle position. Point clouds are not accumulated and evaluated as a cluster.

It should be noted that the efficiency of the feature extraction routines is partially based on the density of the collected point clouds. The density of the point clouds in an actual environment is not expected to be significantly different from the simulated trials since both the prototype and the mock mine have been constructed with the same scale ratio. Moreover, the naturally confined spaces outlined by the room-and-pillar pattern guarantees that the LiDAR scanner beams will get sufficiently reflected back to the shuttle car. Nevertheless, any problems that may arise from unexpected scarcity of data points under actual mining conditions can be mitigated through the acquisition of more advanced versions of the currently utilized LiDAR units, which exhibit faster scanning frequencies, and by fine-tuning the user-specified parameters of the RANSAC algorithm in the actual mining environment.

The reliability of the feature extraction process is of vital significance, because the efficient navigation of the prototype heavily relies on the accurate and timely detection of the salient features of the surrounding environment, i.e., the corners of the closest intersection and the ribs of the entries. The former is the most critical variable since the accurate detection of the location of the intersection corners with respect to the center of the vehicle's front axle directly controls the state transitions of the prototype's FSM.

Despite the performance of the mapping process in estimating the location of the intersection corners, there are cases in which these estimations are inconsistent between consecutive updates of the map of the immediate area. This can be attributed to the stochastic nature of the RANSAC algorithm, as well as the continuously changing density of the LiDAR data as the prototype moves. Therefore, the inherent uncertainties associated with these stochastic elements, as well as the trade-off between the user-specified parameters of the RANSAC algorithm, can lead to an inaccurate detection or lack of a successful detection of all the linear segments that model the pillar ribs near the vehicle. In such cases, if the prototype is positioned at a critical point and fails to correctly transition to the desired turning or intersection passing state of the FSM, this may result in undesired decisions. Another parameter that needs to be considered is the occasional delayed processing of parts of the algorithms, which can lead to slightly delayed triggering of the turning sequence. As a result, although the prototype would start turning, it would then collide with the ribs of the entry/crosscut into which the shuttle car turns. In summary, the experienced failures occurred because of three reasons:

- the lateral controller failed to keep the prototype along the centerline of the entry, due to inefficient detection of the ribs of the entry (processing / analysis problem),
- the mapping algorithm failed to sufficiently detect the intersection and correctly transition the prototype to the correct state of the FSM for turning into the intersection or passing

the intersection, due to inefficient detection of the corners of the intersection (processing / analysis problem), and

- the sensors failed to timely detect an obstacle lying in front of the prototype vehicle, due to inaccurate estimations of the vehicle's orientation (inefficient/unstable algorithm).

Another aspect that is affected by the stochastic nature of the processing/analysis routines is the execution time of the trials. It is evident from the performance data presented in the previous section that the trials of the same scenario exhibit some fluctuation with regard to the execution time. This fluctuation is because the individual movements decided in every time step during a trial are based only on the accuracy of the map in the current position, as well as the safety measurements that issue no movement commands for specific time duration in case any miscalculations are detected by the various error filters of the routines.

Finally, it should be noted that the development of three separate nodes, namely the data collection node, the data management node and the data processing and visualization node (see Figure 4.2 in Chapter 4), that was mandated by the large amount of collected data and the need to ensure uninterrupted and fast data storage and flow proved to be a successful design concept. Utilization of a MySQL database server was a solution that allowed for asynchronous, real-time and reliable data management. Asynchronous access from multiple sources ensured that the data was not lost due to of conflicts between the different processes, while at the same time newly acquired data were recorded in real-time or near real-time. A similar concept applied to data requests from multiple clients.

Appendix G

Full-scale Shuttle Car Retrofitting and Constraints

G.1 Introduction

G.2 Tramming and Braking Considerations

Tramming of MSHA approved shuttle cars is accomplished by adjusting a hydraulic valve that allows hydraulic power to flow to the motors. Each wheel is powered by an independent motor assembly.

Braking is completely independent of electronic components, due to MSHA regulations. Braking, including the panic switch (emergency stop), are completely manual.

Steering on these shuttle cars is accomplished manually, i.e., the movement of the handle bar adjusts a proportional valve that steers the wheels left or right. The wheels are locked in pairs to achieve four-wheel steering.

G.3 Initial Planning

The industry partner in this project was Alliance Coal. Alliance Coal mainly uses custom shuttle cars manufactured by Auxier Welding, a machine shop in Belva, WV. Part of an Auxier Welding shuttle car is shown in Figure G.1. Note that Auxier Welding is a privately owned company and not an Alliance Coal subsidiary.

According to Auxier Welding personnel, currently manufactured/overhauled shuttle cars do not utilize Programmable Logic Control (PLC) technology (Figure G.2 shows the control box currently used in Auxier Welding shuttle cars). However, again according to Auxier Welding, SAMINCO has started on the new generation of shuttle car control boxes, which will implement PLC technology. In addition, it seems that technology is available to remotely control Auxier Welding shuttle cars. This technology (RC unit shown in Figure G.3) is currently being used to remotely control feeder-breakers to assist in their set-up, and should be able to be adapted to the shuttle car. The plan was to adapt this technology to the shuttle car when preparing testing of the full-scale shuttle car.

Figure G.1: Auxier Welding shuttle car, where the operator's cabin is almost flush with the side of the vehicle

Figure G.4 shows the operator's cab in Auxier Welding shuttle cars. The cab has two seats and operators are always facing towards the direction of travel. Controls are on the right or left hand side of the operator depending on the direction of travel.

Again, the initial plan was to test a full-scale shuttle controlled by PLCs. The PLC communicates with the different drive components using CANBus messages on a 50ms basis. The new SAMINCO design should have 4 CANBus ports on their PLC and it would be easy to connect to one of these ports to issue CAN commands to the PLC. The SAMINCO design implements the SAE J1939 protocol.

The PLC only controls tram direction and speed. The actual CAN command given is a torque command and it is in the form of percent of full-load torque. For example, a command of 50% is one-half of the motor full-load (100%) torque. Torque control allows for smooth tramming, especially during turning, because it allows the inside and outside wheels to turn at different speeds.

CANBus networks work by sending defined messages with a specific byte length onto a two-wire bus that is terminated on both ends by 120 Ohm terminators. There are several CANBus standards that define items, such as, the baud rate of the bus, length and contents of the messages, and identification numbers for devices. Many of the sensors used in this project can communicate over the CANBus network, but it is a significantly slower network than ethernet, which in many cases may introduce too much latency.

This is a known constraint of CANBus, which is used in most vehicle applications. The CANBus has no shared clock, so devices transmit at will, which also means they are not concerned with existing traffic on the network at the time of transmission. Within the CAN 2.0B standard, there is a mechanism to handle message collision, but it requires the retransmission of the message lost to

Figure G.2: Control box currently used in Auxier Welding shuttle cars (electronics manufactured by SAMINCO)

the network traffic, adding further time delay. In most vehicle applications, time critical functions, such as torque control, are on their own channel so that there is a minimum opportunity for message collisions. In discussions with SAMINCO, the take-away was that the intention was to put torque control on its own channel within their control box. This would allow for a software switch to and from autonomous torque control, which is an added safety measure.

Initially it was debated whether the ALC should reside outside the shuttle car and communicate via wire the relevant commands to the shuttle car. For example, if the controller were located at the power center there would be the latency in the CANBus network as well as the latency in the communication to the logic controller on the data trip to the controller and then that same latency on the command trip back. Instead, the communication to the human supervisor can be done using the wireless network. A higher latency present during this communication can be tolerated as this data traffic would only involve health and status updates from the shuttle car and mission-level commands from the human.

In consideration of all potential latencies that could be introduced it was decided that the autonomous logic controller (ALC) or the laptop running the ALC should be located on the shuttle car.

Also, in preparation of using a PLC-equipped shuttle car for testing, a steering cylinder retrofitted with a Linear Variable Differential Transducer (LVDT) was designed and assembled by Fluid Power Services, Inc. (based in Madisonville, KY) and donated to UK. This assembly provided feedback on the position of the steering arm that would have been incorporated into the navigation logic.

Figure G.3: Remote control unit

Figure G.4: Operator’s cab in Auxier Welding shuttle cars

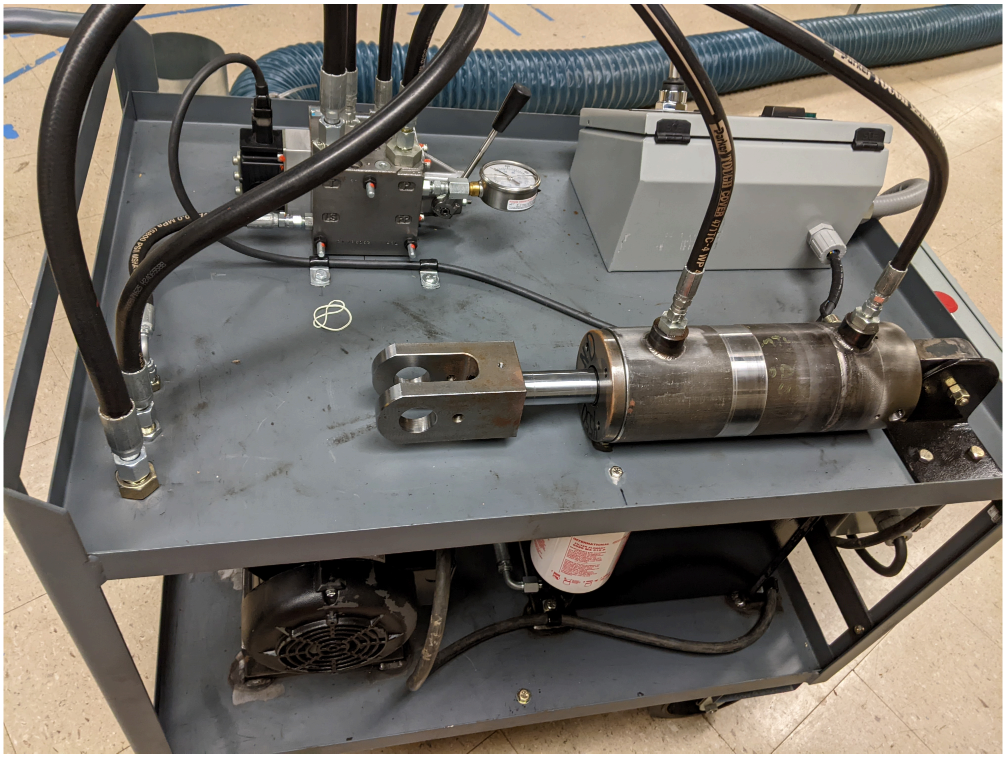

Figure G.5: A steering cylinder retrofitted with a Linear Variable Differential Transducer (LVDT) - System designed and assembled by Fluid Power Services, Inc., Madisonville, Kentucky

This was a necessary step in order to understand the operation of the hydraulic valve that controls steering, which is an on/off valve. In other words, if hydraulic fluid goes through the valve, the wheels turn. When fluid flow is blocked, the wheels remain at their current location.

Figure G.5 shows a picture of this assembly, while Figure G.6 shows a close up view of the hydraulic valve assembly used for steering in shuttle cars.

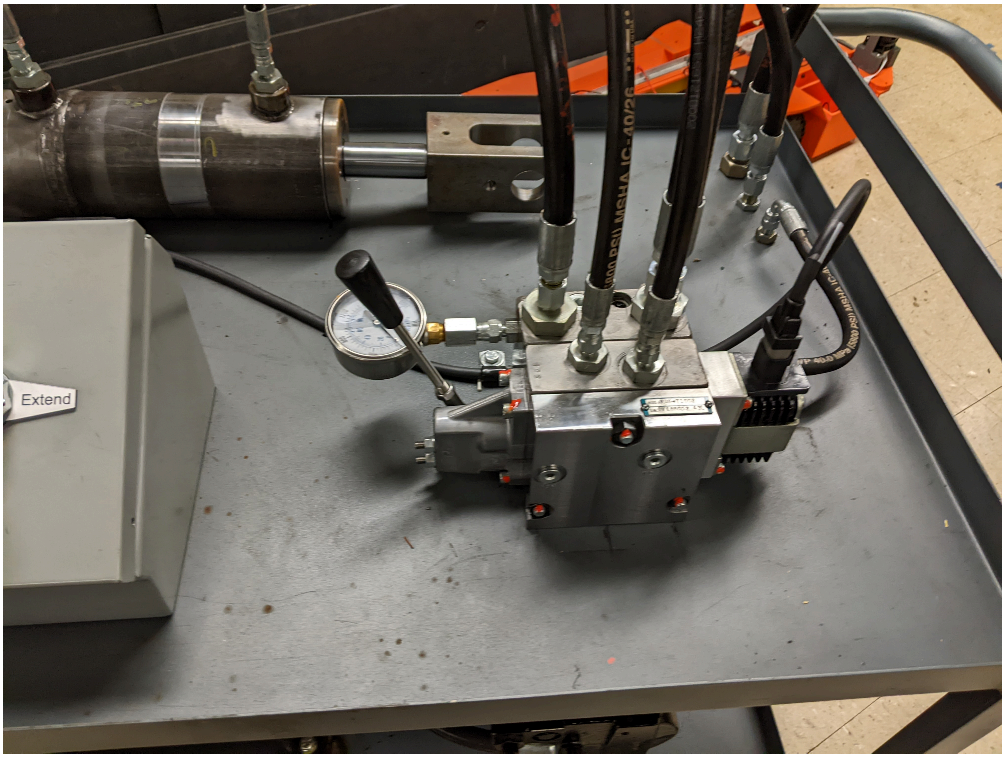

Figure G.6: Closeup view of the hydraulic valve used for steering in shuttle cars - System designed and assembled by Fluid Power Services, Inc., Madisonville, Kentucky

G.4 LiDAR Units for the Full-scale Shuttle Car

Despite the efficiency of the LiDAR scanners used for the lab-scale prototypes in terms of point-cloud density in differently scaled environments, concerns about the operational limitations of this kind of LiDAR sensor in a real environment and especially in an underground environment. Conditions such as temperature, humidity, or the presence of suspended dust could reduce the operational performance of the sensor or even damage it. It should be noted that the model of 2D LiDAR scanner used in the lab-scale simulations has a rotating mechanical part exposed. This could be a significant drawback in a mining environment which typically is characterized by high concentrations of suspended dust. In addition, the range of the LiDAR units used for the lab-scale prototype was not appropriate for the full-scale implementation.

The most popular industrial LiDAR scanning sensor manufacturers that have collaborated with mining equipment manufacturers for developing commercial smart mining solutions (e.g., Hokuyo, Velodyne), as well as other promising manufacturers, were considered and compared. Table G.1 shows a comparison of off-the-shelf units with respect to their performance characteristics. It was decided that the Ouster OS1-32 LiDAR sensor would be the most appropriate for the full-scale shuttle car.

The Ouster OS1-32 LiDAR scanner was deployed in an entry of the WVTCC facility (Figure G.7), and the data collected were used to create a simple map (x-y scatter map) as shown in Figure G.8. It can easily be observed that the created map captures with sufficient accuracy the 2D features of the space, i.e., the entry, the pillars, and the crosscuts.

Figure G.7: LiDAR Unit collecting data at WVTCC

Table G.1: Comparison of features and specifications for most popular LiDAR sensors

	Hokuyo UTM-30LX	Velodyne VLP-16	Ouster OS1-32
			
Channels	N/A	16	32
Function	2D	3D	3D
Range	0.1 m-30 m	100 m	0.8 m - 120 m
Accuracy	$\pm$ 3 cm	$\pm$ 3 cm	1.2 cm
Vertical FOV	N/A	30^o ($+15^o$ to -15^o)	33.2^o ($+16.6^o$ to -16.6^o)
Angular resolution (ver.)	N/A	$\pm 2^o$	$\pm 0.01^o$
Horizontal FOV	270^o	360^o	360^o
Angular resolution (hor.)	0.25^o	0.1^o-0.4^o	$\pm 0.01^o$
Rotation rate	Up to 40 Hz	5-20 Hz	10-20 Hz
Wavelength	905 nm	903 nm	850 nm
IMU Output	No	No	Yes
Power Consumption	<8 W	8 W	16-18 W typical, 20 W peak
Operating Volt.	12 V	9-32 VDC	22-26 V
Dimensions	W60 × D60 × H87 mm	103 mm(diameter) × 72 mm(height)	85 mm(diameter) × 73 mm(height) 3.34 in. × 2.87 in.
Weight	370 grams	830 grams	395 grams
Operating Temperature	-10^o to $+50^o$ C	-10^o to $+60^o$ C	-20C to +50C (with Mount)
Env. Protection	IP64	IP67	IP67
Price	$5000 (2021)	$4000 (2018)	$3500 (2021)

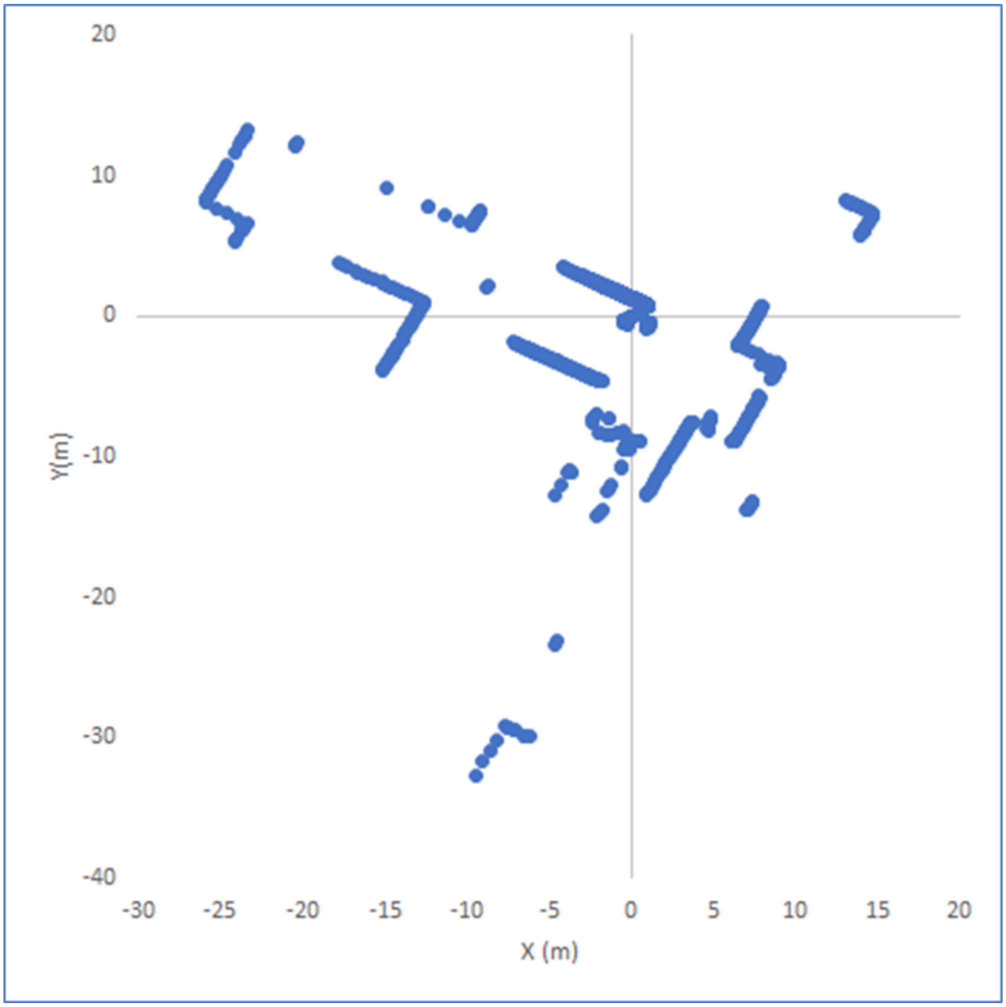

Figure G.8: Mapping of the WVTCC using an Ouster OS1-32 LiDAR

G.5 Implementation

The shuttle car available for testing was an older shuttle car manufactured by Joy (now Komatsu) and is shown in Figure G.9. Figure G.10 shows a partial view of the operator's cabin. The steering arm and the tramming controls are visible. The shuttle car nameplate is shown in Figure G.11.

As that shuttle car is part of the equipment at WVTCC used for mine safety training and demonstration, retrofitting of the car needed to be done in a way that would allow for quick installation and removal of the automation components so that the shuttle car could be used by WVTCC between automation trials.

Figure G.12 shows the tram controls (for speed and direction) of the Joy shuttle car.

Figure G.13 shows the steering arm of the Joy shuttle car. Figure G.14 shows its tram pedal. Figure G.15 shows a partial view of the Joy shuttle car. An Ouster OS1-32 LiDAR unit is mounted using a magnetic base. Figures G.16 and G.17 show an Ouster OS1-32 LiDAR scanner mounted on the shuttle car at WVTCC. The LiDAR units could be easily installed before any automation trials and then removed after automation trials.

Figure G.9: The Joy shuttle car at WVTCC

Figure G.10: A partial view of the operator's cab of the Joy shuttle car at WVTCC

Figure G.11: Nameplate of the Joy shuttle car at WVTCC

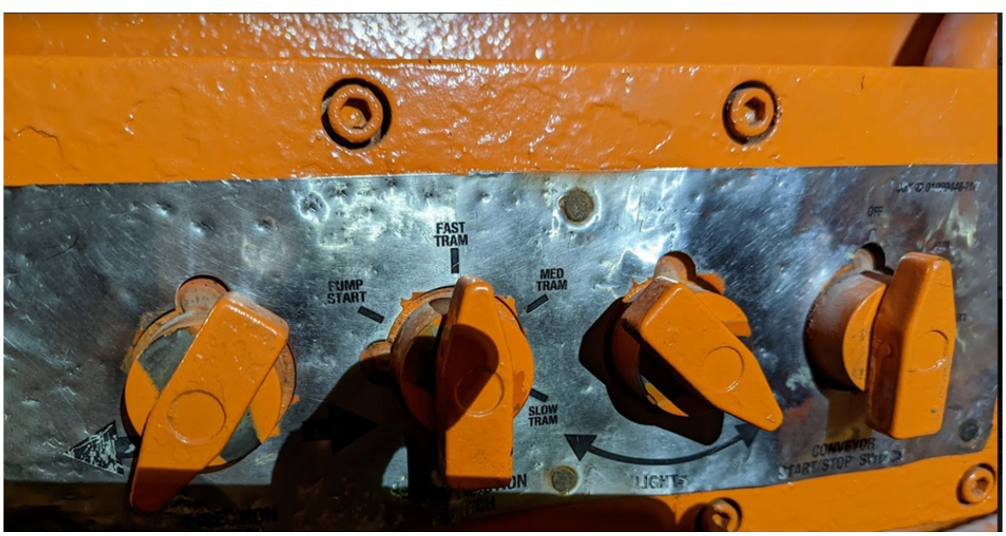

Figure G.12: Tram controls of the Joy shuttle car at WVTCC

Figure G.13: Steering arm of the Joy shuttle car at WVTCC

Figure G.14: Foot pedal of the Joy shuttle car at WVTCC

Figure G.15: Partial view of the Joy shuttle car. An Ouster OS1-32 LiDAR unit is mounted using a magnetic base

Figure G.16: An Ouster OS1-32 LiDAR scanner mounted on the shuttle car at WVTCC

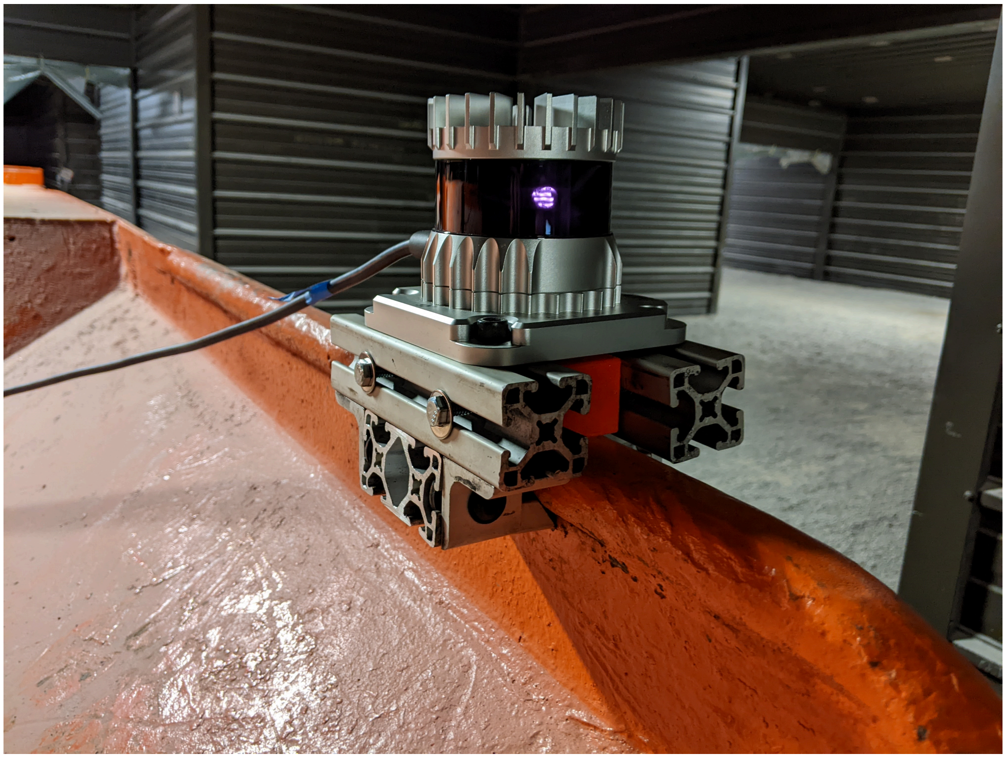

Figure G.17: An Ouster OS1-32 LiDAR scanner mounted on the shuttle car at WVTCC (closeup)

A number of servo actuators (ASMC-04B Robot Servo High power high torque servo Support 12V 24V 180kg.cm) were used to provide precision controls to the shuttle car controls. The actuator technical specifications are shown in Table G.2.

Table G.2: Technical specifications for the ASMC-04B actuator

Parameter	Specification
Operating voltage	12V to 24V (DC)
No-load rotational current	<500mA
Maximum torque	180kg.cm (24V) (measured, non-theoretical value)
	1764N.cm (24V) (measured, non-theoretical value)
	90kg.cm (12V) (measured, non-theoretical value)
	882N.cm (12V) (measured, non-theoretical value)
Angular speed	0.5s / 60^o (60 degrees of rotation required 0.5s), at 24V
	1.0s / 60^o (60 degrees of rotation required 1.0s), at 12V
Rotation angle	300^o max, (0 to 300^o adjustable electronic limit)
Input modes	pulse signal (remote control, multiple servo controller, micro-controller) or analog voltage signal (potentiometer)
Pulse signal input range	0.5ms-2.5ms fits all “multi-channel servo controller”, “1ms-2ms model aircraft remote control”, “SCM”, and so on
Voltage signal input range	0V to + 5V
Control accuracy	0.32^o
Weight	530g
Gear Material	Steel
Dimensions	95.5mm X 60.5mm X 102.6mm

Figure G.18 shows a servomotor assembly (using the ASMC-04B actuator) on a custom mount for controlling the shuttle car steering handle. The custom support base and linkages were built to connect the servomotor to the particular steering arm. The actuator was equipped with a steering plate (Figure G.19), which converted the rotational motion to linear movements as control of the steering arm required linear movements.

Figure G.20 shows a servomotor assembly controlling the shuttle car steering handle after being mounted on the shuttle car. A 3D-printed part was mounted on the steering arm to provide a mounting point for the tie rod that connected the servomotor and the steering arm. The tie rod was connected to the steering arm through a quick-release mechanism so that the shuttle car operator could quickly override any automation commands if needed.

Figure G.21 shows a servomotor assembly (using the ASMC-04B actuator) on a custom mount for controlling the shuttle car gas pedal. The custom support base and linkages were built to connect the servomotor to the particular gas pedal. As before, the actuator was equipped with a steering plate (Figure G.19), which converted the rotational motion to linear movements as control of the gas pedal required linear movements.

Figure G.22 shows a servomotor assembly controlling the shuttle car gas pedal after being mounted on the shuttle car. A crossbar (white) was wedged in place to provide a reaction to the servomotor movements. The tie rod was connected to the gas pedal through a quick release mech-

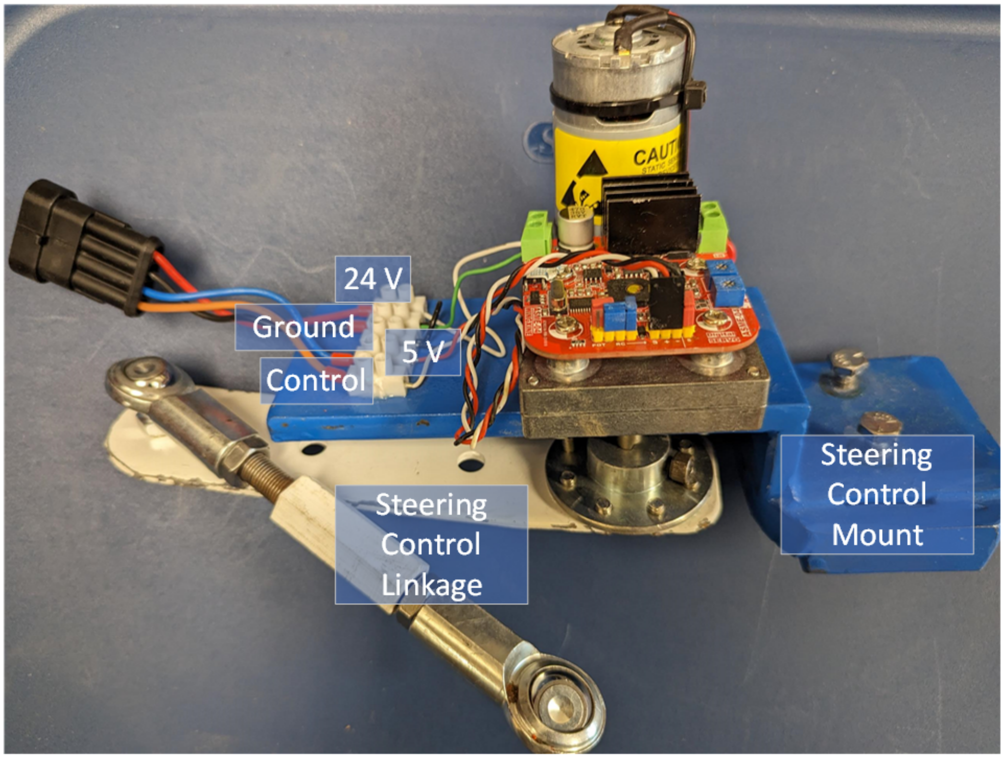

Figure G.18: Servomotor assembly on the custom mount for controlling the shuttle car steering handle

Figure G.19: Dedicated Large Torque Servo Special Arm Plate for the ASMC-04B

Figure G.20: Servomotor assembly controlling the shuttle car steering handle mounted on the shuttle car

anism so that the shuttle car operator could quickly override any automation commands if needed.

Both servomotors are controlled via an Arduino microcontroller which is directly connected to the laptop and receives commands from the ALC (Figure G.23). Also, the actuators and linkages could be easily installed before any automation trials and then removed after automation trials.

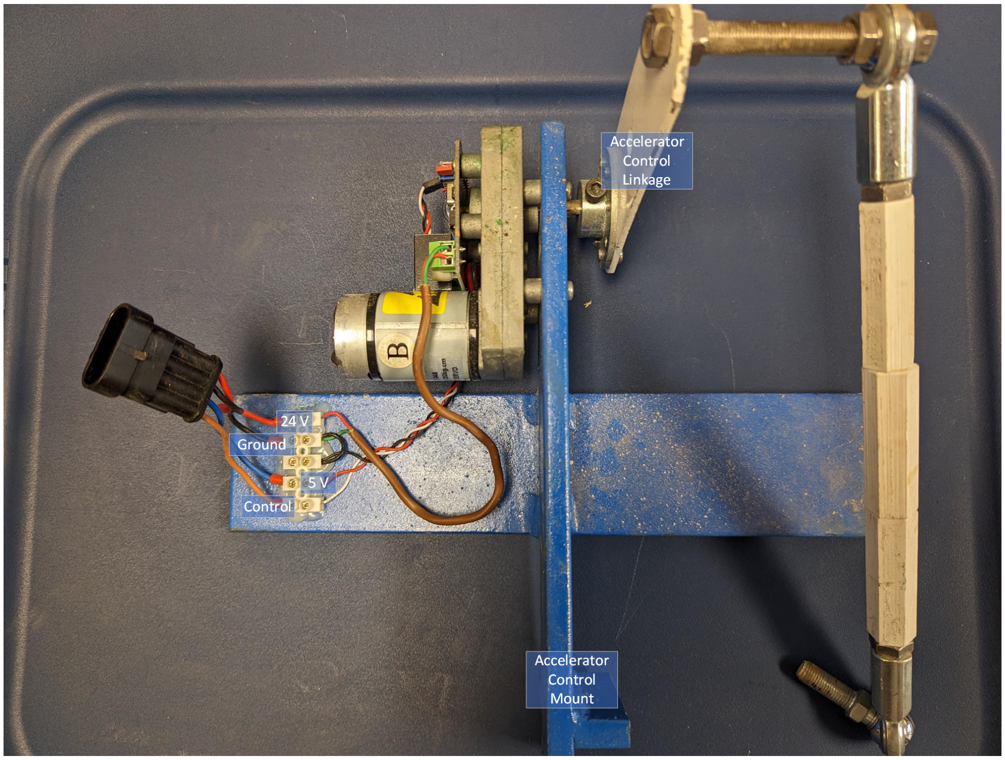

Figure G.21: Servomotor assembly on the custom mount for controlling the shuttle car gas pedal

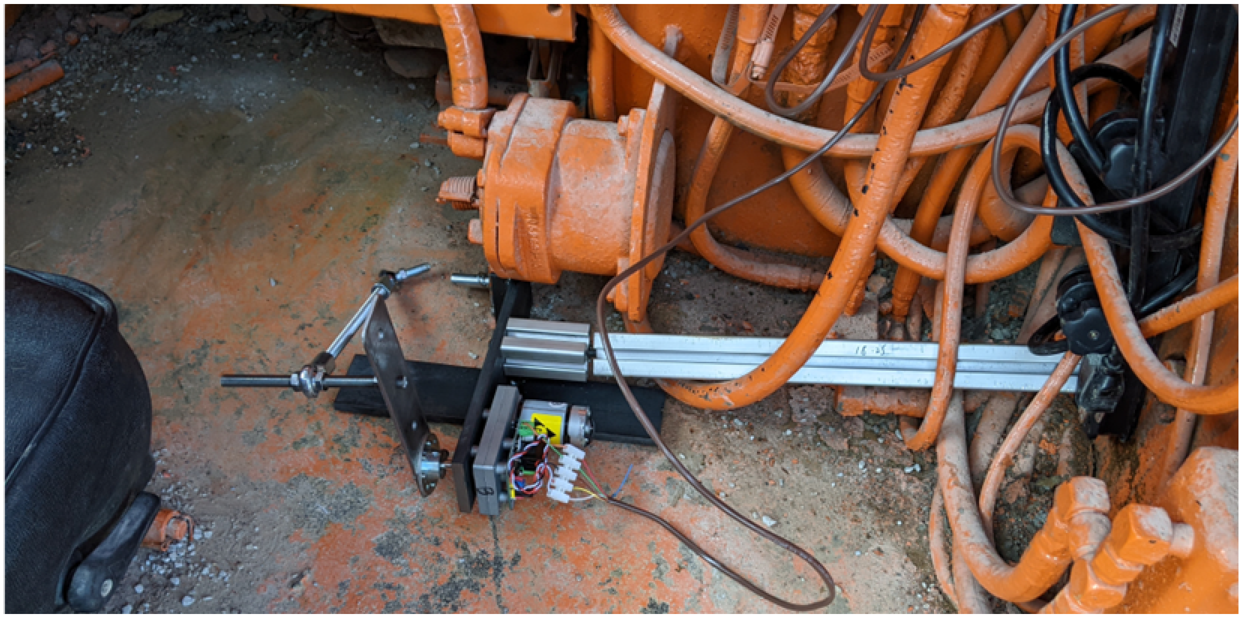

Figure G.22: Servomotor assembly controlling the shuttle car gas pedal mounted on the shuttle car

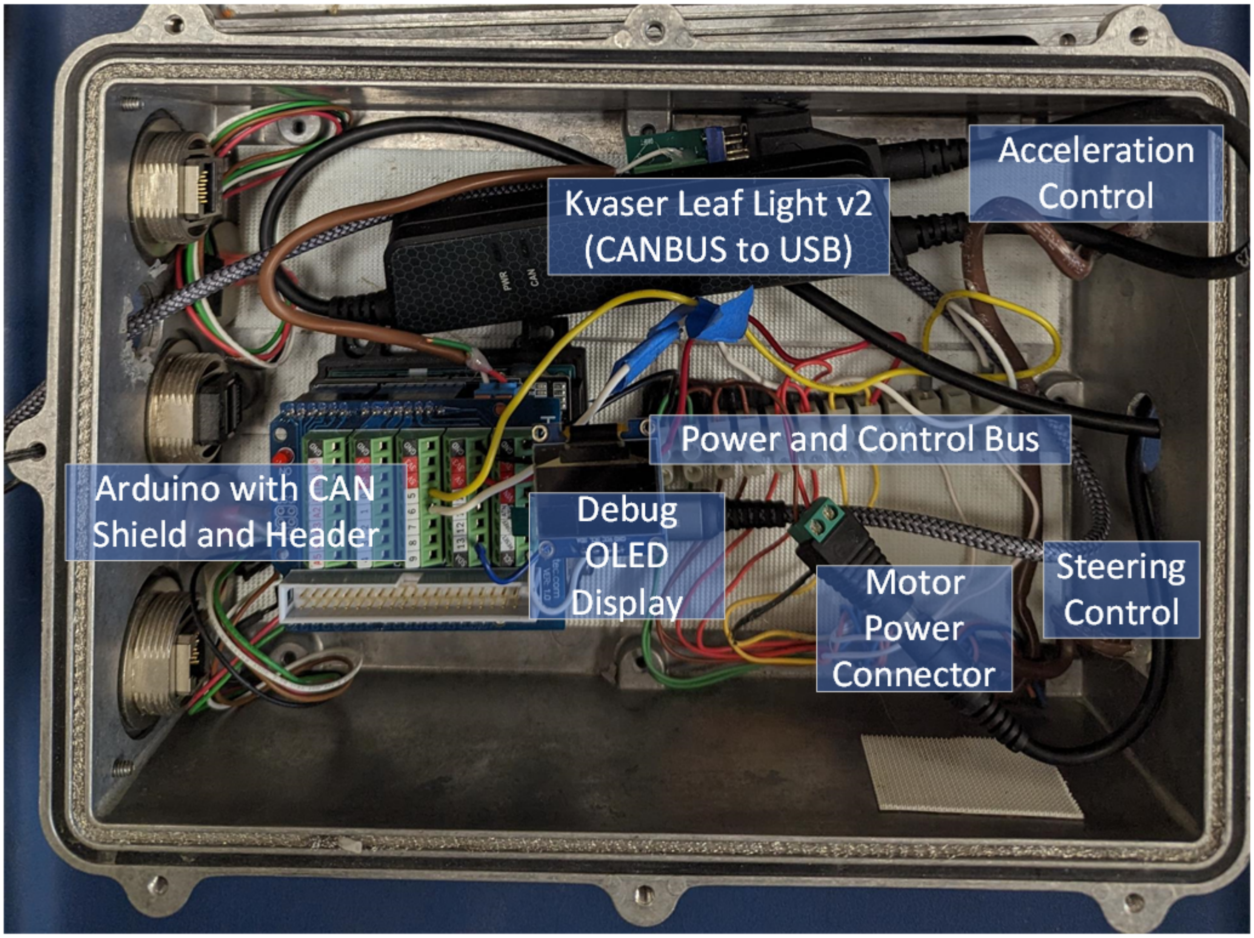

Figure G.23: Arduino microcontroller controlling the servomotor actuators

Appendix H

Performance Evaluation of a Full-Scale Shuttle Car at the Mine Simulator Lab

H.1 Introduction

In order to evaluate the performance of the lab-scale prototypes, two scenarios were planned and tested in the Simulated Mine Lab, as discussed in the following sections. The scenarios were designed to simulate simple missions and not the actual shuttle car operation during a full shift at an underground coal mine. Each of the two scenarios was tested multiple times over several field testing days. The pillar lengths (and widths) of the Simulated Mine Lab were (only) 20 ft, which presented another set of challenges when using the autonomous navigation algorithm. The evaluation metric used for both scenarios was simple and only consisted of overall "success" or "failure". It should be noted that failures due to field testing conditions that were not related to data collection, data processing, or the navigation algorithm were not included in the metric. Such conditions include, for example, power outages, extension cable failures (the extension cable powered an uninterrupted power supply (UPS), which was placed on the shuttle car and provided continuous power to the LiDARs, the laptop, and the servo controller box), testing of the servo controllers, calibration of the servo controllers under hydraulic power, etc.

H.2 Phase 1 Testing

Phase 1 testing included running the ALC that was developed under laboratory conditions after adjusting the dimension parameters to reflect the full-scale shuttle car dimensions and actual mine dimensions. The (python) script for data collection was pointed to the commercial LiDAR units (Ouster OS1-32) that were used in the full-scale shuttle car. Phase 1 testing included only tests that allowed the shuttle car to traverse one or more pillars along a straight line (or along a single entry). The majority of Phase 1 Testing failed because of the following reasons:

- The Python script was not processing data fast enough for the ALC to have fresh data at each decision point. The existing processing loop allowed for a refresh rate of about 2 Hz (data was refreshed about two times in one second).

- The interface to the Arduino driver of the servo controllers was not responding fast enough due to serial port limitations
- The calibration routine for the servo controllers had flaws and, therefore, the calibration was not always successful.
- The full-size shuttle car used in the project is driven by hydraulics, rather than electric motors and, therefore, there is latency in the interpretation of the commands. In addition, a return-from-turn command needed to be implemented as returning the hydraulic valve to the neutral position did not return the wheels to the neutral position.
- Early in the process of field testing, it was recognized that the wheels of the shuttle car were not correctly aligned. Although it was identified that one of the shuttle car tie-rods was loose, it was not feasible to remedy the issue in the framework of this project.

H.3 Phase 2 Testing

As already mentioned, during the course of phase 1 field testing, the full-size shuttle car used in the project is not a new machine and does not accelerate or turn in a way that the lab-scale prototype can simulate. In addition, the original control software was not able to perform as it did in the laboratory, and the data stream, user interface, and decision-making structure did not allow for fast enough edits while working in the mine simulator with a real machine. The research team decided to build on all the lessons learned from the original software and build a new control software that would only work with the full-scale machine, as detailed in the following section.

H.4 Redesign of Control Software

The full-scale control of the shuttle car requires several pieces of information to make decisions and move simple controls that make changes to the vehicle slowly, but need to move quickly. The software was re-imagined based on the experience that was gained from running the first control software both in the lab and in the field. The general principle is that data from the sensors goes into and is queried on demand from the data stream. Commands to the servo motors are determined by the commands in the mission queue as adjusted by the agent.

The hardware configuration was modified for the new software. A CANBus shield was added to the Arduino to bypass the slow and easily overwhelmed serial connection working over the USB to the computer. The serial connection is still in use, but only for the Arduino to computer communications, not for controlling the motors. The communication to and from the Arduino is greatly simplified. The Arduino will output the current location of the motors when they move. The Arduino will reset the servos to their default location after 3 seconds. Messages sent on the CANBus with ID 40 will set the defaults away from the ones programmed into the Arduino. Messages sent on the CANBus with ID 50 will set the current position based on an angle value. The Arduino will move the motors as fast as they can run to that position.

The program allows the user to input the amount of time that motors should be in positions to effect the change to the car. When this shuttle car is in low tram mode, the distance the acceleration pedal is depressed does not put the torque past the minimum setting. Therefore, to go forward and stop, the accelerator only needs two positions, the neutral position, and the acceleration position.

The steering is more complicated. The steering requires three positions, a neutral position, a position at full right, and one at full left. However, the steering on the machine is completely hydraulic on valves that have low and high steps. This means that as the steering lever is moved, the cylinder that controls the steering is moved, but this is controlled by a hydraulic cylinder that can take up to several seconds to completely turn the wheels. Further, the wheels will remain in their position after the steering is returned to neutral. That means the steering controls need to also include a time element to return the wheels to the forward driving position.

The main form for the program (Figure H.1) is setup to connect and control the Arduino for both the angles and the timing. This allows the researchers to manually control the shuttle car using the exact same parameters that the agent will use when controlling the shuttle car. The form allows the user to set arbitrary angles, which is useful for setting the defaults. The nudge commands are used when driving forward, and they achieve a slight adjustment to the left or right while continuing to drive forward. They have two timings, the time in maximum turn in the direction of the adjustment and the time in maximum turn on the opposite side to straighten the wheels. Because of wear in the steering, this is a different adjustment for each side (turn direction).

The program is setup to allow for several debugging scenarios. There are check boxes for using a "Fake Serial" which allows the program to run without sending commands to the Arduino. The program can send commands exclusively using the serial interface, although the program runs too quickly for that interface and commands are lost in the buffer. Also, while querying the data stream getting the most timely answer from the sensors is important, but not necessarily while debugging, so this can be overridden.

There are several sensors being used by the agent to make decisions. As the agent queries the data stream for the sensor values, the value is displayed to the user. A diagram of the sensors and the nomenclature used to describe them is shown in Figure H.2. The simplest sensors are the straight ahead sensors and the 90 degrees from the body sensors. The sensor reporting program will also find the shortest distance in each quadrant of the LiDAR's graph and report the distance and angle to those points. The agent will calculate a virtual wall going through those points, when necessary. Additionally, there are two sensor readings ahead of the 90 degree reading to the wall and further (far) ahead of that reading. These are used by the agent to determine the corner's location, and therefore determine the timing for the turn. This is much faster than the RANSAC routines developed to control the lab-scale prototypes. Also, the python scripts used to collect data from the LiDAR units were optimized with respect to data collection, data management and storage. It should be noted that the commercial LiDAR units (Ouster OS1-32) utilized for the full-scale tests are 3D LiDAR units and scan information on up to 32 planes ($\pm$ 16 rows from the horizontal plane). Following these changes, the cycle time for each LiDAR data collection round was reduced to a few milliseconds that allowed for faster decision making.

The agent is run from the mission planner form (Figure H.3), which is loaded after the controls have been established. The mission planner includes all of the parameters for the agent and displays to the user the current readings from the sensors as requested by the user or the agent. Parameters

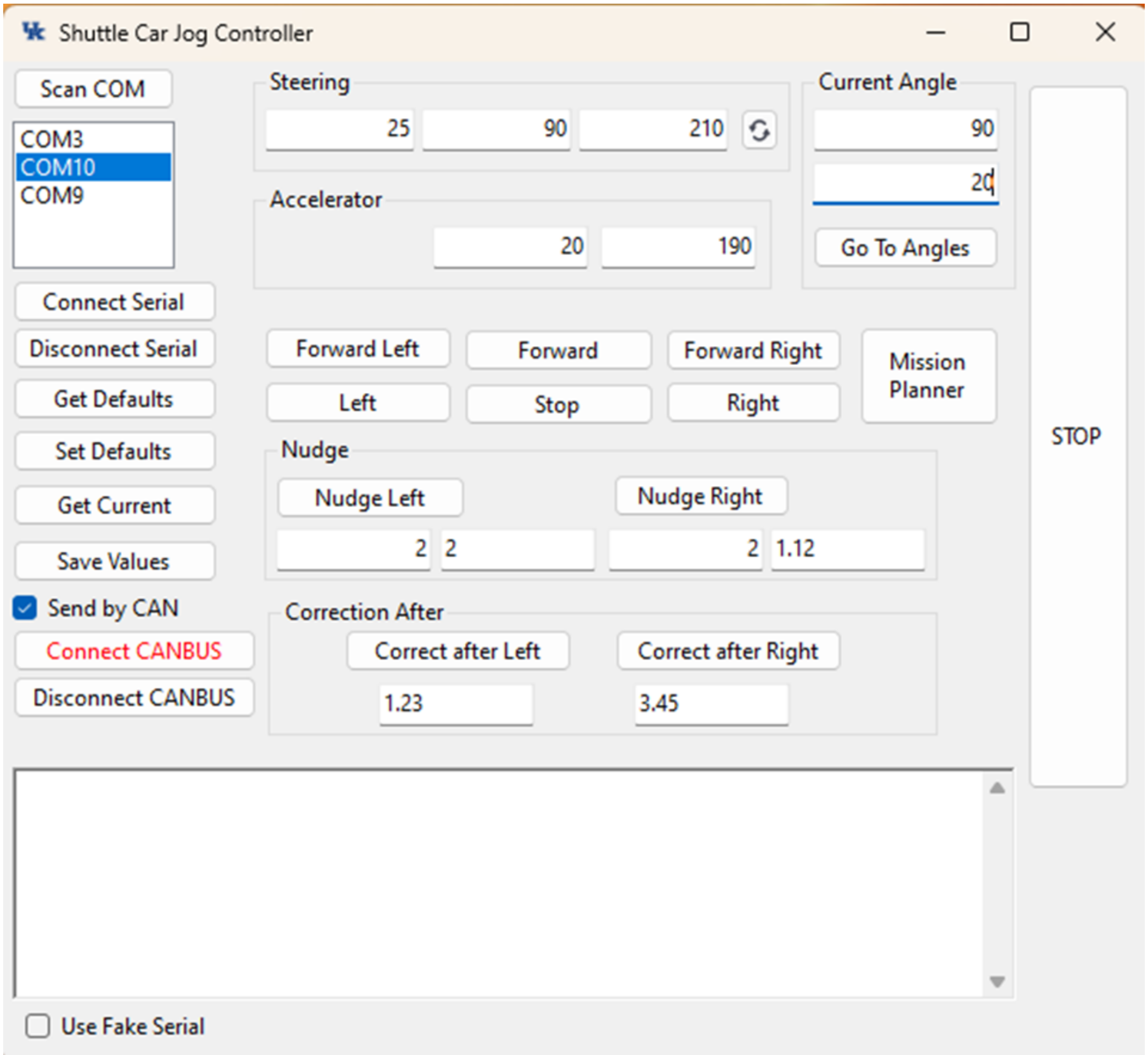

Figure H.1: Main program interface

used in the agent's decision-making can be changed while the program is running.

The mission planner starts with the mission file. This is a simple comma-separated values file that has a command, such as forward, right, or left, a duration to do that command, and then a number of times to do the command. For instance, while setting up, it was determined that this shuttle car takes 3 seconds to get to speed and covers 10 feet while doing so. This could be entered into the mission as a single forward command for 3 seconds, but then only one decision would be made while executing that command. It was better to include this as 6 forward commands for ½ second in duration, allowing for 6 decisions to be made over that same time. Once the shuttle car is up to speed, the duration can be adjusted as the requirements of the current activity demand. Approximations work well in this mission planning because the agent will adjust the queue as

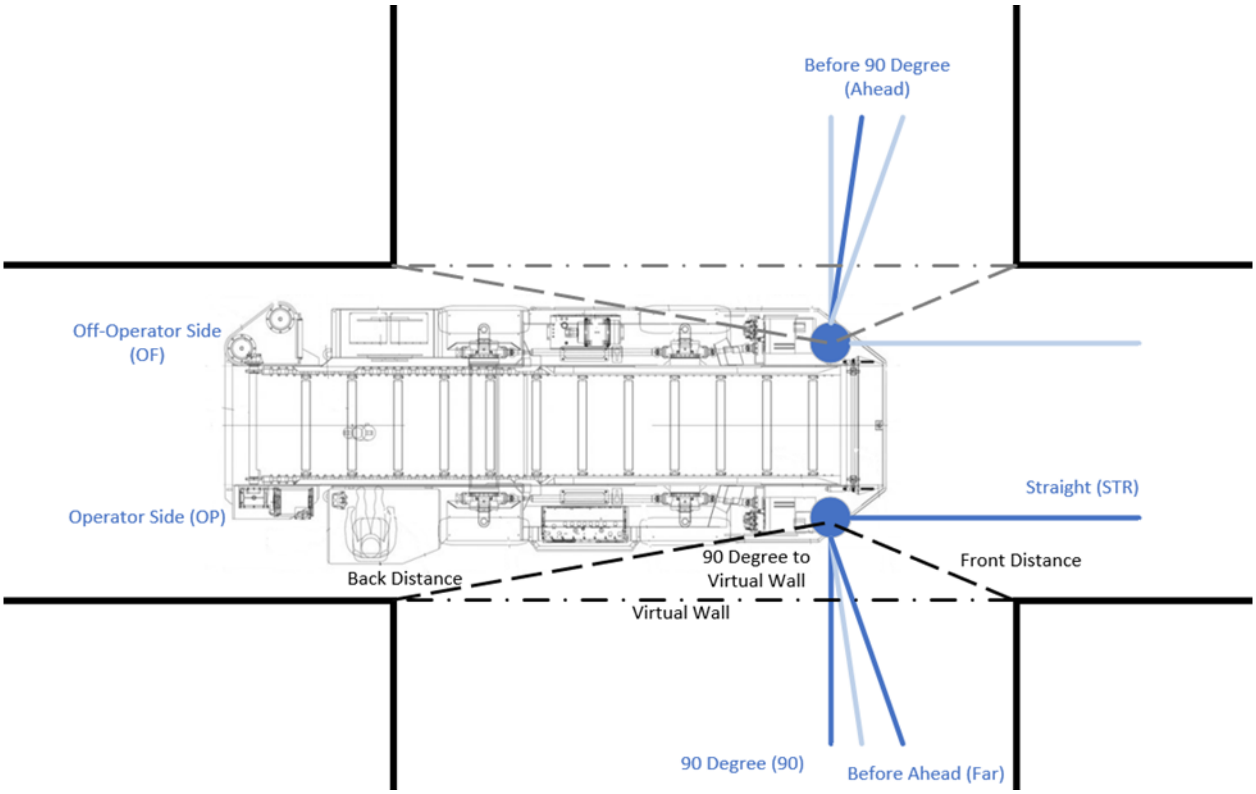

Figure H.2: Sensor names and locations (Figure not to scale)

needed. There are also tools to allow the user to adjust the queue, but these are primarily for debugging purposes.

Several functions in this part of the program were designed to help during field testing. For instance, if the LiDAR data-gathering software is not running, the program lets the user start these processes. During testing, the researchers were able to modify the existing logic stream by adjusting the values and checkboxes on this screen and test major modifications without the need to write code in the field. Importantly the program provided timers so that processes within the program could be checked against real-time conditions. This is especially important while searching for corners and for determining when to insert course corrections (i.e., nudges). The query button is especially useful for checking the sensor readings before and after the automated runs. There is also a button allowing for many queries to run that is useful for determining the database's speed as well as the update speed for each sensor reading while in the field.

When the Run Mission button is depressed, the mission queue will be processed. The current command in the queue is sent to the Arduino to move the servo motors and start the car operating. While that operation is ongoing, the next item in the queue is processed by the autonomous agent. For the very first item in the queue, the agent does not process the item, the human supervisor is responsible for the first command. This command structure allows the sensors to update, the car to move, and decisions to be made simultaneously.

The simplest queue is a set of forward commands. The program will first send the acceleration command to the Arduino. Then the command loop will read that the next command in the queue is

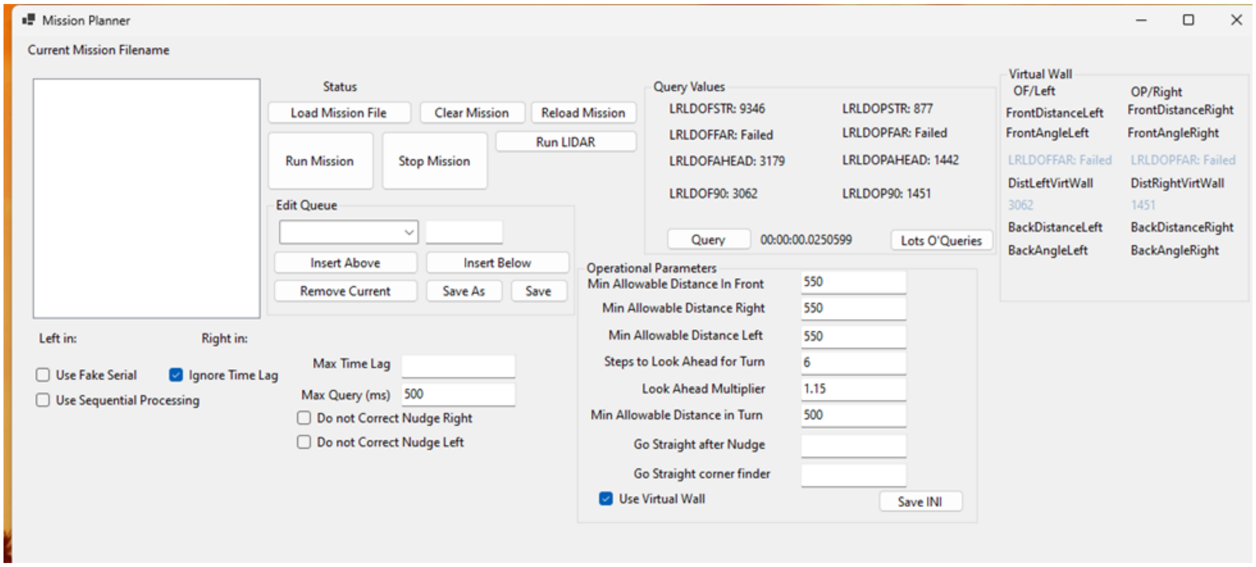

Figure H.3: Mission planner interface

also a forward command, and the agent will evaluate that command. If the program is in parallel processing mode, then the command will be sent as the agent is evaluating the next command. The agent is only allowed to make one decision per command. The researchers found that if the time step is large (i.e., about 500ms), the decision is made too early before the sensors are able to update the current situation. This made the machine appear to be responding slowly when it was, in fact, responding too quickly. When in sequential processing mode, a timer is set at the beginning of the loop. The command is sent to the Arduino, after which the agent will evaluate the next command. The time to do both operations is measured and compared to the current time for the current command, the remaining time passes, and then the loop starts over again. Sequential processing has the effect of slowing down the decision-making routine, it also makes debugging easier. When combined with the expedited queries of the data stream, this was sufficiently fast to control the shuttle car, even in medium and high-speed tram.

There are several options on the screen that allow for the acceleration of queries. There is a maximum time lag, that prevents stale values from being returned from the data stream. There is also a maximum query time, which is a directive sent to the database engine preventing any query from taking too long to execute. The sensors are capable of inserting 10 to 14 values into the database per second. However, it is possible that a sensor was disconnected or any other issue may arise while running. The agent only queries the values that are needed when they are needed, a sensor could be disconnected for longer than the maximum time lag. The researchers found that under the default conditions, when there is no value in the database, the query can take up to 700ms. This could easily be longer than a single step in the command queue and caused hard to diagnose errors. Using the timeout for the queries, the execution time for the agent is less than 15 ms, even when queries for sensor values fail. This allows for a more complicated decision-making process because it's significantly less than the time to move the motors and effect the movement of the car.

When the next command is moving forward, the agent will check the straight-ahead sensors and if they are below the threshold specified on the mission planner form, insert stop as the next command in the queue. The 90-degree sensors are checked, and if either is beyond the threshold, then a nudge back in the other direction is inserted into the queue. If the virtual wall is turned on, then the perpendicular distance from each side of the shuttle car is calculated to the line described by the angle and distance of the nearest point in both the front and back quadrants, as shown in Figure H.2. If these distances is below the threshold, then a nudge is added to the queue.

The skew angle, which is the difference between the distance to the virtual wall and the distance from the 90-degree sensor, is calculated and could be used in future iterations of the agent. Finally, the agent will check if there is a turn coming up in the command queue within the threshold value specified on the form. If there is a turn within the queue, then the far ahead sensor is compared to the ahead and the 90-degree sensors. If the far ahead sensor value is beyond the multiplier on the form to the 90-degree sensor, then it has passed a corner, and forward commands are removed from the queue so that the turn in the next command to be processed.

H.5 Demonstration of the Autonomous Shuttle Car

The Simulated Mine Laboratory at WVTCC is eight 20-foot entries with seven 20-foot crosscuts, and the power center is in the middle of the facility. This limits the amount of distance to run the shuttle car because of the cable length and the belt entry in the middle of the facility. In addition, due to the mechanical issues of the shuttle car used in this demonstration, only two basic cases are discussed.

- Traverse a number of pillars along an entry
- Turn into a crosscut

H.5.1 Traverse a Number of Pillars along an Entry

Under this case the mission was to traverse a number of pillars under full autonomous mode and stop at the end of the entry where a curtain acted as an obstacle. A number of “forward” commands were added into the queue and the nudge option was enabled. As already discussed, the nudge option allows for minor corrections to the trajectory of the shuttle car while traversing the entry. These scenarios were completed successfully a number of times.

Unsuccessful completions were attributed to large oscillations due to the execution time for the nudge command. The nudge is a combination of steering away, to straighten out the trajectory, and then steering toward, to straighten out the wheels. The shuttle car steering has tremendous wear in the actuator and does not consistently turn in either direction. This means that successful timing of the nudges rely on more of them, rather than longer nudges. Measurements of the wheels positions during turning was considered, but rejected because the wheel that lags the steering is not consistent and a complicated algorithm would need to be generated to determine the wheel lagging and its impact on traversing straight. Instead, the existing LiDAR system with shortest possible timing on the nudge commands was utilized and had successful runs. Other issues arose from setting sufficient boundary amounts that allow the shuttle car to turn in time to miss obstacles, such as the wall.

Figure H.4: Full-scale shuttle car traversing an entry under full automation (view from the loading-end)

Figure H.4 shows the shuttle car traversing an entry under full automation. The research team member on the shuttle car is watching the decision making process of the ALC. A safety operator is in the operator cabin that can engage the emergency brake in case automation fails. Figure H.5 presents a view from the discharge end of the shuttle car.

Table H.1 presents the performance metrics for Scenario 1.

Table H.1: Performance metrics for Scenario 1: Traverse a number of pillars along an entry

Number of Pillars	Number of Crosscuts	Speed	Success / Total Trials	Success (%)
2	1	low	6/10	60
3	2	low	3/6	50
4	3	medium	1/1	100

H.5.2 Turn into a Crosscut

Under this case the mission was to turn into a crosscut full autonomous mode. A number of "turn-right" commands were added into the queue and the nudge option was disabled. These scenarios were completed successfully a number of times. Unsuccessful completions were attributed to the shuttle car stopping because it thought there was an obstacle in its path. This was triggered by the close proximity of one of the front LiDAR units to rib that was actually below the range of

Figure H.5: Full-scale shuttle car traversing an entry under full automation (view from the discharge-end)

the LiDAR. When such LiDAR signals out of range were received, or when there was no data to receive the ALC was instructed to stop the shuttle car.

Figures H.6 to H.8 show a sequence of photos depicting different stages during the shuttle car turn process. During a successful turn the clearance between between the operator side and the corner of the pillar and between the front bumper and the rib are in the order of only a few inches,

Table H.2 presents the performance metrics for Scenario 2. As indicated below, turning to the left was unsuccessful and can be attributed to the fact that the wheels of the shuttle car where not straight, even at rest. The shuttle car pulled to the right more than to the left. In addition, a couple of times the shuttle car was stopped while turning to prevent scraping of the metal cladding of the pillars. In an actual mine this would not have been a problem. Also, a variation of Scenario 2 included tramming before turning. That variation was not pursued as the steering mechanism of the shuttle car did not allow appropriate positioning before the turn.

Table H.2: Performance metrics for Scenario 2: Turn into a crosscut

Traverse	Turn	Turn Direction	Speed	Success / Total Trials	Success (%)
yes	yes	right	low	1/3	33
no	yes	right	low	2/3	67
no	yes	left	low	0/3	0

Figure H.6: Full-scale shuttle car turning into a crosscut (sequence 1/3)

Figure H.7: Full-scale shuttle car turning into a crosscut (sequence 2/3)

Figure H.8: Full-scale shuttle car turning into a crosscut (sequence 3/3)

Appendix I

Cognitive Work Analysis Technical Report

I.1 Abbreviations, Acronyms, and Symbols

Table I.1 presents the abbreviations shown in this Appendix.

Table I.1: Abbreviations, Acronyms and Symbols

Acronym	Definition
AH	Abstraction Hierarchy
AV	Autonomous Vehicle
CWA	Cognitive Work Analysis
CAT	Contextual Activity Template
CMO	Continuous Miner Operator
ConTA	Control Task Analysis
IRB	Institutional Review Board
KSAOs	Knowledge, skills, abilities, and other characteristics
O*NET	Occupational Information Network
SCO	Shuttle Car Operator
SOCA	Social Organization and Cooperation Analysis
STRA	Strategies Analysis
USDOL	U.S. Department of Labor
UK	University of Kentucky
VCCER	Virginia Center for Coal and Energy Research
VTTI	Virginia Tech Transportation Institute
WDA	Work Domain Analysis
WCA	Worker Competencies Analysis

I.2 Executive Summary

I.2.1 Purpose

The purpose of this project is to address the organizational challenges involving the introduction of an autonomous shuttle car system to a room-and-pillar coal mining operation. Work analyses support this goal by mapping the general organizational structure, identifying key work processes and activities, defining roles/responsibilities of different actors (humans and machines) in the system, and the ascertaining the values/motivations and cognitive strategies of individual workers.

Work analyses consist of several applications: job analysis, work analysis, and cognitive work analysis. These approaches offer a general framework and a set of specific analytical tools for the analysis of both simple and complex sociotechnical systems. Job and work analyses target work- and worker-oriented activities and attributes specific to job roles. The CWA addresses all levels of an organizational work domain, from the general work domain and organization, to specific activities/tasks, down to the individual worker. The general idea is to start with a thorough analysis of the existing system, which will then serve as the basis for design recommendations related to the introduction of new functions and technologies. Using this approach, an understanding of the existing work domain is gained, which then allows a systematic identification of impacts from introduction of the new system.

I.2.2 Process

This study evaluates the formal and informal organizational hierarchy of an underground room-and-pillar mine utilizing shuttle cars in coal face haulage. This evaluation, performed by the Virginia Tech Transportation Institute (VTTI), consisted of a CWA of the coal mine, which comprised the following steps:

- Role Investigation – A number of resources were consulted in the process of preparing for and performing the CWA. Materials specific to the operation were provided by the mine operators, which included safety training manuals, operational handbooks, and job descriptions.
- Employee Interviews – Thirteen one-on-one interviews were conducted with employees responsible for the room-and-pillar mining operations. Employee interviews consisted of understanding both the prescribed role as well as any unwritten job responsibilities.
- Observational Data Collection – The research team collected observational information about the mining operations during a mining shift.
- Subject Matter Expert Dialogues – The VTTI research team consulted frequently with team members at the Virginia Center for Coal and Energy Research (VCCER) and the University of Kentucky (UK) to develop an understanding of the coalmining operations.

I.2.3 Rationale and Background

Operation of shuttle cars presents inherent occupational risks, specifically to shuttle car operators, to mobile equipment operators near shuttle cars, and to mining personnel in proximity to the shuttle cars. Typical hazards for these individuals include excessive noise, dust generated by equipment movement, and poor visibility in travel-ways caused by dim illumination paired with dust.

The shuttle car is designed for transporting raw coal from the continuous miner to the feeder-breaker at the tail end of the section belt. Shuttle cars are electric-powered, wheel-mounted, self-propelled machines energized through a flexible, trailing cable that extends from the semi-mobile power center to a retractable cable reel in the shuttle car. The cable reel has a motor and drive sprocket to retract the cable as the shuttle car returns to the power center.

The shuttle car consists of an operator cab, a bed for hauling coal, and a chain conveyor. The shuttle car is equipped with four-wheel steering and may be operated in both inby and outby directions to navigate in a limited maneuverability environment. The shuttle car operators are primarily responsible for moving, or tramming, the shuttle car between the feeder-breaker and continuous miner at the working face. The shuttle car operator must be cognizant of the trailing electrical cable, other shuttle cars, mobile and static equipment, and pedestrian workers.

Operator cabs offer limited comfort to operators. Theses cabs are usually open and positioned on the side of the shuttle car. In addition to a having a poor field-of-vision, operators are also left exposed to dust, spray from the continuous miner, and noise from mining operations, without the ability to move away from these hazards. The shuttle car's suspension is designed to function while loaded, which results in significant vertical deflection while traveling unloaded. As a result, the operator is subjected to vibration while moving. Automating shuttle car coal face haulage from the continuous miner to the feeder-breaker would remove the operator from the active mining area, thereby reducing exposure to hazardous and undesirable conditions. Although an autonomous shuttle car would not have a human occupant, equipment operators would still be needed to serve in a supervisory capacity. In order to determine the duties and responsibilities of the operator's role, a series of work analyses must be performed, incorporating all of the affected roles in the underground operations. The automation of shuttle cars would not displace operators but would rather enhance their productive capacity, transform their role, and reduce their exposure to risk.

I.2.4 Work Analyses

Tools and techniques to conduct work analyses have been developed across multiple fields of study, and their outputs generally differ based on the purpose and approach used. The current analysis utilizes a multidisciplinary approach by incorporating techniques from the fields of industrial/organizational psychology and human factors and cognitive science. Techniques in each field are continually developing as they incorporate more information from new discoveries. Job analysis, task analysis, and work analysis have roots in industrial and organizational psychology and stem from the need to formalize job duties through a written job description, resulting in a rigid prescription of job duties (Sachett and Laczo, 2003). CWA has roots in cognitive science and involves efforts to understand unobservable cognitive processes (Vicente, 1999).

I.2.5 Results

Results from the performed work analysis and CWA describe the shuttle car operator as an occupation, including work-oriented activities, worker-oriented attributes, and organizational systems.

These results highlight the organizational structure and occupational roles as they currently function.

I.2.6 Recommendations

Recommendations for task reassignment are included across multiple job considerations given the purpose of restructuring of the organization to accommodate autonomous shuttle cars. Additionally, suggestions and recommendations for implementing autonomous shuttle car systems generated from the work analyses are provided for the following areas:

- Organizational Impact
- Shuttle Car Role Impact
- Communications
- Automated Vehicle Design
- Operator-Interface Design

I.2.7 Conclusions

Careful consideration is required when incorporating any automated system into an organization, and mining operations are no exception. The implementation of an autonomous shuttle car will have both immediate and lasting impacts on the organizational structure and functional systems within the operating mine. It is particularly important to understand the limitations of both vehicle automation and organizational systems when incorporating new technologies into a work domain with significant hazards. The recommendations created based on the work analyses may be used for designing and implementing a demonstration of an autonomous shuttle car in a room-and-pillar mine.

I.3 Introduction

I.3.1 Background and Research Objectives

The environment in underground room-and-pillar coal mines is inherently challenging and presents significant dangers or hazards to mining personnel, such as rib or roof failures, vehicle collisions, suffocation, and roof collapse, among others. Injuries and fatalities related to heavy machinery, specifically powered haulage vehicles, are generally preventable, but are also prevalent. Incidents involving powered haulage vehicles in underground coal mines resulted in roughly 800 injuries and 16 fatalities from January 2000 to September 2010 (Mine Safety and Health Administration, 2010).

Operation of shuttle cars presents inherent environmental and occupational risks, specifically to the shuttle car operators, mobile equipment operators near shuttle car haulage routes, and mining personnel in proximity to the shuttle cars. Typical hazards for these individuals include excessive

Figure I.1: Shuttle car produced by Joy Global Inc (now Komatsu)

noise, stagnant or flowing respirable dust, and poor visibility in travel ways, largely due to low-levels of illumination paired with suspended dust and ventilation controls intersecting the travel paths of the cars.

The shuttle car (Figure I.1) is an electric-powered, wheel-mounted, self-propelled heavy machine designed for transporting raw coal from the continuous miner to the feeder-breaker. Shuttle cars are equipped with a cable reel of large diameter and small axial designed to hold, release, and retract a flexible cable that extends from the power center to the shuttle car. The cable reel has a motor and drive sprocket to retract the cable as the shuttle car returns to the power center. Any cables that are in the pathway of a shuttle car or other connected machinery must be hoisted onto a rib to elevate the cable(s) off travel ways so as to not be driven over, as well as to prevent tripping hazards or provide visual cues for mine personnel.

The shuttle car consists of an operator cab, a bed for hauling coal, and a chain conveyor for transferring material to and from the bed. Due to the working environment, there is limited maneuverability in a room-and-pillar layout. As such, the shuttle car is equipped with four wheel (typically opposite direction) steering and is fully operable in both inby and outby directions. Shuttle car operators are primarily responsible for tramming the shuttle car between the feeder-breaker and continuous miner at the working face. The shuttle car operator must be cognizant of the trailing electrical cable, other shuttle cars, mobile and static equipment, and pedestrian workers.

The shuttle car itself functions with limited regard for operator comfort. Operator cabs are usually open and positioned on the side of the vehicle. In addition to a having a poor field-of-vision, operators are also left exposed to dust, spray from the continuous miner, and noise from mining operations without the ability to move away from these hazards. The shuttle car's suspension is designed to function while loaded, which results in significant vertical deflection while traveling unloaded. As a result, the operator is subjected to constant vibration while travelling.

Automating shuttle car coal face haulage from the continuous miner to the feeder-breaker would remove the operator from the active mining area, thereby reducing exposure to hazardous and undesirable conditions. Although an autonomous shuttle car would not have a human occupant, equipment operators would still be needed to serve in a supervisory capacity. In order to determine the duties and responsibilities of the operator's role, a series of work analyses must be performed, incorporating all of the affected roles in the underground operations. The automation of shuttle cars would not displace operators but would rather enhance their productive capacity, transform their role, and reduce their exposure to risk. Job analysis, work analysis, and cognitive work analysis (CWA) offer a general framework and a set of specific tools for the analysis of both simple and complex sociotechnical systems. Job and work analyses target work- and worker-oriented activities and attributes that are specific to roles. The CWA addresses all levels of an organizational work domain, from identifying key work processes and activities, roles/responsibilities of different actors (humans and machines) in the system, and the values/motivations and cognitive strategies of individual workers.. The general idea is to start with a thorough analysis of the existing system, which will then serve as the basis for design recommendations related to the introduction of new functions and technologies. These sets of analyses will be used in conjunction to provide a thorough understanding of the work domain and how it may be impacted through the introduction of an autonomous shuttle car.

The proposed inclusion of the autonomous shuttle car will enhance and transform the role of the shuttle car operator and reduce the risk of all mining personnel at the working section. The intent of this project is not to replace shuttle car operators but rather to complement their expertise, improve their comfort, and protect their well-being while ensuring that the mine remains competitive in a challenging and changing industry.

The research objectives of this report are two-fold:

- Identify the effects of introducing an autonomous shuttle car on the organizational system, shuttle car operator role, and other affected roles in room-and-pillar coal mining through the use of analyses.

- Create recommendations for incorporating automation in room-and-pillar coal mining using a thorough and systematic approach to understanding the impact on all of its organizational and operational systems.

I.3.2 Project Scope

This study undertakes an independent evaluation of the formal and informal organizational hierarchy of an underground room-and-pillar mining operation involving the use of shuttle cars in coal face haulage, performed by the Virginia Tech Transportation Institute (VTTI). The evaluation consisted of a CWA that was performed at a coal mine, which comprised the following steps:

- Role Investigation – A number of resources were consulted in the process of preparing for and performing the CWA. Materials specific to the mining operation were provided, including safety training manuals, operational handbooks, and job descriptions.

- Employee Interviews – Thirteen one-on-one interviews were conducted with employees responsible for the room-and-pillar mining operations. Employee interviews consisted of understanding both the prescribed role as well as any unwritten job responsibilities.

- Observational Data Collection – The research team collected observational information about the mining operations during a mining shift.

- Subject Matter Expert Dialogues – The VTTI research team consulted frequently with team members at the Virginia Center for Coal and Energy Research (VCCER) and the University of Kentucky (UK) to develop an understanding of the mining operations.

I.3.3 Organization of this Report

The current report details all analyses completed during the conducted CWA. These analyses are briefly described in this section so that the reader can understand the logical progression of events and material.

Work Analysis Techniques

A number of techniques are available for use in identifying organizational hierarchy, role transition, and automation implementation. Available technique methodologies vary widely based on the desired goal and scope of the issue in question, but the methodologies share similarities in the foundation and execution of analyses. These techniques are described in detail in this section.

Methodology

The methodological framework of the study is outlined in this section, including the materials and means by which the analyses were performed, specific issues related to each analytic method, and data collection techniques.

Results

Detailed results from the data collection as well as the CWA, task analysis, and supplemental analyses are presented in this section. Further supplemental results are detailed in section I.16.

Recommendations

Based on the analytics performed through the CWA, task analysis, and supplemental analyses, a list of recommendations were created outlining a number of parameters to consider when implementing an autonomous shuttle car in the underground mining operational setting.

Conclusions

Conclusions found across all methods of evaluation are detailed throughout this section.

I.4 Work Analysis Techniques

Work analyses are used to describe a wide variety of systematic procedures for examining, documenting, and drawing inferences about work activities, worker attributes, and work or environmental context (Sackett and Laczo, 2003). Work analyses are commonly used to assess or support the need for organizational activity, and require some degree of knowledge about job roles and duties.

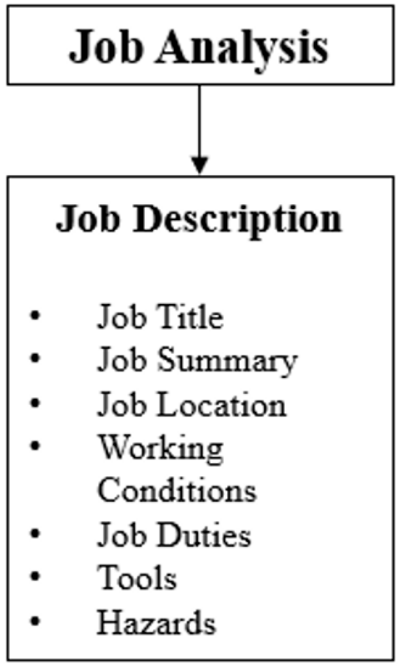

Figure I.2: Job analysis framework

The following section highlights common work analysis techniques, information on how they are conducted, and the implications of using these techniques.

I.4.1 Introduction

Tools and techniques to conduct work analyses have been developed across multiple fields of study and their outputs generally differ based on the purpose and approach used. The current analysis utilizes a multidisciplinary approach by incorporating techniques from the fields of industrial/organizational psychology and human factors and cognitive science. Techniques in each field are continually developing as they incorporate more information from new discoveries. Job analysis, task analysis, and work analysis have roots in industrial and organizational psychology and stem from the need to formalize job duties through a written job description, resulting in a rigid prescription of job duties (Sachett and Laczo, 2003). CWA has roots in cognitive science and involves efforts to understand unobservable cognitive processes (Vicente, 1999).

Job Analysis

Job analysis is the process through which one gains an understanding of the activities, goals, and requirements demanded by a work assignment (Sanchez and Levine, 2012). Job descriptions are a typical output of a job analysis and often incorporate job duties, responsibilities, and other summary information regarding an occupation (Figure I.2).

The process of performing a job analysis has itself been mandated as a legal requirement, as outlined in the Uniform Guidelines for Employee Selection Procedures upon its publication in

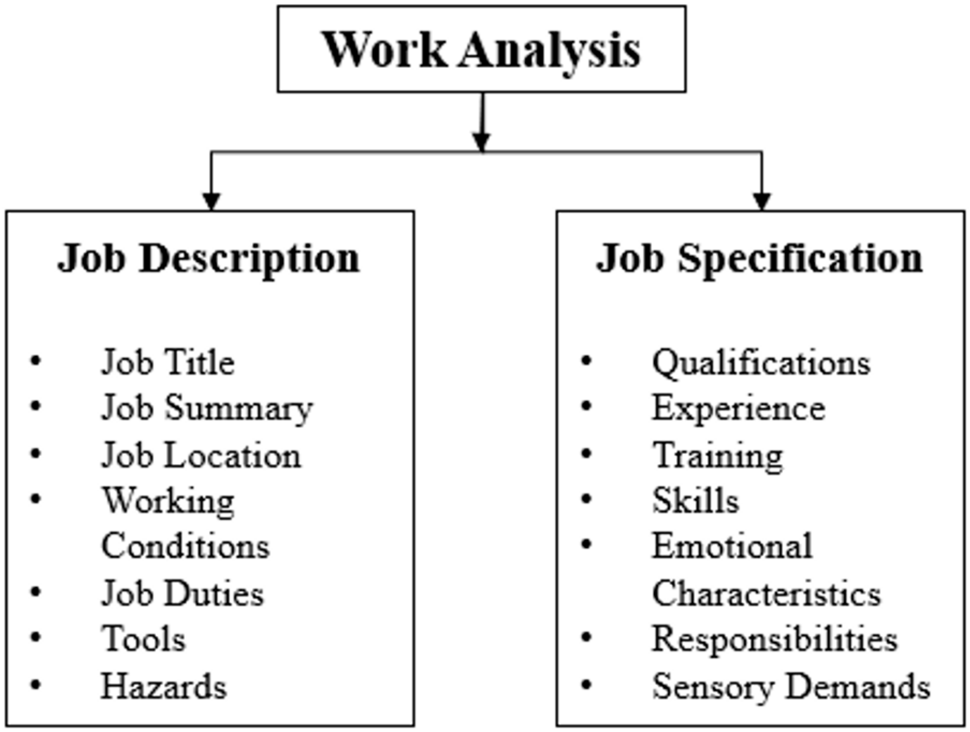

Figure I.3: Work analysis framework

1978. The Uniform Guidelines provide a set of generally accepted principles on employee selection procedures and the means to conduct a job analysis that will meet the standards of the Guidelines. A job analysis is typically expected to produce the basic duties and responsibilities, the knowledge, skills, abilities, and other characteristics (KSAOs) required to perform assigned duties, and the factors that are important in evaluating candidates.

Though the reasons for performing job analysis originated decades ago from a need to standardize job roles, the inputs to, and outputs from, a job analysis have become increasingly complex, in part due to jobs becoming more flexible and less prescribed, and because of improvements in the science and techniques of job analysis. As such, a more appropriate term, work analysis, has been used to reflect the increasing complexity of dynamic work environments (Sanchez and Levine, 2013). Job descriptions alone are often so short that they lack functionality (Wilson et al., 2012), but combined with job specification details (Figure I.3), a well-rounded work analysis is able to provide ample details on the occupation as well as the person fulfilling the role.

Largely, job and work analyses measure the typical performance of an individual on the job. However, when seeking to differentiate between average and good indicators of job performance, competency modeling can be used (Sackett and Laczo, 2003). Competencies, as defined by Chen and Naquin (2006), generally have three central characteristics: 1) they underlie successful performance, 2) are able to distinguish superior from average performers, and 3) are measurable or observable in some way. A table summarizing the three analytic methods is displayed in Table I.2. The work analysis framework and descriptions are detailed in section I.4.2.

Table I.2: Job, work analyses, and competency modeling differences

Dimension Traditional	Traditional Job Analysis	Work Analysis	Competency Modeling
Purpose	Describes behavior	Describes behaviors and attributes	Influences behavior
View of the Job	An external object to be described	An external object to be described	A role to be enacted
Focus	Job	Work	Organization
Time Orientation	Past	Past	Future
Performance Level	Typical	Typical	Maximum
Measurement Approach	Latent trait	Latent trait	Clinical judgment

Cognitive Work Analysis

In the human factors and cognitive science research domain, the CWA provides a comprehensive methodology to understand the functional and structural composition of a complex human-machine system, and is intended to provide a formative, rather than descriptive or normative, multi-scaled explanation of a system's functionality. The goal of such an analysis is to better understand a specific system's constraints in order to consider the broad array of actions that may be undertaken to accomplish that system's objectives. In contrast to traditional methodologies that focus on describing the specific actions and user tasks required to achieve system goals, a CWA describes the system's overall constraints to enable a higher-level understanding of the system's state space solutions. This output presents a significant advantage over more traditional forms of work analysis, as it enables a deeper, more flexible understanding of the range of actions that may be taken to deal with unexpected occurrences.

CWA was originally developed in the 1960s and 1970s to enable safe design and operation of nuclear power plants (Naikar, 2017; Rasmussen, 1999). In its focus on environmental constraints and the emergent behavior of people situated within a physical world, it shared and evolved alongside Gibson's ecological psychology (e.g., Gibson, 1966; Gibson, 1979). The convergence of these two schools of thought may be found in the genesis of Ecological Interface Design, which used CWA methodology to design interfaces representing system constraints in a directly perceivable manner to enable operators to better address unforeseen problems. In addition to nuclear power plants and general interface development, CWA has been successfully used in the domains of health care (Sharp and Helmicki, 1998), command and control (Gous, 2013), petrochemical refinement (Jamieson and Vicente, 2001), and network management (Burns, Kuo and Ng, 2003), as well as numerous other domains (Bisantz and Burns, 2009).

CWA comprises some or all of five phases that can provide important contextual information separately or can be combined to create a fuller picture of the task, environment, and operator constraints. These phases represent components of the analysis, from the organizational systems level, to the tasks level, to the cognitive level. These phases will be described further in section I.4.3 and include:

1. Work Domain Analysis (WDA)
2. Control Task Analysis (ConTA)
3. Strategies Analysis (STRA)
4. Social Organization and Cooperation Analysis (SOCA)
5. Worker Competencies Analysis (WCA)

Each of these phases focuses attention on one aspect of work within a task, from physical and informational to strategic and personnel analyses. The output of each phase is a comprehensive overview of that work aspect, and is generally presented in one or more tables and visual analyses, including hierarchies, multidimensional task breakdowns, workflows, and decision ladders. Individually, or in aggregate, the products of these phases provide researchers with a better understanding of a task's state space, allowing higher-level understanding of the range of variables that affect outcomes and the ways in which action can be taken when unexpected errors or problems occur.

As this framework is comprehensive and flexible, with the goal of providing constraint information across all physical and informational levels of a complex task, it provides a highly flexible platform for numerous work domains. Mining is a prime example of a task for which CWA can provide meaningful analysis and design input, as it combines a complex, dynamic work environment with overarching goals divided into subtasks for which responsibility is spread across human and machine actors. In particular, as the mining task shifts from primarily human control to a fusion of human control with automated machinery, it is critical to understand four key components, 1) the domain of tasks that must be accomplished, 2) the current and potential future roles of each actor, 3) the range of higher-order factors that may influence failure states, and 4) the complex interactions among all of these that affect both productivity and safety.

To enable this understanding and support the transition to automation, a CWA of the current coal mining operation work domain at a partner mine was conducted. The CWA focused specifically on the first four phases of this transition, which are most relevant to the introduction of shuttle car automation: WDA, ConTA, STRA, and SOCA. The CWA framework is described in more detail in the following section, with details of the methodology and findings of the CWA in subsequent sections.

I.4.2 Job Analysis Framework

A typical job analysis involves making numerous decisions to match the purpose and expected goals of the analysis. As such, a number of dimensions must be considered in the introduction of an autonomous shuttle car. These dimensions and taxonomies are outlined in Sackett and Laczo (2003) and are presented in this section.

Activity Versus Attribute

The most significant distinction in job analysis is whether the specific focus will target work-oriented activities or worker-oriented attributes. Generally, work-oriented activities involve the explicit examination of tasks or behaviors performed on the job. Conversely, worker-oriented attributes involve an examination of the characteristics that contribute to successful job performance. These attributes are generally defined as the KSAOs required for functional job completion.

Changing the organizational structure through redefining a role and incorporating new tools and equipment is complex. As such, the job analysis employed techniques that utilize an understanding of activities and outlined requisite attributes under differing circumstances when incorporating an autonomous shuttle car system. Shifting responsibilities between occupational roles as well as shifting task duties from human to machine requires a collective approach to understanding both affected task duties and worker-oriented attributes. For the current job analysis, assessing work-oriented activities is the first step in understanding how the organizational systems are impacted, followed by applying worker-oriented attributes towards newly generated task structures based on occupational capabilities.

General Versus Specific

The subsequent decision in a job analysis is to determine the level of detail and specificity needed. The same job activities can be described using highly specific terms, moderate specific terms, or very general terms. For the purposes of this job analysis, highly specific terms are used.

Qualitative Versus Quantitative and Taxonomy-Based Versus Blank Slate

Quantitative ratings or numeric evaluations of job duties based on standardized questionnaires are possible, but due to the level of specificity needed, qualitatively listing the job- and worker-oriented descriptors via narratives and lists is recommended. Similarly, a taxonomy-based analysis relies heavily on rating general job characteristics or worker-attributes and in the case of this project is less useful compared with a blank slate approach, which allows for increased flexibility due to its nature of bottom-up information generation and incorporation.

Observer-Based Versus Informant-Based

With regard to gathering information for conducting a job analysis, sources generally include trained analysts directly observing activities and attributes or the use of informants, usually job incumbents, supervisors, or others familiar with job roles.

Primary data collection in the current analysis relied heavily on informant-based information, either between direct interaction with job incumbents and their supervisors or via material written by subject matter experts. Due to the limitations of a confined work environment and related safety constraints, observational data was supplemental to informant-based data collection.

Descriptive Versus Prescriptive

Traditionally, job analysis has used reflective means to describe current occupations; however, there are cases where the goal is to prescribe jobs that do not yet exist. In the current analysis, both descriptive and prescriptive methods are used to first assess the roles within the section crew and to then provide procedures, activities, and attributes related to the introduction of an autonomous shuttle car.

I.4.3 Cognitive Work Analysis Framework

Work Domain Analysis

A work domain analysis (WDA) is undertaken to understand the constraints on behavior given the physical resources, purposes, values and priorities in which the work is conducted, and presents relevant information through the use of an abstraction hierarchy (AH) describing the abstraction-decomposition space (Naikar, 2016). An AH consists of five different levels, each containing information regarding the work domain to be modeled. Links between the levels of the AH are means-ends or how-why relationships. An AH can be decomposed by system levels, represented by a decomposed abstraction hierarchy.

WDAs are fundamental to understanding the constraints of a task because they serve to describe the structure of the system independent of any individual actor (Vicente, 1999). As Vicente proposes, this is analogous to the distinction between a map and a set of directions; while both can get an individual to a destination given ideal conditions, a map provides significantly more context that allows flexible routing if and when an idealized route is blocked or interrupted. Similarly, providing a higher-level understanding of a system's structure enables flexible behavior toward a goal when a prescribed set of goal-directed behaviors is perturbed.

Control Task Analysis

While the WDA provides a comprehensive understanding of the structure of a task system, control task analysis (ConTA) enables analyses of "the requirements associated with known, recurring classes of situations" (Vicente, 1999). In other words, ConTA seeks to capture the requirements and constraints necessary to achieve the purpose of a work domain (Naikar, 2016) as opposed to its physical structure. It describes the logical cascade of information-processing activities and resultant knowledge states comprising a single control-related task, and describes activity in the context of work functions and control tasks. As a preliminary step to capture work functions and situations, a contextual activity template (CAT) can be developed that details functions outlined in an abstract hierarchy and breaks them into context-dependent areas. Control Task Analysis is designed to provide one or more decision ladders for each individual task across contexts. These decision ladders are representations of the information-processing activities contained in a task, and capture the process from an initial perception that a control action may be necessary to the execution of an appropriately formulated control response.

Strategies Analysis

The purpose of a strategies analysis is to investigate the different ways in which each of the control tasks could be accomplished, regardless of the actor performing them; in contrast to a ConTA that describes the product to be completed, the strategies analysis describes the range of processes that would enable successful completion (Vicente, 1999). Indeed, individual actors may choose different control strategies under different circumstances (Jenkins et al., 2009). Information flow maps for each strategy are typically produced during this phase of analysis.

Social Organization and Cooperation Analysis

While the previous three phases have enabled detailed descriptions of the work domain in terms of structure, control tasks, and control strategies, the fourth phase, offers a comprehensive analysis of the ways that multiple actors (including both human and machine actors) may communicate and cooperate to achieve the task goals within the system (Vicente, 1999). The purpose of this analysis is to identify potential schemes for allocating responsibility for the domain's individual information-processing activities and knowledge states. This allows for a breakdown of tasks by actor that may incorporate both human and machine actors and examines the work content associated with each control task.

Competencies Analysis

The purpose of this analysis is to identify the competencies required by members of the operational team to effectively accomplish the domain's numerous control tasks (Vicente, 1999), with the ultimate goal of identifying additional psychological constraints applicable to system design. Behavior exists within three levels: skill-based, or behavior that emerges from internalized skills enabling direct engagement with the environment; rule-based, or behavior that emerges from the following of simple cue-action rules; and knowledge-based, or behavior that emerges from explicit cognition enabling formulation of a response. This phase of analysis closely resembles work analysis, having both similar inputs and outputs targeting the individual.

I.5 Methodology

The following section provides an overview of the information collected and details the collection methodology. A number of sources were consulted to garner information on the organizational structure and job responsibilities needed to conduct the work analyses. These sources included on-site observations, interviews, and material review. These are broken down in further detail throughout this section.

I.5.1 Work Analyses Target Location

General usage of work analyses includes understanding the typical job under a given classification or title, making relatively sweeping generalizations to that specific job. For example, an investigation of shuttle car operators would provide information regarding the shuttle car operator as a role across a number of different environments, parameters, or types of operations.

For the purposes of the work analyses conducted in this report, data and information were primarily generated from, and are applicable to, the coal mine that the data were collected from a partner mine in eastern US. Though much of the work analyses may translate to similar settings in which shuttle car operators operate, the context of this work analysis is limited to this specific coal mine.

The partner mine uses the room-and-pillar mining method, employing continuous miners for cutting and loading and shuttle cars for face haulage. The shuttle cars transport mined coal from the continuous miner to the section belt conveyor. Active mining areas, or sections, at this mine apply two to three shuttle cars depending on conditions. This mine also has at least one super-section, which employs two continuous miners with four to five shuttle cars. At the time of the CWA, the mine had 15 active sections.

I.5.2 Observational Data Collection

Observational data was a primary source of data for the analysis. The research team observed two hours of routine mining operations, such as coal extraction and haulage, in a single mining section and one hour of supplemental activities, which included safety training and equipment reviews. Any questions from the research team were answered and recorded. No emergency or pre-operational/post-operational activities were observed.

I.5.3 Interviews

Interviews were performed after referencing other job-related material and collecting observational data. This background research was used to frame questions for the subject matter experts, who, in this context, were the employees assigned to underground operations.

Interviews were conducted to gain in-depth insights regarding the breadth and depth of each individual's role, duties, and interactions with equipment and others in order to recreate the system of responsibilities and constraints within the mining operation. This information allowed researchers to gain an understanding of job specifics from subject matter experts that would not be easily translated from written or observed material.

The organizational hierarchy of our partner mine is provided in Figure I.4. Other positions and operations, such as maintenance, safety, outby labor, processing, etc., were beyond the scope of this study and thus were not included in the work analyses.

Internal Review Board

Approval was sought through Virginia Tech's Institutional Review Board (IRB) to conduct a CWA that involved live interviews. An IRB protocol document detailing the involvement of human subjects for the CWA was completed and formal IRB approval was granted. The research team completed interviews in the eastern US near the partner mine.

Sample

Thirteen interviews were conducted with subject matter experts. Personnel fulfilling the subject matter expert roles are described below (numbers in parentheses indicate the number of interviews conducted with personnel in this role):

- Mine Manager (1)
- Shift Foreman (1)
- Section Foreman (3)

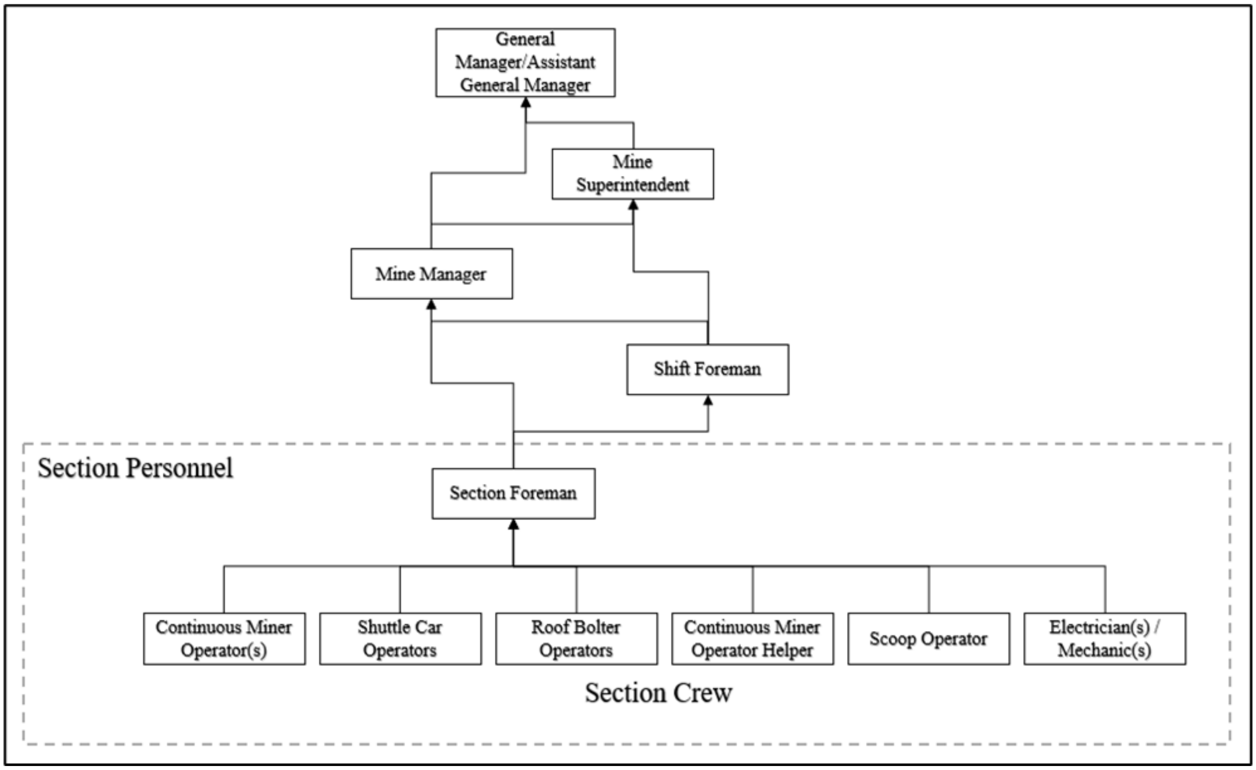

Figure I.4: Organizational hierarchy of management and underground mining operations

- Continuous Miner Operator (2)
- Shuttle Car Operator (3)
- Roof Bolter Operator (1)
- Continuous Miner Operator Helper (1)
- Scoop Operator (1)

All individuals were employees at the partner mine. Individuals' experience in his or her current job roles ranged from 6 months to more than 10 years. Multiple section foremen, continuous miner operators, and shuttle car operators were interviewed to provide more insight into facets of the job roles that may be impacted most by the introduction of an autonomous shuttle car.

Additionally, the General Manager and Assistant General Manager of the partner mine were also interviewed to provide insight and information at a mine-wide level, but were not questioned about routine shuttle car operations.

Interview Measures

Interviews were conducted in 20–25 minutes, and assessed a broad range of categories using subject matter experts with in-depth knowledge about their particular job and its associated duties and responsibilities.

Section I.17 details an initial set of questions used during the interviews. From these, questions targeting section crew and management were differentiated to attain a rounded view of the underground mining operations. The questions covered a number of relevant pieces of information used to complete the work analyses, and spanned the five CWA topics as well as additional task analysis information.

These topics included, but were not limited to, the following:

- Job Characteristics
- Work Domain
- Resource Functions
- Critical Errors and Decisions
- Decision Making
- Social and Organizational Analysis
- Communication or Information Flow Relationships
- Ecological Relationships

Questions to management also included the topics of performance management, safety culture, and personnel management. Not all topics were addressed during each interview. Instead, the research team identified the most relevant topics given the job role and information gathered from previous interviews.

I.5.4 Material Review

Various material sources were reviewed, including publicly available sources, literature, and documents provided by the partner mine. These materials are described in more detail below.

Occupational Information Network (O*NET)

The Occupational Information Network (O*NET) is a comprehensive job analysis system designed to replace the U.S. Department of Labor's (USDOL) Dictionary of Occupational Titles (DOT, 1991). O*NET contains hundreds of standardized and occupation-specific descriptors on approximately one thousand occupations, as developed by the USDOL and Employment and Training Administration.

O*NET's descriptors include tasks (e.g., control conveyors that run the entire length of shuttle cars to distribute loads as loading progresses), tools, and KSAOs (e.g., Mechanical - knowledge of machines and tools, including their designs, uses, repair, and maintenance; Operation and Control - controlling operations of equipment or systems). The tasks and KSAOs also contain metrics of importance for each specific descriptor, conveying the tasks and KSAOs expected to be most relevant to the occupation.

Although there are a number of occupations included in the O*NET system, they are limited in specificity for the sake of generalizability. The following underground-mining-related occupations are represented on O*NET:

- 47-5041.00 Continuous Mining Machine Operators
- 47-5044.00 Loading and Moving Machine Operators, Underground Mining (includes deprecated 53-7111.00 Mine Shuttle Car Operators and 53-7033.00 Loading Machine Operators, Underground Mining)
- 47-5049.00 Underground Mining Machine Operators, All Other (included deprecated 47-5042.00 Mine Cutting and Channeling Machine Operators)
- 47-5061.00 Roof Bolters, Mining
- 47-5081.00 Helpers-Extraction Workers
-

Job Descriptions

A set of occupational task descriptors was provided by the partner mine for the roles of shuttle car operator, continuous miner operator, and section foreman. These documents separated the daily routine performed in each occupational role by duties. The high-level duties and responsibilities listed for the shuttle car operator are as follows:

1. Start-of-Shift Activities
2. Conduct Examinations
3. Control Functions
4. Pre-op on Shuttle Car – Power off
5. Pre-op on Shuttle Car – Power on
6. Tramming
7. Loading
8. Dumping
9. End-of-Shift Activities
10. Unusual Situations, Emergencies, Non-routine duties

These duties are separated into specific tasks in accordance with the operation. The tasks are highly specified for both the occupational role as well as the operational environment. The section foreman and continuous miner operator have similar duties, but the tasks are specific to their respective occupational role.

Training Material

The Training and Retraining Guidelines for Virginia Coal Miners Manual published through the Virginia Department of Mines, Minerals and Energy (2004) was reviewed for relevant details regarding underground operations and involved occupations.

Safety Procedures

Various safety procedures were provided or detailed during observational data collection and written safety standards were also obtained from the partner mine. Other documents, including training guides and general occupational descriptions, contained material relevant to safety procedures and the occupations responsible for emergency protocols.

Employee Handbook

The partner mine provided the research team with a job standards handbook that details specifics regarding general underground operation standards, standards for specific occupations, and location-specific information. Specifics regarding occupational information include pre-operational, operational, and post-operational checks and procedures. Each occupation within the section crew was included.

Other Material

Literature covering mining operations, work analyses, and introducing automation to the industry were reviewed for relevant information. Little research has been done involving performing work analyses in mining environments, though Xiao et al. (2015) have conducted the first stage of a CWA on mine emergency systems. Other human factors issues were addressed in Horberry et al. (2011).

This and other literature provided a framework for how to begin collecting information and performing the job analysis and CWA.

I.5.5 Subject Matter Expert Consultation

Members of the research project responsible for prototype and development of the autonomous shuttle car from VCCER as well as members from the UK's Mining Department were available for material and document review and answered any questions as needed. These individuals provided an overview of mining operations and set up the relationship with the partner mine to further conduct the work analyses.

I.5.6 Analysis Data Implementation

The goal of performing work analysis and CWA is the incorporation of the analyses' outputs into real-world implications. A number of recommendations can be made based on the parameters of the work analyses, but they are ultimately recommendations that are meant to guide the research team in implementing an automated shuttle car system. A number of other considerations outside the scope of the current project may affect the execution of, or adherence to, recommendations, such as the legal application of automation, or the current personnel capabilities with regard to operating a new system or performing new duties.

I.6 Results

Results from the performed work analysis and CWA are detailed in this section. These results highlight the organizational structure and occupational roles as they currently function. Suggestions and recommendations for implementing automated shuttle car systems are detailed in the following section.

I.6.1 Work Analysis – Shuttle Car Operator

Work-oriented activities and worker-oriented attributes are presented here for the shuttle car operator occupation. These are largely represented by tasks, KSAOs, and competencies.

Tasks, Abbreviated

- Controlling machines and processes
- Operating vehicles, mechanized devices, or equipment
- Inspecting equipment, structures, or material
- Monitoring processes, materials, or surroundings
- Evaluating information to determine compliance with standards
- Communicating with supervisors, peers, or subordinates
- Identifying objects, actions, and events
- Handling and moving objects
- Repairing and maintaining mechanical equipment
- Performing general physical activities

Tasks, Detailed

Work-oriented activities are broken down into nine categories encompassing the shuttle car operator's daily routine and one category involving emergency-related situations. These activities range from general shuttle car operations to mine-specific conduct.

Start-of-Shift Activities

- Check-in via the tag-in/tag-out system
- Ensure correct clothes are worn
- Obtain self-contained self-rescuer
- Obtain radio
- Obtain personal protective equipment
- Obtain tools
- Meet with foreman and crew to discuss section activities
- Meet with foreman and crew to attend safety talk
- Meet with foreman and crew to discuss roof control plan
- Enter the mine

Conduct Environmental Examinations

- Examine roof, ribs, and floor
- Check ventilation
- Inspect roof bolts
- Examine floor
- Visually inspect shuttle car cable for condition of splices
- Visually inspect shuttle car cable for cuts, nicks, or other deformities
- Visually inspect shuttle car cable anchor and hanging cable
- Examine tail piece and feeder-breaker for proper equipment
- Examine tail piece and feeder-breaker for hazards
- Turn on belt
- Turn on feeder-breaker
- Conduct travel way examination for damaged or loose top, ribs, and floor
- Check fly pads before tramming
- Correct any unsafe conditions
- Report any unsafe conditions

Pre-operational Inspections – Power Off

- Start at sheave wheel
- Check sheave wheel for material build up
- Check to see if sheave wheel turns
- Grease the sheave wheels
- Check cable compartment
- Check for material build up on cable compartment
- Check level-wind chain for tightness
- Check the diversion valve for on position
- Check drive chain for oiler operation
- Check cable slack on reel
- Check for oil leaks
- Check wheel units
- Check to ensure wheel bolts are in place and tight
- Check tire condition
- Check tie rods
- Check for material build up
- Check body lift jacks to ensure they are in up position
- Check pump compartment
- Check two diversion valves to ensure they are off
- Check filter for leaks
- Check tram motor (right)
- Check fire suppression activator
- Check wet brakes
- Grease tail shaft and grease manifold (right)
- Conduct visual exam of chain from load end of shuttle car

- Check to see if lights are missing or damaged
- Check tram motor (left)
- Check for material buildup
- Check fire suppression activator
- Check wet brakes
- Grease tail shaft (left)
- Examine body lift jacks valve bank
- Examine main contactor panel
- Visually check packing glands
- Check loose or missing bolts
- Check lead seals
- Check rub rail for damage
- Ensure panel is secure
- Ensure breakers are in the on position
- Grease two manifolds
- Examine operator's compartment
- Check bell
- Check slate bar
- Check fire suppression button
- Check shuttle car counters or chalk
- Check mechanical function of brake pedal, tram pedal and panic bar
- Check the manual brake release
- Check condition of seat and seat belt
- Check canopy bolts
- Check screen between compartment and conveyor chain
- Check conveyor motor
- Check conduit and packing gland
- Visually examine lights for damage

Pre-operational Tasks – Power Off

- Walk cable from sub to shuttle car twice a shift and check for routing, damage, hazards, and splicings near anchor
- Check panic bar
- Check to see if lights are working, correctly attached, and free from cracks
- Check for loose leads or damaged conduits
- Check level-wind chain for tightness
- Check brakes for proper operation
- Check warning bell or horn
- Check operational control switches for proper operation and for any loose or missing bolts
- Be sure tram pedals are free of obstruction or objects
- Check amount of cable on reel
- Check car anchor to be sure it is secure and not anchored to roof bolts that are part of bolt pattern
- Check that fire suppression buttons and tubes are in operative condition
- Check that sheave wheel is not frozen
- Check that canopy tab is securely attached to canopy
- Check lug nuts
- Correct and report any unsatisfactory or hazardous conditions to responsible party
- Make sure cameras are operational

Pre-operational Tasks - Power On

- Check lights
- Turn pump on
- Turn pump off with panic bar
- Check start/stop speed control
- Check park brakes
- Check steering

- Check forward and reverse switch and tram function
- Check conveyor chain on/off switch
- Check boom raise/lower lever
- Look for cable pick up

Tramming

- Put seat belt on
- Keep all body parts within the deck compartment
- Clear persons out of shuttle car
- Set directional switch
- Sound audible alarm before tramming (voice or bell)
- Start pump
- Adjust tram speed using tram dial
- Release park brake
- Push button in (palm valve)
- Check brake pressure
- Check steering
- Turn lights on in direction of travel
- Listen for anchor/slap
- Depress tram pedal
- Keep car centered in roadway
- Check cable in outside places. Have enough cable for the current and next shifts.
- Tape up or secure all low hanging cables that may be susceptible to damage
- Keep slack cable hung or against rib for protection
- Re-hang any curtain that is damaged by the shuttle car
- Keep lights on toward nearest curtain when parked.
- Use the first row of bolts off the rib to judge the positioning of car

- Use existing tire tracks to judge position of car
- Make a turn traveling inby by lining up front tires with break corners and turning wheels left or right as hard as possible
- Make a turn traveling outby by lining up boom end tires with break corners and turning wheels left or right as hard as possible
- Observe for persons and obstructions in travel ways
- Ring bell or flash lights
- Stop car for persons on offside of shuttle car
- Traveling through ventilation controls/fly pads/curtains
- Slow down
- Sound audible alarm
- Flash lights
- Replace any damaged ventilation controls
- Operate at speed under which control of the shuttle car can be maintained
- Be aware of other equipment and cables in travel ways
- Shut car off before exiting

Loading

- Tram to continuous miner
- At the continuous miner, hold car over to the left rib
- Avoid continuous miner cable and operator
- Center the shuttle car (as much as possible) under boom
- Turn shuttle car wheels toward continuous miner operator while loading (sitting under the boom)
- Observe roof over continuous miner operator for loose roof or ribs/Red Zones
- Do not bump back of continuous miner
- Maintain communication with continuous miner operator
- Ensure continuous miner operator is not near the load end of the shuttle car during loading

- Change the direction of your lights
- Watch the tail boom of the continuous miner and as coal builds up, run the chain to load car as evenly as possible without overloading/spilling
- Stop loading coal within a foot of the end of boom
- Use the outby end of deck compartment as a guide
- Listen for spillage
- Observe for continuous miner operator signal when car is loaded
- Observe second row of fully intact roof bolts
- Ring bell
- Tram to feeder-breaker
- Be aware of other car switch out points and scoop activity

Dumping

- Look for any activity around feeder-breaker
- Slow down
- Raise boom (≈ 1 ft.)
- Center car on feeder-breaker
- Position boom so coal drops in center of feeder-breaker
- Use reflectors to center car on feeder-breaker
- Make sure feeder-breaker is on prior to dumping
- Dump load
- Raise boom as coal load is dumped
- Slow down dumping when discharging rock to allow the crusher ample processing time
- Report excessive spillage to supervisor
- Turn lights in direction travel
- Sound audible alarm
- Pull off the feeder-breaker

- Look and listen for unusual sounds, smells in the feeder-breaker area
- Lower boom
- Return to continuous miner

End-of-shift Activities

- Ensure car is empty
- Park car at the feeder-breaker
- Turn wheels toward rib
- Clean out deck compartment
- Clean spillage off sides of car
- Ensure slate bar is left on car
- Trip breaker on feeder-breaker
- Trip breaker on car
- Check ventilation controls/fly pads/curtains
- Check tail piece for spillage
- Report any maintenance problems/clean up needed, etc. to supervisor/electrician
- Walk to mantrip

Unusual Situations, Emergencies, Non-routine Duties

- In the event of a fire, #1 Shuttle Car operator assists continuous miner operator in gathering water line and fighting fire
- In the event of a fire, #2 Shuttle Car operator mans phone and communicates with outside person
- In the event of a loss of brakes, stay in your seat
- In the event of a loss of brakes, steer into rib
- In the event of a loss of brakes, hit panic bar
- Show escapeways
- Assist with mechanical repairs

Knowledge

- Control conveyors that run the entire length of shuttle cars to distribute loads as loading progresses.
- Drive loaded shuttle cars to ramps and move controls to discharge loads into mine cars or onto conveyors.
- Clean, fuel, and service equipment, and repair and replace parts as necessary.
- Move mine cars into position for loading and unloading, using pinchbars inserted under car wheels to position cars under loading spouts.
- Guide and stop cars by switching, applying brakes, or placing scotches, or wooden wedges, between wheels and rails.
- Push or ride cars down slopes, or hook cars to cables and control cable drum brakes, to ease cars down inclines.
- Observe hand signals, grade stakes, or other markings when operating machines.
- Open and close bottom doors of cars to dump contents.
- Direct other workers to move stakes, place blocks, position anchors or cables, or move materials.
- Monitor loading processes to ensure that materials are loaded according to specifications.
- Measure, weigh, or verify levels of rock, gravel, or other excavated material to prevent equipment overloads.
- Read written instructions or confer with supervisors about schedules and materials to be moved.
- Maintain records of materials moved.

Skills

- Operation and Control - Controlling operations of equipment or systems.
- Operation Monitoring - Watching gauges, dials, or other indicators to make sure a machine is working properly.
- Monitoring - Monitoring/Assessing performance of yourself, other individuals, or organizations to make improvements or take corrective action.
- Equipment Maintenance - Performing routine maintenance on equipment and determining when and what kind of maintenance is needed.

Abilities

- Control Precision - The ability to quickly and repeatedly adjust the controls of a machine or a vehicle to exact positions.
- Manual Dexterity - The ability to quickly move your hand, your hand together with your arm, or your two hands to grasp, manipulate, or assemble objects.
- Multi-limb Coordination - The ability to coordinate two or more limbs (for example, two arms, two legs, or one leg and one arm) while sitting, standing, or lying down. Does not involve performing the activities while the whole body is in motion.
- Near Vision - The ability to see details at close range (within a few feet of the observer).
- Reaction Time - The ability to quickly respond (with the hand, finger, or foot) to a signal (sound, light, picture) when it appears.
- Depth Perception - The ability to judge which of several objects is closer or farther away from you, or to judge the distance between you and an object.
- Rate Control - The ability to time your movements or the movement of a piece of equipment in anticipation of changes in the speed and/or direction of a moving object or scene.
- Oral Comprehension - The ability to listen to and understand information and ideas presented through spoken words and sentences.
- Problem Sensitivity - The ability to tell when something is wrong or is likely to go wrong. Does not involve solving the problem, only recognizing there is a problem.

Other Characteristics

- Wear common protective or safety equipment such as safety shoes, glasses, gloves, hearing protection, hard hats, or life jackets.
- Spend time using your hands to handle, control, or feel objects, tools, or controls.
- Spend time making repetitive motions.
- Face-to-face discussions.
- Spend time sitting.
- Consequence of error - “Extremely serious.”
- Work with work group or team - “Extremely important.”
- Pace determined by speed of equipment.
- Frequency of decision making - “Every day.”

- Responsible for others' health and safety.
- In an open vehicle or equipment.
- Impact of decisions on co-workers or company results.
- Constant contact with others.
- Continual time pressure.
- Importance of being exact or accurate.
- Spend time bending or twisting the body.

Environmental Context

- Exposed to contaminants - "Every day."
- Sounds, noise levels are distracting or uncomfortable - "Every day."
- Exposed to hazardous equipment - "Every day."
- Cramped work space, awkward positions - "Every day."
- Exposed to whole body vibration - "Every day."
- Exposed to hazardous conditions - "Every day."
- Extremely bright or inadequate lighting - "Every day."

Tools and Equipment

- Belt conveyors
- Bulk material carriers - shuttle cars
- Ear plugs
- Electric actuators
- Locking pliers
- Mining headlamp
- Protective gloves
- Pry bars
- Respirators
- Safety boots

- Safety glasses
- Safety vests
- Two way radios
- Utility knives
- Valve actuators

Competencies

- Dependability - Job requires being reliable, responsible, and dependable, and fulfilling obligations.
- Cooperation - Job requires being pleasant with others on the job and displaying a good-natured, cooperative attitude.
- Concern for Others - Job requires being sensitive to others' needs and feelings and being understanding and helpful on the job.
- Stress Tolerance - Job requires accepting criticism and dealing calmly and effectively with high stress situations.
- Persistence - Job requires persistence in the face of obstacles.
- Achievement/Effort - Job requires establishing and maintaining personally challenging achievement goals and exerting effort toward mastering tasks.
- Initiative - Job requires a willingness to take on responsibilities and challenges.
- Independence - Job requires developing one's own ways of doing things, guiding oneself with little or no supervision, and depending on oneself to get things done.
- Integrity - Job requires being honest and ethical.

I.7 Cognitive Work Analysis

This section details the following phases of cognitive work analysis:

1. Work Domain Analysis (WDA)
2. Control Task Analysis (ConTA)
3. Social Organization and Cooperation Analysis (SOCA)

Strategies Analysis (STRA), phase 3 of cognitive work analysis, is demonstrated throughout the recommendations. Work Competencies Analysis (WCA), phase 5 of cognitive work analysis, is presented through work analysis competencies.

Work Domain Analysis

Figure I.5 and Figure I.6 demonstrate the AH and Decomposed AH, respectively, in Underground Mining Operations. These provide a tiered representation of the work domain as a system as it currently operates.

To understand and identify shuttle car-related constraints, AH for shuttle car operations and pre-operations were created and are demonstrated in Figure I.7 and Figure I.8, respectively. A supplemental AH was created for continuous miner operations, as they have a significant role in shuttle car operations (see Figure I.9).

Control Task Analysis

ConTA was used to identify three main systems. First, location-based functions were identified and outlined in a Contextual Activity Template (CAT) to demonstrate where tasks were occurring (see Figure I.10). This highlights where current tasks are being conducted (task narratives) to allow impact identification of automation.

To supplement the CAT, decision ladders at each task narrative were created. A decision ladder (Figure I.11) provides a template for mapping the sub-tasks involved in decision making. Each decision ladder contains cognitive states and cognitive processes, represented in the graph as ovals and rectangles, respectively. A decision ladder has three main stages, the left-hand leg involves situation analysis, the top section involves value judgment, and the right-hand leg involves planning and execution. A decision ladder represents the expected decision-making steps typically involved in a specific work narrative. These steps involve following the perimeter of the decision ladder from the lower-left node to the lower-right node, however, a heuristic decision process can start and finish anywhere in the ladder and can transition via shortcuts across the ladder. The heuristic decision process represents shortcuts made to circumvent specific steps of the decision ladder.

A CAT with task narrative decision ladders is displayed in Figure I.12. The CAT communicates which stage of the task is being completed at any particular combination of work situation and function and indicates the typical area of the decision-ladder involved for workers. The heuristic decision process is represented by the darkened ovals and rectangle of each decision ladder.

The second use of a ConTA highlighted the communications systems as a critical function of removing the shuttle car operator from the vehicle. The CAT in Figure I.13 demonstrates communication methods between active operations.

The last output from the ConTA includes a CAT for shuttle car tramming (Figure I.14) demonstrating typical interactions between crew members and contextual situations in the active face. Responsibilities are often shared between individuals to preserve safety and mining efficacy, as represented in the CAT.

Social Organization and Cooperation Analysis

SOCA was performed on each of the previously mentioned CWA products. This analysis models the constraints governing the division of tasks between the resources and functions and addresses how the team cooperates in completing related job duties. These social and technical factors are represented in Figures I.15 to I.21.

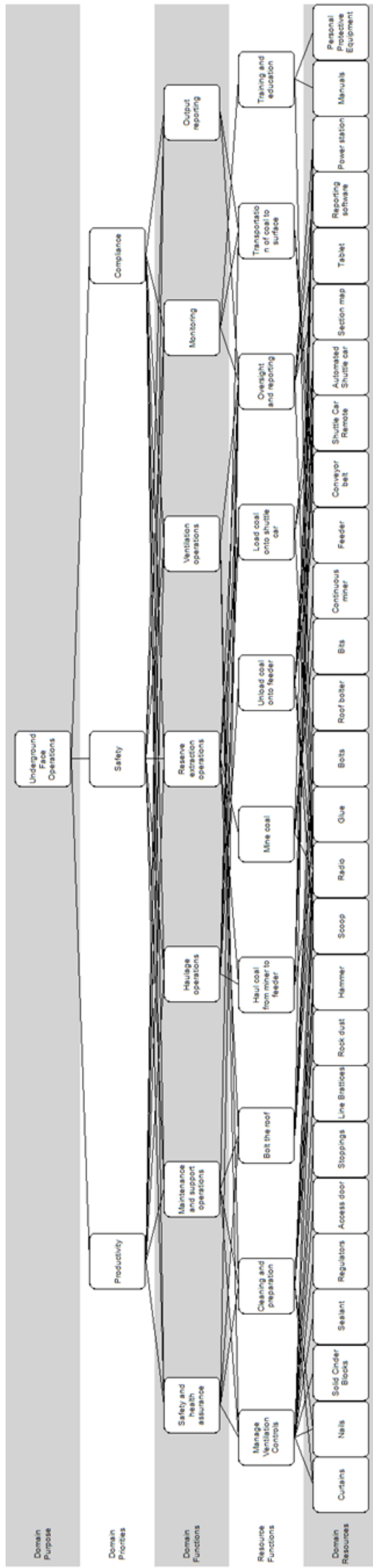

Figure I.5: Underground operations – abstraction hierarchy

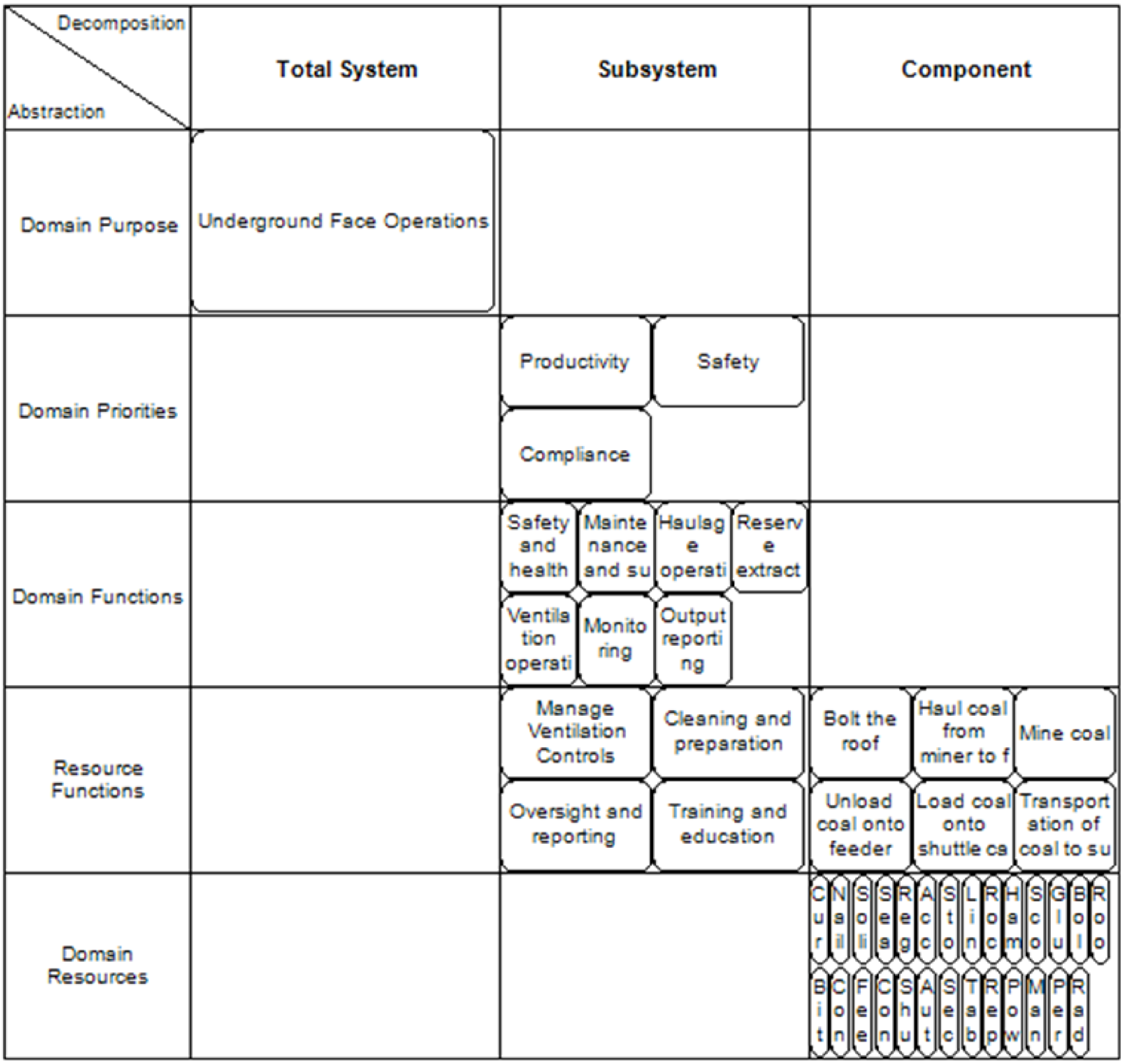

Figure I.6: Underground operations – decomposed abstraction hierarchy

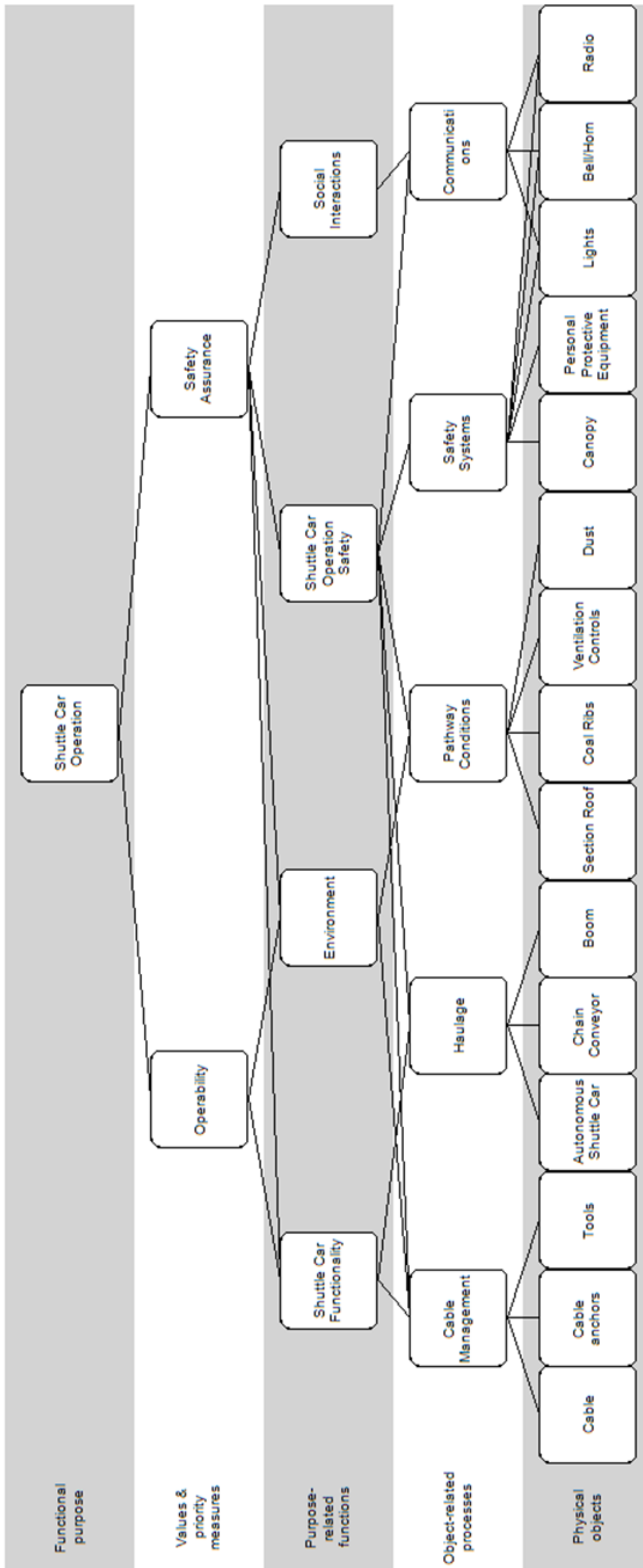

Figure I.7: Shuttle car operations – abstraction hierarchy

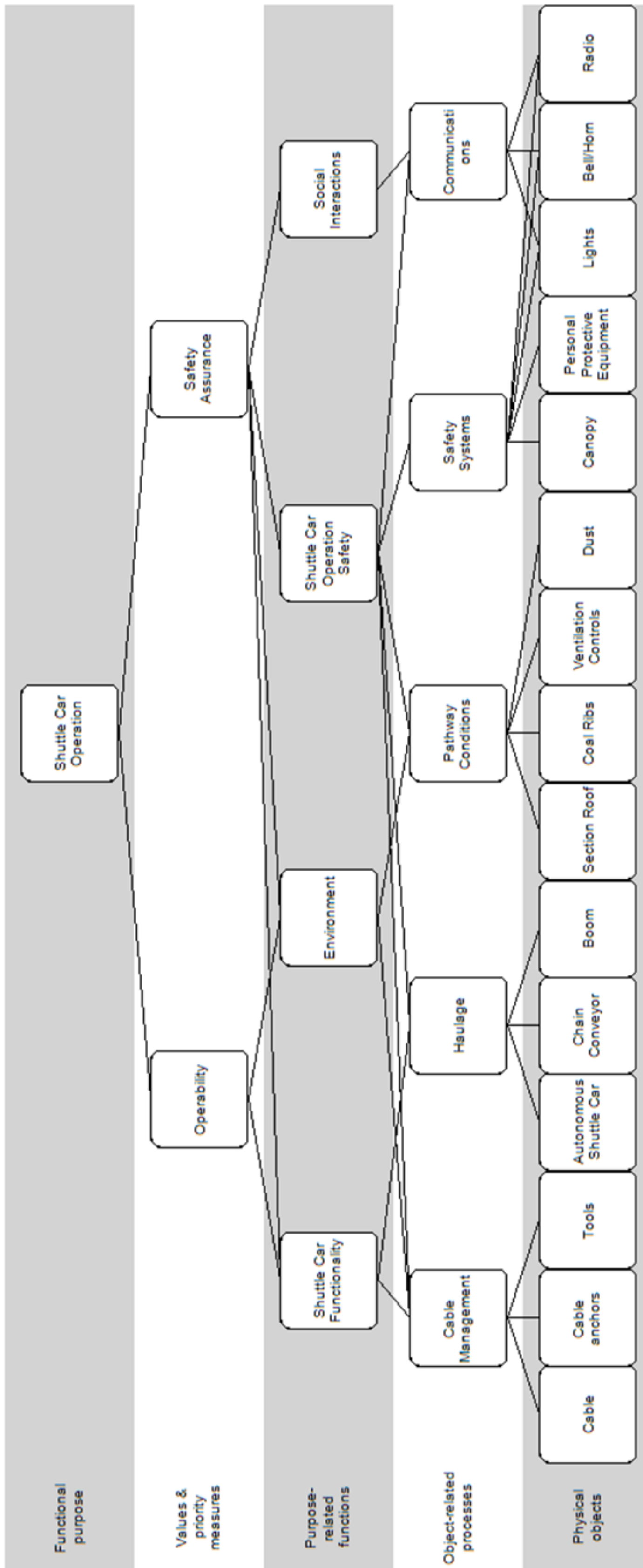

Figure I.8: Shuttle car pre-operations – abstraction hierarchy

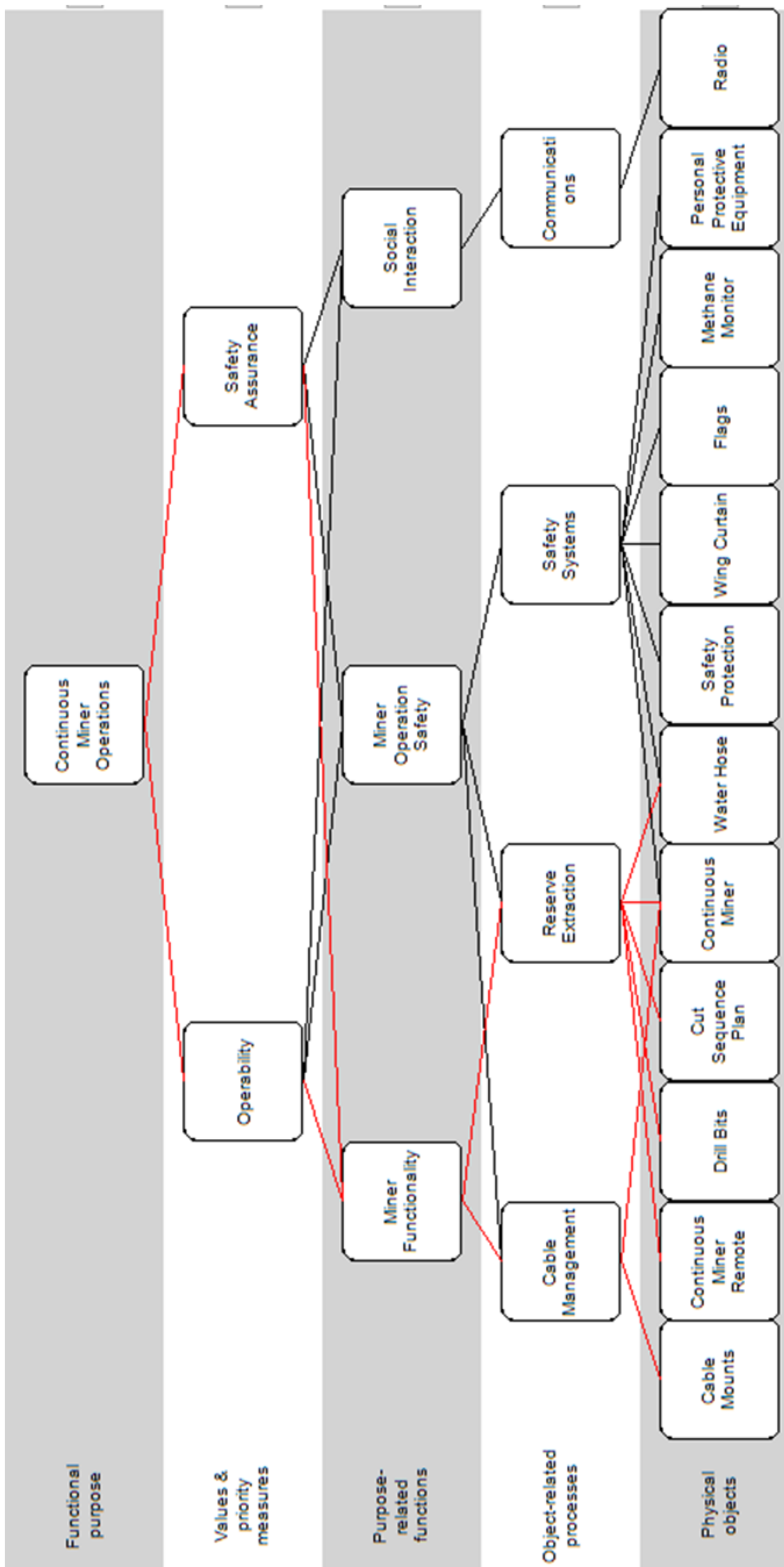

Figure I.9: Continuous miner operations – abstraction hierarchy

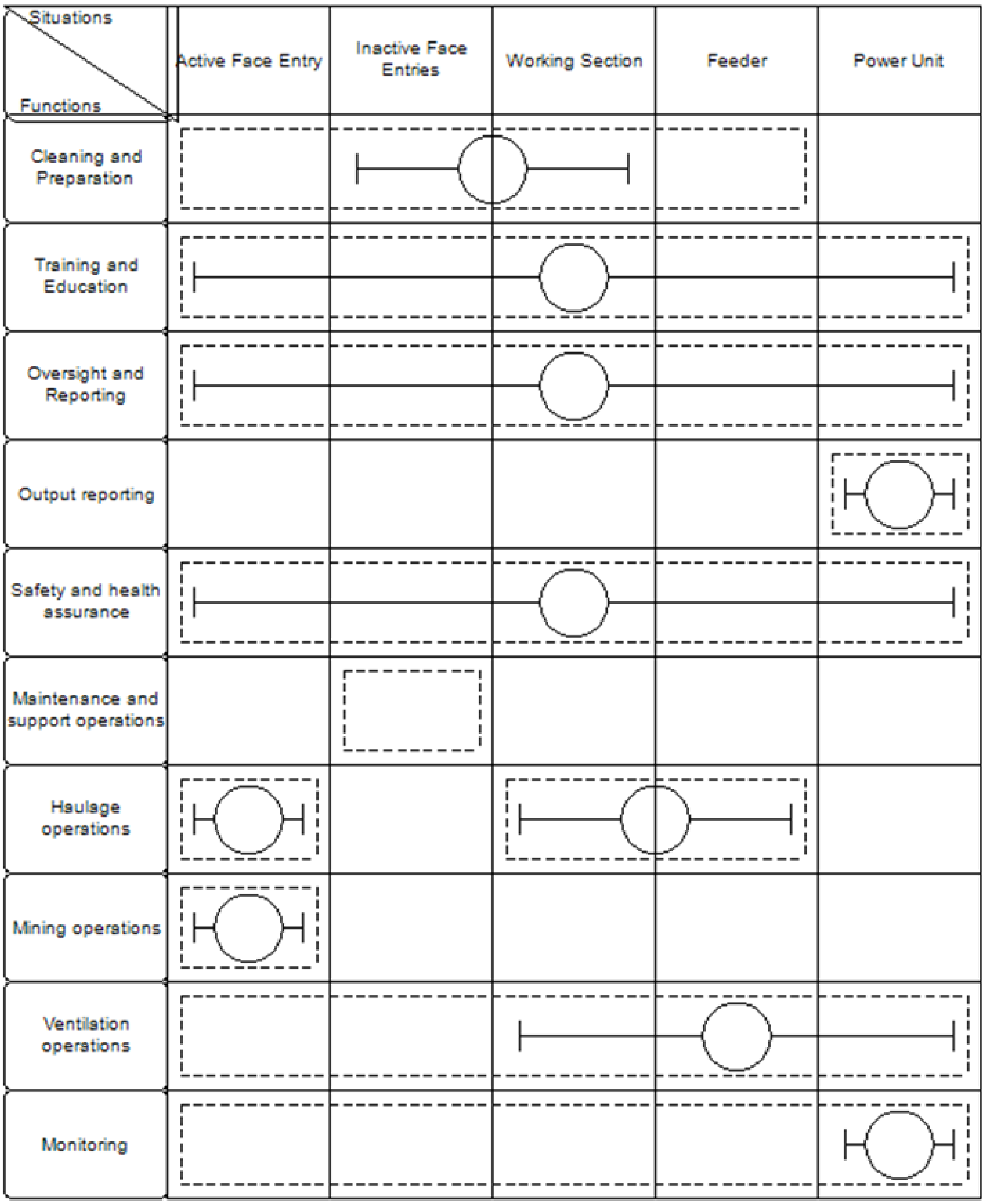

Figure I.10: Underground operations resource function by location – contextual activity template

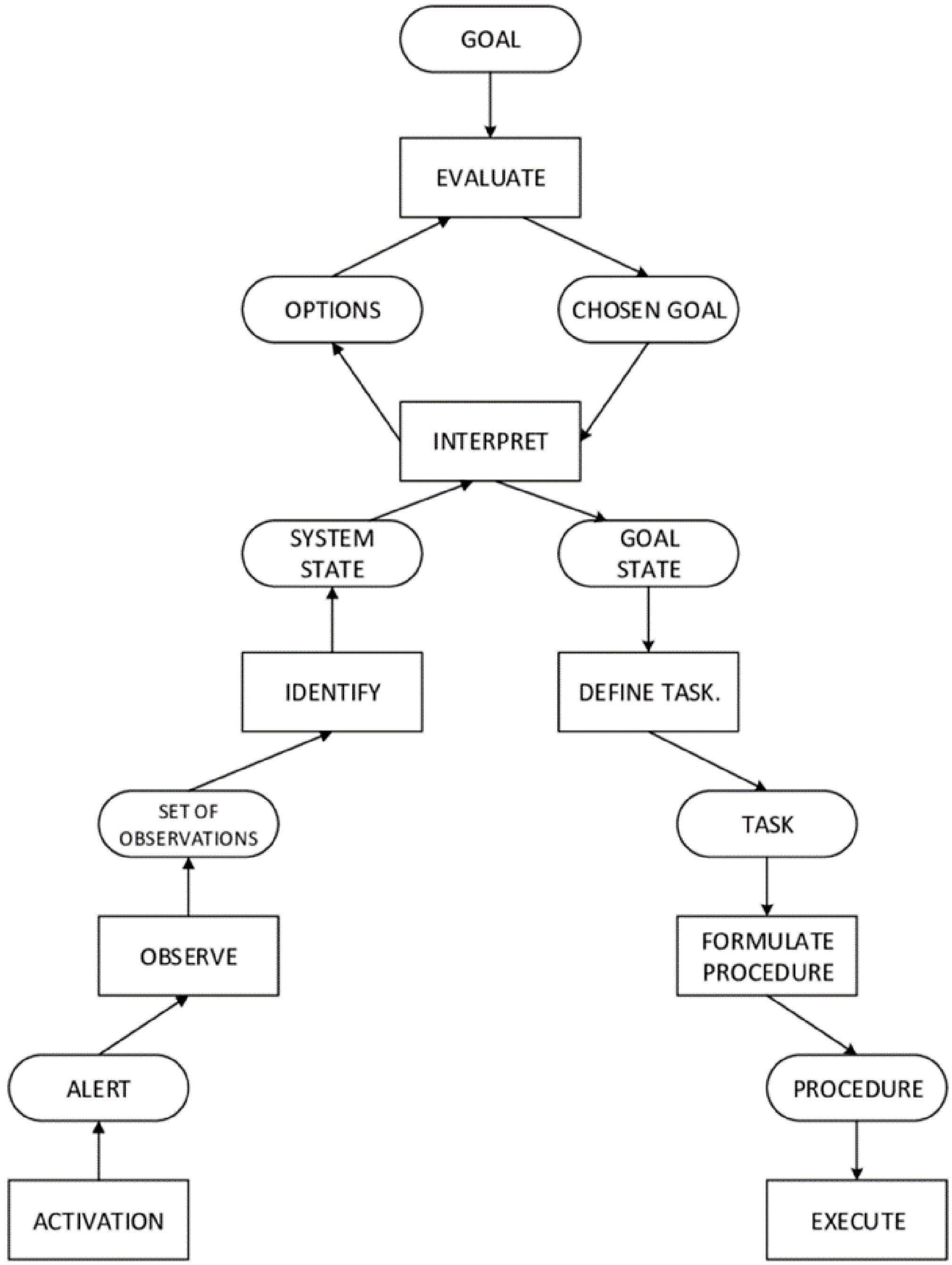

Figure I.11: Decision ladder - general flow

Figure I.12: Underground operations contextual activity template with decision ladders

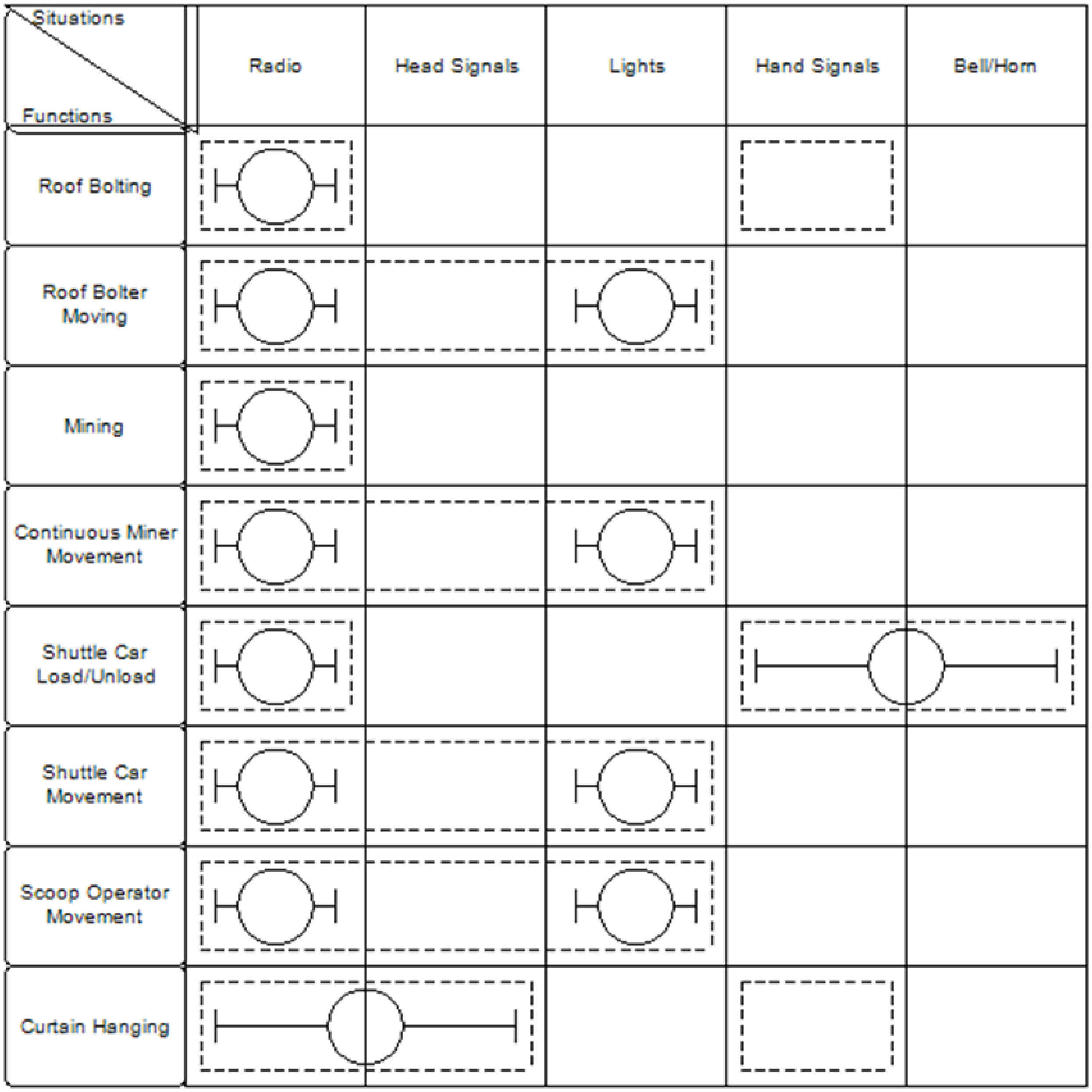

Figure I.13: Resource function by communication type – contextual activity template

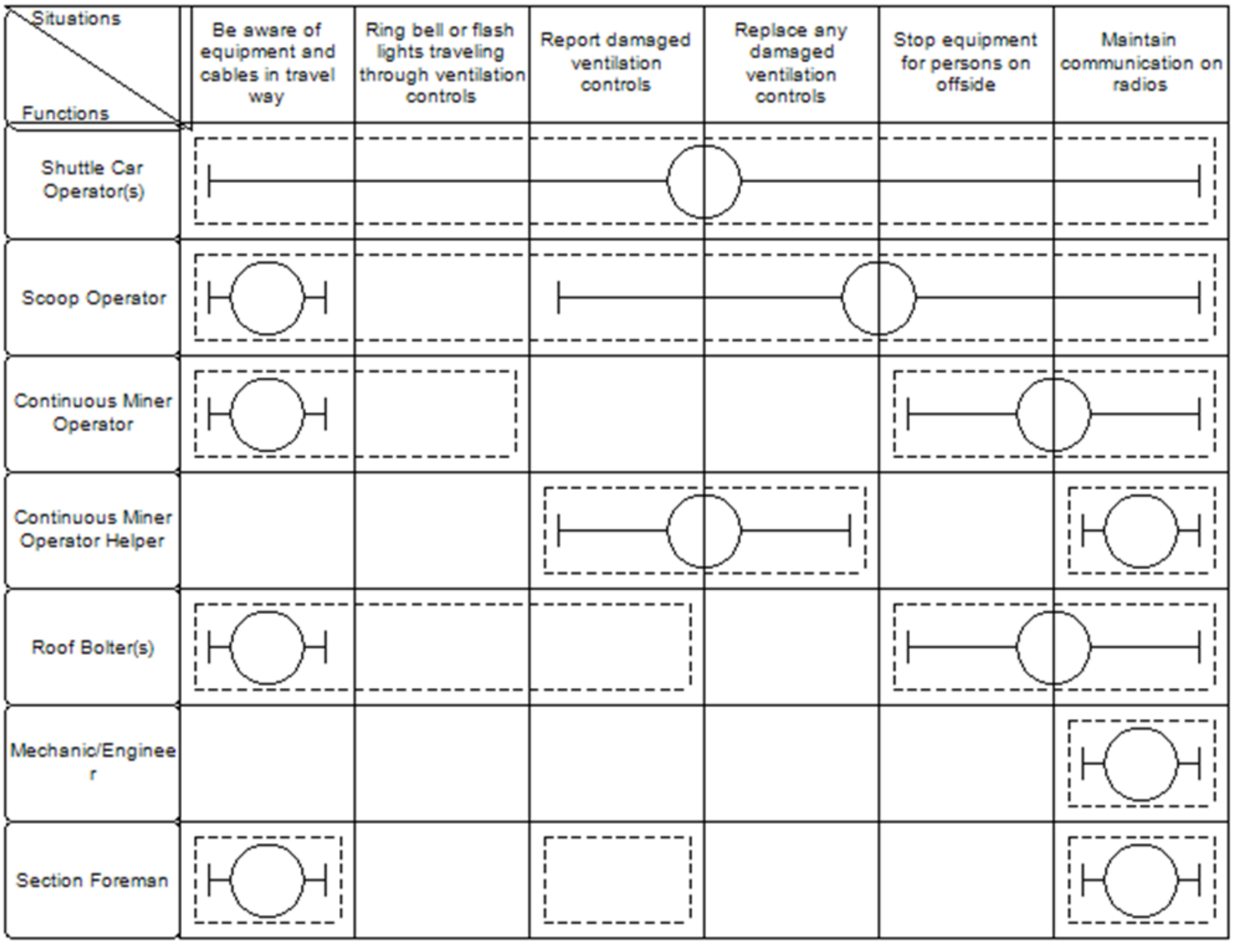

Figure I.14: Resource personnel by situational context – contextual activity template

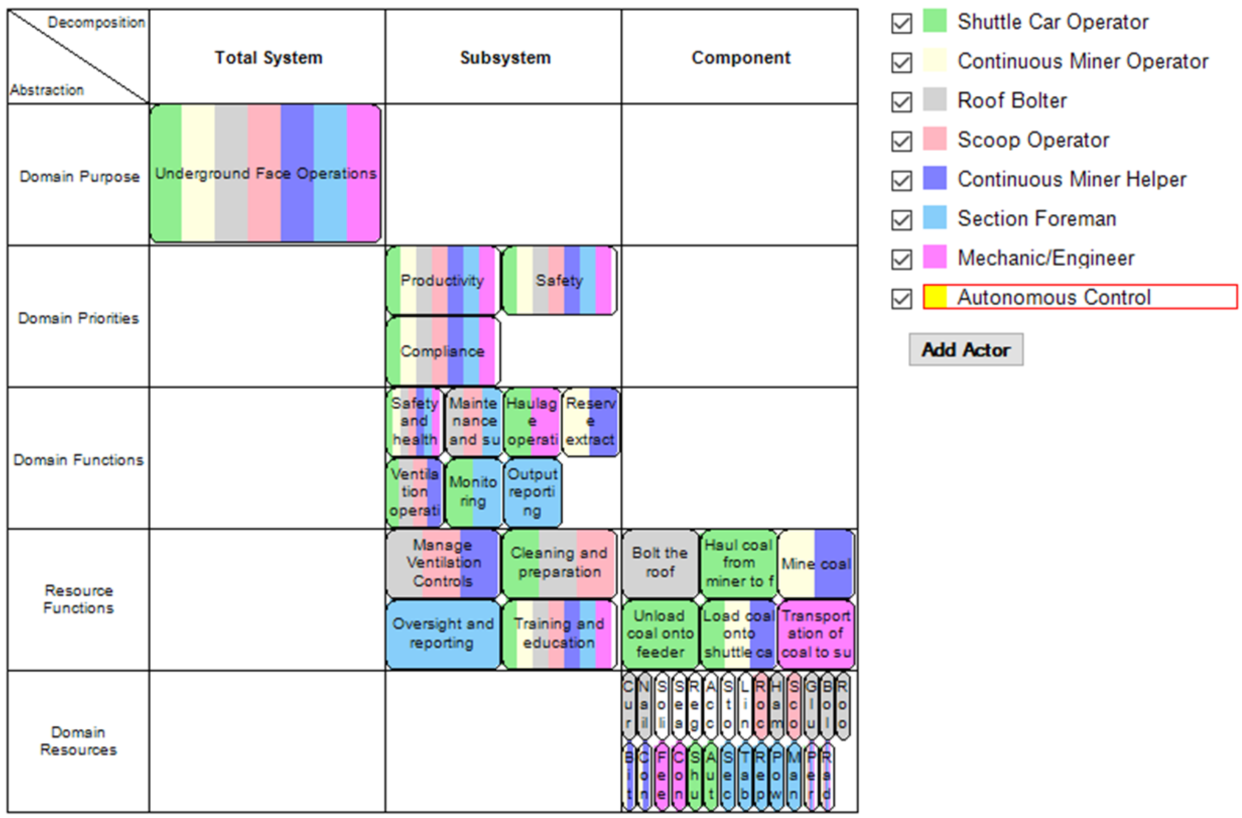

Figure I.15: Underground operations – decomposed abstraction hierarchy with personnel activities

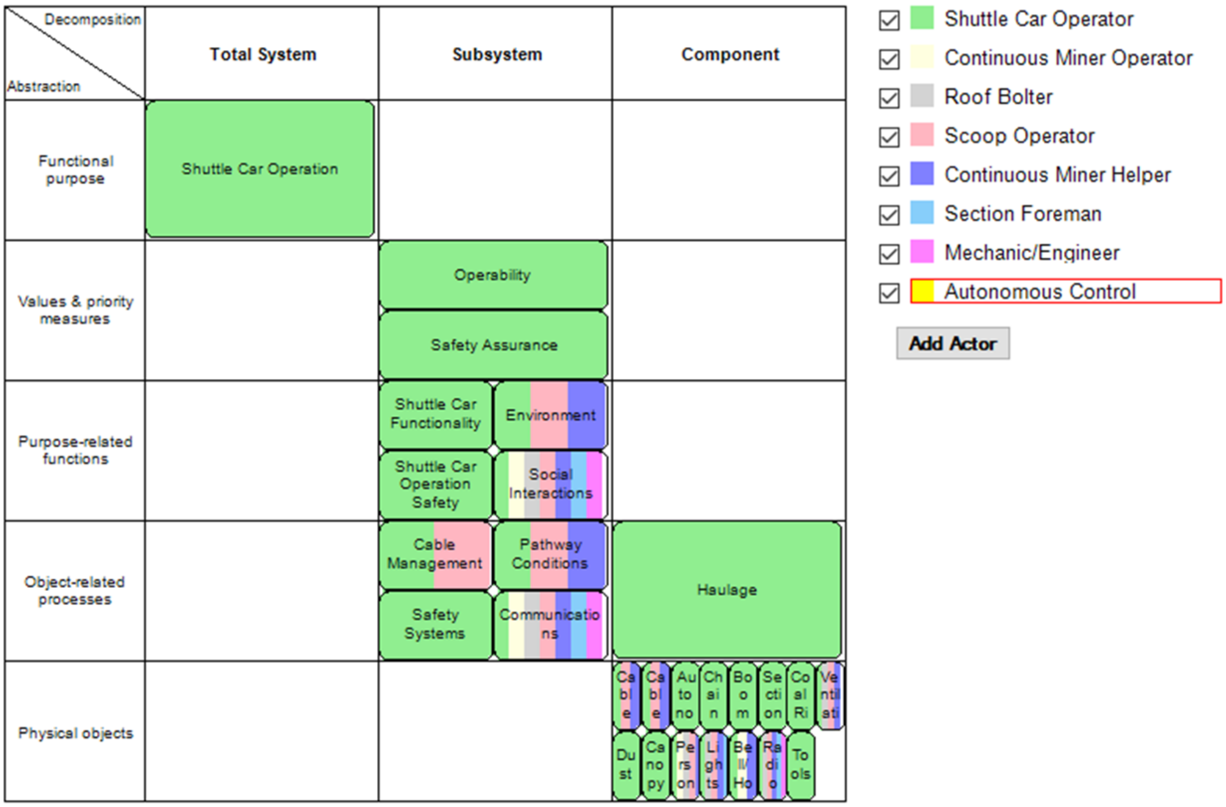

Figure I.16: Shuttle car operations – decomposed abstraction hierarchy with personnel activities

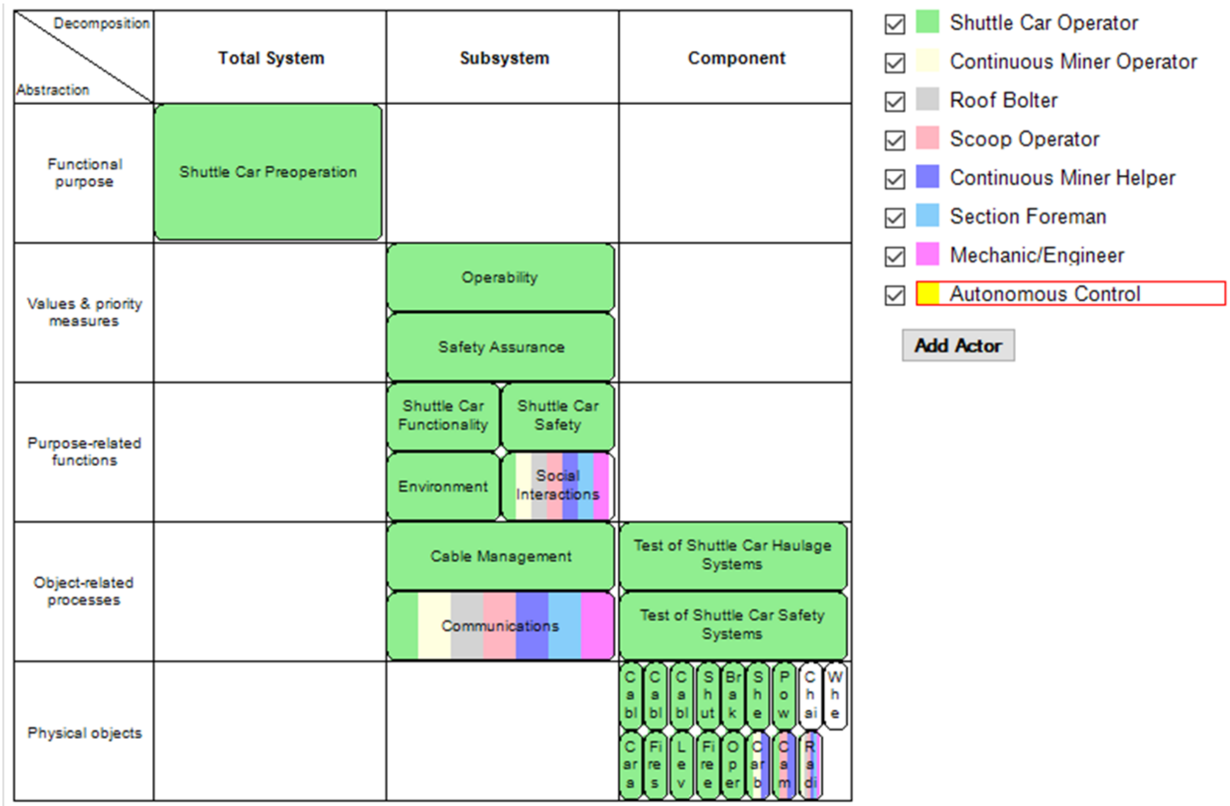

Figure I.17: Shuttle car pre-operations – decomposed abstraction hierarchy with personnel activities

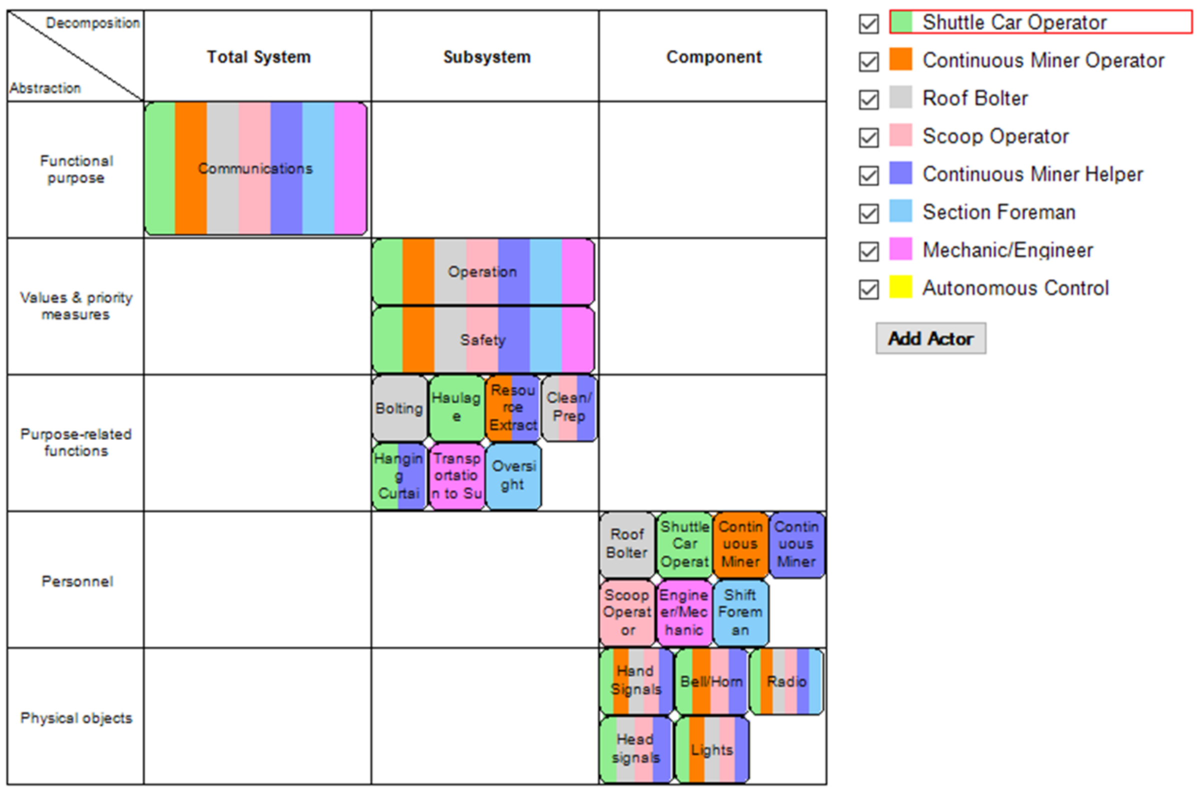

Figure I.18: Communications – decomposed abstraction hierarchy with personnel activities

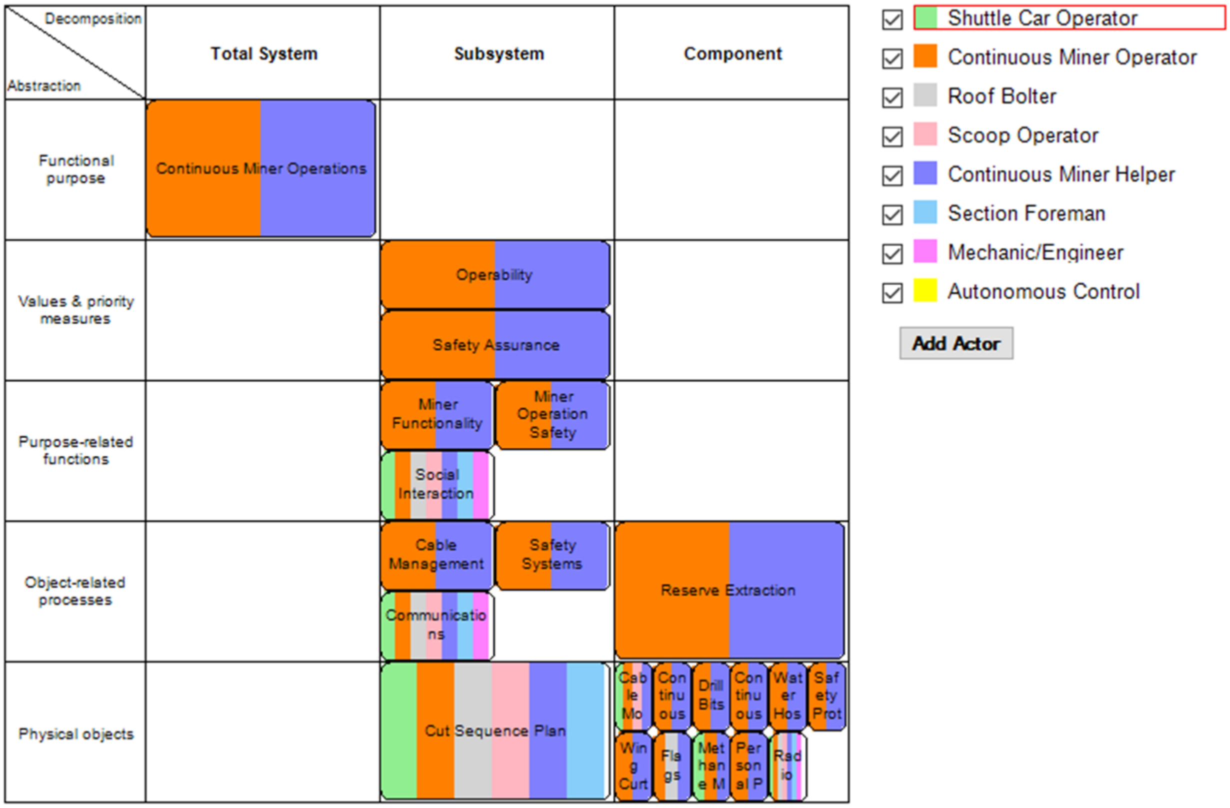

Figure I.19: Continuous miner operations – decomposed abstraction hierarchy with personnel activities

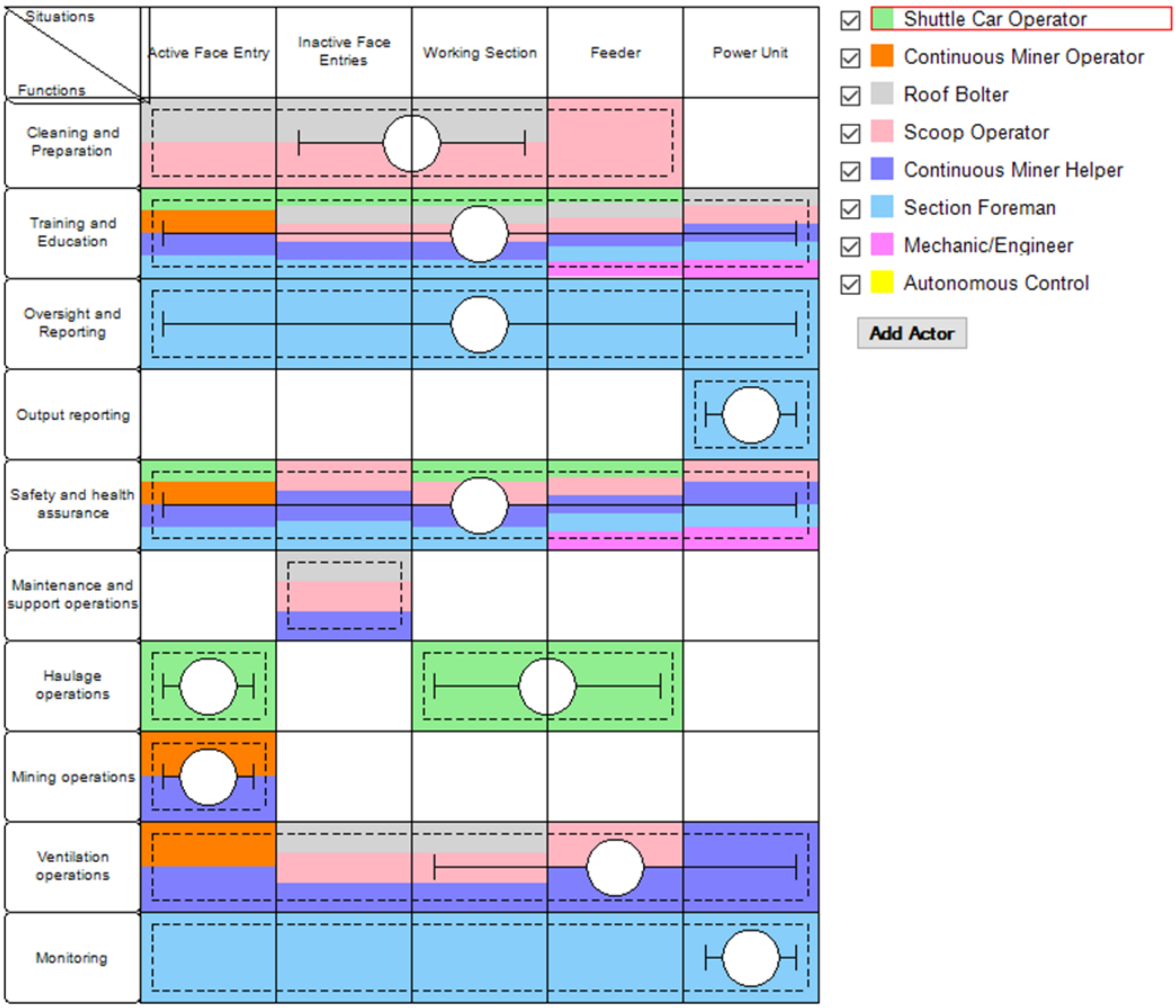

Figure I.20: Underground operations resource function by location and personnel activities

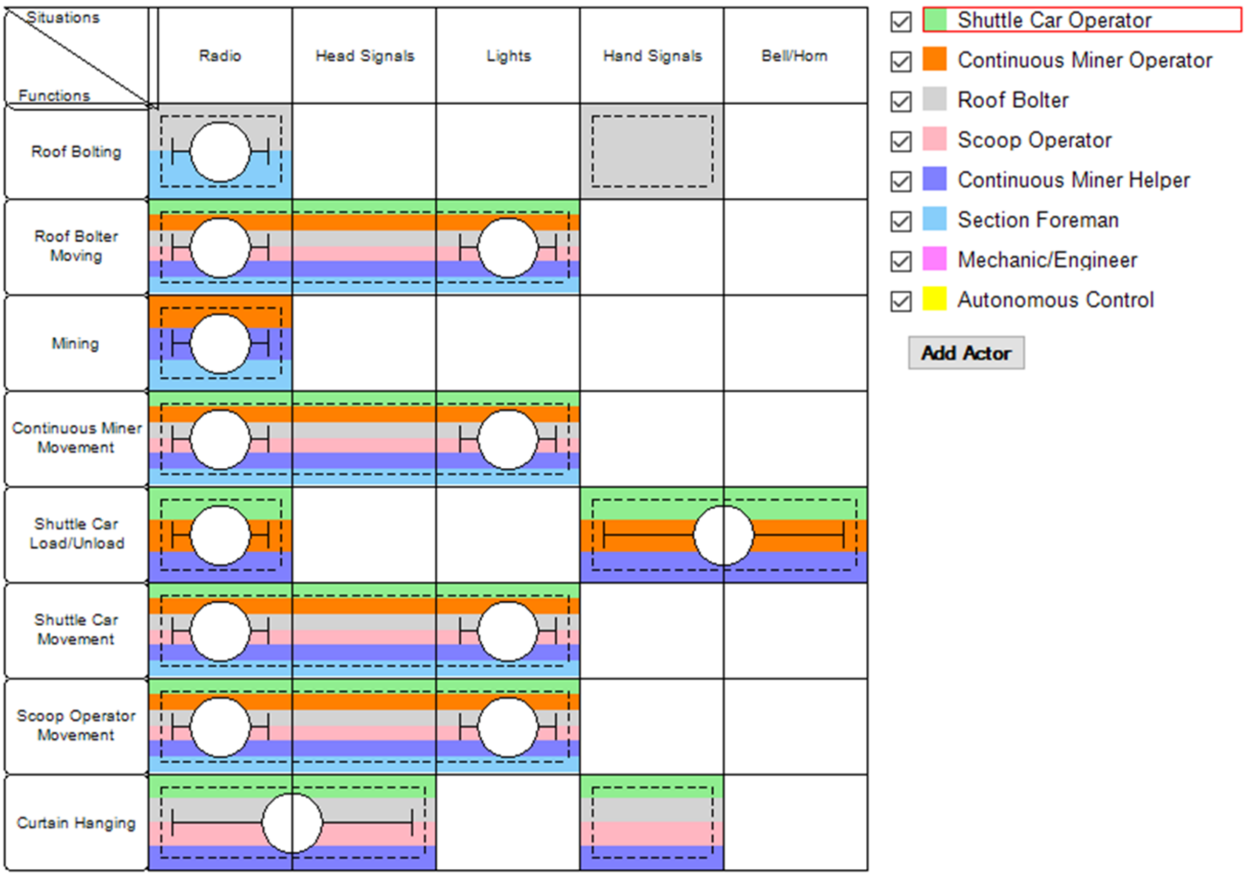

Figure I.21: Communications - resource function by communication type and personnel activities

I.8 Recommendations

The following section details the recommendations for the implementation of an autonomous shuttle car. This includes providing an overview of tasks that would be altered or reassigned, assumptions on how the autonomous shuttle car will work, and details regarding organizational or occupation impact. The following recommendations are not all-inclusive and some may also be irrelevant given unascertained assumptions of automation capabilities or other organizational or occupational limitations.

I.9 Task Reassignment

The introduction of an autonomous shuttle car will most significantly impact the functions of tramming, loading, and dumping. Other functions, such as pre-operational or end-of-shift activities, may be affected, but to a lesser degree. Task reassignment involves identifying work-oriented activities that are either altered for the shuttle car operator or other personnel, re-assigned to the shuttle car for functional purposes, or removed entirely from the breakdown of tasks. Further considerations or assumptions are required for altering or reassigning tasks, and are detailed in subsequent sections.

Tramming Task Reassignment

Tramming involves the haulage of the coal between the continuous miner at the active face and the feeder-breaker at the back of the section. The detailed task reassignments are described in Table I.3.

Loading Task Reassignment

Loading involves the loading of the coal from the continuous miner at the active face onto the bed of the shuttle car through use of a conveyor belt. The detailed task reassignments are described in Table I.4.

Dumping Task Reassignment

Dumping involves the dumping of the coal from the bed of the shuttle car into the feeder-breaker apron with the use of a conveyor and boom. The detailed task reassignments are described in Table I.5.

Table I.3: Reassignment of detailed tasks during tramming operations

Tasks Assigned to Shuttle Car	Tasks Altered for Personnel	Tasks Removed
• Sound audible alarm before tramming (voice or bell) • Depress tram pedal • Keep car centered in roadway • Make a turn traveling inby by lining up front tires with break corners and turning wheels left or right as hard as possible • Make a turn traveling outby by lining up boom end tires with break corners and turning wheels left or right as hard as possible • Observe for persons and obstructions in travel ways • Ring bell or flash lights • Stop car for persons on offside of shuttle car • Traveling through ventilation controls/fly pads/curtains • Sound audible alarm • Flash lights • Operate at speed under which control of the shuttle car can be maintained	• Set directional switch • Start pump • Adjust tram speed using tram dial • Release park brake • Push button in (palm valve) • Check brake pressure • Check steering • Turn lights on in direction of travel • Replace any damaged ventilation controls • Be aware of other equipment and cables in travel ways	• Put seat belt on • Keep all body parts within the deck compartment • Clear persons out of shuttle car • Listen for anchor/slap • Use the first row of bolts off the rib to judge the positioning of car • Use existing tire tracks to judge position of car

Table I.4: Reassignment of detailed tasks during loading operations

Tasks Assigned to Shuttle Car	Tasks Altered for Personnel	Tasks Removed
• At the continuous miner, hold car over to the left rib • Avoid continuous miner cable and operator • Center the car (as much as possible) under boom • Turn shuttle car wheels toward continuous miner operator while loading (sitting under the boom) • Do not bump back of continuous miner • Ensure continuous miner operator is not near the load end of the shuttle car during loading • Change the direction of your lights • Ring bell • Tram to feeder-breaker • Operate at speed under which control of the shuttle car can be maintained	• Tram to continuous miner • Observe roof over continuous miner operator for loose roof or ribs/Red Zones • Maintain communication with continuous miner operator • Watch the tail boom of the continuous miner and as coal builds up, run the chain to load car as evenly as possible without overloading/spilling • Stop loading coal within a foot of the end of boom • Listen for spillage • Observe for continuous miner operator signal when car is loaded • Observe second row of fully intact roof bolts • Be aware of other car switch out points and scoop activity	• N/A

Table I.5: Reassignment of detailed tasks during dumping operations

Tasks Assigned to Shuttle Car	Tasks Altered for Personnel	Tasks Removed
• Slow down • Center car on feeder-breaker • Position boom so coal drops in center of feeder-breaker • Dump load • Turn lights in direction travel • Sound audible alarm • Pull off the feeder-breaker • Return to continuous miner	• Look for any activity around feeder-breaker • Make sure feeder-breaker is on prior to dumping • Lower boom • Raise boom as coal load is dumped • Slow down dumping when discharging rock to allow the crusher ample processing time • Report excessive spillage to supervisor • Look and listen for unusual sounds, smells in the feeder-breaker area	• N/A

I.10 Organizational Impact

The tasks that significantly alter other members of the section crew are presented in these recommendations. The impact that the introduction of automation has is detailed by the task, along with strategies for coping with, solving, or altering personnel or machinery functionality to manage the identified task changes. The recommendations are presented in Table I.6.

Table I.6: Recommendations

Task	Status	Automation Impact	Strategies
Training crew members on interactions with autonomous shuttle car	New Task	Introducing an autonomous shuttle car will impact the means of tramming, loading, dumping, and communicating.	(i) Create training material for section crew members on how to interact with autonomous shuttle car (ii) Create training material for shuttle car operators on interacting with others using automated controls
Replace any damaged ventilation controls	Existing Task	Shuttle Car Operators (SCO) will not know when ventilation controls have been damaged or knocked down	(i) Scoop Operators, Continuous Miner Helpers, or Section Foreman may play increasing role in observing ventilation controls (ii) Incorporating shuttle car camera displays into the remote will allow SCOs to note damaged ventilation controls
Observe roof over continuous miner operator for loose roof or ribs/Red Zones	Existing Task	SCO will not be in car to observe roof or ribs en route or in Red Zones	(i) Scoop Operator or Continuous Miner Helper may play larger role in identifying environmental hazards (ii) Continuous Miner Operator (CMO) or Continuous Miner Helper may communicate with SCO that vehicle is in appropriate spot (iii) Red Zones may be adjusted to compensate for driver-less shuttle car

Continued on next page

Task	Status	Automation Impact	Strategies
Watch the tail boom of the continuous miner and as coal builds up, run the chain to load car as evenly as possible without overloading/spilling	Existing Task	SCO will not be in car or at continuous miner to manage coal loading	(i) CMO or Continuous Miner Helper may communicate with SCO for car loading (ii) Continuous Miner Helper may assist with controls on shuttle car for loading (iii) SCO may be stationed at continuous miner to observe car loading
Stop loading coal within a foot of the end of boom	Existing Task	SCO will not be in car or at continuous miner to manage coal loading	(i) CMO or Miner Helper may communicate with SCO for car loading (ii) Continuous Miner Helper may assist with controls on shuttle car for loading (iii) SCO may be stationed at continuous miner to observe car loading (iv) Sensors (e.g. weight) may indicate to SCO that bed is full
Listen for spillage	Existing Task	SCO will not be in car or at continuous miner to listen for spillage	(i) CMO or Continuous Miner Helper may listen or watch for spillage and communicate with SCO (ii) Continuous Miner Helper may assist with controls on shuttle car for loading (iii) SCO may be stationed at continuous miner to observe car loading and look for spillage (iv) Sensors (e.g. ultrasonic) may assist in recognizing excess coal spillage

Continued on next page

Task	Status	Automation Impact	Strategies
Equipment or pedestrian maneuvering around with autonomous shuttle cars active	Existing Task	SCO will not be in shuttle car for direct communication or observation of pedestrians or hazards	(i) Maintain constant communication through radios when moving equipment (ii) SCO can be provided access to shuttle car camera displays through cable connections (iii) Additional proximity sensors on personnel to account for pedestrians (iv) Additional proximity sensors on moving equipment to account for other heavy machinery (v) Automation sensors can provide feedback to SCO on unusual activity

Organizational Impact in CWA

The impact on the underground operations with the inclusion of an autonomous shuttle car is represented in the abstraction hierarchy in Figure I.22. The decomposed abstraction hierarchy is shown in Figure I.23, and Figure I.24 displays the decomposed abstraction hierarchy by personnel or machine role. The impact of autonomous control of a shuttle car is demonstrated across these CWA analyses.

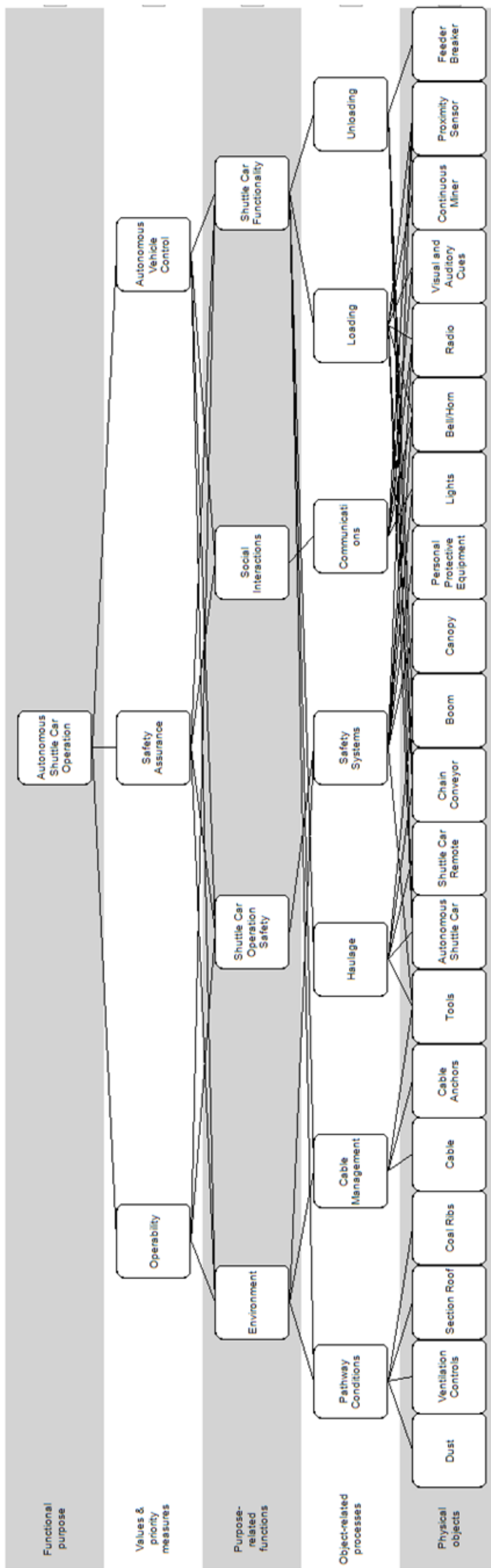

Figure I.22: Abstraction hierarchy of underground operations with an autonomous shuttle car

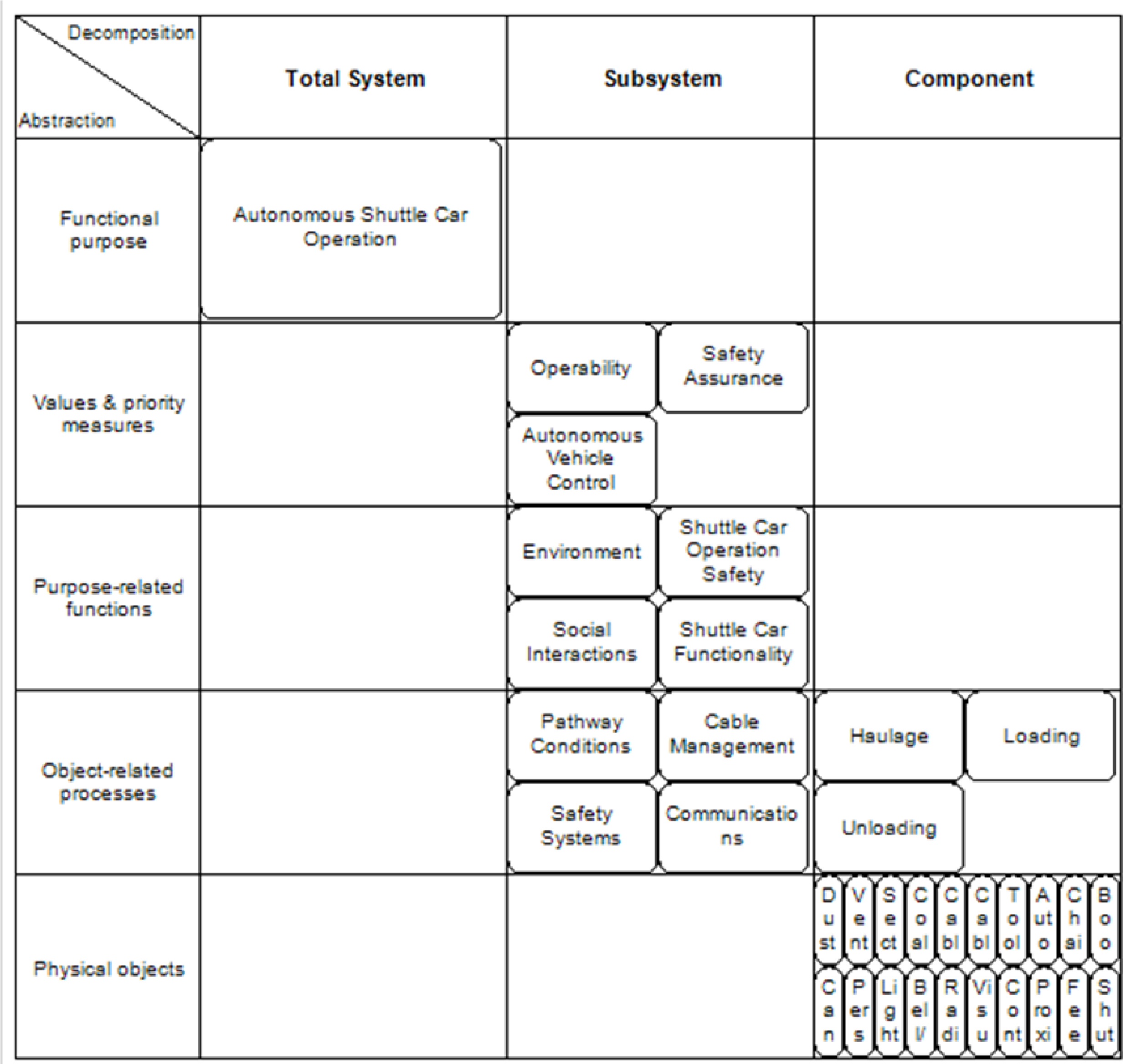

Figure I.23: Decomposed abstraction hierarchy of underground operations with an autonomous shuttle car

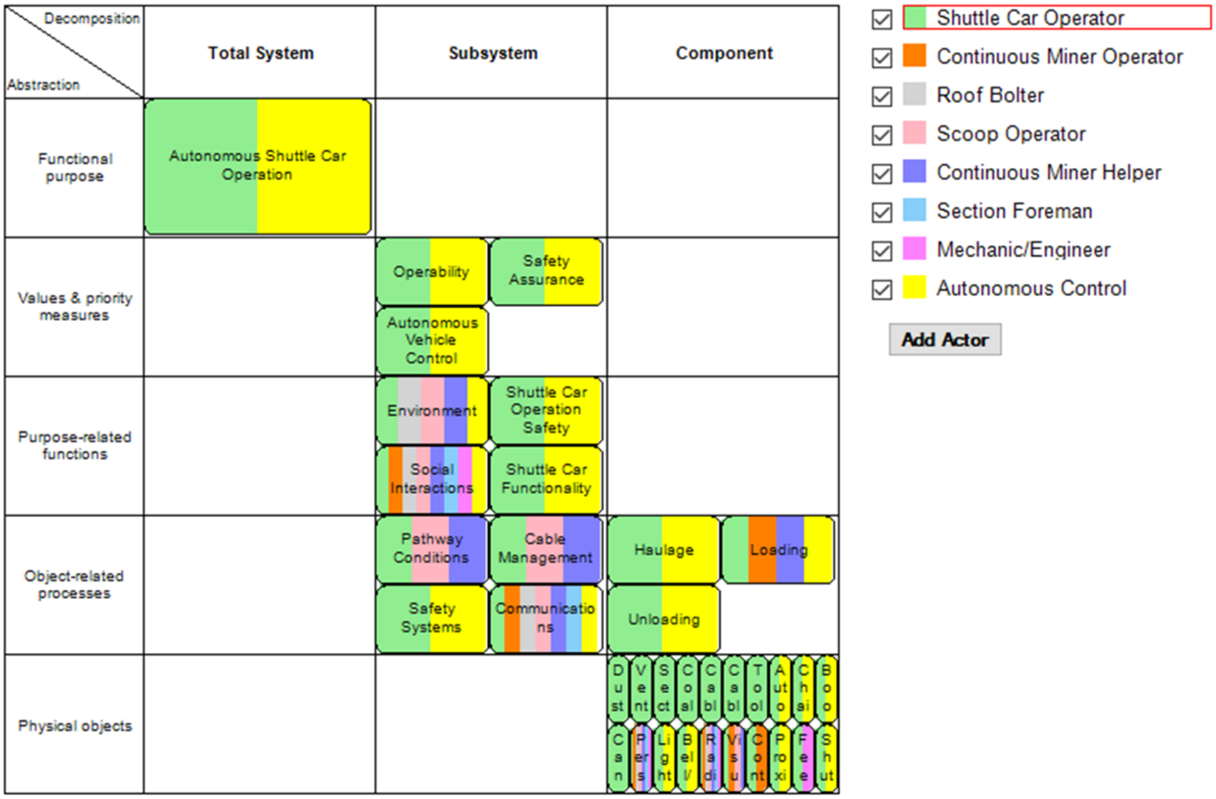

Figure I.24: Decomposed abstraction hierarchy of underground operations with an autonomous shuttle car with personnel and machine activities

I.11 Shuttle Car Role Impact

The tasks that significantly alter the shuttle car operator's role are presented in these recommendations. The impact that the introduction of automation has is detailed by the task, along with strategies for coping with, solving, or altering personnel or machinery functionality to manage the identified task changes. The recommendations are given in Table I.7.

Table I.7: Recommendations

Task	Status	Automation Impact	Strategies
Training on equipment	New Task	Introducing an autonomous shuttle car will impact the means of tramming, loading, dumping, and communicating.	Create training material for shuttle car operators on automation controls, remote functionality, maintenance, controlling, and emergency procedures
Be aware of other car switch out points and scoop activity	Existing Task	SCO may be unaware of other vehicle activities	(i) Radio communication between section crew (ii) All connected shuttle car activities may be reported through the shuttle car remote including status, current path, location, and speed (iii) Scoop operator may alter typical behaviors when tramming in or around active haulage paths
Look for any activity around the feeder-breaker	Existing Task	SCO may not be in car or at feeder-breaker to identify activity	(i) Mechanic, scoop operator, or Continuous Miner Helper may communicate activity with SCO (ii) Mechanic or section foreman may assist with controls on shuttle car for dumping activities (iii) SCO may be stationed at feeder-breaker to observe car dumping operations (iv) SCO may be able to monitor activity at feeder-breaker remotely through cameras or other sensors

Continued on next page

Task	Status	Automation Impact	Strategies
Make sure feeder-breaker is on prior to dumping	Existing Task	SCO may not be in car or at feeder-breaker to identify active feeder	(i) Communication with Mechanic or section foreman to ensure feeder is on (ii) Station SCO at feeder-breaker to observe dumping activities
Slow down dumping when discharging rock to allow the crusher ample processing time	Existing Task	SCO may not be in car or at feeder-breaker to identify dumping activities	(i) Communication with Mechanic or section foreman to ensure feeder is on (ii) Station SCO at feeder-breaker to observe dumping activities
Look and listen for unusual sounds, smells in the feeder area	Existing Task	SCO may not be in car or at feeder-breaker to identify unusual sounds or smells	(i) Mechanic or other crew may listen or watch for spillage and communicate with SCO (ii) Mechanic may assist with controls on shuttle car for dumping (iii) SCO may be stationed at feeder-breaker to observe car dumping and attend to unusual activities (iv) Sensors (e.g., detectors) may assist in recognizing unusual smells

I.12 Communications

The tasks that significantly alter the communication that occur during operations are presented in these recommendations. The impact that the introduction of automation has is detailed by the task, along with strategies for coping with, solving, or altering personnel or machinery functionality to manage the identified task changes. The recommendations are given in Table I.8.

Table I.8: Recommendations for communications

Task	Status	Automation Impact	Strategies
Maintain communication with continuous miner operator (CMO)	Existing Task	SCO is removed from direct communication from continuous miner	(i) Radio communication between operators (ii) SCO can trigger audible alerts through controller (iii) CMO can trigger alert to SCO through controller
Sound audible alarm before tramming (voice or bell)	Existing Task	SCO is unable to ring bell or honk remotely when beginning to tram	(i) SCO can trigger audible alerts through controller (ii) SCO has ability to trigger bell, horn, or additional types of alerts (iii) Differing alert pitches or sounds between beginning and ending tramming
Observe for persons and obstructions in travel ways	Existing Task	SCO is unable to locate persons or obstacles when removed from the vehicle	(i) SCO can be provided access to shuttle car camera displays through cable connections (ii) Additional proximity sensors on personnel to account for pedestrians (iii) Automation sensors can provide feedback to SCO on unusual activity (iv) Automation sensors can alter behavior based on obstructions in travel way
			Continued on next page

Task	Status	Automation Impact	Strategies
Traveling through ventilation controls, sound audible alarm	Existing Task	SCO is unable to locate ventilation controls or obstacles when removed from the vehicle	(i) SCO can trigger audible alerts through controller (ii) SCO can be provided access to shuttle car camera displays through cable connections (iii) Automation sensors can provide feedback to SCO on ventilation controls (iv) Autonomous shuttle car can recognize and sound alert on its own accord (v) Continuous audible alert can be present during tramming on autonomous shuttle car
Observe for continuous miner operator signal when car is loaded	Existing Task	SCO is removed from direct communication from continuous miner	(i) Radio communication between operators (ii) CMO can trigger alert to SCO through controller
AV Stop work when signaled by pedestrian	New Task	SCO is removed from direct communication of pedestrians	(i) Radio communication between operators (ii) Additional proximity sensors on personnel to account for pedestrians

I.13 Automated Vehicle Design

The tasks that determine autonomous shuttle car functionality are presented in these recommendations. The impact that the introduction of automation has is detailed by the task, along with strategies for coping with, solving, or altering personnel or machinery functionality to manage the identified task changes. The recommendations are given in Table I.9.

Table I.9: Recommendations for automated vehicle design

Task	Status	Automation Impact	Strategies
Depress tram pedal	Existing Task	SCO is not present in the vehicle to perform control-related duties	(i) SCO should be able to adjust tram speed remotely (ii) Shuttle car should be able to depress tram pedal electronically (iii) Shuttle car speeds may adjust automatically within the systems design to maximize efficiency while maintaining lower speeds and idle periods
Keep car centered in roadway	Existing Task	SCO is not present in the vehicle to perform control-related duties	(i) Shuttle car should recognize distances between coal ribs through sensors and move along the center of the roadway
Make a turn traveling inby by lining up front tires with break corners and turning wheels left or right as hard as possible	Existing Task	SCO is not present in the vehicle to perform control-related duties	(i) Shuttle car should be able to turn inby through location recognition using sensors to turn accordingly without SCO input
Make a turn traveling outby by lining up boom end tires with break corners and turning wheels left or right as hard as possible	Existing Task	SCO is not present in the vehicle to perform control-related duties	(i) Shuttle car should be able to turn outby through location recognition using sensors to turn accordingly without SCO input
At the continuous miner, hold car over to the left rib	Existing Task	SCO is not present in the vehicle to perform control-related duties	(i) CMO or Continuous Miner Helper may communicate with SCO for car loading and placement (ii) Continuous Miner Helper may assist with controls on shuttle car for loading and placement (iii) SCO may be stationed at continuous miner to observe car loading and placement

Continued on next page

Task	Status	Automation Impact	Strategies
Avoid continuous miner cable and operator; do not bump back of continuous miner	Existing Task	SCO is not present in the vehicle to perform control-related duties	(i) CMO or Continuous Miner Helper may communicate with SCO for car loading and placement (ii) Continuous Miner Helper may assist with controls on shuttle car for loading and placement (iii) SCO may be stationed at continuous miner to observe car loading and placement
Center the car (as much as possible) under boom	Existing Task	SCO is not present in the vehicle to perform control-related duties	(i) CMO or Continuous Miner Helper may communicate with SCO for car loading (ii) Continuous Miner Helper may assist with controls on shuttle car for loading (iii) SCO may be stationed at continuous miner to observe car loading
Turn shuttle car wheels toward continuous miner operator while loading (sitting under the boom)	Existing Task	SCO is not present in the vehicle to perform control-related duties	(i) SCO should be able to adjust wheels remotely (ii) Continuous Miner Helper may assist with controls on shuttle car for wheel placement (iii) SCO may be stationed at continuous miner to rotate wheels
Center car on feeder-breaker ; position boom so coal drops in center of feeder-breaker	Existing Task	SCO is not present in the vehicle to perform control-related duties	(i) Mechanic may communicate with SCO for car placement while dumping (ii) Mechanic may assist with controls on shuttle car for dumping (iii) SCO may be stationed at feeder-breaker to observe car loading

Continued on next page

Task	Status	Automation Impact	Strategies
Dump load	Existing Task	SCO is not present in the vehicle to perform control-related duties	(i) SCO should be able to operate chain conveyor and boom to dump load (ii) Shuttle car may register feeder-breaker point destination and automate dumping (iii) Mechanic may assist with controls on shuttle car for dumping (iv) SCO may be stationed at feeder-breaker to perform dumping operations

I.14 Operator-Interface Design

The tasks that significantly impact the interface or design elements of the operator controller are presented in these recommendations. The impact that the introduction of automation has is detailed by the task, along with strategies for coping with, solving, or altering machinery functionality to manage the identified task changes. The recommendations are given in Table I.10.

Table I.10: Recommendations for operator-interface design

Task	Status	Automation Impact	Strategies
Adjust tram speed using tram dial	Existing Task	SCO is not present in the vehicle to perform control-related duties	(i) SCO should be able to adjust tram speed remotely (ii) Shuttle car speeds may adjust automatically within the systems design to maximize efficiency while maintaining lower speeds and idle periods
Check brake pressure	Existing Task	SCO is not present in the vehicle to perform control-related duties	(i) Shuttle car brake pressure status should be available to driver remotely (ii) Additional camera set up on controls for SCO to monitor meters and gauges displayed on SCO controller

Continued on next page

Task	Status	Automation Impact	Strategies
Lower or raise boom	Existing Task	SCO is not present in the vehicle to perform control-related duties	(i) SCO should be able to adjust boom controls remotely (ii) SCO may engage boom controls in-vehicle during loading or dumping operations
Engage palm valve	Existing Task	SCO is not present in the vehicle to perform control-related duties	(i) SCO should be able to adjust pressure through palm valve remotely (ii) SCO may adjust pressure using palm valve when shuttle car is idle or at feeder-breaker or continuous miner
Engage or release park brake	Existing Task	SCO is not present in the vehicle to perform control-related duties	(i) SCO should be able to engage or release parking brake remotely (ii) SCO should know if the parking brake is engaged or disengaged remotely (iii) SCO may engage or release parking brake when shuttle car is idle or at feeder-breaker or continuous miner
Set directional switch	Existing Task	SCO is not present in the vehicle to perform control-related duties	(i) Shuttle car should recognize autonomous path and set direction switch accordingly (ii) SCO should be able to adjust shuttle car direction remotely (iii) Shuttle car may change direction according to SCO controlling entry or pathway navigation
Start pump	Existing Task	SCO is not present in the vehicle to perform control-related duties	(i) SCO should be able to start or stop pump remotely (ii) SCO may start or stop pump when shuttle car is idle or at feeder-breaker or continuous miner

Continued on next page

Task	Status	Automation Impact	Strategies
Turn lights on in direction of travel	Existing Task	SCO is not present in the vehicle to perform control-related duties	(i) SCO should be able to engage or disengage lights during operations for both directions (ii) Shuttle car may automatically engage lights when direction of travel is switched or it commences tramming from a stop

Prototype Shuttle Car Remote Design Elements

A preliminary supplemental prescriptive CWA was performed on the requirements of a prototype autonomous shuttle car remote for use by a shuttle car operator. This analysis demonstrates some of the necessary components on an autonomous shuttle car. The AH, decomposed AH, and decomposed AH with personnel and machine activities are detailed in Figure I.25, Figure I.26, and Figure I.27, respectively.

I.14.1 Prototype Operator-interface Design

Given the list of recommendations, a prototype control is displayed in Figure I.28. This design addresses a number of recommendations, including pathway navigation, control of vehicle, vehicle information, and crosscut. Further iterative designs will be created as a future task on the project.

I.14.2 Summary of Recommendations

A number of strategies were detailed addressing the shift in tasks from the shuttle car operator to the autonomous shuttle car and other members of the section crew. Certain work domain issues have critical importance relative to the safety and feasibility of incorporating automation.

Communications

Maintaining proper communications between all individuals in the section crew is a critical issue regarding the safety of all workers. Given that a number of available options to communicate between shuttle car operator and other individuals in the roadway would be removed due to automation, new measures must be taken to ensure safe travels. These measures may include increased and proper radio communication, increased auditory cues for shuttle tramming, and multiple fail-safes for individuals traveling in the shuttle car path.

Cable Management

Handling the cable and cable reel for the shuttle car while avoiding running over other heavy machinery cables will be critical with an autonomous shuttle car. Proper cable management will be key in preventing damage and avoiding hazards, including increased attention to cable hanging

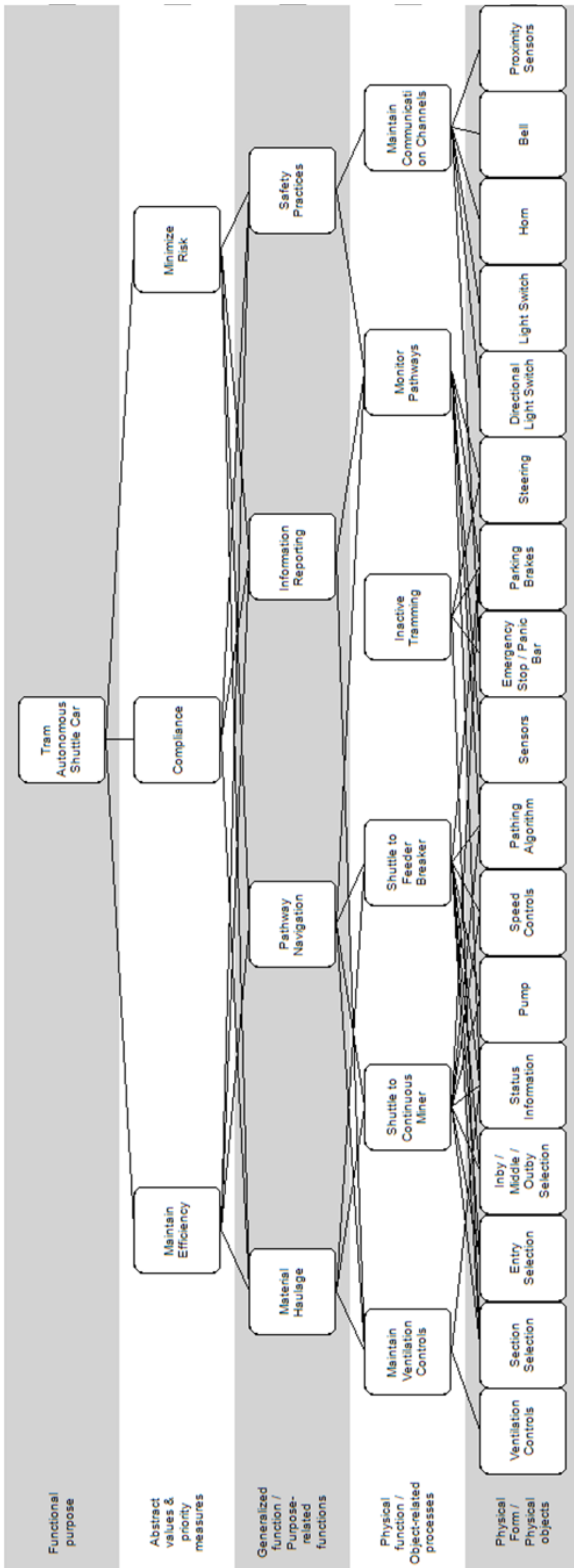

Figure I.25: Abstraction hierarchy of prototype autonomous shuttle car remote

Abstraction \ Decomposition	Total System	Subsystem	Component
Functional purpose	Tram Autonomous Shuttle Car		
Abstract values & priority measures		Maintain Efficiency Compliance Minimize Risk	
Generalized function / Purpose-related functions		Material Haulage Pathway Navigation Information Reporting Safety Practices	
Physical function / Object-related processes		Maintain Ventilation Controls Monitor Pathways Maintain Communication Channels	Shuttle to Continuous Miner Shuttle to Feeder Breaker Inactive Tramming
Physical Form / Physical objects		Status Information Pathing Algorithm Steering	Ventilati Section Entry Sel Inby / Mi Pump Speed Sensors Emergen Parking Direction Light Sw Horn Bell Proximit

Figure I.26: Decomposed abstraction hierarchy of prototype autonomous shuttle car remote

and anchoring, pathway navigation that incorporates proper cable reeling, and increased checks for cables in the roadway.

Interface Logistics

The means by which the shuttle car operator is able to remotely operate an autonomous shuttle car is critical in adoption of the technology. The remote needs to be functional, informative, and intuitive when considering the number of tasks that are reassigned from the shuttle car operator to the autonomous system. The remote system must incorporate enough detailed status information to remain reliable without a shuttle car operator in the vehicle.

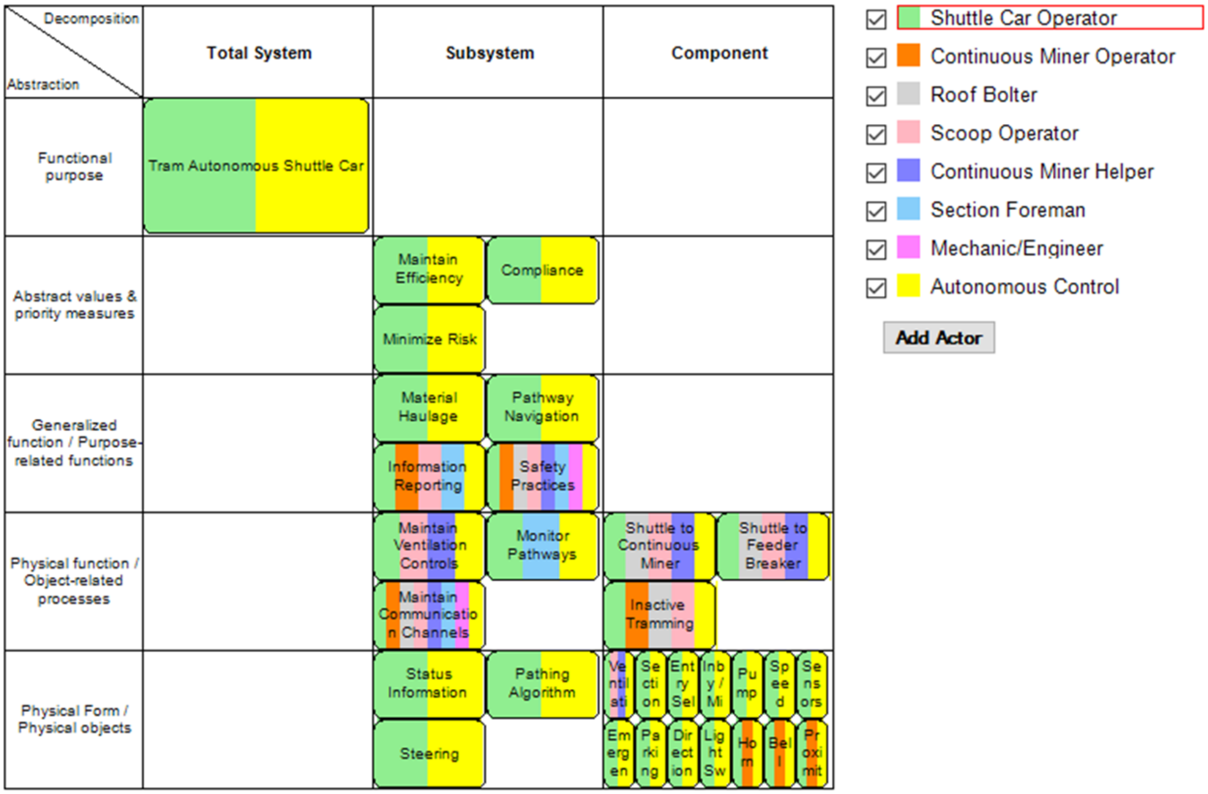

Figure I.27: Decomposed abstraction hierarchy of prototype autonomous shuttle car remote with personnel and machine activities

Ventilation Controls

Ventilation controls, both in the maintenance of and navigation through, provide a set of potential hazards for members of the section crew. Shuttle cars are often responsible for the knocking down of ventilation curtains. Without a shuttle car operator present in the vehicle it may be more challenging to identify when a curtain has been knocked down. Additionally, continuous miner operator helpers and scoop operators are commonly responsible for rehanging the curtains, frequently in the path of the shuttle car. Increased attention to communications and awareness of vehicle travel paths are critical in the safety of the section crew members.

Shuttle Car Operator Location

Given the high demand on the shuttle car operator at both the continuous miner and feeder-breaker for loading and dumping activities, it may be a necessity to station a shuttle car operator at both locations with the capability of controlling the shuttle car for placing it correctly, docking, and managing the chain conveyor and boom. This provides a challenge where shuttle car remote operators must be able to access controls for both shuttle cars, either through selection on the remote or automated selection given pathway navigation algorithms.

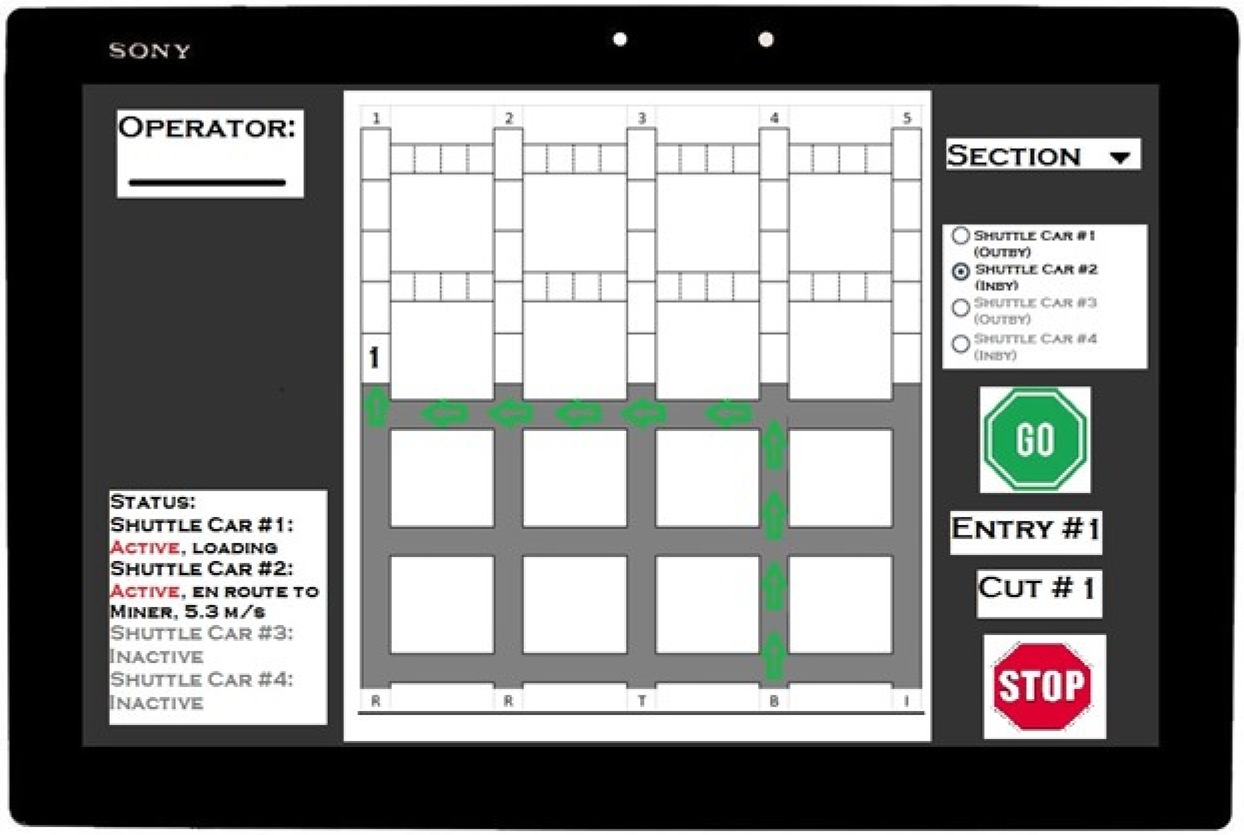

Figure I.28: Tablet-based prototype design of shuttle car operator's controller

I.15 Conclusions

Careful consideration is required when incorporating any automated system into an organization, and mining operations are no exception. The implementation of an autonomous shuttle car will have both immediate and lasting impacts on the organizational structure and functional systems within the operating mine. It is particularly important to understand the limitations of both vehicle automation and organizational systems when incorporating new technologies into a work domain with significant hazards. The recommendations created based on the work analyses may be used for designing and implementing a demonstration of an autonomous shuttle car in a room-and-pillar mine.

I.15.1 Work Analyses Results

The work analyses detail a comprehensive depiction of the current state of the underground mining operations at the partner mine. These include results from the industrial and organizational psychology domain of work analysis, which incorporates work-oriented activities and worker-oriented attributes, as well as results from the human factors and cognitive science domain of CWA, which depicts the constraints and systems that are present within the mining operations. These results are used as the basis for a set of recommendations for incorporating an autonomous shuttle car into the work domain space.

I.15.2 Recommendations

The outlined recommendations cover numerous occupational and organizational functions and address a number of concerns. However, they are not fully comprehensive. During the development of the autonomous shuttle car, continual changes may be made that may or may not align with recommendations outlined in this report.

I.16 Supplemental Cognitive Work Analysis Figures

Additional figures used in the CWA for underground operations are presented below.

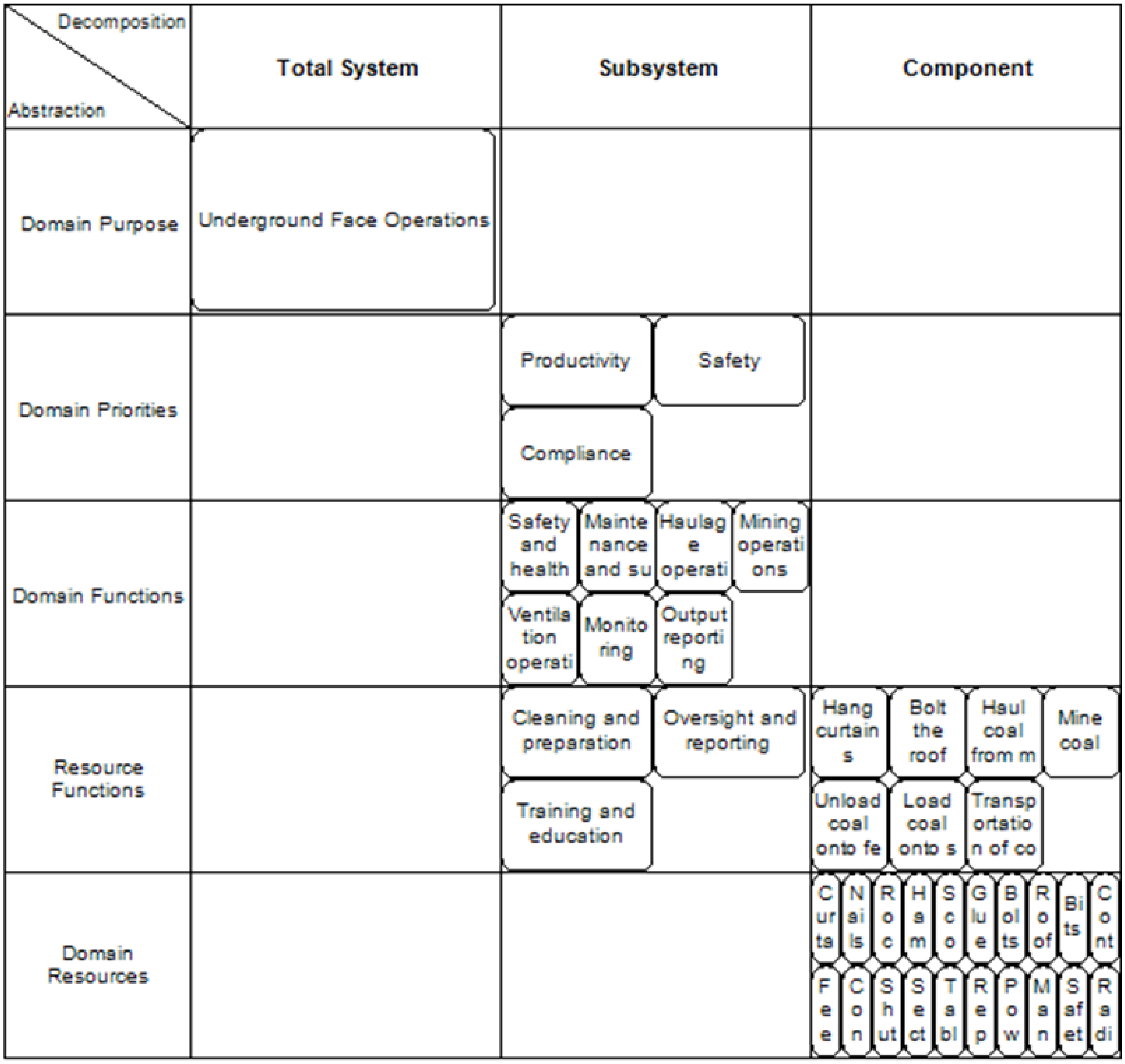

Figure I.29: Decomposed abstraction hierarch of underground face operations

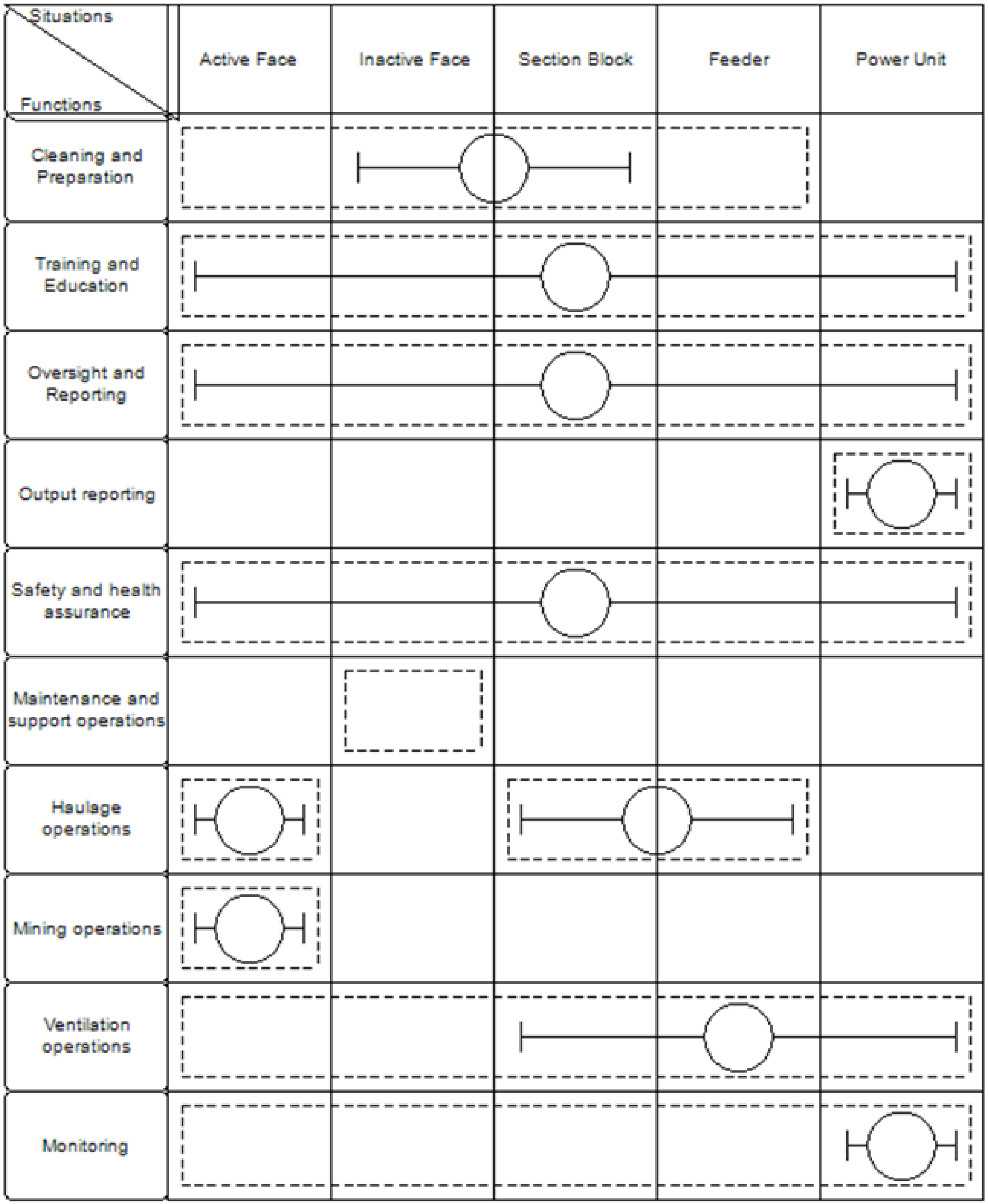

Figure I.30: Contextual activity template for worker role or function by area of operation

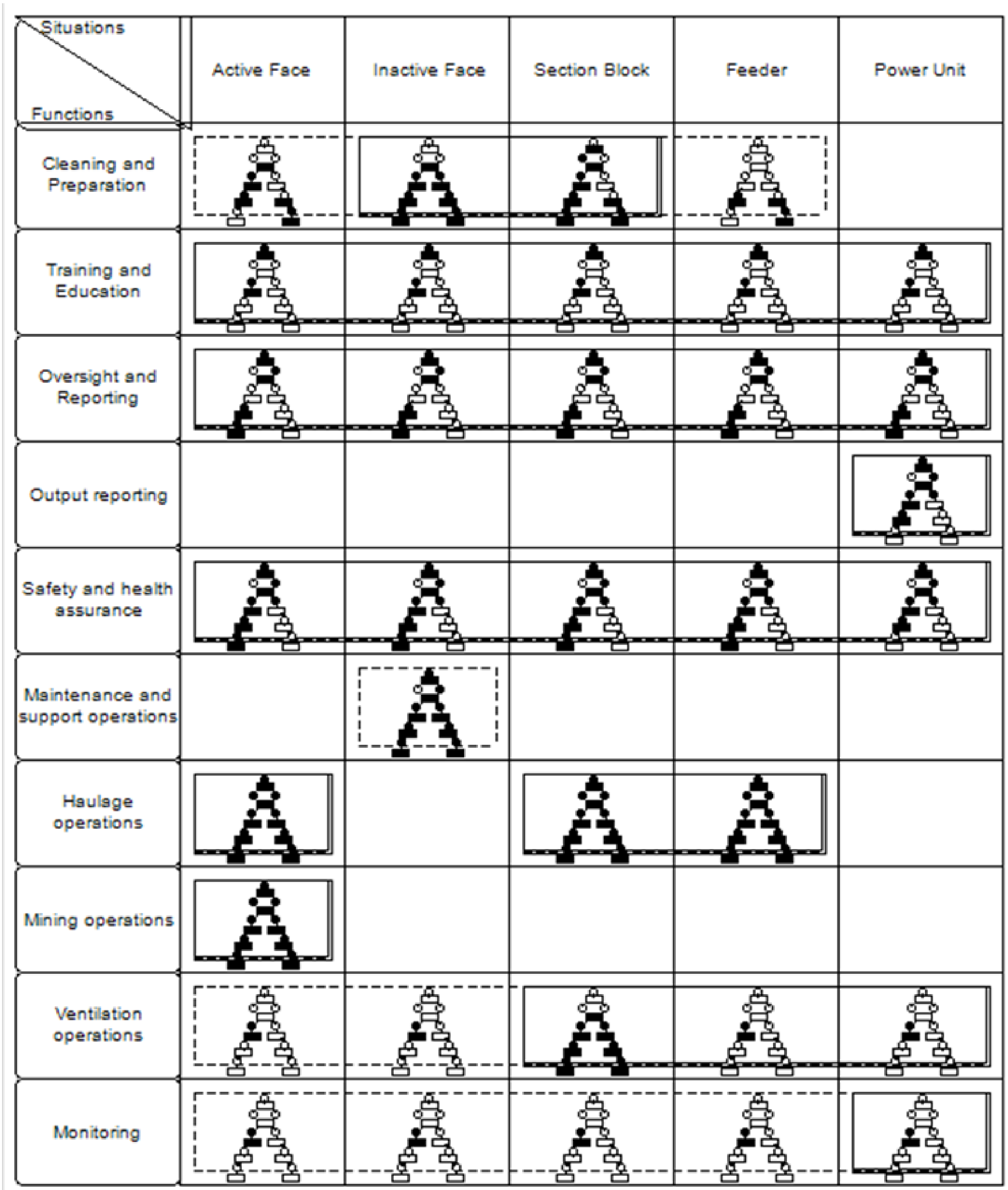

Figure I.31: Contextual activity template with decision ladders for worker role or function by area of operation

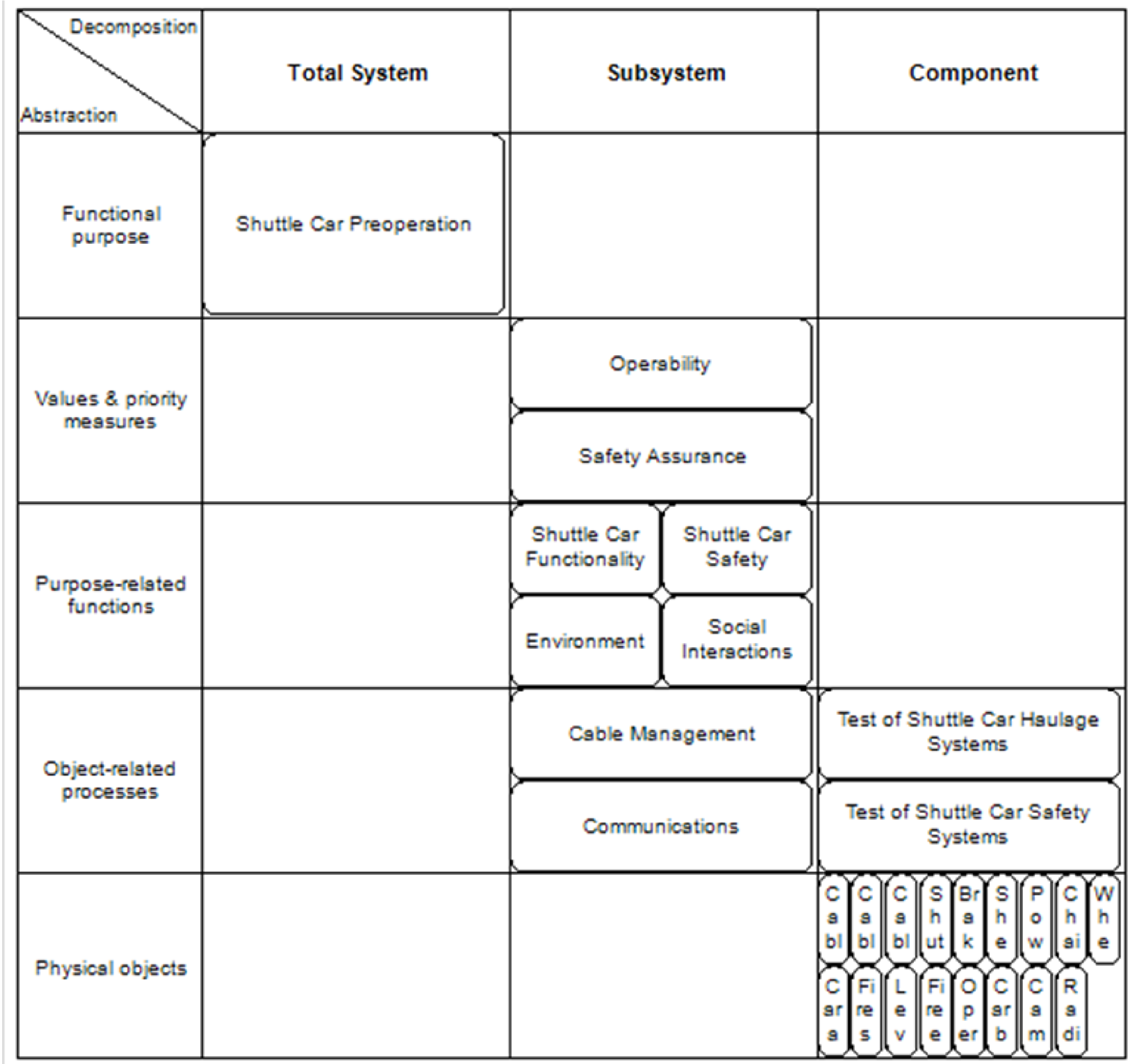

Figure I.32: Decomposed abstraction hierarchy of shuttle car pre-operations

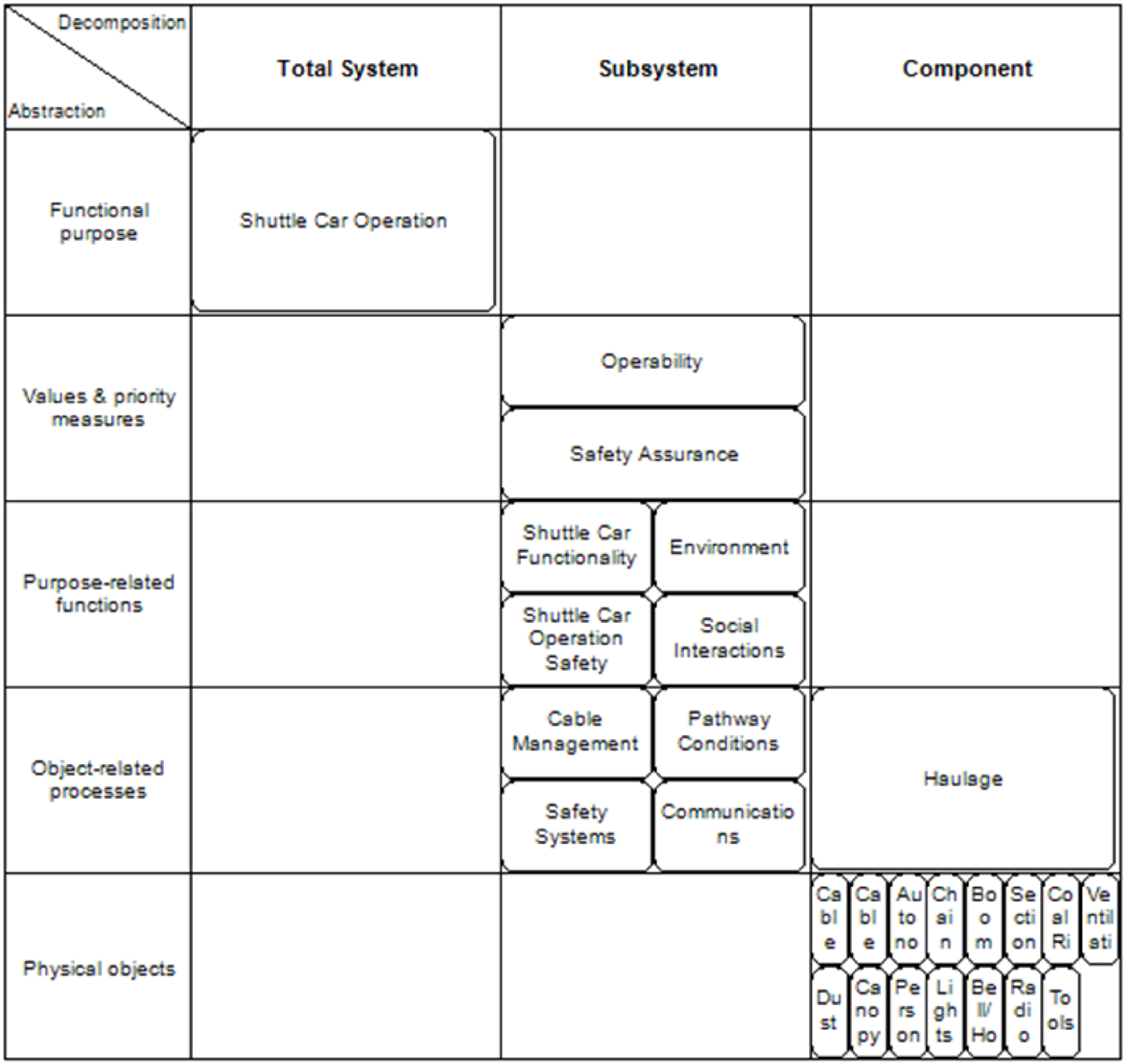

Figure I.33: Decomposed abstraction hierarchy of shuttle car operations

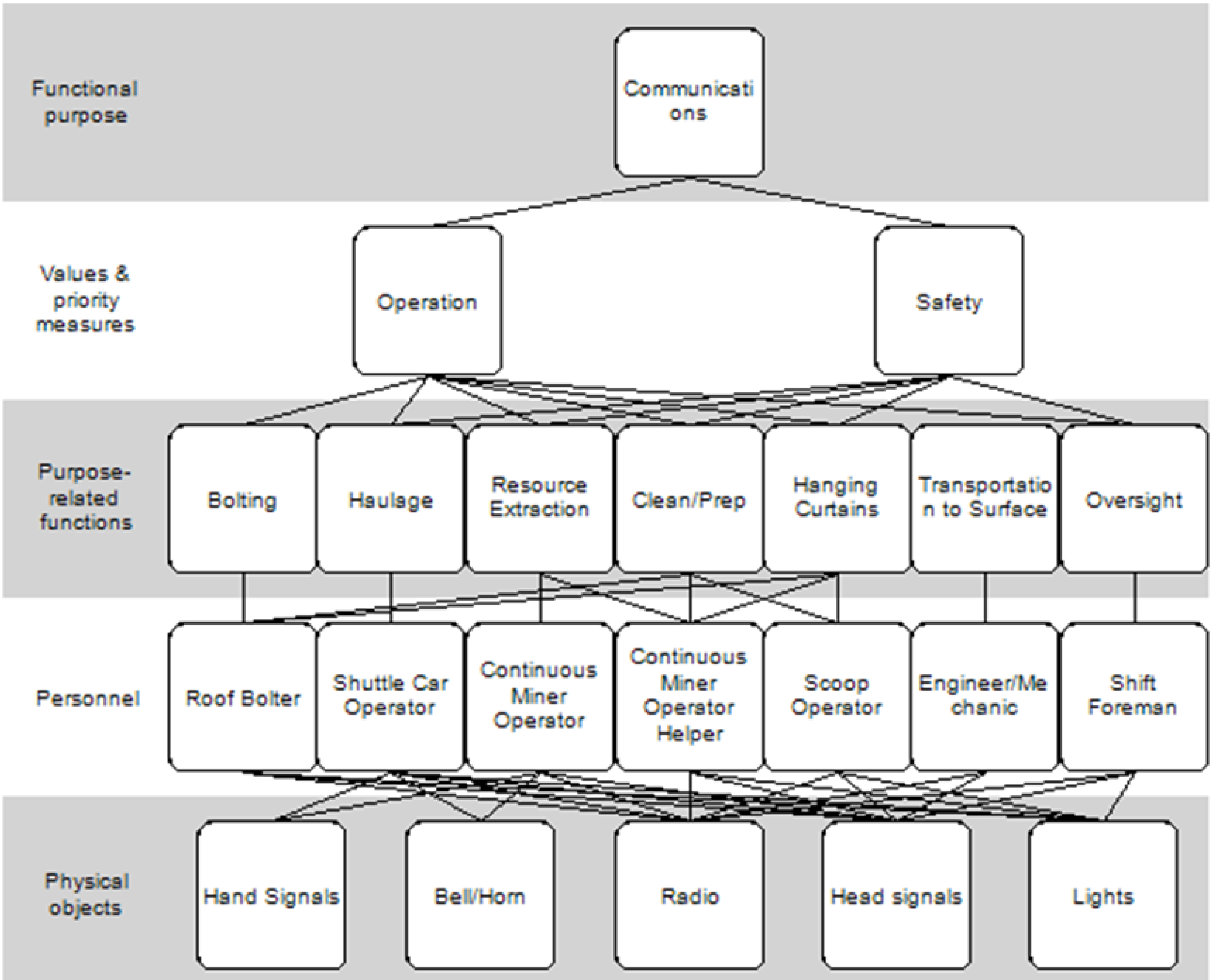

Figure I.34: Abstraction hierarchy of on-site communications

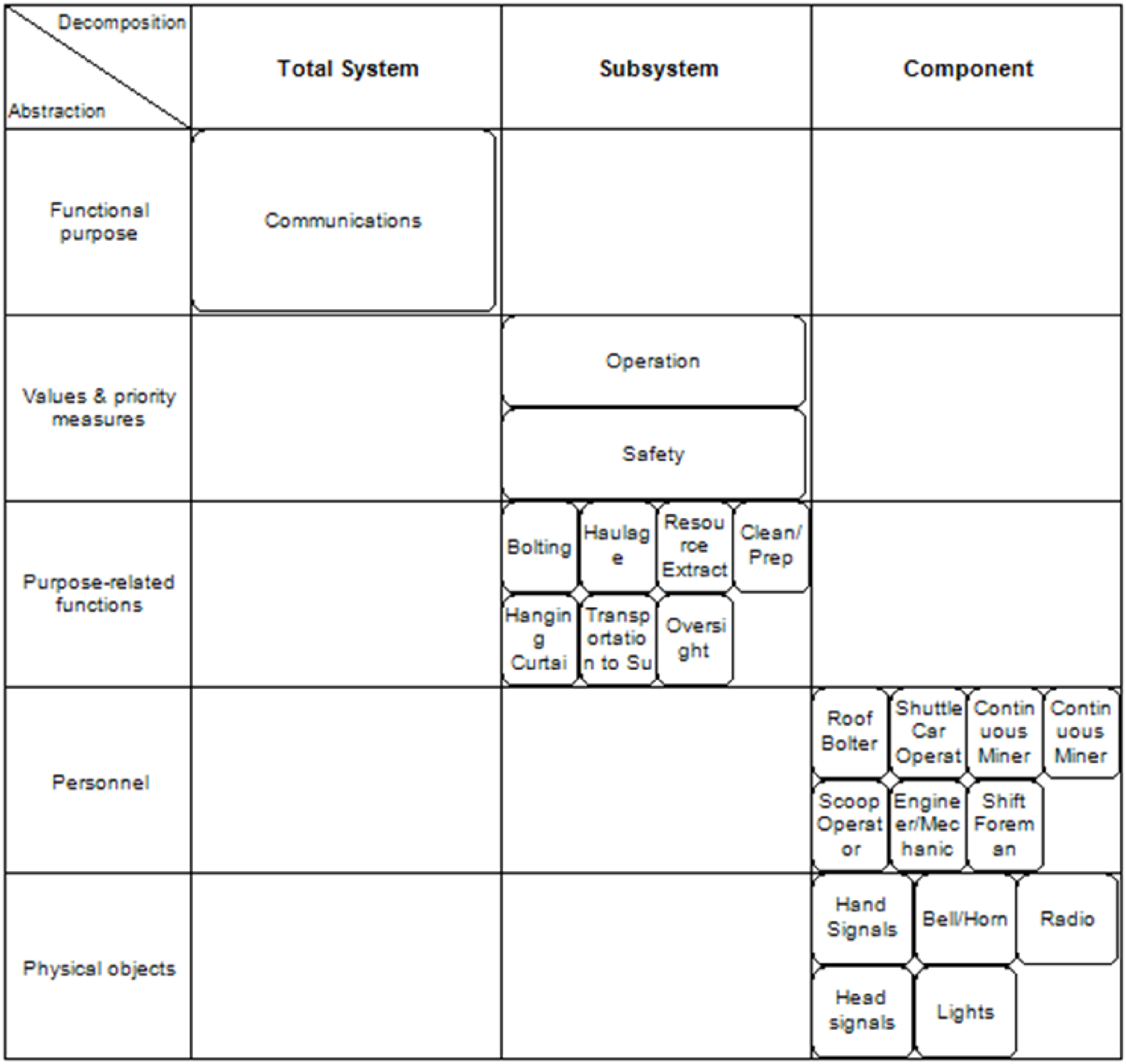

Figure I.35: Decomposed abstraction hierarchy of on-site communications

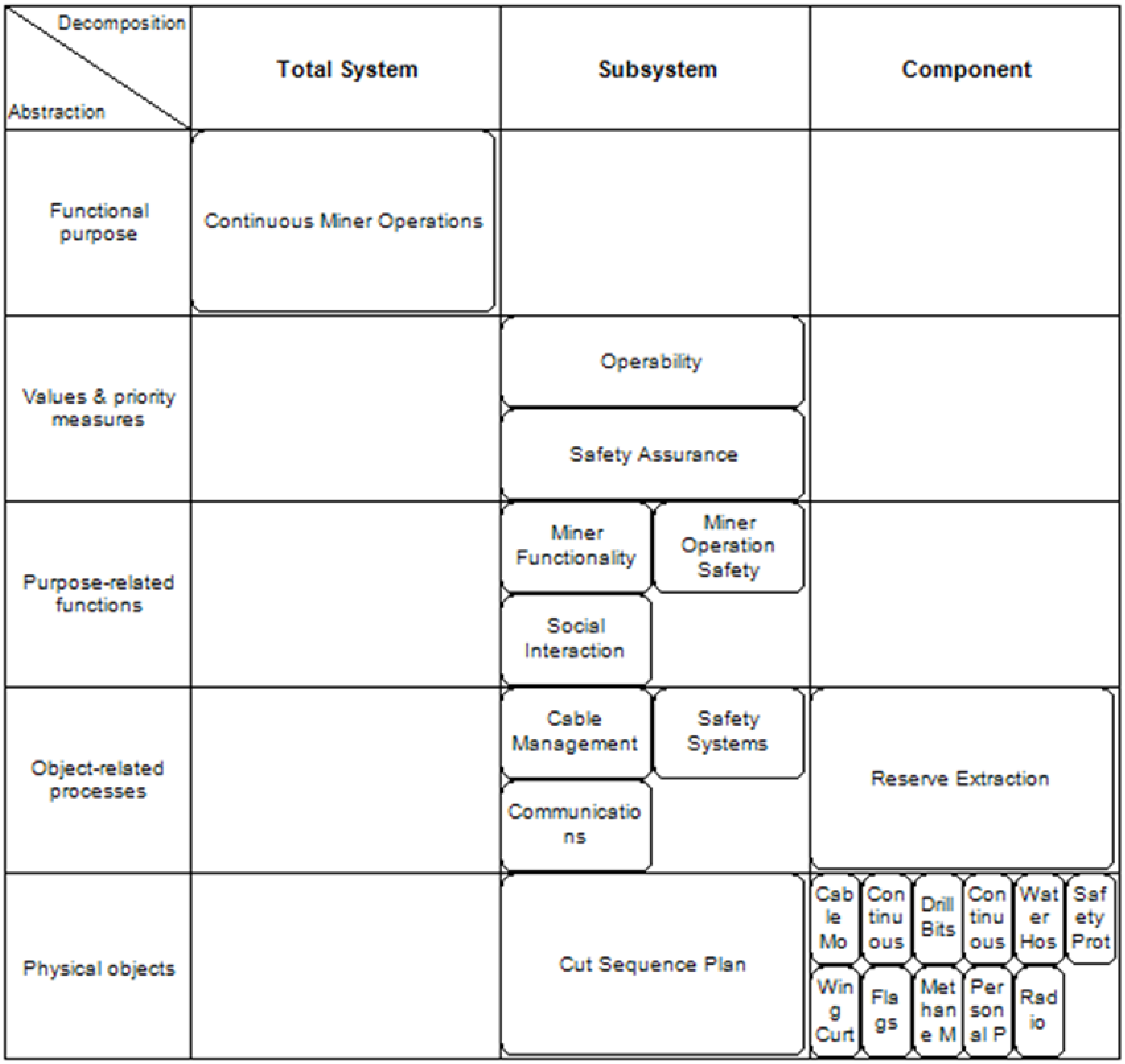

Figure I.36: Decomposed abstraction hierarchy of continuous miner operations

I.17 Interview/Focus Group Protocols

Table I.11 presents the expert focus group agenda (in person)

Table I.11: Tentative expert focus group agenda- in person

Time Allotted	Activity Description
≈ 2 minutes; 2 minutes total	Greetings, Informed Consent, Demographics
≈ 8-27 minutes; 10-29 minutes total	Interview/Focus Group Questions
≈ 1 minute; 30 minutes total	Closing

I.17.1 Welcome Activities

The welcome activities include the following:

- Participants will be greeted and escorted to the interview/focus group room.
- If participants wish to participate, they will be asked to sign the last page of the Informed Consent Form. One form will be collected by the experimenter and the second will be given to the participant to keep for his/her own records.
- Those who choose not to participate may leave.
- Participants will be reminded that they may refuse to answer any questions and may leave at anytime.

I.17.2 Interview/Focus Group Script - Introductions

- Introductions: Hello, our names are (xxx). We are researchers at VTTI. We want to thank you for taking the time to share your thoughts and experiences with us today.
- Purpose: During the interview/focus group we will ask you for your thoughts and experiences on organizational roles and practices that are part of your work. We are going to ask you a series of questions and need you to respond as openly and honestly as possible. There are no right or wrong answers-we just want your opinions. This discussion is strictly for research purposes, we are not selling anything and we will not connect anything you say with your name. Do you/does anyone have any questions before we get started? Please sign the informed consent form you were given earlier and we will collect it/them.

I.17.3 Specific Interview and Focus Group Questions

Note: The following questions are guidelines. Some questions may be skipped based on role. Work domain refers to the specific role of the interviewee (i.e., shuttle car operator, plant foreman). Each role should have a sufficient number of questions answered across work domain, critical errors and decisions, and social and organizational analysis. All questions will not be answered by all individuals. Focal areas include: Domain purpose, domain priorities, domain functions, domain resources and resource functions.

Facilitator Questions

- Work Domain
  - Domain purpose
    * What is the fundamental purpose of the work domain?
    * Why does the work domain exist?
    * What is the work domain trying to achieve?
  - Domain priorities
    * What are the values and priorities in this work domain?
    * What are the criteria by which you can assess the effectiveness of the work domain?
    * What are the measures of success for this work domain?
    * What is this work domain trying to get better at (i.e., maximize)?
  - Domain functions
    * What are the core functions that are necessary for the work domain to achieve its purpose?
    * What are the main tasks and activities performed in the work domain?
    * What are the major roles in this work domain and what are their responsibilities?
    * What departments and units exist in this work domain?
  - Resource functions
    * What are the capabilities of the resources in this work domain?
    * What can the resources in this work domain do?
    * What processes are performed by the physical resources in the work domain?
    * What can be achieved by the resources in this work domain?
  - Domain resources
    * What are the physical objects and resources in this work domain?
    * What are the physical characteristics of the resources in the work system (e.g., size, shape, configuration)?
    * What are the man-made objects and resources in this work domain?
    * Are there any natural objects and resources in this work domain?
    * What tools and equipment are available in this work domain?
    * What types of technology are used in this work domain (e.g., software, hardware, machinery)?
    * What types of non-digital tools and artifacts are used in this work domain (e.g., notice boards, white boards, paper forms)?

    * Are there any intangible resources used in this work domain (e.g., knowledge, expertise)?

- Critical Errors and Decisions: The facilitator will ask the following: "Think about errors that workers in your role can possibly make. This may include forgetting to perform safety checks or providing information to other individuals, or any error that is the worker's responsibility."
  – What are the errors? (Given a specific error, inquire as needed or appropriate.)
    * Why would a worker not detect the error?
    * How can the worker recover from the error?
    * How does a worker detect the error?
    * Is there critical information that a worker would fail to observe?
    * What information or cues would the worker observe?
    * Did the worker find it difficult to diagnose the situation?
    * What was the worker's diagnosis of the situation?
    * Did the worker find it difficult to evaluate options?
    * What options did the worker consider?
    * Why did the worker select/reject options?
    * Did the worker give precedence to alternative goals?
    * What are the worker's goals?
    * Did the worker find it difficult to plan the tasks and resources required for dealing with the situation?
    * What tasks and resources did the worker plan to use to recover from the error?
    * Did the worker find it difficult to plan or select procedures for dealing with the situation?
    * What procedures did the workers formulate to recover from the error?
    * What standard procedures did the worker select to recover from the error?
    * Did the worker fail to execute the procedure as intended?
    * What procedures did the worker execute to recover from the error?
  – Decision Making: The facilitator will ask the following: "We would like to understand your processes for making decisions. The following questions are related to the needs for workers to identify, understand, and react to specific cues. What are all possible ways or cues that an operator can be alerted to the need for an activity? For each cue answer appropriate questions below.
    * What are all possible examples of what it "looks like" when someone has noticed the need to act?
    * What are all possible processes through which observations are collected?
    * What are all possible inferences based on known information?
    * What are all possible reasons why we might still be unsure with this means for the mission? Where is the uncertainty?

    * What are all possible ways to interpret this data, so we can get a probability idea of what it means?
    * What are all possible ways this ambiguous information can change my goal? How?
    * What are all possible outcomes in progress toward accomplishing goals?
    * What are all possible was that sub-goals may be modified/added/removed to accomplish the ultimate goal?
    * What possible ways can I achieve my new goals from my current starting point?

- Social and Organizational Analysis
  - Communication or Information Flow Relationships
    * Who communicates with whom in the work domain?
    * How often do communications occur? That are related to the work? That are organizational or social?
    * What is the pattern of communications relative to other events? To the introduction of a new process or technology?
    * What general type of data or information is communicated to assist in the completion of tasks?
    * How does the content of the message influence its communication?
    * What types of communication media are used?
    * How does the medium influence communication?
  - Organization or Coordination/Consensus Relationships
    * Who coordinates with whom in the work domain?
    * Who participates in the work?
    * Who depends on whom to support their work?
    * Who is responsible for a task being completed?
    * What is the structure of the group responsible for a task?
    * What are the perceived organizational risks/consequences associated with the work?
    * What specific information is communicated as part of trajectories through abstraction-decomposition space?
    * How does a groups' structure impact intragroup communication?
    * Who distributes tasks?
    * Who coordinates activities of a group?
    * Who works to build consensus among entities?
    * What structure has emerged to cope with the work? With a new technology or process?
  - Ecological Relationships
    * What are the affective, familial, political, or cultural relationships likely to impact work?

* Which of these relationship types impair, enhance, or otherwise transform processes for communication, coordination, cooperation, and or/consensus?
* What organization structure are likely to influence these relationship types?
* Who shares similar belief and attitudes about work and about the organization structures needed to accomplish particular tasks?
* What personal affinities are present between workers in the domain?
* What are likely sources of heterogeneity in perspectives about work and organization structure?
* What are the physical relationships that impact work performance?
* Which group members are distributed verses collocated?

Closing

The facilitator will close the session by asking: "Have we missed anything? Tell us anything you want us to know that we did not ask about." Then the facilitator will close the session with the following statement: "This concludes our interview/focus group. I'd like to thank you for your time, it is greatly appreciated. Please feel free to contact me if you have any questions, or if you have anything in particular that you would like to add that you did not have a chance to. Thank you again for your help."

I.18 Acknowledgements

This report was developed by Andrew Miller and Justin Owens at the Virginia Tech Transportation Institute. Additionally, the mention of trade names, commercial practices, or organizations does not imply endorsement by the Alpha Foundation. The authors would also like to acknowledge our partner mine for their willingness to participate in the work analyses through provision of materials and observational data as well as opportunities for meeting with employees of the organization for interviews.

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Appendix K

Human Machine Interface Design Proposal for the Autonomous Shuttle Car

K.1 Abbreviation and Acronyms

This abbreviations and acronyms used in this appendix are included in Table K.1.

Table K.1: Abbreviations

Acronym	Definition
cm	centimeter
CMO	Continuous Miner Operator
ConOps	Concept of Operations
ft.	foot/feet
HMI	human-machine interface
IEEE	Institute of Electrical and Electronics Engineers
in.	inch(es)
kg	kilogram
KSAs	Knowledge, Skills, and Abilities
kW	kilowatt
LED	Light-emitting diode
m	meter
mm	millimeter
MSHA	Mine Safety and Health Administration
RPLiDAR	Light Inspection, Detection and Ranging
SC	Shuttle Car
SCO	Shuttle Car Operator(s)
UKY	University of Kentucky
VCCER	Virginia Center for Coal and Energy Research
VTTI	Virginia Tech Transportation Institute

K.2 Introduction

This Concept of Operations (ConOps) serves as the engineering and human factors document for the first iteration of design proposal for the demonstration of an autonomous system on individual shuttle cars in an underground room-and-pillar coal mining system. The purpose of the ConOps is to convey the purpose, requirements, constraints, and evaluation metrics of automating specific functions of shuttle cars. The ConOps includes operational, safety, and human-machine interface (HMI) considerations for deployment. This ConOps defines how the shuttle car should automate the tasks allocated to it in the requirements and how it should interact with its operator and other humans surrounding it. Furthermore, at the system level, the ConOps addresses functional changes such as new work processes enabled by the automation, new role assignments, adjusted decision structures, and training curricula. This report forms the basis for subsequent operational concepts that iterate upon the automation technology, the HMI design, or the use cases for automation.

The structure of this appendix is tailored from the Institute of Electrical and Electronics Engineers (IEEE) Standard 1362-1998 and includes the following sections:

- Introduction, which provides a high-level overview of the general concepts and nature of the autonomous shuttle car project.
- References, which identifies all documents referenced in developing this document.
- Current System, which describes the current system and problem(s) to be addressed.
- Justification and Nature of Changes, which describes the features that motivate the project's development.
- Concept for the New System, which provides a high-level description of the proposed system resulting from the features described in previous sections.
- Operational Scenarios, which presents how the project is envisioned to operate from various perspectives or under certain conditions.
- Summary of Impacts, which describes the impacts the project will have on the organization and users.
- Analysis of the Autonomous Shuttle Car, which provides an analysis of the impacts presented in previous sections.
- Implementation of HMI prototypes, which discusses the proposed HMI prototypes.

The ConOps provides a framework for conceptualizing an autonomous underground shuttle car within the existing work system, methods for measuring accuracy and reliability, metrics for evaluating impacts, and a deployment plan for a functional prototype. Additionally, the ConOps provides recommendations for iteration as automation technology, HMI design, and use cases change in the future. Importantly, the ConOps is specifically for demonstration of prototype autonomous shuttle car technology. While the ConOps lays out methods of evaluating impacts of this prototype, it is expected that the technology, HMI, use cases, and the ConOps itself will be iterated in order to consider fully integrated deployment.

Note that this appendix addresses all aspects of the human-machine interface for autonomous shuttle car navigation from the change point at the continuous miner (approximately) to the change point at the feeder-breaker (approximately) in a production setting. Many of these aspects are not part of the lab-scale and full-scale navigation testing that was performed.

K.3 References

Table K.2 lists resources relevant to the autonomous shuttle car project.

Table K.2: Autonomous Shuttle Car References

Document Number	Title	Publication Date
-	Human-Centered Design for Mining Equipment and New Technology	2018
-	Joy (Komatsu) Shuttle Car Information https://mining.komatsu/product-details/shuttle-cars#!upgrades	-
-	Shuttle Car 10SC32B Specifications	-
30 CFR	MSHA https://arlweb.msha.gov/regs/30cfr/	1978+
IEEE 1362	Guide for Information Technology – System Definition – Concept of Operations (ConOps) Document	1998
-	Cognitive Work Analysis Technical Report for Autonomous Underground Mining Systems to Improve Safety - Intelligent Coal Mining Project	2018
-	Cognitive Work Analysis: Coping with Complexity	2009
-	Applications of Cognitive Work Analysis	2009
-	Human Factors for the Design, Operation, and Maintenance of Mining Equipment	2011
APC #20087478	Job Standard Sheets	August 2017
-	Cognitive Work Analysis	1999

K.4 Current System

K.4.1 Background and Objectives

Operation of shuttle cars presents inherent environmental and occupational risks, specifically to the shuttle car operators, mobile equipment operators near shuttle car haulage routes, and miners in proximity to the shuttle cars. Typical hazards for these individuals include excessive noise, stagnant or flowing respirable dust, and poor visibility in travel ways, largely due to low-levels of illumination paired with suspended dust and across-path ventilation controls.

The research objectives of this report are as follows:

1. Justify the introduction of an autonomous shuttle car on the organizational system,
2. Identify the impacts on the shuttle car operator role and other affected roles,
3. Create recommendations for the HMI design of the operator's controller, and
4. Outline future steps for the iterative development of the system.

To attain these objectives, a 1:6 scale shuttle car prototype was developed to demonstrate operation and functionality of a shuttle car within a controlled environment. During this time, the research team conducted an iterative HMI design process involving interviewing and testing with operators of shuttle cars as well as performing prototype demonstrations. Performing this research with current shuttle car operators allowed the incorporation of the appropriate user input into the development and eventual demonstration of the overall shuttle car system and its room-and-pillar implementation.

K.4.2 Operational Policies and Constraints

Current regulations governing mining operations are outlined in Title 30 of the Mine Safety and Health Administration (MSHA) Federal Regulation Codes. MSHA administers the provisions of the Federal Mine Safety and Health Act of 1977 and enforces compliance of standards and regulations. These federal regulations are listed in Table K.3.

Table K.3: MSHA Regulations Relevant to Coal Mining and Extraction

Mine Safety and Health Administration (MSHA) – Title 30 – Mining Resources
• Chapter I - MSHA - Department of Labor • Subchapter O - Coal Mine Safety and Health • 70.1 To 70.1900 - Mandatory Health Standards - Underground Coal Mines • 71.1 To 71.702 - Mandatory Health Standards - Surface Coal Mines and Surface Work Areas of Underground Coal Mines • 72.1 To 72.800 - Health Standards for Coal Mines • 74.1 To 74.18 - Coal Mine Dust Sampling Devices • 75.1 To 75.1916 - Mandatory Safety Standards - Underground Coal Mines • 77.1 To 77.1916 - Mandatory Safety Standards, Surface Coal Mines and Surface Work Areas of Underground Coal Mines • 90.1 To 90.301 - Mandatory Health Standards-Coal Miners Who Have Evidence of the Development of Pneumoconiosis

Further organizational policies, standards, and practices outline additional constraints. These rules and policies are organization-specific and will be considered during the demonstration of both the prototype shuttle car as well as the operable retrofitted shuttle car.

K.4.3 Description of Current System

A shuttle car is designed for transporting raw coal from the continuous miner to the semimobile feeder-breaker at the tail-end of the section conveyor belt. Shuttle cars are electric¬-powered, wheel-mounted, self¬-propelled machines energized through a flexible cable that extends from the semimobile power center to a retractable reel in the shuttle car. During shuttle car operation, the cable is connected to an anchor close to the feeder-breaker and spools out on the mine floor. Sometimes, if the cable is in the pathway of a shuttle car or other connected machinery, the cable is hoisted onto a rib to elevate the cable off travel ways so as to not be driven over, as well as to prevent tripping hazards or provide visual cues for mine personnel.

The shuttle car consists of an operator cab, a bed for hauling coal, and a chain conveyor for transferring material on to and off of the bed. Due to the working environment (see Figure 2), there is limited maneuverability in a room-and-pillar layout. As such, the shuttle car is equipped with four wheel steering and is fully operable in both inby and outby directions, through a switch that alters the driving direction of the machinery.

Shuttle car operators are primarily responsible for tramming the shuttle car between the feeder-breaker and continuous miner at the working face. The shuttle car operator must be cognizant of the trailing electrical cable, other shuttle cars, mobile and static equipment, and pedestrian workers. During mining operations, each shuttle car operator is responsible for tramming to the continuous miner from the feeder-breaker, then docking at the continuous miner to load coal while operating the chain conveyor, then retracing the path to the feeder-breaker, to unload the run-of-mine (ROM) coal into the feeder-breaker, retracting the connected electrical cable as it returns. This process is repeated as the continuous miner progresses through the cut sequence.

Shuttle Car Features

The shuttle car used in the current project, in both the prototype and retrofitting is model 10SC32B. The specifications for this specific configuration are displayed in Table K.4.

In addition to the above specifications, the information available to the operator within the shuttle car operator's compartment is displayed in Table K.5.

Shuttle Car Operations

An overview of the general tasks for shuttle car operators is detailed in Table K.6. These tasks provide a sense of the responsibilities and duties of operators as they currently function in room-and-pillar mining.

Work-oriented activities for shuttle car operators are broken down into nine categories encompassing the operators' daily routine and one category involving emergency-related situations, displayed in Table K.7. These activities range from general shuttle car operations to mine-specific conduct.

This ConOps highlights the areas of the above task activities in which automation is expected to have an impact, through introduction of additional task activities or adjustment and reassessment of tasks according to automation's impact. These areas include normal operating functions as well as the management and maintenance of the automation controller and shuttle car in the start-and end-

Table K.4: Shuttle Car Model 10SC32B Specifications

Specification	Details
Rated load capacity	14 tonnes
Machine Weight	25,000 kg
Ground pressure at max. rated load	10 kg/cm^2
Tire	14 x 20
Length	9 m
Width with 56 in. conveyor	3.42 m
Chassis height	1.3 m
Load end height	1.3 m
Minimum canopy height	1.6 m
Minimum seam height	1.9 m
Ground Clearance	290 mm
Pump 50 Hz/60 Hz	1-30kW/1-25 kW
Conveyor 50 Hz/60 Hz	1-25kW/1-24 kW
Traction 50 Hz/60 Hz	2-85 kW/2-85 kW

Table K.5: In-Cab Operator Feedback

Information
• Steering circuit pressure • Brake circuit pressure • Conveyor elevate pressure • Cable reel pressure • Tire position • Bidirectional forward video feed • Troubleshooting LED lights (side of machine)

of-shift activities. The current tasks for the shuttle car operators as they exist without automation are represented in Tables K.8 to K.13.

Table K.6: Shuttle Car Operator General Duties Overview

General Duties of Shuttle Car Operators
• Controlling machines and processes • Operating vehicles, mechanized devices, or equipment • Inspecting equipment, structures, or material • Monitoring processes, materials, or surroundings • Evaluating information to determine compliance with standards • Communicating with supervisors, peers, or subordinates • Identifying objects, actions, and events • Handling and moving objects • Repairing and maintaining mechanical equipment • Performing general physical activities • Maintaining personal protective equipment

Table K.7: Overview of Shuttle Car Operator Task Activities

Task Activities Overview for Shuttle Car Operators
• Start-of-Shift Activities • Conduct Environmental Examinations • Pre-operational Inspections – Power Off • Pre-operational Tasks – Power Off • Pre-operational Tasks - Power On • Tramming • Loading • Dumping • End-of-shift Activities

Table K.8: Start-of-shift Activities for Shuttle Car Operators

Start-of-shift Activities
• Check-in via the tag-in/tag-out system • Ensure correct clothes are worn • Obtain self-contained self-rescuer • Obtain radio • Obtain personal protective equipment • Obtain tools • Meet with foreman and crew to discuss section activities • Meet with foreman and crew to attend safety talk • Meet with foreman and crew to discuss roof control plan • Enter the mine

Table K.9: Pre-operational Activities for Shuttle Car Operators with Shuttle Car Powered On

Pre-operational Tasks – Power On
• Check lights • Turn pump on • Turn pump off with panic bar • Check start/stop speed control • Check park brakes • Check steering • Check forward and reverse switch and tram function • Check conveyor chain on/off switch • Check boom raise/lower lever • Look for cable pick up • Assist with mechanical repairs (*) (*) Unusual Situations, Emergencies, Non-routine Duties

Table K.10: Tramming Activities for Shuttle Car Operators

Tramming
• Put seat belt on • Keep all body parts within the deck compartment • Clear persons out of shuttle car • Set directional switch • Sound audible alarm before tramming (voice or bell) • Start pump • Adjust tram speed using tram dial • Release park brake • Push button in (palm valve) • Check brake pressure • Check steering • Turn lights on in direction of travel • Listen for anchor/slap • Depress tram pedal • Keep car centered in roadway • Check cable in outside places. Have enough cable for the current and next shifts • Tape up or secure all low hanging cables that may be susceptible to damage • Keep slack cable hung or against rib for protection • Re-hang any curtain that is damaged by the shuttle car • Keep lights on toward nearest curtain when parked • Use the first row of bolts off the rib to judge the positioning of car • Use existing tire tracks to judge position of car • Make a turn traveling inby by lining up front tires with break corners and turning wheels left or right as hard as possible • Make a turn traveling outby by lining up boom end tires with break corners and turning wheels left or right as hard as possible • Observe for persons and obstructions in travel ways • Ring bell or flash lights • Stop car for persons on offside of shuttle car • Traveling through ventilation controls/fly pads/curtains • Slow down • Sound audible alarm • Flash lights • Replace any damaged ventilation controls • Operate at speed under which control of the shuttle car can be maintained • Be aware of other equipment and cables in travel ways • Shut car off before exiting
Continued on next page

Tramming
• In the event of a loss of brakes, stay in your seat (*) • In the event of a loss of brakes, steer into rib (*) • In the event of a loss of brakes, hit panic bar (*) • In the event of a fire, #1 Shuttle Car operator assists miner operator in gathering water line and fighting fire (*) • In the event of a fire, #2 Shuttle Car operator mans phone and communicates with outside person (*) • Show escapeways (*) (*) Unusual Situations, Emergencies, Non-routine Duties

Table K.11: Loading Activities for Shuttle Car Operators

Loading
• Tram to continuous miner • At the miner, hold car over to the left rib • Avoid miner cable and operator • Center the car (as much as possible) under boom • Turn shuttle car wheels toward miner operator while loading (sitting under the boom) • Observe roof over miner operator for loose roof or ribs/Red Zones • Do not bump back of miner • Maintain communication with miner operator • Ensure miner operator is not near the load end of the shuttle car during loading • Change the direction of your lights • Watch the tail boom of the miner and as coal builds up, run the chain to load car as evenly as possible without overloading/spilling • Stop loading coal within a foot of the end of boom • Use the outby end of deck compartment as a guide • Listen for spillage • Observe for miner operator signal when car is loaded • Observe second row of fully intact roof bolts • Ring bell • Tram to feeder • Be aware of other car switch out points and scoop activity • In the event of a fire, #1 Shuttle Car operator assists miner operator in gathering water line and fighting fire (*) • In the event of a fire, #2 Shuttle Car operator mans phone and communicates with outside person (*) • Show escapeways (*) • Assist with mechanical repairs (*) (*) Unusual Situations, Emergencies, Non-routine Duties

Table K.12: Dumping Activities for Shuttle Car Operators

Dumping
• Look for any activity around feeder • Slow down • Raise boom (≈ 1 ft.) • Center car on feeder • Position boom so coal drops in center of feeder • Use reflectors to center car on feeder • Make sure feeder is on prior to dumping • Dump load • Raise boom as coal load is dumped • Slow down dumping when discharging rock to allow the crusher ample processing time • Report excessive spillage to supervisor • Turn lights in direction of travel • Sound audible alarm • Pull off the feeder • Look and listen for unusual sounds, smells in the feeder area • Lower boom • Return to continuous miner • In the event of a fire, #1 Shuttle Car operator assists miner operator in gathering water line and fighting fire (*) • In the event of a fire, #2 Shuttle Car operator mans phone and communicates with outside person (*) • Show escapeways (*) • Assist with mechanical repairs (*) (*) Unusual Situations, Emergencies, Non-routine Duties

Table K.13: End-of-shift Activities for Shuttle Car Operators

End-of-shift Activities
• Ensure car is empty • Park car at the feeder • Turn wheels toward rib • Clean out deck compartment • Clean spillage off sides of car • Ensure slate bar is left on car • Trip breaker on feeder • Trip breaker on car • Check ventilation controls/fly pads/curtains • Check tail piece for spillage • Report any maintenance problems/clean up needed, etc. to supervisor/electrician • Walk to mantrip

K.4.4 User Attributes

Worker-oriented attributes involve the characteristics that contribute to successful job performance. Shuttle car operators currently rely on the knowledge, skills, and abilities (KSAs) that are presented in Tables K.14 to K.16 to complete daily mining operations.

Table K.14: General Knowledge Required of Shuttle Car Operators

Knowledge
• Control conveyors that run the entire length of shuttle cars to distribute loads as loading progresses. • Drive loaded shuttle cars to ramps and move controls to discharge loads into mine cars or onto conveyors. • Clean and service equipment, and repair and replace parts as necessary. • Move mine cars into position for loading and unloading, using pinchbars inserted under car wheels to position cars under loading spouts. • Guide and stop cars by switching, applying brakes, or placing scotches, or wooden wedges, between wheels and rails. • Push or ride cars down slopes, or hook cars to cables and control cable drum brakes, to ease cars down inclines. • Observe hand signals, grade stakes, or other markings when operating machines. • Open and close bottom doors of cars to dump contents. • Direct other workers to move stakes, place blocks, position anchors or cables, or move materials. • Monitor loading processes to ensure that materials are loaded according to specifications. • Measure, weigh, or verify levels of rock, gravel, or other excavated material to prevent equipment overloads. • Read written instructions or confer with supervisors about schedules and materials to be moved. • Maintain records of materials moved.

Table K.15: General Skills of Shuttle Car Operators

Skills
• Operation and Control - Controlling operations of equipment or systems. • Operation Monitoring - Watching gauges, dials, or other indicators to make sure a machine is working properly. • Monitoring - Monitoring/Assessing performance of self, other individuals, or organizations to make improvements or take corrective action. • Equipment Maintenance - Performing routine maintenance on equipment and determining when and what kind of maintenance is needed. • Communications – Understanding, comprehension, and effective communication are required for safe operations.

Table K.16: General Abilities of Shuttle Car Operators

Abilities
• Control Precision - The ability to quickly and repeatedly adjust the controls of a machine or a vehicle to exact positions. • Manual Dexterity - The ability to quickly move each hand, hands together with arm(s), or two hands to grasp, manipulate, or assemble objects. • Multi-limb Coordination - The ability to coordinate two or more limbs (for example, two arms, two legs, or one leg and one arm) while sitting, standing, or lying down. Does not involve performing the activities while the whole body is in motion. • Near Vision - The ability to see details at close range (within a few feet of the observer). • Reaction Time - The ability to quickly respond (with the hand, finger, or foot) to a signal (sound, light, picture) when it appears. • Depth Perception - The ability to judge which of several objects is closer or farther away, or to judge the distance between self and an object. • Rate Control - The ability to time movements or the movement of a piece of equipment in anticipation of changes in the speed and/or direction of a moving object or scene. • Oral Comprehension - The ability to listen to and understand information and ideas presented through spoken words and sentences. • Problem Sensitivity - The ability to tell when something is wrong or is likely to go wrong. Does not involve solving the problem, only recognizing there is a problem.

K.5 Justification and Nature of Changes

K.5.1 Justification For Changes

The shuttle car itself functions with limited regard for operator comfort. Operator cabs are usually open and positioned on the side of the vehicle. In addition to a having a poor field-of-vision, operators are also left exposed to dust, spray from the continuous miner, and noise from mining operations without the ability to move away from these hazards. The shuttle car's suspension is designed to function while loaded, which results in significant vertical deflection while traveling unloaded. As a result, the operator is subjected to constant vibration while travelling.

Automating shuttle car coal face haulage from the continuous miner to the feeder-breaker would remove the operator from the active mining area, thereby reducing exposure to hazardous and undesirable conditions. Although an autonomous shuttle car would not have a human occupant, equipment operators would still be needed to serve in a supervisory capacity.

K.5.2 Description of Desired Changes

The introduction of an autonomous shuttle car will most significantly impact the functions of tramming, loading, and dumping. Other functions, such as pre-operational or end-of-shift activities, may be affected, but to a lesser degree. Tasks must be reassigned as appropriate, involving the necessary parties beyond the shuttle car operator. Work-oriented activities that are either altered for the shuttle car operator or other personnel must be identified, then re-assigned to the shuttle car for functional purposes, other operators, or removed entirely from the breakdown of tasks.

The ultimate goal of the project is to demonstrate utility and functionality of an autonomous shuttle car, its impacts on the shuttle car operator and other section personnel, and the overall underground operations system.

K.5.3 User Needs

A list of specific user needs is summarized in Table K.17. These user needs are expected to be supported through the deployment of the autonomous shuttle car application and are also targeted for the demonstration of the automation system.

Table K.17: User Needs

Description	Rationale
Ability to issue command to begin autonomous tramming	Because loading and unloading will be handled manually with an operator in the vehicle, the operator with control of the shuttle cars will need to issue a command to begin autonomous tramming when manual tasks have been completed
Ability to issue command to pause autonomous tramming	If a vehicle or miner needs to cross paths with the shuttle car, the operator needs to be able to pause tramming until the path is clear.
Ability to issue command to stop autonomous tramming	If there is an emergency situation or any operators deems the shuttle car needs to stop immediate they can issue a command to stop the vehicle and prevent autonomous tramming from resuming until a human overrides the stop.
Ability to observe operational parameters of the vehicle remotely	While only one operator will have the ability to issue go and pause commands, both operators will be able to be aware of the status of each vehicle and issue emergency stop commands if necessary. Both operators will therefore need information on the location, mode of operation, speed, and other parameters in real-time.
Physical emergency stop button	In case of emergency any miners near the vehicle will need the ability to shut down its operation. A conspicuous, physical button on the vehicle itself will allow any users to shut down.
Shuttle car should display information regarding the mode of operation / automation visible to personnel at a distance	All personnel should be able to quickly assess the shuttle car's operational status to ensure safety of operations

K.5.4 Related Performance Measures

The following metrics display a preliminary list of performance measure objectives that will be used to assess the effectiveness of the autonomous shuttle car and accompanying system:

- Safety Measures
  - Frequency of safety incidents
  - Severity of safety incidents
  - Frequency of emergency stops
  - Frequency of proximity alert shut-offs
  - Percentage of time operator spends in return air during a shift
- Operational Measures
  - Frequency of cable management issues
  - Frequency of ventilation maintenance difficulties
  - Speed of shuttle car while tramming
  - Speed of complete unloading to unloading cycle
  - Percentage of time operator spends in vehicle during a shift
  - Frequency of operator entering and exiting the shuttle car during a shift
- HMI Measures
  - Operator error rate
  - Operator time to complete tasks
  - Frequency of non-operator interactions with shuttle car
- Subjective Acceptance Measures
  - Operator acceptance of automation
  - Operator trust of automation
  - Automation ease of use

The above metrics are applicable for full implementation of the autonomous shuttle car. A subset of these metrics will be measured for the demonstration purposes of the autonomous shuttle car operations.

K.5.5 Priorities Among Changes

Communications

Maintaining proper communications between all individuals in the section crew is a critical issue regarding the safety of all workers. Given that a number of available options to communicate between shuttle car driver and other individuals in the roadway would be removed due to automation, new measures must be taken to ensure safe travels. These measures may include increased and proper radio communication, increased auditory and visual cues for shuttle car tramming, direct communication between shuttle car operators, and multiple fail-safes for individuals traveling in, or near, the shuttle car path.

Cable Management

Handling the cable and cable reel for the shuttle car while avoiding running over other heavy machinery cables will be critical with an autonomous shuttle car. Proper cable management will be key in preventing damage and avoiding hazards, including increased attention to cable hanging and anchoring, pathway navigation that incorporates proper cable reeling, and increased checks for cables in the roadway.

Interface Logistics

The means by which the shuttle car operators are able to remotely operate an autonomous shuttle car is critical in adoption of the technology. The remote needs to be functional, informative, and intuitive when considering the number of tasks that are reassigned from the shuttle car operator to the autonomous system. The remote system must incorporate enough detailed status information to remain reliable without a shuttle car operator in the vehicle. This is discussed in detail in a subsequent section.

Ventilation Controls

Ventilation controls, both in the maintenance of and navigation through, provide a set of potential hazards for members of the section crew. Shuttle cars are often responsible for the knocking down of ventilation curtains. Without a shuttle car operator present in the vehicle, it may be more challenging to identify when a curtain has been knocked down. Additionally, continuous miner operator helpers and scoop operators are commonly responsible for rehanging the curtains frequently in the path of the shuttle car. Increased attention to communications and awareness of vehicle travel paths are critical in the safety of the section crew members.

Shuttle Car Operator Location

Given the high demand on the shuttle car operator at both the continuous miner and feeder-breaker for loading and dumping activities, it is a necessity to station a shuttle car operator at both locations with the capability of manually operating the shuttle car for placing it correctly, docking, and managing the chain conveyor and boom. This provides a challenge where a shuttle car remote operator must be able to access controls for both shuttle cars, either through selection on the remote or autonomous selection given pathway navigation algorithms.

K.5.6 Changes Considered But Not Yet Included

A number of considerations for automation of the shuttle car exist and may be implemented in future iterations of the prototype or retrofitted shuttle car. These changes are difficult to execute successfully and would drastically alter the loading and unloading task activities.

- Docking to the feeder
- Start/Stop chain conveyor
- Docking to the continuous miner
- Raise/position the boom

K.6 Concept for The New System

K.6.1 Background

The autonomous shuttle car project has a number of goals designed to achieve its vision of reducing the shuttle car operator's exposure to harsh working conditions. This project plays a role in achieving the goal of introducing automation to haulage systems in room-and-pillar mining. Based on the goals of the project, initial discussions with stakeholders, and a review of current operational procedures, an initial concept for system operations was created. This concept began with a set of constraints on operation, requirements for operation derived from those constraints, and assumptions about operation that were tested in the course of the design process. This is followed by a task analysis, including initial concepts for how tasks will be impacted by the introduction of an autonomous shuttle car into the system.

K.6.2 Operational Constraints, Requirements, and Assumptions

Along with continued adherence to MSHA federal regulations as well as internal safety procedures, the following operational policies or constraints are highlighted as critical information for the automation of the shuttle car during haulage.

- The shuttle car cannot require more than two operators
- The shuttle car cannot impede overall work flow
- The shuttle car cannot damage or require changes to ventilation systems

- The shuttle car cannot require wireless communication
- Shuttle cars must be manually operable in event of failures
- The shuttle car cannot impede modes of communication (wired connectivity, radio, visual signals).
- The shuttle car cannot introduce un-mitigatable safety hazards

Based on these constraints, an initial set of requirements has been derived:

- The autonomous shuttle car must operate up to 6 mph under normal conditions
- The autonomous shuttle car must be able to navigate the existing entries and crosscuts dimensions
- The autonomous shuttle car must be able to detect external indicators of when to initiate turns
- The autonomous shuttle car must be able to detect the endpoint of tramming operations and initiate controlled stops
- The autonomous shuttle car must be able to signal that it has initiated a controlled stop and is awaiting manual input
- The autonomous shuttle car must be controllable via a wired, external device
- The autonomous shuttle car must communicate status information such as position, speed, load status, and mode of operation (i.e., autonomous driving, manual loading/unloading, etc.) to the operator at all times and to other miners as needed
- The autonomous shuttle car must detect potential conflicts in the direction of travel and be able to initiate emergency stops
- The autonomous shuttle car must communicate conflicts and emergency stops to the operator
- Shuttle cars must have multiple fail-safes for conflicts

Finally, there are assumptions about how the autonomous shuttle car can operate which are being included in current design efforts. However, the validity of these assumptions may not hold under real-world conditions. The assumptions were evaluated at each step of the iterative design and constraints or requirements will be modified as needed. These assumptions include:

- Ribs can be marked with infrared or other technology for the purposes of conveying signals to the autonomous shuttle car
- Cameras on the front and rear of shuttle cars can be streamed to the operator or other miners as needed for oversight or decision-making
- One operator can oversee and control up to three separate autonomous shuttle cars

The constraints, requirements, and assumptions are all initial lists derived from current operational procedures and standards. All three were refined through an iterative elicitation process with stakeholders, anticipated end users, and expert review.

K.6.3 Description of the Proposed System

Table K.18 displays the components of a shuttle car that are currently expected to be autonomous and/or remotely controlled.

Table K.18: Shuttle Car Functions to be Autonomous

Component/Function	Specific Control(s)
Directional switch	Inby to outby Outby to inby
Audible alarm	Horn Other equipped auditory system
Lights	Inby Outby
Hydraulic Pump	Enable Disable
Park Brake	Enable Disable
Tram dial (speed)	Inby Outby
Steering	Four wheel steering to the left (left turn) Four wheel steering to the right (right turn)
Brake	Brake pressure

Shuttle Car Design Elements and Functionality

The design elements and functionality of the autonomous shuttle car are listed below:

- Underground mapping/path planning: It is expected that there will be an initial pass where the shuttle car will be driven or remote controlled into the pathway to use for a particular cut. That pathway may be stored and reused if similar conditions appear in future cuts.
- Underground localization: Currently, the autonomous shuttle car will be able to calculate its current location at any point along the prescribed path. Multiple sensor inputs will be used for localization.
- Underground navigation: Navigation will consist of lateral and longitudinal control-related subtasks.
- Obstacle avoidance: When obstacles are encountered the autonomous shuttle car will have to stop operation until the obstacles are cleared and permission to move is re-established. Obstacles will include but will not be limited to the following:
  - Rocks and or other massive objects on the floor obstructing the path
  - Rocks and other objects narrowing the path

- Low roof conditions narrowing the vertical travel path
- Personnel equipped with proximity sensors

Table K.19 details sensor options for a fully retrofitted shuttle car capable of autonomous navigation. The full-scale tests were conducted in this project utilized LiDAR sensors only.

Table K.19: Sensor options for a fully retrofitted shuttle car capable of autonomous navigation

Sensor	Location	Measurement	Remarks
4 Time-of-Flight Laser sensors (VL53L0X)	Front, sides, back	Distance	
2-4 Laser proximity sensors (VCNL4010)	Front, sides, back	Proximity alert	
2-4 Ultrasonic sensors (HC-SR04)	Front, sides, back	Distance	(may not be used in final lab-scale shuttle car)
9 Degrees of Freedom inertial measurement unit sensor (MPU9250)	Center of rear axle	Motion and Distance	3-axis acceleration, 3-axis angular velocity, 3-axis magnetic field measurements
LiDAR or 360^o laser scanner	Top	Distance	Multiple distances into 0-360^o angular range with 1^o resolution, requires a lot of storage and processing power
Camera (including Forward-looking infrared and 360)	Multiple Locations	Objects, obstacles and Distance	As far as it can see, up to 100 feet, requires a lot of processing power
Active radio-frequency identification reader and tag system	Front or back	Objects, obstacles and distance	50 foot resolution
Feeler Gages	All sides	Obstacles	2-3 foot resolution
Passive Infrared sensors and Reflective sensors	All sides	Location	5-20 feet, by reflectiveness
Proximity Detection (Magnetic)	All sides, 4 generators on the corners	People	Generator and tag system

K.6.4 User Classes and Other Involved Personnel

User classes are broken down into three groups. The three user classes are based on the design principal that a single operator should have control of the autonomous shuttle car under normal operations, all operators or personnel observing the autonomous shuttle car's operation should have the ability to issue an emergency stop, and personnel who encounter the vehicle should be able to quickly understand its current mode of operation or changes in mode of operation.

User Class 1 – Controlling Operator

The controlling operator has the ability to monitor the vehicle using a handheld HMI, issue commands to start or pause normal operations via the handheld HMI, and the ability to issue emergency stops via the handheld HMI. The current design principal is that a single operator will be given the role of Controlling Operator, to prevent conflicting commands, duplicate commands, or uncertainty about the issuing of commands. If personnel from other user classes would like the shuttle car to change operation (except for an emergency stop), they must request it via radio to the Controlling Operator. This user class will receive extensive training on the shuttle car's operations and the HMI of the controls.

User Class 2 – Monitor (also: Monitoring Operator)

Personnel who need the ability to monitor the activity of the autonomous shuttle car will be classified as Monitors. The main person who will be in this user class is the operator at the continuous miner who will manually maneuver the autonomous shuttle car to perform loading operations. The section supervisor or engineer may also be included in this user class based on subsequent interviews and pilot testing. Users in this class will have access to a modified version of the Controlling Operator's HMI. This modified HMI will remove the commands for Starting or Pausing operation. If a Monitor determines that an autonomous shuttle car needs to Start or Pause, they would communicate this to the Controlling Operator for the commands to be issued. However, any users in this class will have the ability to issue emergency stop commands to each autonomous shuttle car as a safety precaution. This user class will also receive extensive training on the shuttle car's operations and the HMI of the controls, though they will only have access to a limited version of the HMI.

User Class 3 – Observer

Last, any personnel who work in proximity of the autonomous shuttle cars but are not responsible for controlling or monitoring are classified as Observers. Observers will be able to discern the current mode of operation from external HMI displays (i.e., lights, colors, sounds, or other audio/visual signals). Observers need to be aware of the shuttle car's status and have the ability to communicate potential issues to the Controlling Operator or Monitors via radio. For example, an observer may notice an obstruction in the path of the shuttle car and radio the Controlling Operator to pause the operation so that it can be cleared. This user class will receive training on the shuttle car's operation for safety purposes, but will not be trained on the HMI of the controls. As a safety

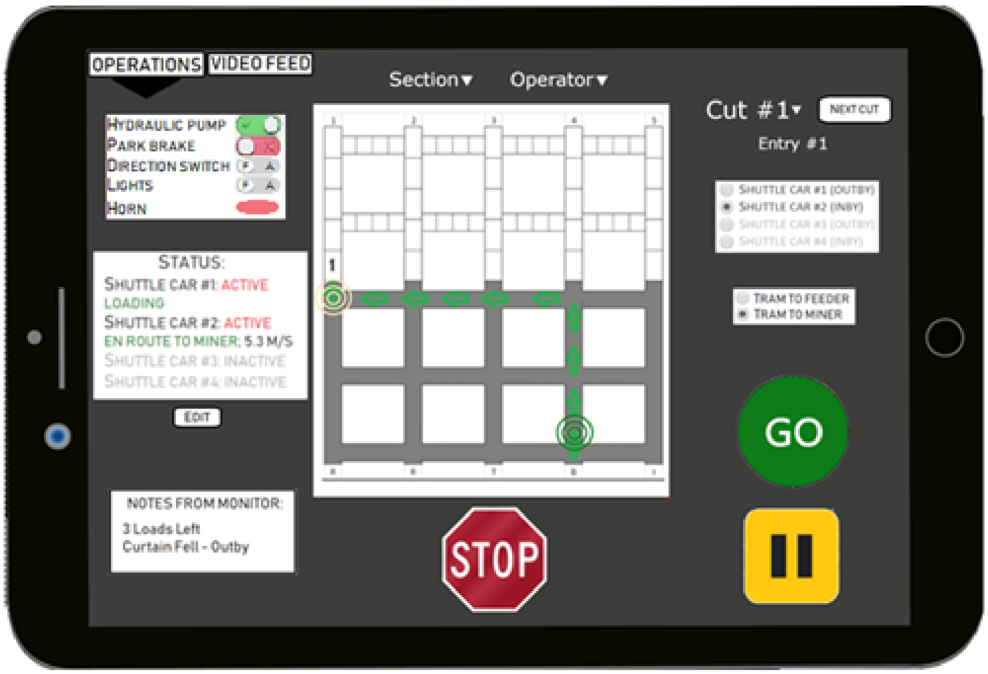

Figure K.1: Tablet-based Prototype Design for Operations Mode for the Controlling Operator

precaution, any personnel working in proximity of the shuttle car for any amount of time will automatically be considered observers and be required to receive necessary training unless they are already a Controlling Operator or Monitor. HMI Design Elements and Functionality

Another critical aspect of the HMI design are the miners who need to interact with the vehicles or need information about the vehicles. There are three major types of HMI that will be necessary based on the requirements for the shuttle car:

- An HMI for the operator with control over the vehicle (Figure K.1 and Figure K.2)
- An HMI for the other non-controlling operator or other miners who need to know the status of the vehicles (Figure K.3)
- An HMI on the exterior of the shuttle car to communicate status or mode of operation to any miners within visual proximity of the shuttle car

The HMI for all the operators who need to monitor the autonomous shuttle cars is critical as they will need to make operational or safety decisions based on this information. All operators will be able to issue emergency stop commands from the interface in safety critical situations, while the controlling operator will be able to issue standard operating commands to initiate a tramming operation or pause a tramming operation. There are several components to the HMI which will be necessary for the controlling operator to perform these duties. First, the HMI will need a graphical layout of the current mining location, along with position information for both shuttle cars in real-time. The graphical layout may also require color coding or changes in icons to represent the modes of operation (tramming, loading, unloading, paused, emergency stop, etc.) each autonomous shuttle

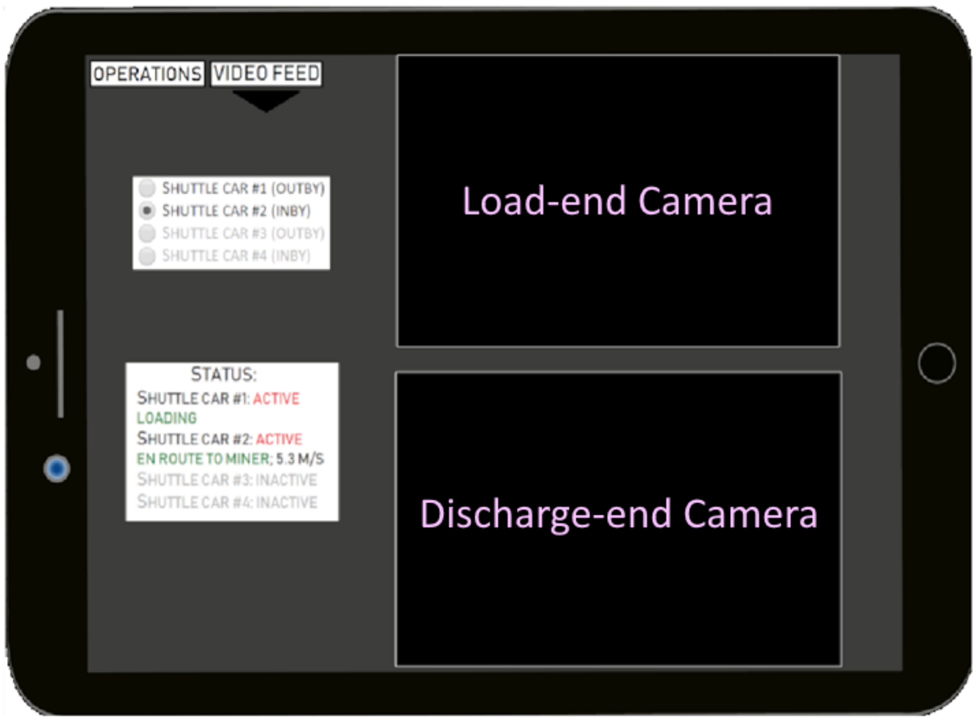

Figure K.2: Tablet-based Prototype Design for Video Feed Mode for the Controlling and Monitoring Operator

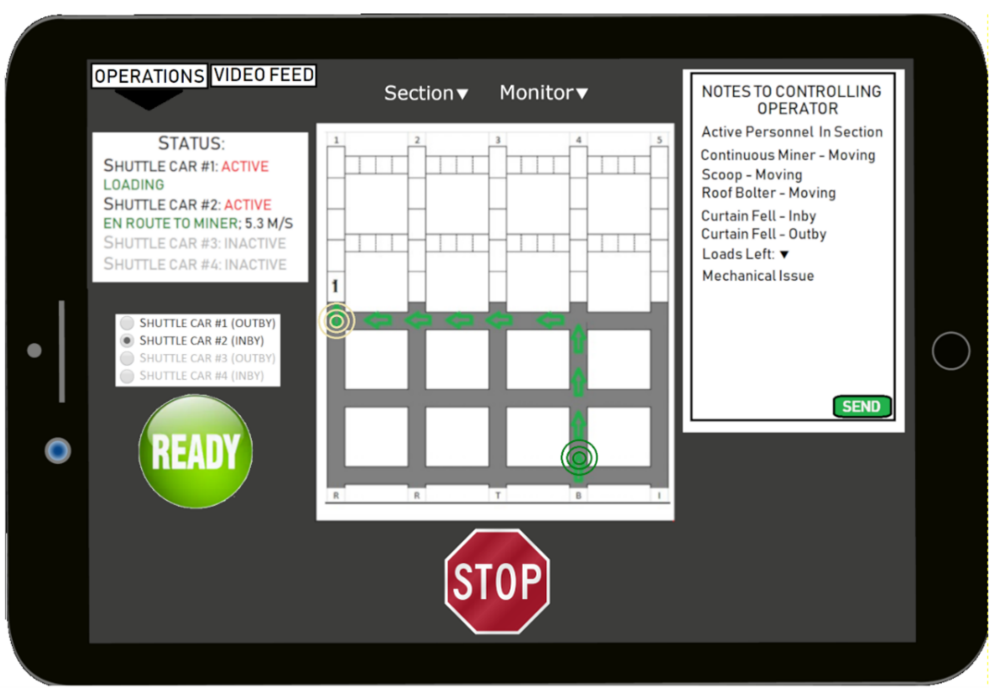

Figure K.3: Tablet-based Prototype Design for Operations Mode of the Monitor car is in. Second, operators need summary information on all shuttle cars in list form. The summary information should include the current mode of operation, the current speed, and the expected time until reaching destination (if the current mode of operation is tramming). Third, the operators will need a control with which to issue an emergency stop command to one or all shuttle cars. This can be a physical control on the device or a touchscreen button, but needs to be clearly labeled and color-coded appropriately for easy recognition. Finally, the HMI should provide information about the current section in which the shuttle cars are operating, and the ability to select different sections if a particular shuttle car is moved to a different section.

In addition to the HMI elements described above, the controlling operator needs the ability to issue start and pause commands to individual autonomous shuttle cars. In order to perform this responsibility, the controlling operator will need a way to select individual autonomous shuttle cars from a list. The list should only allow one shuttle car to be selected, and it should clearly indicate the currently selected shuttle car at all times. Appropriately labeled and color-coded buttons should be available to issue start and pause commands to the selected shuttle car, with the mode of operation displayed in the list described above being updated appropriately. The HMI should also provide a method of opening a live video feed for the currently selected shuttle car to assist with monitoring or decision-making.

In addition to the HMI of devices for monitoring or controlling the shuttle cars, the shuttle cars themselves need an external HMI to communicate their status quickly and effectively through visual signals to an observer. This can be done via lights that are color-coded similar to the buttons on the operator's HMI. There are currently five states that have been identified for external communication. The states are communicated with a combination of colors and flashing of lights. The colors are chosen to be analogous to the meaning of street lights while driving, with green corresponding to movement, yellow corresponding to yielding, and red corresponding to stopping. A solid green light is used to indicate that the shuttle car is tramming in autonomous mode, while a flashing green light is used to indicate that the shuttle car is ready to begin tramming in autonomous mode (for example, after loading or unloading is completed and waiting commands from the operator). A solid yellow light is used to indicate the autonomous vehicle has paused tramming due to a potential conflict or due to the operator issuing a pause command. A flashing yellow light indicates the system is paused and specifically waiting for an operator to assume manual control for loading or unloading. A flashing red light is used to indicate that an emergency stop has been issued, either physically on the shuttle car or remotely via the operator's control panel. Additionally, an audible alarm alerts operators and other nearby miners when the shuttle car is changing modes of operation (i.e., arriving to or departing from a loading/unloading operation). The external HMI was refined through a series of iterations based on feedback from the project team as well as feedback from operators and other miners that need to visually understand the shuttle car mode of operation with quick visual inspection. Table K.20 lists the external shuttle car lights schemas discussed above.

K.6.5 Task Assignment/Reassignment

The introduction of an autonomous shuttle car will most significantly impact the functions of tramming, loading, and dumping. Other functions, such as pre-operational or end-of-shift activities, are affected, but to a lesser degree. Task assignment/reassignment involves identifying work-oriented

Table K.20: External Shuttle Car Light Colors and Meanings

Color	Meaning
Green	Shuttle car is in autonomous or manual driving mode and is moving.
Green (flashing)	Shuttle car has been cleared for moving by the monitor and is awaiting command to begin tramming by the controller
Yellow	Shuttle car is stopped due to an obstacle or operator issuing a pause command.
Yellow (flashing)	Shuttle car has reached its destination and is awaiting manual takeover or remote designation.
Red (flashing)	Shuttle car is stopped due to an emergency stop command.

activities that are either altered for the shuttle car operator or other personnel, re-assigned to the shuttle car for functional purposes, or removed entirely from the breakdown of tasks.

Pre-operational/Post-operational Task Assignment

With involvement of automation, additional pre- and post- operational tasks are required to verify equipment is in operating condition. Additional checks for automation are detailed in Table K.21.

Table K.21: Task Assignment for Pre-operational and Post-operational Tasks

Start-of-Shift Activities	Pre-operational Inspections	End-of-Shift Activities
• Obtain operators' controllers	• Check controller functionality • Check section blocks are accurate • Check cut sequence is uploaded to controller • Check shuttle car active/inactive status • Check remote operation of hydraulic pump • Check remote operation of park brake • Visually examine sensors for damage • Check for placed beacons (if used)	• Return operators' controllers to power center • Record and report any automation issues

Tramming Task Reassignment

Tramming involves the haulage of the coal between the continuous miner vehicle at the active face and the feeder-breaker at the tail-end of the section conveyor belt. The detailed task reassignments are described in Table K.22.

Table K.22: Detailed Task Reassignment during Tramming Operations

Tasks Assigned to Shuttle Car	Tasks Altered for Personnel	Tasks Removed
• Depress tram pedal • Keep car centered in roadway • Make a turn traveling inby by lining up front tires with break corners and turning wheels left or right as hard as possible • Make a turn traveling outby by lining up boom end tires with break corners and turning wheels left or right as hard as possible • Observe for persons and obstructions in travel ways • Traveling through ventilation controls/fly pads/curtains • Operate at speed under which control of the shuttle car can be maintained	• Set directional switch (remote) • Start hydraulic pump (remote) • Adjust tram speed using tram dial (remote or autonomous) • Release park brake (remote or autonomous) • Check brake pressure • Check steering • Turn lights on in direction of travel (remote) • Replace any damaged ventilation controls • Be aware of other equipment and cables in travel ways • Ring bell or flash lights (remote)	• Put seat belt on • Keep all body parts within the deck compartment • Clear persons out of shuttle car • Listen for anchor/slap • Use the first row of bolts off the rib to judge the positioning of car • Use existing tire tracks to judge position of car

Loading Task Reassignment

Loading involves the loading of the coal from the continuous miner vehicle at the active face onto the bed of the shuttle car vehicle through use of a chain conveyor. Currently, the loading and dumping operational tasks are expected to be performed manually by the controlling operator (unloading) or the monitoring operator (loading). If full automation is attainable, which includes docking to the continuous miner and operating the chain conveyor to load the coal on the shuttle car, tasks would be significantly altered. The detailed task reassignments with full automation engaged are described in Table K.23.

Unloading Task Reassignment

Unloading involves the unloading of coal from the shuttle car into the feeder-breaker through use of a boom and lift. Currently, the loading and dumping operational tasks are expected to be performed

Table K.23: Detailed Task Reassignment during Loading Operations with Full Automation

Tasks Assigned to Shuttle Car	Tasks Altered for Personnel	Tasks Removed
• At the miner, hold car over to the left rib • Avoid miner cable and operator • Center the car (as much as possible) under boom • Turn shuttle car wheels toward miner operator while loading (sitting under the boom) • Do not bump back of miner • Ensure miner operator is not near the load end of the shuttle car during loading • Change the direction of your lights • Ring bell • Tram to feeder	• Tram to continuous miner • Observe roof over miner operator for loose roof or ribs/Red Zones • Maintain communication with miner operator • Watch the tail boom of the miner and as coal builds up, run the chain to load car as evenly as possible without overloading/spilling • Stop loading coal within a foot of the end of boom • Listen for spillage • Observe for miner operator signal when car is loaded • Observe second row of fully intact roof bolts • Be aware of other car switch out points and scoop activity	N/A

manually by the controlling operator (unloading) or the monitoring operator (loading). If full automation is attainable, which includes docking to the feeder-breaker and operating the boom/lift to unload the coal into the feeder-breaker, tasks would be significantly altered. The detailed task reassignments with full automation engaged are described in Table K.24.

Communication Activities

Certain tasks are significantly altered regarding communication that occurs during routine or emergency operations. The impact that the introduction of automation has is detailed in Table K.25 by the task activity, along with strategies for coping with, solving, or altering personnel or machinery functionality to manage the identified task changes.

Table K.24: Detailed Task Reassignment during Unloading Operations with Full Automation

Tasks Assigned to Shuttle Car	Tasks Altered for Personnel	Tasks Removed
• Slow down • Center car on feeder • Position boom so coal drops in center of feeder • Dump load • Turn lights in direction travel • Sound audible alarm • Pull off the feeder • Return to continuous miner	• Look for any activity around feeder • Make sure feeder is on prior to dumping • Lower boom • Raise boom as coal load is dumped • Slow down dumping when discharging rock to allow the crusher ample processing time • Report excessive spillage to supervisor • Look and listen for unusual sounds, smells in the feeder area	N/A

Table K.25: Recommended Strategies for Communication Systems

Task	Status	Automation Impact	Strategies
Maintain communication with cont. miner operator (CMO)	Existing Task	Controlling operator is removed from direct communication with continuous miner operator	• Monitoring operator will be stationed near continuous miner operator. • Increased Radio communication between operators • Controlling operator can trigger audible alerts through controller • Monitoring operator can send controlling operator information

Continued on next page

Task	Status	Automation Impact	Strategies
Sound audible alarm before tramming (voice or bell)	Existing Task	Controlling operator is unable to ring bell or honk from within shuttle car when beginning tram	• Controlling operator can trigger audible alerts through controller • Controlling operator has ability to trigger horn or other alerts • Differing alert pitches or sounds between beginning and ending tramming
Observe for persons and obstructions in travel ways	Existing Task	Shuttle car operator (SCO) is unable to locate persons or obstacles while autonomous shuttle car is tramming	• Controlling operator can be provided access to shuttle car camera displays through cable connections • Additional proximity sensors on personnel to account for pedestrians • Automation sensors can provide feedback to Controlling operator on unusual activity • Automation sensors can alter behavior based on obstructions in travel way
Travel through ventilation controls, sound audible alarm	Existing Task	SCO is unable to locate ventilation controls or obstacles when removed from vehicle	• Controlling operator can trigger audible alerts through controller • Controlling operator can be provided access to shuttle car camera displays through cable connections • Automation sensors can provide feedback to Controlling operator on ventilation controls • Continuous audible alert can be present during tramming on autonomous shuttle car

Continued on next page

Task	Status	Automation Impact	Strategies
Observe for continuous miner operator signal when car is loaded	Existing Task	SCO is removed from direct communication with continuous miner operator	• Radio communication between operators • CMO can trigger alert to SCO through controller
Stop work of autonomous vehicle when signaled by pedestrian	New Task	SCO is removed from direct communication with pedestrians	• Radio communication between operators • Additional proximity sensors on personnel to account for pedestrians

Emergency and Unusual Activities

A number of emergency activities may exist with the presence of automation. Table K.26 contains additional emergency task assignments. A number of scenarios related to automation fail-safes and will be developed in tandem with the shuttle car automation.

Table K.26: Emergency and Unusual Scenario Tasks and Duties

Unusual Situations, Emergencies, Non-routine Duties
• In the event of a fire, immediately use the 'Stop' button on controller • In the event of a ceiling collapse, immediately use the 'Stop' button on controller and alert all personnel • In the event of a loss of brakes, immediately alert all personnel • In the event of a loss of communication with the autonomous shuttle car, immediately alert all personnel • In the event of a workplace injury, immediately use the 'Stop' button on controller and alert all personnel • In the event of loss of communication between the shuttle car and either controller, the shuttle car will stop, shut down tramming and pump and sound an alarm or give a visual indication of what happened

K.7 HMI Design Elements

This section provides a detailed breakdown of all elements on the operating controller and monitor controller. Figure K.4, Figure K.5 and Figure K.6 display numbered elements with matching descriptions.

The controlling operator will have primary control of all active shuttle cars, designating the travel paths and engaging automation. The user interface displays all information and options available to the controlling operator during routine underground mining operations. The components of the interface are broken into the following items:

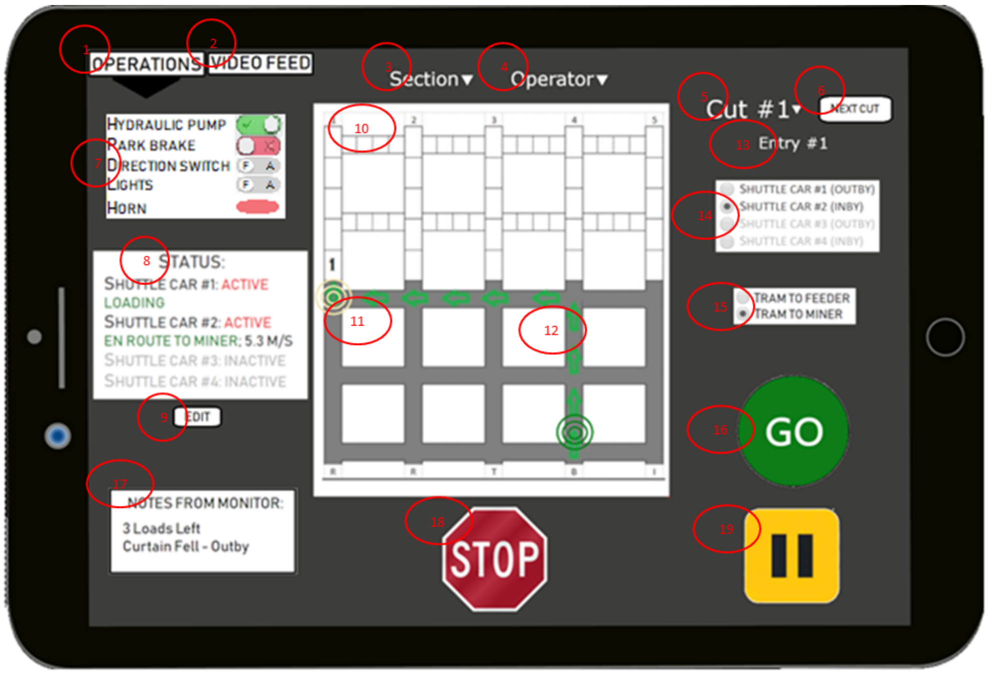

Figure K.4: Element Notation for Controlling Operator’s Controller in Operations Mode

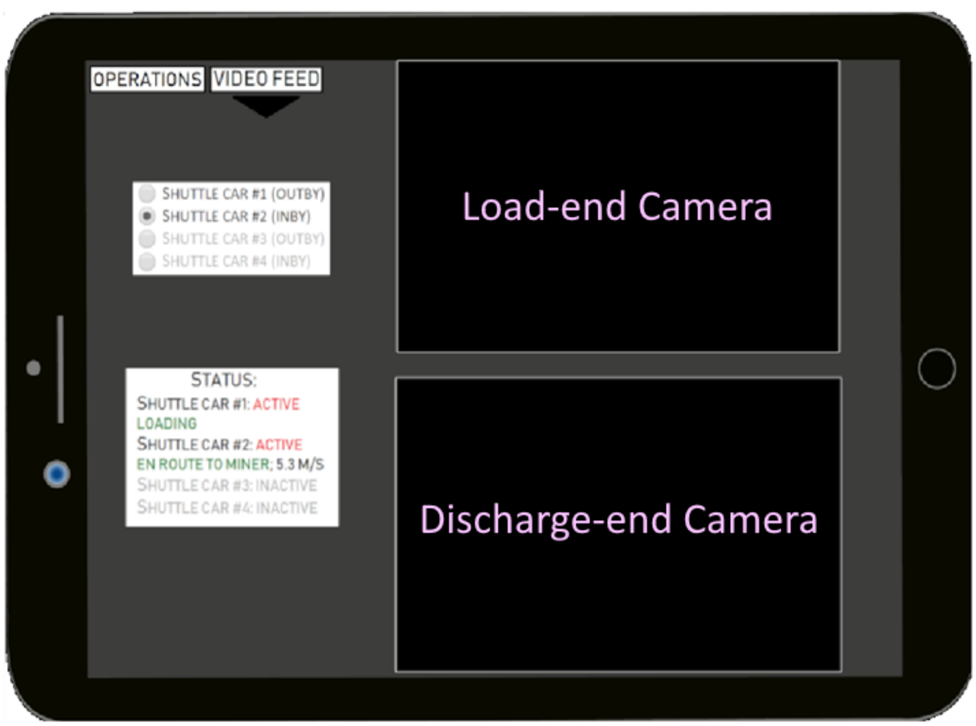

Figure K.5: Element Notation for Controlling Operator’s and Monitoring Operator’s Controller in Video Feed Mode

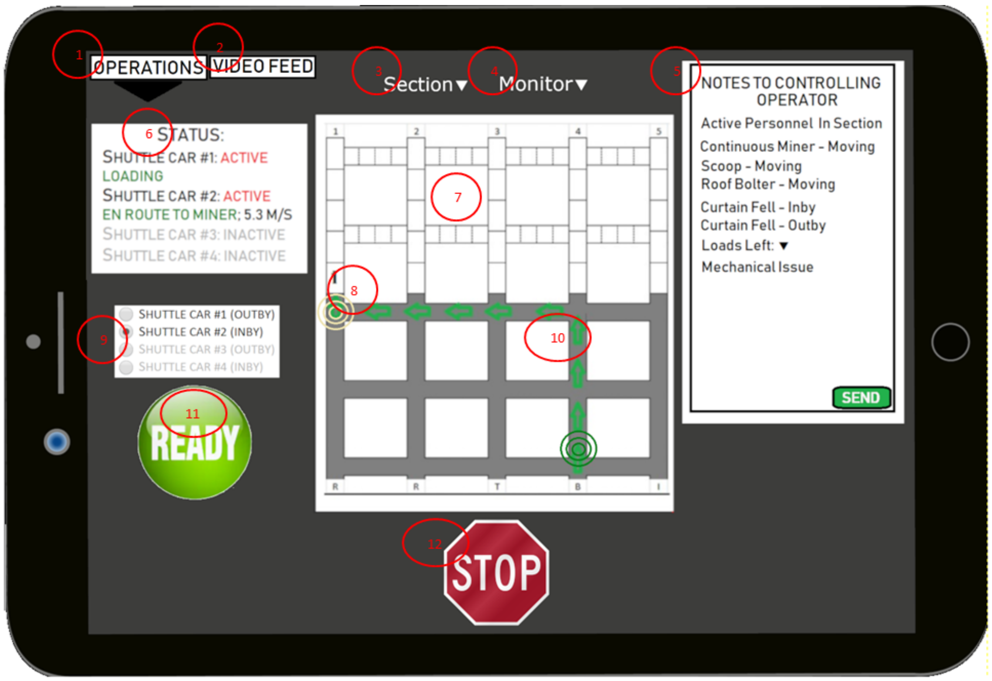

Figure K.6: Element Notation for Monitoring Operator's Controller in Operations Mode

1. Operations Tab: A selectable tab that displays the current operational status of the selected section (as displayed in Figure K.4). Switching between tabs is performed by tapping the desired tab.

2. Video Feed Tab: A selectable tab that displays the shuttle car selection choices and connected video feeds (as displayed in Figure K.5; see notation in the following section for more details).

3. Section Selection: All working sections will be available in a drop down menu per site or organization. Selecting between working sections will alter the material presented to the controlling operator. For example, certain sections may have additional shuttle cars (see Item 14: Shuttle Car Selection) or a different number of entries or cut sequence (see Item 10: Section Map). To prevent user error or interference, only one operator may operate the shuttle cars within the section, and will do so by enabling a 4-digit user passcode after selecting their operator ID (see Item 4: Operator Selection). This will prevent multiple users from having control access to the same shuttle cars at the same time.

4. Operator Selection: All working sections will have designated operators, preventing users from erroneously or intentionally interfering in another section's face haulage operations. Within a section crew, the shuttle car operator(s), section foreman, and mechanic will have access to operate the shuttle car controller, typically in the event of an emergency. Tapping on the operator tab will produce a drop-down menu to select the user, which will prompt entry of a 4-digit passcode.

5. Cut Number Selection: All cut numbers within a cut sequence will be available for selection, as updated by management and engineers every 3rd shift. After a cut is complete, the number will be removed from selection.

6. Cut Complete/ Next Cut: The 'Next Cut' button allows the controlling operator to designate that the current cut is complete as well as easily switch to the next cut in the cut order. If a cut is started but not completed, the controlling operator should not use this button and instead use the drop down cut selection. If the controlling operator is returning to an incomplete cut to mark complete, the cut number must be re-selected and marked complete. This will provide the autonomous shuttle car more information during tramming operations.

7. Shuttle Car Features: These features display toggles or buttons that display options as well as current status of the shuttle car.

   (a) Hydraulic Pump: The pump must be activated before beginning operations and should remain active for the duration of the operations as needed. If the user attempts to disable the pump from the interface, a confirmation pop-up will appear. Red and green colors allow quick visual checks by the operator. Remotely disabling the hydraulic pump from the interface will not be allowed when the vehicle exterior toggle is in manual operation.

   (b) Park Brake: The park brake must be deactivated before beginning tramming operations. If the user attempts to enable the park brake while the vehicle is in motion, a confirmation pop-up will appear. Red and green colors allow quick visual checks by the operator. Remotely enabling the park brake from the interface will not be allowed when the vehicle is in manual operation.

   (c) Direction Switch: The directional switch allows the controlling operator to switch between inby and outby (i.e., towards miner and away from miner, respectively) driving modes. This will occur automatically when the miner toggles tram direction (See Item 15: Tramming Options), or after the shuttle car is cleared as 'ready' by the monitoring operator (see Figure K.6). Remotely switching direction from the interface will not be allowed while the shuttle car is in motion nor when the vehicle is in manual operation.

   (d) Lights: The lights may be toggled between inby and outby using the interface. Additionally, holding down the lights switch will toggle both inby and outby lights on/off. Remotely switching direction from the interface will not be allowed while the vehicle is in manual operation.

   (e) Horn: This button will allow the controlling operator to remotely activate the horn. Remotely pressing the horn from the interface will not be allowed while the vehicle is in manual operation.

8. Shuttle Car Status: Relevant information for the controller operator regarding shuttle car status will be available for easy reference. Active/Inactive status, current operational activity, tram speed, and other information may be presented to the controller operator. The information displayed can be customized based on user needs (See Item 9: Shuttle Car Status Edit).

With tramming-only automation, the status box can also convey paused or stopped shuttle cars, or when it is in manual operations mode.

9. Shuttle Car Status Edit: The edit button allows the controlling operator to adjust the information displayed in the shuttle car status box. Such information would not be critical for continual monitoring, but could be inspected. For example, the controlling operator may cycle through information that is normally presented to them within the shuttle car, such as steering or brake circuit pressure, cable reel pressure, or tire position. Certain information would not be able to be customized to not be displayed, such as the manual operations mode status.

10. Section Map: The section maps and cut sequences for each section would be uploaded into the tablet as they are updated by the engineers and management. All labeled cuts would be displayed on the tablet to identify upcoming cuts. Further, information regarding intake and return air, feeder-breaker location, and power center may be labeled. The map will be customizable according to the number of entries and section blocks. The map will be critical in the path planning of the autonomous shuttle car.

11. Shuttle Car Location: Shuttle car estimated locations will be displayed on the section map based on localized information obtained from shuttle car sensors, and may be corrected when at or passing a beacon (if any). The shuttle cars locations will be displayed as green, yellow, or red pulsing pings that reflect a shuttle car in transit, paused, or stopped, respectively.

12. Shuttle Car Path: The shuttle car path will be displayed as arrows showing the direction of travel for the selected shuttle car (See Item 14: Shuttle Car Selection). This path is automatically generated based on the selected tramming direction option (See Item 15: Tramming Options). Rerouting will be available by holding and dragging a path from the feeder-breaker to the continuous miner. A confirmation pop-up must be acknowledged when deviating from the generated path. Paths that overlap other shuttle cars generated paths will not be allowable. In the event that both paths must be rerouted, the controlling operator would have to perform one reroute at a time. The automation-related tramming of the shuttle car will follow the outlined path after pressing “Go” (See Item 16: Operational “Go”).

13. Entry Number Reference: The entry number reference will display the entry number of the selected cut and will be automatically generated. If an entry is erroneously associated with a cut, the controlling operator will be manually able to adjust entry after entering a 4-digit passcode.

14. Shuttle Car Selection: The controlling operator must choose a shuttle car before performing any actions (i.e., selecting travel path, beginning tram). The display will show the active and inactive shuttle cars after a section is chosen (see Item 3: Section Selection). Shuttle cars will be labeled by their operating route. Typically, ‘A’ and ‘B’ options will be shown for a dual shuttle car operation, but a third car would be designated as a ‘C’ option for denoting to the controlling operator.

15. Tramming Options: The tramming options will display the current automation options for the shuttle car when in automation mode. Expanded functionality to display additional options will be possible if docking to the continuous miner or the feeder-breaker is developed during the course of the project. Once the monitoring operator readies the vehicle, the tramming option will switch to the appropriate route. Altering the tramming option will change the shuttle car path arrows (see Item 12: Shuttle Car Path).

16. Operational "Go": The "Go" button will begin the automation according to the chosen section, cut number, entry number, shuttle car, and tramming options. This button is not available when the vehicle is in manual operation or before the monitoring operator confirms that it is able to depart the continuous miner safely (in the event of partial automation). Only the controlling operator's controller has access to begin automation. When tramming, the shuttle car will display a green light to observers to display the status of the vehicle.

17. Notes from Monitor: The monitoring operator will be able to provide notes to the controlling operator without interrupting radio communications. This allows the controlling operator to know status at the continuous miner from the feeder-breaker (e.g., number of loads left in the cut).

18. Operational "Stop": The "Stop" button will immediately stop the shuttle car regardless of its current operation. The hydraulic pump will be disengaged and the parking brake will be enabled when safe to do so. When this emergency stop is enabled, the monitoring operator will be responsible for ensuring safe operations can be continued or will manually assume control of the shuttle car. When stopped, the shuttle car will display a red light to observers to display the status of the vehicle. This button is not available when the vehicle is in manual operation.

19. Operational "Pause": The "Pause" button will temporarily stop the vehicle while it is in automation mode. The vehicle will pause automation when it arrives at its set destination. When paused, the shuttle car will display a yellow light to observers to display the status of the vehicle. This button is not available when when the vehicle is in manual operation.

The user interface displays all information and options available to the controlling and monitoring operator during routine underground mining operations. The components of the interface are broken into the following items:

1. Operations Tab: A selectable tab that displays the current operational status of the selected section (as displayed in Figure K.4 for controlling operator). Switching between tabs will be performed through tapping the desired tab.

2. Video Feed Tab: A selectable tab that displays the shuttle car selection choices and connected video feeds (as displayed in Figure K.5; see notation in following section for more details).

3. Inby Camera View: The inby camera view will display the video feed of the camera on the front of the vehicle, while tramming to the continuous miner.

4. Shuttle Car Selection: The controlling operator must choose a shuttle car to view the video feeds of the shuttle car. The display will show the active and inactive shuttle cars after a section is chose (see Item 3: Section Selection in previous list). Shuttle cars will be labeled by their operating route.

5. Shuttle Car Status: Relevant information for the controller operator regarding shuttle car status will be available for easy reference. Active/Inactive status, current operational activity, tram speed, and other information may be presented to the controller operator. The information displayed can be customized based on user needs (See Item 9: Shuttle Car Status Edit in the previous list). With tramming-only automation, the status box can also convey paused or stopped shuttle cars, or when it is in manual operations mode.

6. Outby Camera View: The outby camera view will display the video feed of the camera on the rear of the vehicle, while tramming to the feeder-breaker.

The monitoring operators will have limited control of all active shuttle cars. The monitoring operators will be able to stop a shuttle car when a problem comes to their attention, they will be able to send notes to the operator controller, and notify the operator controller when the reason/problem that caused the mission to pause is resolved and a shuttle car is ready to resume the mission (only the operator controller has permission to start a shuttle car). The user interface for the monitoring controller displays all information and options available to the monitoring operator during routine underground mining operations. The components of the interface are broken into the following items:

1. Operations Tab: A selectable tab that displays the current operational status of the selected section (as displayed in Figure K.6). Switching between tabs is performed by tapping the tab.

2. Video Feed Tab: A selectable tab that displays the shuttle car selection choices and connected video feeds (as displayed in Figure K.5; see notation in the following section for more details).

3. Section Selection: All working sections will be available in a drop-down menu per site or organization. Selecting between working sections will alter the material presented to the controlling operator. For example, certain sections may have additional shuttle cars (see Item 9: Shuttle Car Selection) or a different number of entries or cut sequence (see Item 7: Section Map). To prevent user error or interference, only one operator may operate the shuttle cars within the section, and will do so by enabling a 4-digit user passcode after selecting their operator ID (see Item 4: Monitor Selection). This will prevent multiple users from having access to the same shuttle cars at the same time.

4. Monitor Selection: All working sections will have designated operators, preventing users from erroneously or intentionally interfering in another section's face haulage operations. Within a section crew, the shuttle car operator(s), section foreman, and mechanic will have access to operate the shuttle car controller, typically in the event of an emergency. Tapping

on the monitor tab will produce a drop-down menu to select the user, which will prompt entry of a 4-digit passcode.

5. Notes to Controlling Operator: The monitoring operator will be able to provide notes to the controlling operator without interrupting radio communications. This allows the controlling operator to know status at the continuous miner from the feeder-breaker (e.g., number of loads left in the cut). The monitoring operator will select the note to send to the controlling operator and push send. The note will remain active until the monitoring operator unselects a note.

6. Shuttle Car Status: Relevant information for the controller operator regarding shuttle car status will be available for easy reference. Active/Inactive status, current operational activity, tram speed, and other information may be presented to the controller operator. With tramming-only automation, the status box can also convey paused or stopped shuttle cars, or when it is in manual operations mode.

7. Section Map: The section maps and cut sequences for each section would be uploaded into the tablet as they are updated by the engineers and management. All labeled cuts would be displayed on the tablet to identify upcoming cuts. Further, information regarding intake and return air, feeder-breaker location, and power center may be labeled. The map will be customizable according to the number of entries and section blocks. The map will be critical in the path planning of the autonomous shuttle car.

8. Shuttle Car Location: Shuttle car estimated locations will be displayed on the section map based on localized information obtained from shuttle car sensors, and may be corrected when at or passing a beacon (if any). The shuttle cars locations will be displayed as green, yellow, or red pulsing pings that reflect a shuttle car in transit, paused, or stopped, respectively.

9. Shuttle Car Selection: The controlling operator must choose a shuttle car before performing any actions (i.e., readying for return trip; see Item 7: Operational "Ready"). The display will show the active and inactive shuttle cars after a section is chose (see Item 3: Section Selection). Shuttle cars will be labeled by their operating route. Typically, 'A' and 'B' options will be shown for a dual shuttle car operation, but a third car would be designated as a 'C' option for denoting to the controlling operator.

10. Shuttle Car Path: The shuttle car path will be displayed as arrows showing the direction of travel for the selected shuttle car (See Item 9: Shuttle Car Selection). This path is automatically generated based on the selected tramming direction option on the controlling operator's controller. Rerouting is available only to the controlling operator.

11. Operational "Ready": The "Ready" button will designate to the controlling operator that the automation may be resumed when a shuttle car is returning from the continuous miner in automation mode. This button is not available when the is in manual operation. When ready, the shuttle car will display a flashing yellow light to observers to suggest automation is ready to resume.

12. Operational “Stop”: The “Stop” button will immediately stop the shuttle car regardless of its current operation. The hydraulic pump will be disengaged and the parking brake will be enabled when safe to do so. When this emergency stop is enabled, the monitoring operator will be responsible for ensuring safe operations can be continued or will manually assume control of the shuttle car. When stopped, the shuttle car will display a red light to observers to display the status of the vehicle. This button is not available when the vehicle is in manual operation.

K.8 HMI Background Components

The following components are not available to controlling or monitoring operators during routine operations:

1. Back-end Section Development: The sections must be created by management and/or engineers before allowing automation to be implemented. These sections will reflect measured distances in the active section to provide the autonomous shuttle car appropriate information. Further, cut sequences must be updated every time the belt is moved and new cut sequences are generated.
2. Automation Logic: The algorithmic logic will consider multiple sources of information when performing automation. This logic is not available to the operators and cannot be altered.
3. Cut Sequence Change: The cut sequence may need to be changed in case of a roof fall or other situation in a particular entry. This logic is not available to the operators; it will only be available to the shift supervisor.

K.9 Modes of Operation

K.9.1 Mode 1: Tramming

The Tramming Mode is when the autonomous shuttle car is in transit between the continuous miner and the feeder-breaker. The individual shuttle cars will take different routes during Tramming Mode, but the operation will be similar for each one. Tramming Mode consists of two sub-modes which correspond to vehicle states: In Transit and Paused. A vehicle that is In Transit while Tramming is in motion, while a vehicle that is Paused while Tramming is at a controlled stop. A vehicle may enter the Pause state due to a command from the Controlling Operator (ex: someone has requested the vehicle pause while they cross its path of travel), or the vehicle can put itself into a pause state due to the inability to proceed (ex: there is an obstruction in the path of the vehicle). There may be minor changes in the external HMI displays to differentiate each kind of pause. Figure K.7 and Figure K.8 demonstrate the strategies analysis for tramming operations. Note that tramming refers from the continuous miner change point to the feeder-breaker.

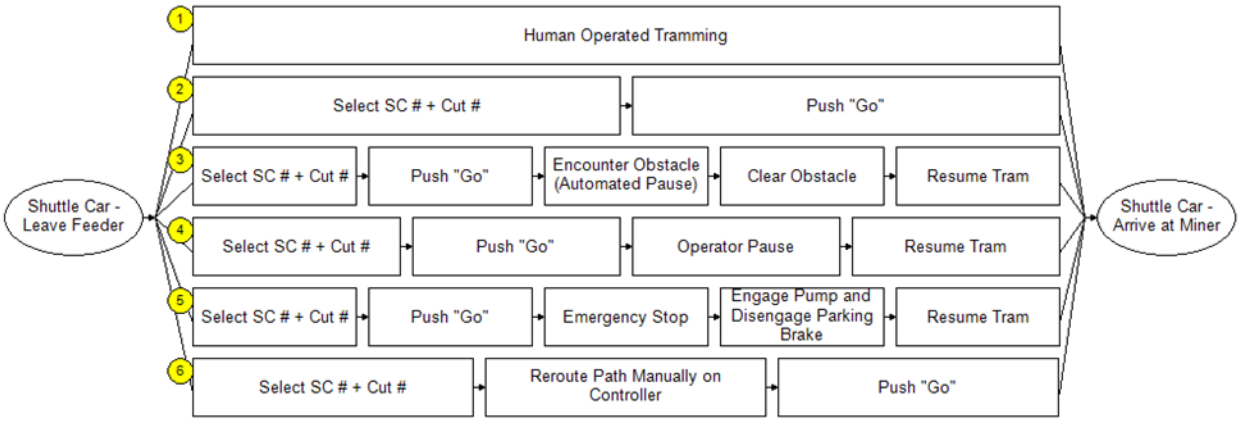

Figure K.7: Strategies Analysis for Tramming-to-continuous-miner Shuttle Car Operations

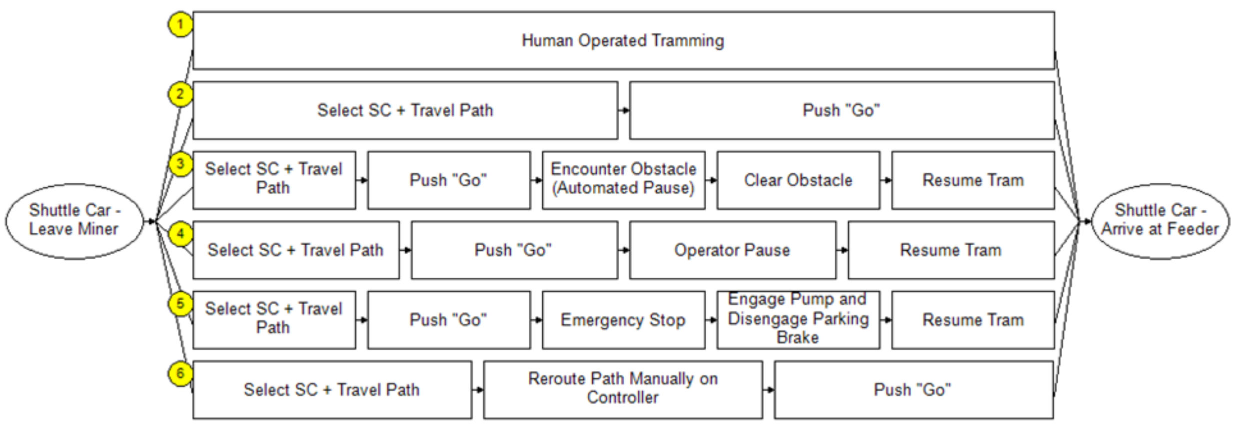

Figure K.8: Strategies Analysis for Tramming-to-feeder-breaker Shuttle Car Operations

Use Case Strategies Analysis: Tramming-to-continuous-miner

1. This scenario involves human-operated tramming from feeder to miner with no automation involved.

2. This scenario involves remote-operated tramming in which the controlling operator chooses the relevant information (section, cut, entry, shuttle car number, direction) and engages the autonomous tramming.

3. This scenario involves remote-operated tramming in which the controlling operator chooses the relevant information (section, cut, entry, shuttle car number, direction) and engages the autonomous tramming. During the tram, the shuttle car automation pauses due to an obstacle (e.g., rock, ventilation curtain) that must be cleared before automation can resume. The controlling operator can resume tramming from the controller or assume manual control.

4. This scenario involves remote-operated tramming in which the controlling operator chooses the relevant information (section, cut, entry, shuttle car number, direction) and engages the

autonomous tramming. During the tram, the controlling operator pauses automation for any reason (e.g., moving miner or bolter, repairing ventilation curtain). The controlling operator can resume tramming from the controller or assume manual control.

5. This scenario involves remote-operated tramming in which the controlling operator chooses the relevant information (section, cut, entry, shuttle car number, direction) and engages the autonomous tramming. During the tram, the shuttle car in automation mode, the controlling operator, or the monitoring operator uses the emergency stop. Before beginning tram again, the hydraulic pump must be engaged (remotely or manually) and the park brake must be disengaged (remotely or manually). The controlling operator can resume tramming from the controller or assume manual control.

6. This scenario involves remote-operated tramming in which the controlling operator chooses the relevant information (section, cut, entry, shuttle car number, direction), but must deviate from the prescribed path by rerouting the shuttle car, and then engages the autonomous tramming.

Use Case Strategies Analysis: Tramming-to-feeder-breaker

1. This scenario involves human-operated tramming from continuous miner to feeder-breaker with no automation involved.

2. This scenario involves remote-operated tramming in which the controlling operator chooses the relevant information (section, shuttle car number, travel direction) and engages the autonomous tramming.

3. This scenario involves remote-operated tramming in which the controlling operator chooses the relevant information (section, shuttle car number, travel direction) and engages the autonomous tramming. During the tram, the shuttle car automation pauses due to an obstacle (e.g., rock, ventilation curtain) that must be cleared before automation can resume. The controlling operator can resume tramming from the controller or assume manual control.

4. This scenario involves remote-operated tramming in which the controlling operator chooses the relevant information (section, shuttle car number, travel direction) and engages the autonomous tramming. During the tram, the controlling operator pauses automation for any reason (e.g., moving miner or bolter, repairing ventilation curtain). The controlling operator can resume tramming from the controller or assume manual control.

5. This scenario involves remote-operated tramming in which the controlling operator chooses the relevant information (section, shuttle car number, travel direction) and engages the autonomous tramming. During the tram, the shuttle car in automation mode, the controlling operator, or the monitoring operator uses the emergency stop. Before beginning tram again, the hydraulic pump must be engaged (remotely or manually) and the park brake must be disengaged (remotely or manually). The controlling operator can resume tramming from the controller or assume manual control.

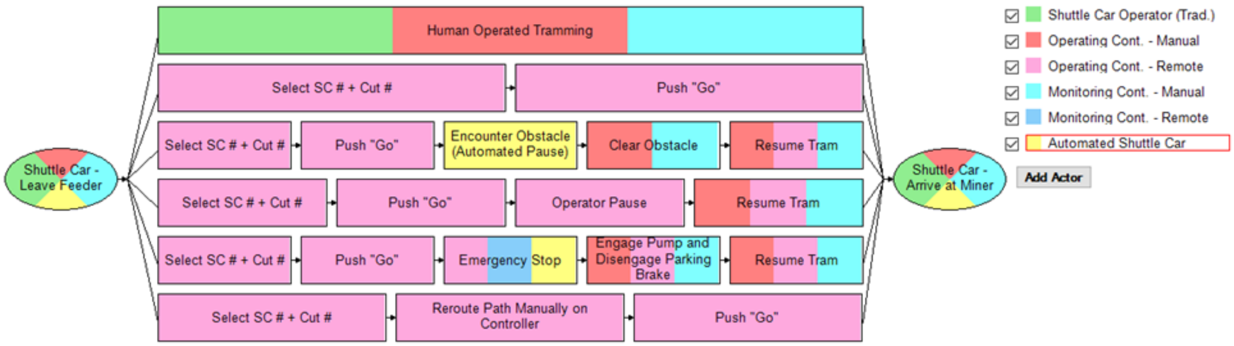

Figure K.9: Strategies Analysis Tramming-to-miner Shuttle Car Operations by Organizational Element

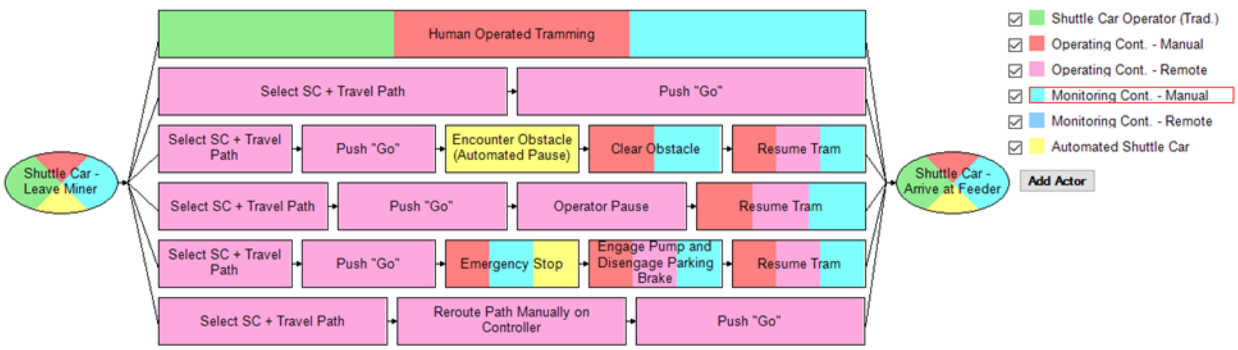

Figure K.10: Strategies Analysis Tramming-to-feeder Shuttle Car Operations by Organizational Element

6. This scenario involves remote-operated tramming in which the controlling operator chooses the relevant information (section, shuttle car number, travel direction), but must deviate from the prescribed path by rerouting the shuttle car, and then engages the autonomous tramming.

Figure K.9 and Figure K.10 demonstrate tramming operations broken down by actor type (i.e., responsible parties).

The actors in the figures represent either personnel or the autonomous shuttle car. Only shuttle car operators and their new roles are represented. The new roles of controlling operator or monitoring operator can either perform the activity manually (i.e., entering vehicle to manually dock) or remotely (i.e., engaging or disengaging automation). Each actor is represented in the legend, and the color of an activity reflects the actor who is responsible for performing the activity. The inclusion of multiple actors within a strategy does not necessarily denote that an action is required from each actor, rather, each actors may independently or collectively perform the activity.

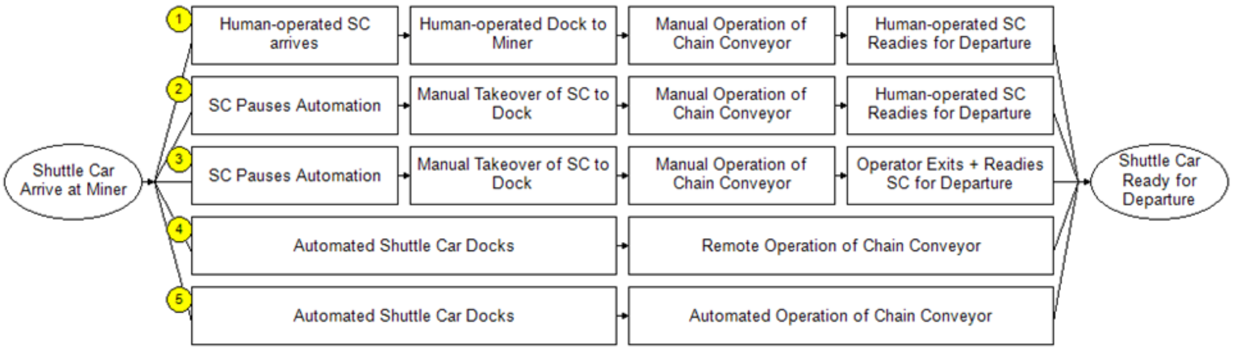

Figure K.11: Strategies Analysis for Loading Shuttle Car Operations

K.9.2 Mode 2: Loading

The autonomous shuttle car enters loading mode once it has completed tramming to the continuous miner. Upon completion of the tramming the shuttle car will enter a pause state to await human input. The human operator will then disable the autonomous controls and enter the shuttle car. Alternatively, the shuttle car could be loaded using remote control provided that the shuttle car is equipped with this functionality. Disabling the automation at this location will change the shuttle car into loading mode. While in loading mode, the human operator manually maneuvers it into position to receive coal on the conveyor belt, and then manually maneuvers it a safe distance away from the continuous miner once loading is complete. Once the shuttle car is in position to resume tramming, the human operator exits the shuttle car, enables autonomous controls, and radios to the Controlling Operator that the shuttle car is ready to begin tramming (or initiates the tramming, if he/she is the Controlling Operator).

Figure K.11 shows the strategies analysis for loading shuttle car operations.

Use Case Strategies Analysis: Loading

1. This scenario involves the continuation of human-operated tramming, in which a human is in control of the vehicle as it arrives at the continuous miner. The operator will then dock to the continuous miner and load coal manually by operating the chain conveyor. The human-operator will then prepare to tram back to the feeder. No automation is engaged in this strategy.

2. This scenario involves the shuttle car arriving at the continuous miner while in automation, then pausing automation until the monitoring operator is able to manually take control to perform docking maneuvers. The monitoring operator will dock to the continuous miner and load coal manually by operating the chain conveyor. The monitoring operator will then prepare to tram back to the feeder without re-engaging automation.

3. This scenario involves the shuttle car arriving at the continuous miner while in automation, then pausing automation until a monitoring operator is able to manually take control to perform docking maneuvers. The operator will dock to the continuous miner and load coal

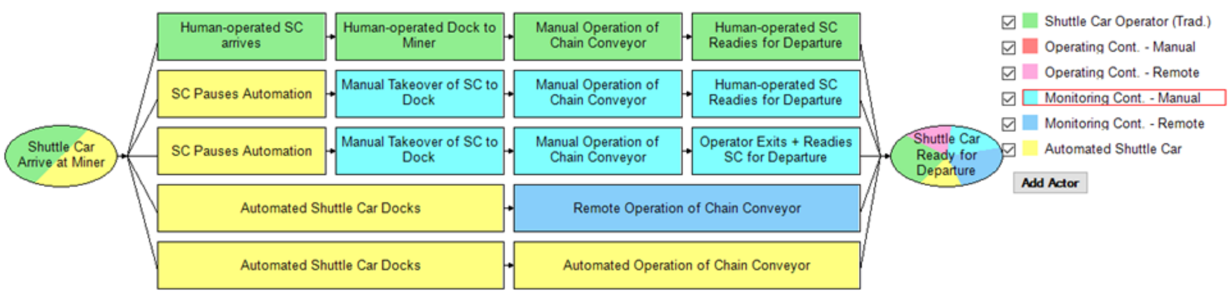

Figure K.12: Strategies Analysis for Loading Shuttle Car Operations by Organizational Element

manually by operating the chain conveyor. The monitoring operator will then exit the vehicle, toggle the exterior switch to resume automation, and remotely ready the vehicle to have automation engaged to tram back to the feeder.

4. This scenario involves the shuttle car docking to the continuous miner while in autonomous mode, then having the monitoring operator remotely engage the chain conveyor for loading coal. This scenario is not slated for demonstration but may be available for eventual integration of automation into the mining operations.

5. This scenario involves the shuttle car perform both docking and loading activities while in autonomous mode. This scenario is not slated for demonstration but may be available for eventual integration of automation into the mining operations.

Figure K.12 demonstrates the loading shuttle car operations broken down by actor type (i.e., responsible parties).

K.9.3 Mode 3: Unloading

The autonomous shuttle car enters unloading mode once it has completed tramming to the feeder-breaker. Upon completion of the tramming the vehicle will enter a pause state to await human input. The human operator will then disable the autonomous controls and enter the vehicle. Disabling the automation at this location will change the vehicle into unloading mode. While in unloading mode, the human operator manually maneuvers it into position to deposit coal into the feeder-breaker, and then manually maneuvers it a safe distance away from the feeder-breaker once unloading is complete. Once the shuttle car is in position to resume tramming, the human operator exits the vehicle, enables autonomous controls, and radios to the Controlling Operator that the shuttle car is ready to begin tramming (or initiates the tramming, if he/she is the Controlling Operator).

Figure K.13 shows the strategies analysis for unloading shuttle car operations.

Use Case Strategies Analysis: Unloading

1. This scenario involves the continuation of human-operated tramming, in which a human is in control of the vehicle as it arrives at the feeder-breaker. The operator will then dock to the continuous miner and unload coal manually by operating the boom/lift. The human-operator

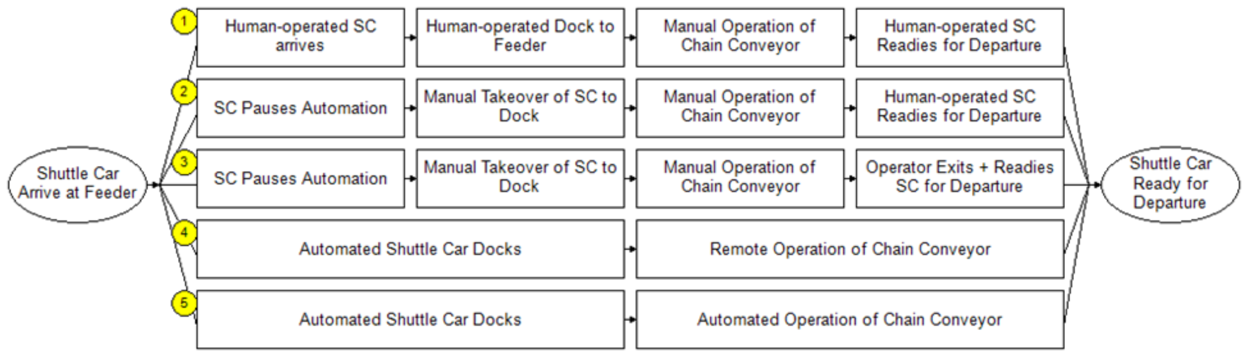

Figure K.13: Strategies Analysis for Unloading Shuttle Car Operations

will then prepare to tram back to the continuous miner. No automation is engaged in this strategy.

2. This scenario involves the shuttle car arriving at the feeder-breaker while in automation, then pausing automation until the controlling operator is able to manually take control to perform docking maneuvers. The controlling operator will dock to the continuous miner and unload coal manually by operating the boom/lift. The controlling operator will then prepare to tram back to the continuous miner without re-engaging automation.

3. This scenario involves the shuttle car arriving at the feeder-breaker while in automation, then pausing automation until a controlling operator is able to manually take control to perform docking maneuvers. The operator will dock to the feeder-breaker and dump coal manually by operating the boom/lift. The controlling operator will then exit the vehicle, toggle the exterior switch to resume automation, and prepare to engage automation to tram back to the continuous miner.

4. This scenario involves the shuttle car docking to the feeder-breaker while in autonomous mode, then having the controlling operator remotely engage the boom/lift for unloading coal. This scenario is not included in this scope of work, but may be available for eventual integration of automation into the mining operations.

5. This scenario involves the shuttle car perform both docking and unloading activities while in autonomous mode. This scenario is not included in this scope of work, but may be available for eventual integration of automation into the mining operations.

Figure K.14 demonstrates the loading shuttle car operations broken down by actor type (i.e., responsible parties).

K.9.4 Mode 4: Emergency Stop

An emergency stop is a mode in which the controlling operator or the monitoring operator has issued an emergency stop command to stop the vehicle, or an observer has pressed a physical emergency

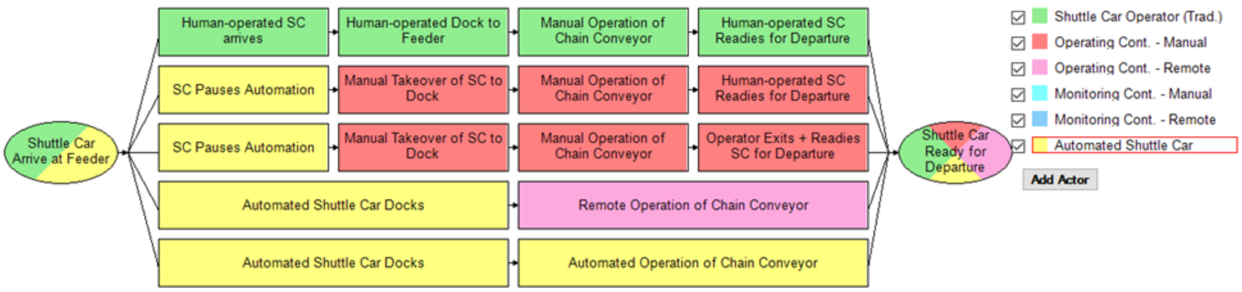

Figure K.14: Strategies Analysis for Unloading Shuttle Car Operations by Organizational Element

stop button on the vehicle (if available). This mode is not part of typical operations, but allows the vehicle to be stopped abruptly with an emergency brake that prevents the vehicle from moving until the mode has been cleared. The controlling operator has the ability to clear the emergency stop, with additional radio protocols to ensure it is safe to do so. Once the emergency stop is cleared, typically through re-engaging the hydraulic pump, the vehicle will return to its previous mode. If the previous mode was tramming, it will resume into the pause state.

K.10 Normal Operations Summary

Normal operations, which consist of tramming, loading, and unloading, will proceed in the following step-by-step process:

1. The shuttle car with perform at least one circuit to ensure accurate mapping of the underground section blocks. This will also allow the automation to determine localization of the shuttle car by measuring distance and referencing any placed beacons.

2. The controlling operator will assume position at the feeder-breaker and the monitoring operator will assume position at the continuous miner with respective controllers.

3. As shuttle cars are available to begin tramming to the continuous miner from the feeder-breaker, the controlling operator will select the appropriate section, cut, shuttle car, and travel direction. The controlling operator then has the authority to engage automation by pressing "Go" on the controller.

4. Both controlling operator and monitoring operator will track the status of numerous shuttle car-related metrics while shuttle cars are active. Video feed will also be available to watch for coal rib or ceiling issues, fallen curtains, and other obstacles in the path.

5. As a shuttle car arrives at the continuous miner, the monitoring operator will be responsible for docking the car appropriately to the continuous miner. The monitoring operator will first ensure the shuttle car is paused before approaching, and will toggle the vehicle exterior switch, disabling automation functionality.

6. The monitoring operator will then dock the shuttle car and load coal as usual by operating the chain conveyor and communicating with the continuous miner operator.
7. Once the shuttle car has been loaded, the monitoring operator may pull away from the continuous miner if the shuttle car needs to be straightened, particularly in the case of miners operating in the cross-cut.
8. The monitoring operator would then exit the vehicle and re-enable the vehicle exterior switch, enabling automation to be re-engaged.
9. The monitoring operator returns to the controller and presses the “Ready” button to let the controlling operator know that it is safe to engage automation. The monitoring operator may provide other notes to the controlling operator as needed.
10. Once available, the controlling operator will ensure the correct shuttle car and tram direction are selected and will press the “Go” button to engage automation and return the loaded shuttle car to the feeder-breaker.
11. As a shuttle car arrives loaded at the feeder-breaker, the controlling operator will be responsible for docking the car appropriately over the feeder. The controlling operator will first ensure the shuttle car is paused before approaching, and will disable the automation functionality.
12. The controlling operator will then dock the shuttle car and unload coal as usual by operating the boom and lift.
13. Once the shuttle car has been emptied, the controlling operator will exit the shuttle car and re-enable the automation by switching the vehicle exterior toggle. The controlling operator will then return to the controller and the process will be repeated from step #3.

K.11 Summary of Impacts

This section provides a summary of the expected operational and organizational impacts of the autonomous shuttle car system. The impacts will be measured by the metrics identified in section K.5.4. The impacts will also be measured within each mode of operation in order to understand if certain modes have different performance. The impacts will also be measured via subjective surveys of system performance, user acceptance, and HMI design.

- Safety Measures
  - Frequency of safety incidents
  - Severity of safety incidents
  - Frequency of emergency stops
  - Percentage of time operator spends in stale air during a shift

- Operational Measures
  - Frequency of cable management issues
  - Frequency of ventilation difficulties
  - Speed of shuttle car while tramming
  - Speed of complete unloading to unloading cycle
  - Percentage of time operator spends in vehicle during a shift
  - Frequency of operator entering and exiting the shuttle car during a shift
- HMI Measures
  - Operator error rate
  - Operator time to complete tasks
  - Frequency of non-operator interactions with shuttle car
- Subjective Measures
  - System performance
  - User acceptance
  - HMI design

K.12 Operational and Organizational Impacts

Changes made to the shuttle car through the addition of automation impacts both operational and organizational systems.

As such, careful consideration is required when incorporating any autonomous system into an organization. Although the project seeks primarily to demonstrate the possibility of automation, the deployment and implementation of an autonomous shuttle car would have both immediate and lasting impacts on the organizational structure and functional systems within the operating mine.

Primarily, depending on automation level during implementation, the functions and responsibilities for the shuttle car operator would shift from the operator in-cab to the controlling operator at the feeder-breaker, the monitor at the continuous miner, and other personnel as various functions and responsibilities are removed with the shuttle car operator driving during tramming.

It is particularly important to understand the limitations of both vehicle automation and organizational systems when incorporating new technologies into a work domain with significant hazards. Ensuring proper training for all section crew and other involved personnel (e.g., engineers or visiting mine managers) on how to operate or engage with the system is a critical component for eventual deployment of automation.

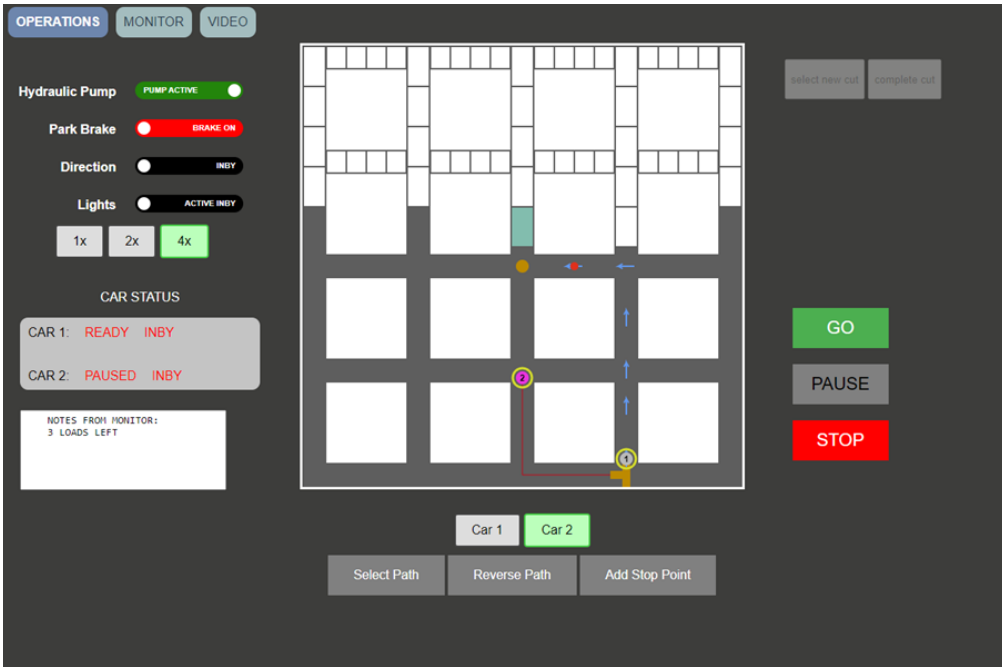

Figure K.15: User end interface highlighting a two-car operation with routing and change points

K.13 HMI Prototype

K.13.1 Prototype development - Phase I

The development of the HMI prototype was designed as a web application with the backend written in Python using the Django web framework and the frontend written as a minimal Vue application with a small collection of static CSS and JS files. Naturally, during the development of the application a number of modifications to the preliminary HMI design was adopted for reasons related to applicability of elements and functionalities in regard to programming language capabilities and limitations, as well as graphic design issues. However, the main functionalities remained unaltered. Screenshots of the HMI interface during the Phase I of the HMI development can be seen in Figures K.15 to K.20.

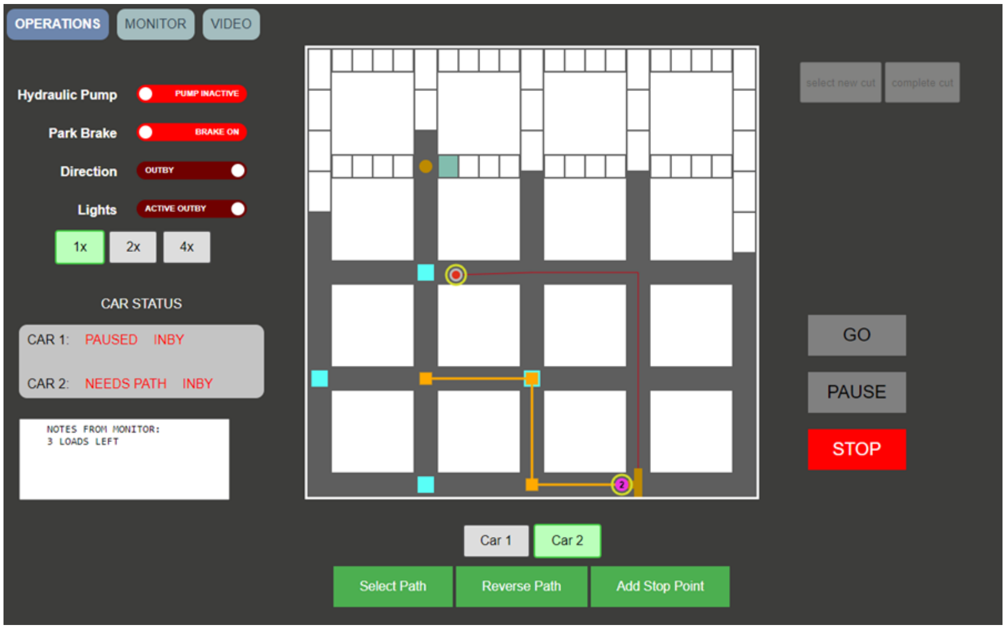

Figure K.16: User end interface highlighting path selection towards the continuous miner in a crosscut

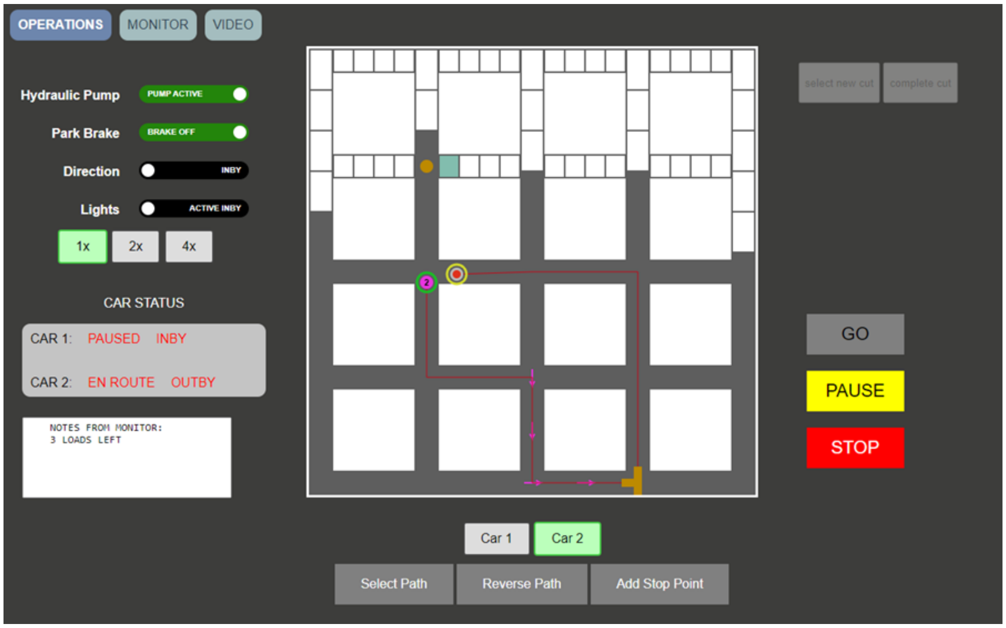

Figure K.17: User end interface displaying shuttle car #2 in automation mode returning to the feeder following the cable path

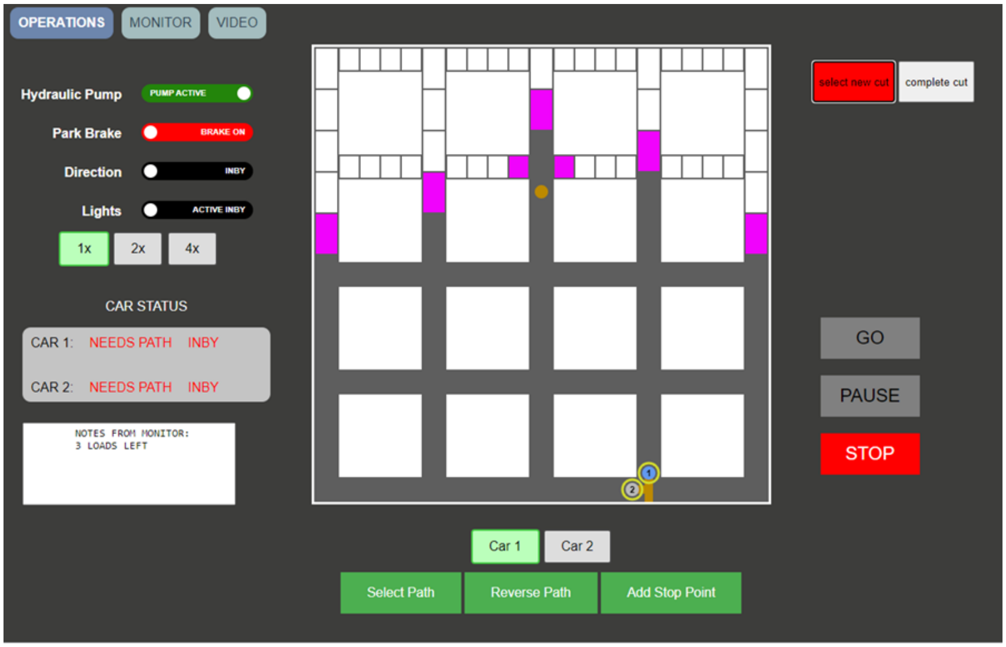

Figure K.18: User end interface highlighting the cut selection choices for the continuous miner

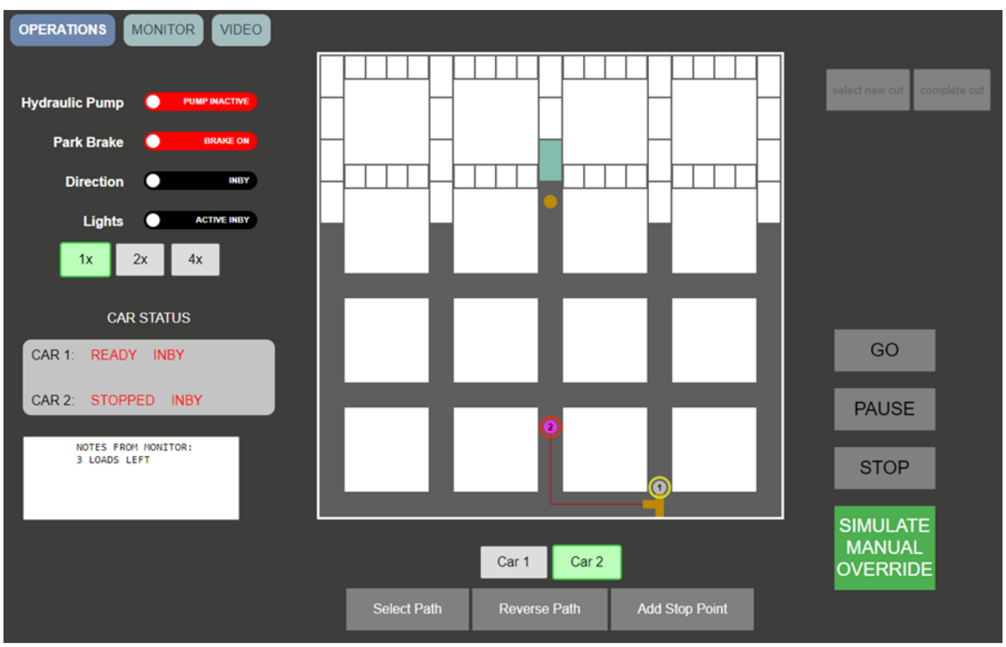

Figure K.19: User end interface highlighting an emergency stop with simulated manual override

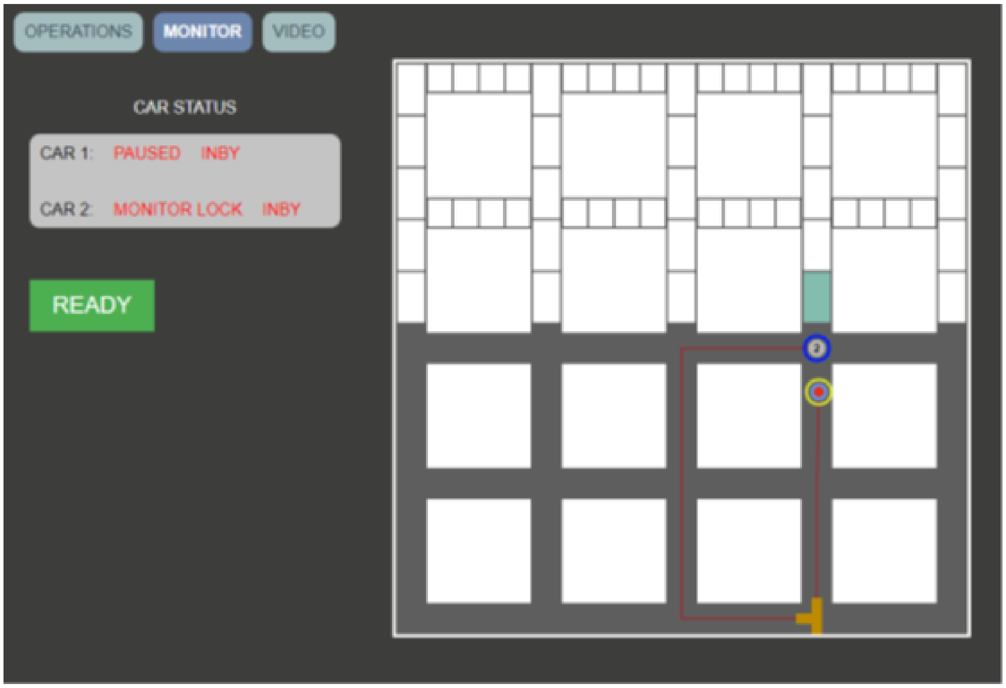

Figure K.20: User end interface of the monitor tab displaying the lockout of the shuttle car automation until the docker releases control after loading the shuttle car

K.13.2 Prototype Development - Phase II

Subsequently the team decided to migrate the frontend to a React web application, while keeping the back-end in the Python language under the Django web framework. At the same time, a number of modifications to the elements of the originally proposed HMI were established:

- The status information regarding main mechanical and operational elements of the shuttle car (e.g., hydraulic pump, brake, lights) were removed. The reason for this modification is that PLC based shuttle cars (as the one that was initially planned to use in this project) do not typically provide any means of retrieving this information. Moreover, both the hydraulic pump and the brake can be activated/deactivated only manually because of current regulations. As a result, it was deemed redundant and impractical to occupy space of the HMI with these elements. However, this did not affect the goal of the project.
- The Video Feedback was omitted since neither the prototypes nor the plans for retrofitting a full-scale shuttle car included visual camera sensors.
- The Monitoring tab was omitted for the sake of simplicity and alleviation of the developing workload.
- The ‘Cut Number Selection’ and ‘Cut Completion’ features were also omitted for the sake of simplifying and expediting finalization of this task.

The final HMI includes the following functionalities:

- Login/Authentication page (see Figure K.21)
- Operator Role Selection page (the user is prompted to select whether s/he is located at the feeder-breaker or at the active face; this can be changed later through the Operator Controller tab; see Figure K.22)
- Operator Controller tab (see Figure K.23) with the following elements/functionalities:
  - Shuttle car selection panels,
  - Operator role switching button (color coded interactive label on the top right corner of the page: blue for the operator at the face, orange for the operator at the feeder-breaker),
  - Current mine section map and path visualization,
  - Path selection drop-down menu,
  - Start/Pause/Resume button,
  - Emergency stop button,
  - Shuttle car status flashing LED (flashing patterns are different for different status in order to facilitate the operator’s understanding),
  - Sensor status warning icon (appears only when at least one of the sensors needs attention)

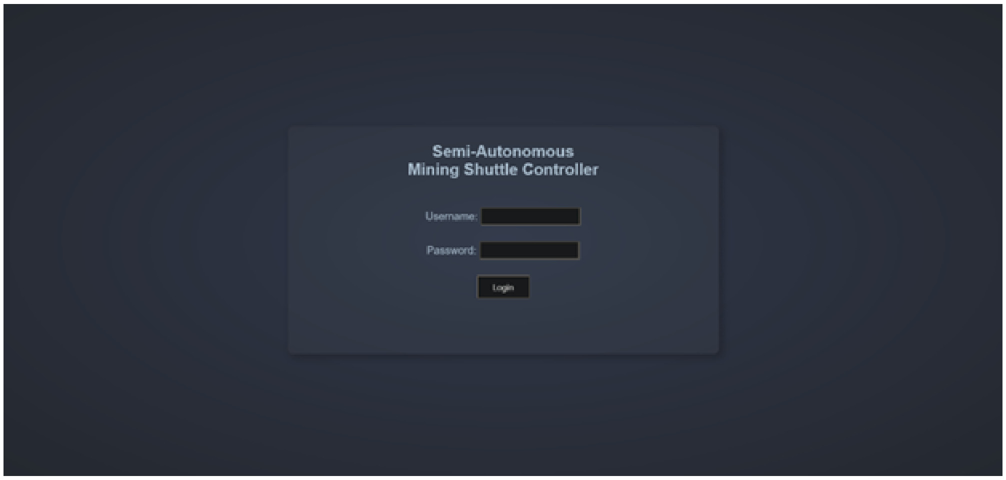

Figure K.21: Login page

Figure K.22: Operator role selection page

  - Stop all shuttle car button (override emergency shutdown)
  - Basic Information display (information about real-time tramming/turning and speed is provided)

- Sensor status pop-up window (appears if the warning icon is clicked, see Figure K.24)
- Options menu sidebar (for development/debugging purposes only, see Figure K.25)
- Errors occurring on the ALC side (e.g., mapping errors, emergency stops initiation, etc.) brought to the attention of the HMI operator (see Figure K.26)

Figure K.23: Main window of Operator Controller tab

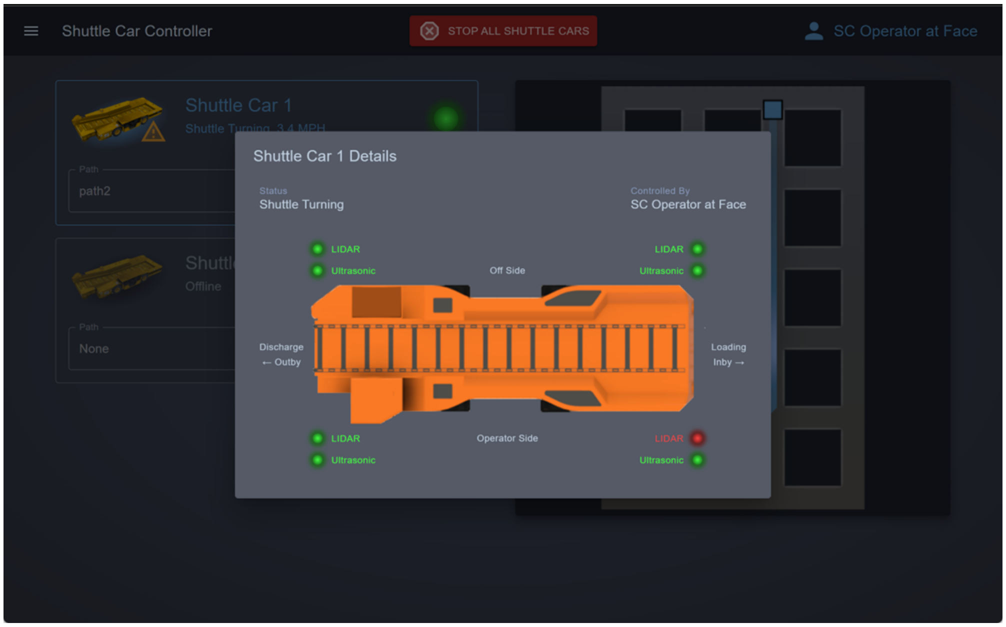

Figure K.24: Sensor status warnings pop-up window

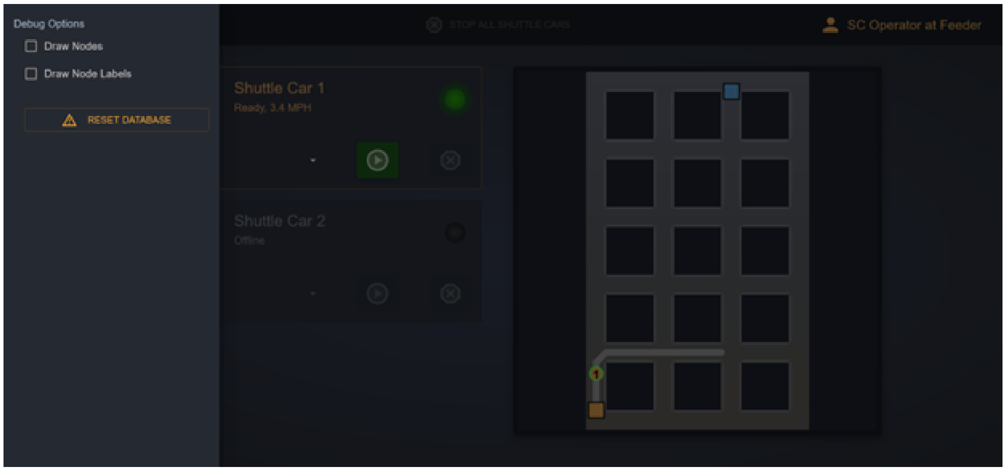

Figure K.25: Options menu sidebar in main window (for development and debugging purposes only)

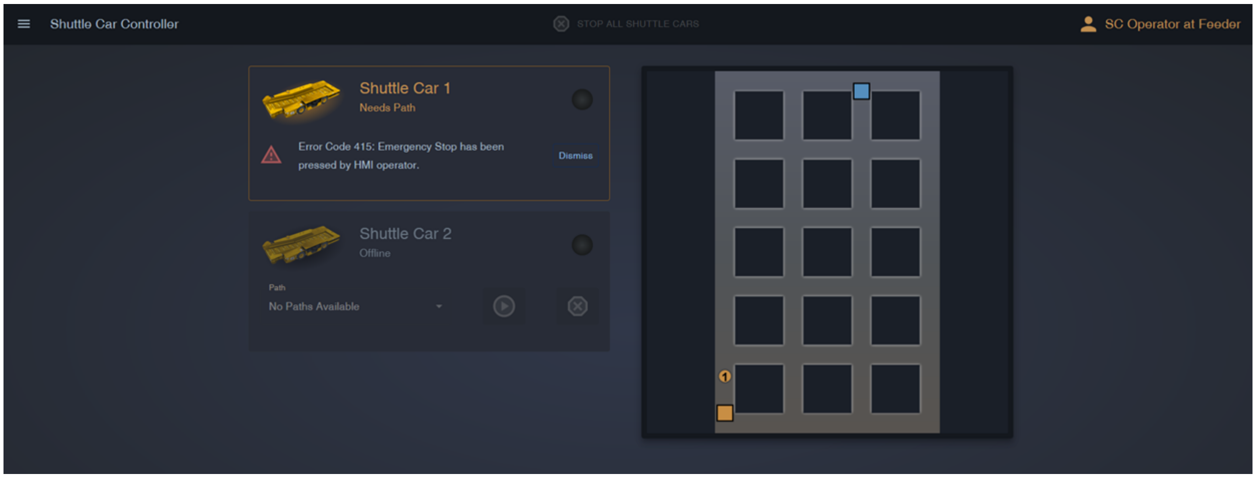

Figure K.26: Example of error/warning pop-up on the HMI side (altern/warning is logged to the MySQL database by the ALC))

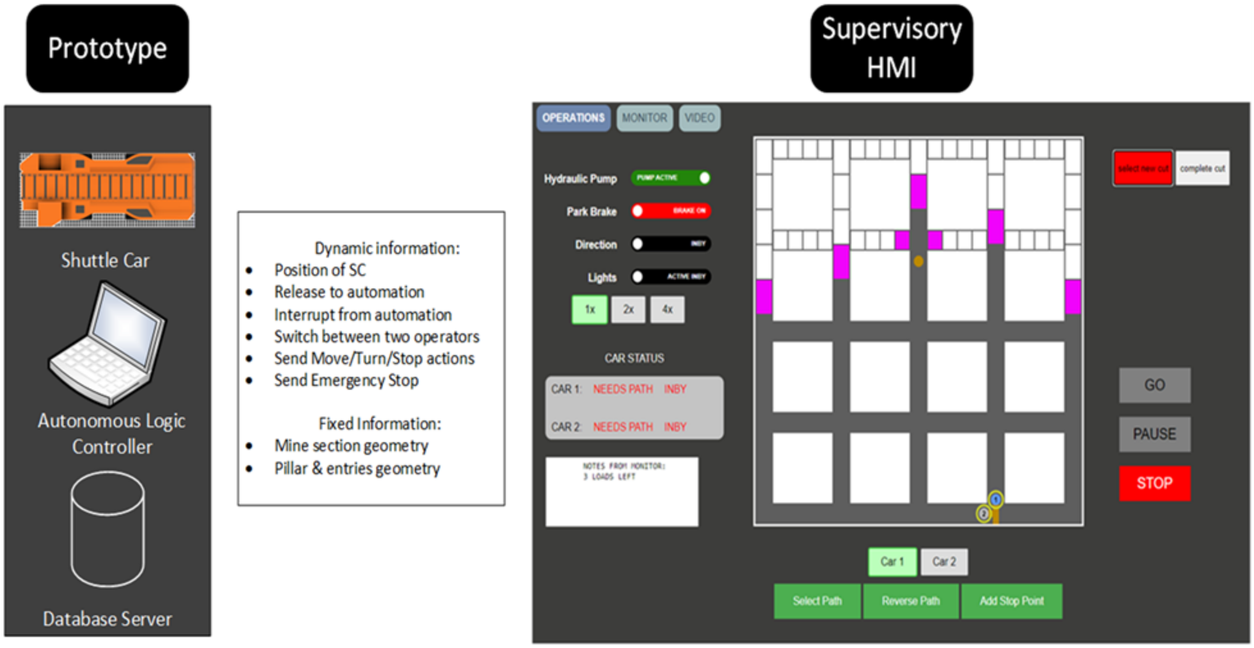

Figure K.27: ALC and HMI schematic interactions

K.13.3 Interaction Regulation between HMI and ALC

Communication Flowchart

The ALC that controls the navigation of the shuttle car and the HMI (that the supervisors located at the feeder-breaker or the continuous miner have on their hands and allow control of the semi-autonomous shuttle car) need to communicate effectively through a framework for information sharing. The HMI should allow selection of the path, initiation/termination of the mission, start/pause/resume actions of the shuttle car movement, and emergency shutdown trigger of the shuttle car. However, because the HMI is designed as a lite application, able to run on a simple, portable tablet, most of this information must be retrieved from the ALC. The ALC is located onboard the autonomous system, where it has direct access to the sensor data (thus minimizing the workload on the wireless network bandwidth) as well as a power source and memory space that will enable the uninterrupted processing of the collected data and the execution of the decision-making algorithms. In other words, the HMI is merely a display of the basic function of the ALC and a tool for remotely controlling the start/stop button of the ALC, as well as for path selection. The information that needs to be shared can either be low-frequency information, such as mine section geometry, pillar, and entry geometry, etc., or high-frequency, such as control triggers (e.g., the status of the mission, the status of shuttle car movement, emergency stop initiation/clearance) and localization of the shuttle car (see Figure K.27).

In order to share the necessary information and control signals, there needs to be an entity that will allow this interaction between the ALC and the HMIs. In the proposed framework, this means was selected to be a MySQL database (Figure K.28). Both applications have access to the database and can register data or retrieve data. Each application has been assigned dedicated tables in the

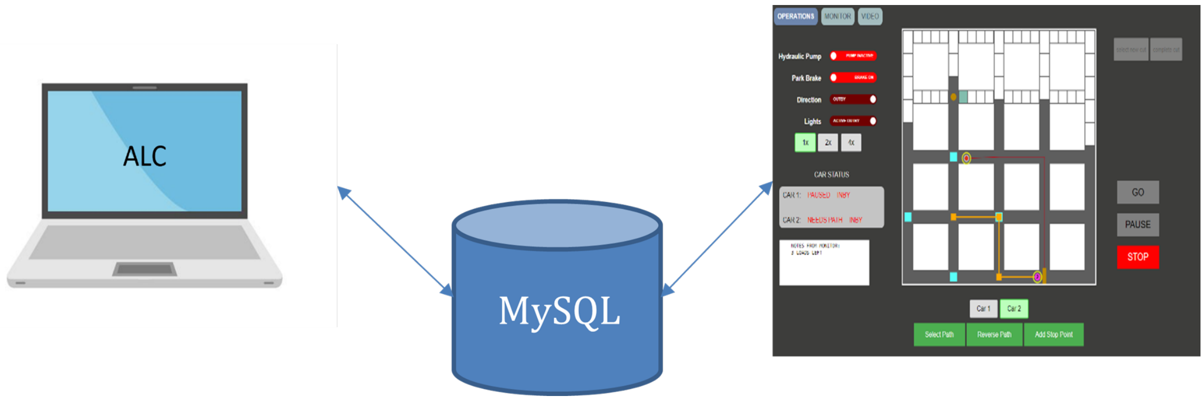

Figure K.28: ALC-SQL-HMI flowchart

database for writing the information that produces itself and at the same time has been assigned read-only permission to the tables assigned to the other application.

Database Schema

The MySQL database consists of 11 tables. These tables can be divided into three categories, with respect to the type of the information they store. These categories include:

- Geometry and paths: Six tables that store the geometry of the mining section, the positions of the feeder-breaker and the continuous miner (in the scope of the project these are assumed fixed for the sake of simplicity) and the possible paths that correspond to the specific geometry (Figure K.29),
- Sensors: Two tables that store the data collected from the on-board sensors and the status of these sensors (Figure K.30), and
- Controls and movement status: three tables that store the control triggers, the status of the mission and the shuttle car movement (Figure K.31).

The tables are described briefly below.

- geometry: Stores the geometric parameters of the current mining section. The information contained in this table will be created by the ALC whenever the geometric parameters of the mining section are modified. This information changes with low frequency and will have to be retrieved from the HMI only when the geometry of the mining section is changed.
- nodes: Stores the x - y coordinates of the map nodes along with a primary key, ‘node_id’ which uniquely identifies each node of the map. The information contained in this table will be created by the ALC whenever the geometric parameters of the mining section are modified. Therefore, this table may change in which case it will have to be retrieved from the HMI every time a new mission is entered by the supervisor.
- paths: Stores the identity and name keys of all the possible paths that are associated with a specific geometry.

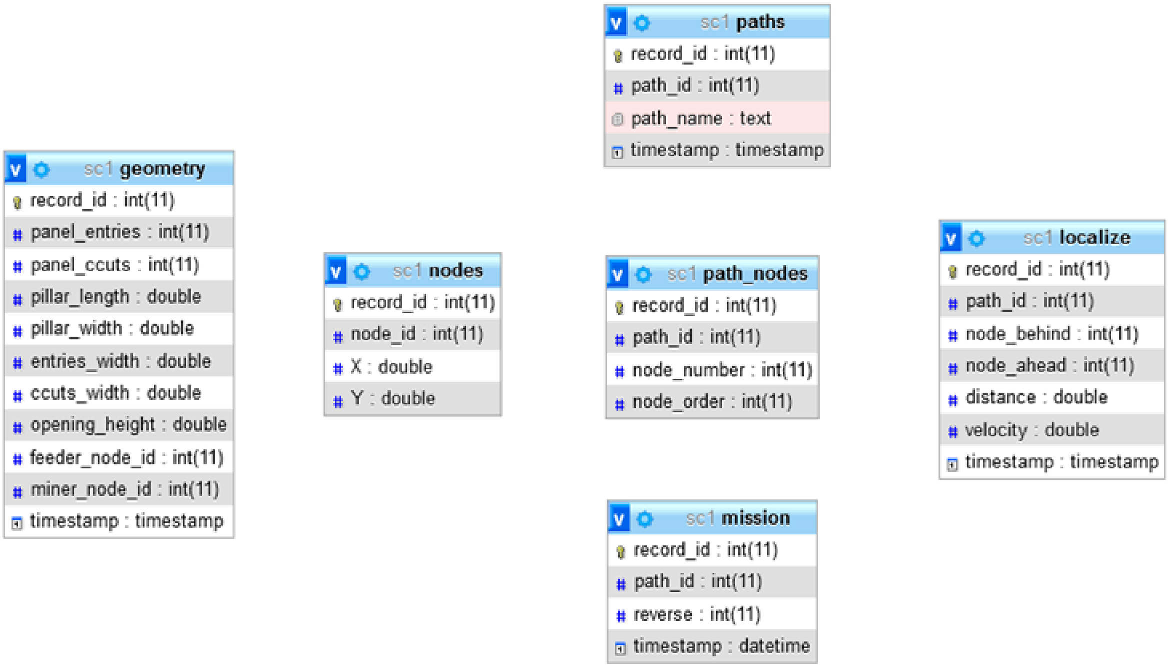

Figure K.29: Geometry and path tables of the MySQL database

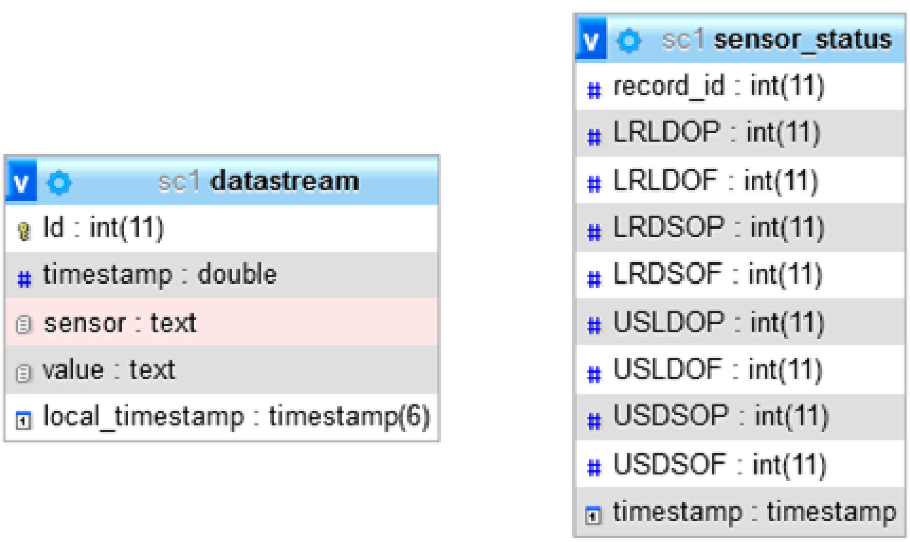

Figure K.30: Sensors tables of the MySQL database

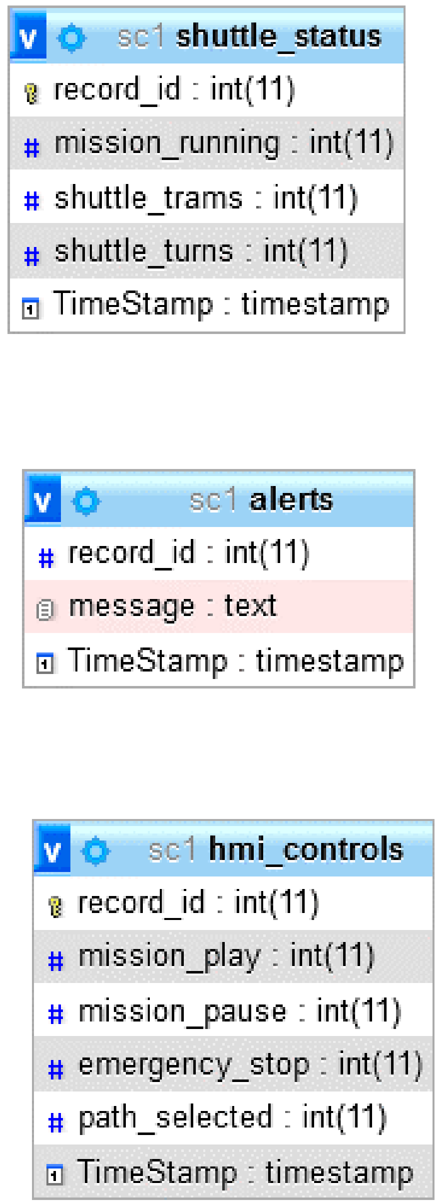

Figure K.31: Controls tables

- path_nodes: Stores in detail every possible path, as these are defined by the ALC interface. A path is specified by the consecutive nodes of the map that make up the path and the corresponding order that they must be traversed. The paths are created by the ALC and retrieved by the HMI when the user logs-in (for visualization purposes).
- mission: Stores the primary parameters that define a mission. The 'path_id' parameter is specified by the HMI user (supervisor) when selecting the desired path from the path library

(drop-down menu). The ALC interface will retrieve that parameter before the mission starts.

- localize: Stores the current position of the shuttle car prototype, as it is calculated by the ALC in real time. The position is defined in terms of the closest node ahead (of the selected path) and the distance of the shuttle car from that node. This information is retrieved by the HMI for visualization and monitoring purposes.

- datastream: Stores the sensor data as it is posted from the Raspberry Pi microcontrollers on-board the prototype. Only the ALC uses that data, i.e., this table is used only by the ALC.

- sensor_status: Stores the sensor status of all on-board sensors (value of 1 if sensor works properly and updates data in the 'datastream' table, value of 0 otherwise). This information is defined by the ALC in real time and retrieved by the HMI for visualization and monitoring purposes while a mission is running.

- alerts: Stores warnings generated by the ALC routines (text message and timestamp) to be displayed to the HMI user.

- shuttle_car_status: Stores a number of boolean parameters (along with a timestamp) that indicate whether the shuttle car is running a mission, as well as whether it is tramming or turning. This information is defined by the ALC in real time and retrieved by the HMI to modify accordingly the status of the HMI buttons.

- hmi_controls: Stores a number of boolean parameters (along with a timestamp) that change every time the control buttons of the HMI are pressed. This information is defined by the HMI in real time and retrieved by the ALC to start/pause/stop according to the given mission.

The information of the last two tables is updated iteratively (high frequency changing information) from both the ALC and HMI interfaces. At the same time, each interface must 'listen' (retrieve from the database) to the control status reported from the other interface. Some exemplary cases are the following:

- the HMI must know whether the ALC stops or resumes the movement of the shuttle car, in order to update its map (primary visual aid of supervisory HMI),

- the ALC must know if the supervisor has initiated, stopped, or resumed the beginning of a given mission, or the emergency stop/shut down has been initiated (HMI has priority over these actions),

- the HMI must know if the decision-making processes of the ALC have terminated the mission due to sensor failures or inadequacy of collected data for decision-making,

- other information to be discussed (e.g., indicators of turning process, etc.)

ALC-HMI Communication and Interaction Specifications

The primary use of the HMI application is to conduct a demonstration of the semi-autonomous shuttle car for the current project objectives. Specific assumptions and specifications apply for the purposes of the initial demonstration. These specifications define how the shuttle car HMI application and the shuttle car control software interaction. Where specific behavior has been defined, the terms WILL or WILL NOT are used. The terms READ ONLY, WRITE ONLY, and READ/WRITE are used to indicate whether the HMI or the ALC is responsible for updating a database table.

1. Paths
    - Paths WILL be generated by the ALC only, the paths table is READ ONLY to the HMI.
    - The HMI WILL NOT do any path validation. It is assumed that all current paths are generated by the ALC and are therefore valid.
    - New paths WILL be generated by the ALC whenever the shuttle car is stopped by an HMI operator (but not when paused). In case of emergencies or critical malfunctions, the operator must stop the shuttle car (and not pause it) so that any commands from the ALC commands queue are cleared for safety. When the situation is cleared, the operator will input a new mission through that HMI.
    - When a new set of valid paths is generated, the new paths will be inserted into the paths table and they all WILL have the same timestamp value.
    - The HMI WILL receive new paths with the 2 Hz update.
    - Paths WILL be valid in only the inby direction. The outby path is identical to the inby path, where the travel direction is reversed.
2. Shuttle Cars
    - There was only one shuttle car used in the demonstration.
    - Where possible, the HMI has been developed to support multiple shuttle cars in the future.
3. HMI Controls
    - The hmi_controls table is READ ONLY to the ALC.
    - The HMI WILL cause a new row to be written into the hmi_controls table with a frequency of 2 Hz. This not only keeps the state of the controls updated; it is used as a heartbeat failsafe, so the shuttle car operator knows the HMI is still running.
    - The ALC WILL stop the shuttle car if it stops receiving hmi_controls updates from the HMI.
    - When the HMI operator clicks on the start button, the HMI WILL write a new row immediately to the mission table containing the path_id of the path selected by the HMI operator.

- When the HMI operator clicks on the start button, the HMI WILL write a new row immediately to the hmi_controls containing the following data: ‘mission_play=1, mission_pause=0, emergency_stop=0, path_selected=1‘
- If the HMI operator clicks on the pause button while the mission is running, the HMI WILL immediately write a new row to the hmi_controls containing the following data: ‘mission_play=1, mission_pause=1, emergency_stop=0, path_selected=1‘
- If the HMI operator clicks on the resume button while the mission is paused, the HMI WILL immediately write a new row to the hmi_controls containing the following data: ‘mission_play=1, mission_pause=0, emergency_stop=0, path_selected=1‘
- If the HMI operator clicks on the stop button while the mission is running or paused, the HMI WILL immediately write a new row to the hmi_controls containing the following data: ‘mission_play=0, mission_pause=0, emergency_stop=1, path_selected=0‘
- The ALC WILL generate new paths when it detects the path_selected value transition from 1 to 0.
- When a new mission is started, the HMI WILL NOT allow for the selection of any other path except the mission path until the mission is stopped and the HMI has received a new set of valid paths from the ALC.
- When a new mission is started, the HMI WILL pass control of the shuttle car to the HMI operator that is closest to the mission end point, which is determined by a simple distance calculation.

4. Shuttle Car Status

- The shuttle_car_status table is READ ONLY to the HMI.
- When the shuttle car is moving the ALC WILL write a row to the shuttle_car_status table with a 1 in one or both of the shuttle_car_trams or the shuttle_car_turns columns.
- When the ALC begins a mission, it WILL cause a new row to be written to the shuttle_car_status table with a 1 in the mission_running column.
- When the mission is completed or if the mission is stopped by an HMI operator or a safety operator, the ALC WILL cause a new row to be written to the shuttle_car_status table with a 0 in the mission_running column.

5. Localize

- The shuttle_car_status table is READ ONLY to the HMI.
- The ALC WILL write a new row to the localize table whenever the shuttle car position has been updated.
- The current position of the shuttle car WILL NOT rely on any information except what is in the localize table.
- The HMI will render the shuttle car position based only on the values contained in the node_ahead, node_behind, and distance columns.

6. Geometry and Nodes
    - The geometry and nodes tables are READ ONLY to the HMI.
    - The HMI WILL NOT update the geometry or nodes tables while it is running. If these tables are updated while the software is running, the HMI will have to be restarted by refreshing the page to update the changes.

It should be noted that one of the most critical pieces of information shared between the ALC and the HMI is stored in the hmi_controls table of the SQL database. As described above, this table stores the state of the machine as defined by the HMI user (every time the control buttons of the HMI are pressed a new state is registered into the SQL database along with a timestamp). The ALC regularly checks this state to start/pause/stop the given mission. In other words, this state allows the HMI user to remotely control the ALC that resides on-board the shuttle car. Additionally, this state is also reflected back to the HMI. The HMI doesn't update its internal state until it receives this information back from the server so that it knows the command is successfully stored in the database. For example, when the HMI user clicks the play button to start a mission, a request is sent to the server, which updates the hmi_controls table in the database. This updated hmi_controls state is sent back to all HMI apps on the next 2 Hz update, and only then will the HMI UI be updated to indicate that the play button was clicked on the ALC app, and the mission is now running.

Storing this important application state centrally not only keeps the ALC in sync with the HMI, but it also allows multiple instances of the HMI running on separate devices to keep their application state in sync. Similarly, it allows a new instance of the HMI to be started in the appropriate state (or to sync up after a browser refresh, which has the effect of completely restarting the app).

K.14 Outlook for the Autonomous Shuttle Car HMI

This section provides an analysis and summary of the benefits, limitations, advantages, disadvantages, and alternatives and tradeoffs considered for the HMI.

K.14.1 Summary of Expected Improvements and Benefits

Expected improvements associated with an autonomous shuttle car include:

- Data on sensor performance in the unique operating environment of room-and-pillar mining
- Data on HMI performance and operator needs for monitoring and controlling autonomous shuttle cars in room-and-pillar mining
- Complete contextual information provided via the user interface and HMI properties of the operating and monitoring controllers

In addition to potential improvements to the quality of working environment for shuttle car operators, The HMI design of the controllers and other information provided to involved personnel are a critical step in the deployment and integration of automation. The effectiveness of these HMIs and lessons learned will be valuable not only for future automation deployments in mining operations but automation deployments in general. Additionally, the performance measures developed through the project may be useful for future automation deployments in mining.

K.14.2 Expected Disadvantages and Limitations

The autonomous shuttle car developed for this project is intended to demonstrate the feasibility of an autonomous shuttle car and the impact on the surrounding organizational and operational systems. All interviews conducted in previous tasks, as well as a review of critical material, was limited to the specific mine and mine personnel. This limits the generalizability of introducing autonomous shuttle cars across mines with different parameters (e.g., different models of shuttle cars, battery-operated shuttle cars, mines with lower air filtration or decreased visibility, etc.).

One disadvantage of the current design for the shuttle car automation is an increase of shuttle car operators entering and exiting the shuttle car during routine operations. Without the ability to dock at the continuous miner for loading nor the feeder-breaker for unloading, the operators may be subject to excessive strain. Introducing automation or partial automation for either the loading or unloading task would greatly reduce the strain on the individual shuttle car operator from increased physical stress due to tight space maneuvering. In addition, new tasks or modified tasks involving the automation during loading and unloading could lead to errors or delays, especially before operators gain experience with the shuttle cars.

K.14.3 Alternatives and Trade-Offs

As mentioned throughout the ConOps, differing levels of automation present unique challenges and changes to the organizational structure and working environment. Responsibilities for shuttle car operators and other mine personnel are altered depending on the level and amount of automation attained during development.

K.15 Acknowledgements

The authors would also like to acknowledge Alliance Coal for their participation and continued support throughout the project.