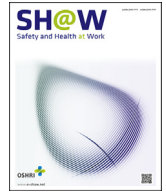




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Internet of Things–Based Command Center to Improve Emergency Response in Underground Mines



Ankit Jha*, Alex Verburg, Purushotham Tukkaraja

Department of Mining Engineering and Management, SDSM&T, Rapid City, SD, 57701, USA

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ABSTRACT

Background: Underground mines have several hazards that could lead to serious consequences if they come into effect. Acquiring, evaluating, and using the real-time data from the atmospheric monitoring system and miner's positional information is crucial in deciding the best course of action.

Methods: A graphical user interface–based software is developed that uses an AutoCAD-based mine map, real-time atmospheric monitoring system, and miners' positional information to guide on the shortest route to mine exit and other locations within the mine, including the refuge chamber. Several algorithms are implemented to enhance the visualization of the program and guide the miners through the shortest routes. The information relayed by the sensors and communicated by other personnel are collected, evaluated, and used by the program in proposing the best course of action.

Results: The program was evaluated using two case studies involving rescue relating to elevated carbon monoxide levels and increased temperature simulating fire scenarios. The program proposed the shortest path from the miner's current location to the exit of the mine, nearest refuge chamber, and the phone location. The real-time sensor information relayed by all the sensors was collected in a comma-separated value file.

Conclusion: This program presents an important tool that aggregates information relayed by sensors to propose the best rescue strategy. The visualization capability of the program allows the operator to observe all the information on a screen and monitor the rescue in real time. This program permits the incorporation of additional sensors and algorithms to further customize the tool.

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1. Introduction

Underground mines are at risk of hazards, including fire, dust and gas explosion, ground control, water inundation, and toxic contaminants [1]. The confined atmosphere of underground mines escalates the consequence of hazards should they come into effect. Safety considerations and hazards mitigations are the foremost factors in the planning and operation of underground mines. Nevertheless, accidents have occurred in the past, leading to many fatalities and injuries to miners. Many accidents have occurred in the past, both in metal and nonmetal mines that have time and again challenged the adequacy of adopted safety considerations and outlined the requirement to better the rescue response. Major accidents in underground operations across the United States include the Sago mine explosion that occurred in 2006, which led to 12 fatalities [2]. Sago

mine is an underground coal operation in West Virginia, United States. An explosion occurred behind the sealed worked-out area, leading to the inundation of carbon monoxide (CO) in the mine environment. After nearly 41 hours of the event, the rescue team finally discovered 12 deceased miners. The absence of information from the underground mine environment was one of the main causes of delay. Moreover, CO poisoning led to impaired judgment on the miner's part to traverse through the escape route. The initial rescue efforts to restore ventilation and locate miners failed as the rescue team could not clear the smoke and gases. The smoke and gases generated from the explosion spread near the location of the explosion and the nearby region, severely impairing the visibility of the miners. Numerous instances of unclear communication and poor flow of information were documented in the report. The Upper Big Branch mine disaster occurred in West Virginia when a methane

Ankit Jha: <https://orcid.org/0000-0002-5593-0702>; Purushotham Tukkaraja: <https://orcid.org/0000-0002-8360-1797>

* Corresponding author. Department of Mining Engineering and Management, SDSM&T, Rapid City, SD, 57701, USA.

E-mail address: ankitkrjha@gmail.com (A. Jha).

explosion led to a coal dust explosion, resulting in 29 fatalities. The main cause of this accident was a lack of proper maintenance on equipment at the longwall. Furthermore, the miner positioning system that provides the position of miners in real time was missing, and the manual miner tagging system was dysfunctional. Again, the accident report documented the confusion and delayed decision-making about the rescue process [3]. Soma mine disaster (SMD) in Turkey resulted in 301 fatalities due to CO poisoning, which ensued after a fire outbreak. There were major lapses, including the absence of a refuge chamber, partial mechanization, confusion of mine officials, and miners to safely exit the mine. Among the notable findings in accident reports were the various factors that resulted in many fatalities, including inadequate knowledge of the miner's location, leading to the fatal mistake of airflow reversal, causing more fatalities. Furthermore, smoke generated due to raging fire prevented the mine official to access the location of the fire to contain it. Although 142 miners accessed and stayed at a panel that was initially smoke-free, shortly, the management changed the direction of ventilation that led to intrusion of smoke at the panel, leading to fatalities. The management was unaware of the location of miners and the outcome of changes in the ventilation direction, which could have been prevented in case of pertinent information in terms of location of miners, sensor readings, and airflow direction was existing. It was concluded that the "extraordinary number of fatalities in the SMD is not for the fact that a fire started in the mine, rather the decisions taken in the mine after the fire broke out" [4].

Although the causes for the previously outlined accidents are diverse, they have one thing in common: the scope of improvement in emergency response, which has the potential to save lives, especially in situations of a confined atmosphere where saving lives is a race against time. Regulatory organizations concerning the mining and mineral industry have published documents outlining the regulations, compliance and enforcement, procedures, and training and education of the involved personnel. In the United States, Mine Safety and Health Administration (MSHA) has published an instruction guide, which describes in detail the procedures to be followed during a mine emergency [5]. This document acts as a guide to be followed during mine emergency, and provisions included in this document are to be implemented in a site-specific manner. All aspects of emergency response, including initiation of mine evacuation, organization of a command center, communicating information, coordinating and deploying fire-fighting equipment, deployment of a mine rescue team, and establishing a fresh air base, are detailed in this document. Furthermore, 30 CFR Part 49 (Code of Federal Regulations) elaborates detailed structure, functions, and requirements to carry out mine rescue in respect of underground metal and coal mines [6]. A detailed literature review was conducted to study the command center that is established to counter emergencies of various kinds. MSHA has developed a Mine Emergency Response Development that lets participants act out on various roles in a command center. Another training exercise involves actual mock mine drills where the teams are presented with a realistic emergency scenario. Mine Emergency Response Interactive Training Simulation is a computerized mine emergency program that simulates the underground and surface events to the disaster. Emergencies with continuously changing scenarios are presented to participants, and their decisions about events are recorded. At the completion, the participants are provided with a performance score based on the patterns of their responses. The performance on the test is based on mastery of knowledge, skills, and strategies included in the exercise [7]. In collaboration with West Virginia University, West Virginia Office of Miners Health, Safety and Training developed a comprehensive emergency preparedness planning manual for underground mining operators. This document details dealing with mine

emergencies by elaborating on important points, including establishing the planning team, analyzing capabilities and hazards, developing the plan, testing the plan, and implementing the plan. Furthermore, all the sections are discussed in detail for guidelines, regulations, and best practices to be followed in case of an emergency. A literature review was conducted to know more about the incident command center that is used in emergencies beyond mining industry. Center for Disease Control uses an Incident Management System (IMS) model for responding to emergencies. IMS consists of facilities, equipment, personnel, procedures, and communications operating with a common organizational structure. IMS is an organization structure wherein the government and private organizations can work seamlessly. Furthermore, individuals contributing to IMS are assigned a specific role and follow a command structure. Primarily, IMS helps direct specific incident operations, coordinating, and delivering resources and share information with the public. IMS has three levels of emergency response activation based on which the people and resources are involved. Furthermore, detailed responsibilities of personnel involved in the command center are elaborated such that clear communication and functioning are ensured. IMS provides an Emergency Operation Center (EOC) that supports emergency response and communication activities. EOC center is used to obtain and analyze situation analysis, incident briefing, incident action plan, resource management, and incident management [8]. The state of South Australia has developed emergency management provisions and guidelines. These provisions incorporate the installation of a system to locate miners, training of rescue persons, and placement of rescue equipment. In addition, detailed provisions regarding exits, availability of personal rescue equipment are included in the plan. The emergency plans for a mine depend on factors including the size and complexity and the number of workers working in the operation. Furthermore, stakeholders, including miners, local and other emergency services, and local authorities, are consulted in the development of the emergency management plan [9]. The basic characteristics of emergency response systems were highlighted that would be effective in managing emergency responses. The emergency response system should be robust to alterations within the mine, simple to implement, respond in minimal time, devoid of paperwork, automate response decisions, robust data management system, and interact with stakeholders. In addition, these systems should go beyond the prescriptive regulatory requirements to harness the capabilities of mine environmental monitoring systems and software technologies in emergency response. Information obtained from different sources should be readily accessible on a screen to facilitate easier decision-making in a distress situation [10]. Moreover, emergency preparation guidelines are published by regulatory organizations detailing specific emergency scenarios such as fire. The Department of Industry and Resources published a guideline that details the recognizing of fire hazards, equipment's fire scenario, training requirements, communication, and warning system, tracking of miners, the provision relating to escape routes, rescue equipment, and mine rescue team [11]. The underground response plan is usually based on the technological maturity of an operation. For example, the emergency response management plan for Indian underground coal operations is very prescriptive in terms of organizing a response team, communicating the information across officials, assigning tasks to different personnel in communication, delineating missing miners from manual tagging system, signaling, managing the control room, coordinating with local official and external rescue team, etc. As the technological advancement in terms of atmospheric monitoring systems (AMSs), miner's location monitoring, and monitoring of other vital parameters is introduced, a software-based system would be more effective and prudent that

would enhance the response time in the emergency [12]. Internet of Things (IoT)-based software for emergency response was examined for application, usage, and features in the emergency response. Focus FS emergency response software establishes a communication platform between the command center and rescue team to manage the flow of information in real time. Furthermore, the real-time oxygen levels of the rescue team member and other information flow from the rescue team relating to the refuge chamber, rescue person, or obstructions are communicated back and forth to the command center [13]. Another product, RealTrac provides the real-time positioning information of miners and machinery deployed in the underground mines. The capability of software includes geofencing to prevent personnel from working in specific areas, an emergency notification system to provide warnings to miners, and positional information of miners for real-time evacuation. The software can also enable voice-over communication with miners equipped with intercoms [14]. IoT automation developed a product for the evacuation of miners based on smart lighting technology. The technology is based on using intelligent illumination to guide miners to a safe route in case of seismic events in the underground operation. The trigger for any seismic event can be generated by the mine manually or by a real-time mechanism by integrating the mine seismic monitoring software into the smart lighting system. The smart lighting technology then delineates safe and unsafe zone by switching the smart light of specific colors [15]. A commercial underground ventilation modeling software has incorporated features that include the calculation of the shortest path between sections selected by the user. Furthermore, the software can query real-time atmospheric sensor data and display it on the graphical user interface (GUI) [16]. The integrated command center developed by this research study is more focused on establishing an integrated command center that could capture and display all the data obtained in real time from the underground mines. Furthermore, real-time miners' positional information, dynamic utilization of shortest path algorithm, and information widget to record the information obtained from different sources are collectively implemented in this platform that makes it a unique product in the domain.

2. Materials and methods

2.1. Underground mining methods

Underground mining operations are different in terms of the method of working and development of the deposit. The main criteria for selecting a mining method are based on factors, including location and geology of the deposit, depth of deposit, the strength of ore and surrounding rocks, processing requirements, availability of workforce, and political and social conditions. Underground mines have a maze of tunnels excavated to exploit mineral reserves. The design of underground mines is primarily based on the mineralogical range of the resource such that mining can be accomplished safely and economically. Furthermore, different mining methods are used based on the mineral being mined, including coal, trona, or metals. Primarily, underground coal mining is accomplished using two techniques: room and pillar and the longwall mining method. Metal mines are developed using mining methods, including shrinkage stopping, sublevel stoping, cut and fill mining, block caving, and panel caving. Detailed characteristics of the deposit are taken into account in deciding the mining method to be used for development [17]. The factors involved in deciding the mining method to be chosen for a deposit are outside the purview of this paper. All the underground mines have peculiar hazards that can affect the health and safety of miners working. The prominent hazards found in underground coal

operations include methane and coal dust, which can cause an explosion, whereas mine collapse and fire are the main hazards in underground metal operations [18–20]. Irrespective of the mine layout, all the underground operations have miners working in different sections, sensors to monitor the atmospheric condition, and fans to accomplish ventilation. This paper develops an integrated command center by considering the real-time atmospheric sensor data, miner's positional information, and mine ventilation characteristics to develop a GUI-based software. This software can collect, store, and integrate the real-time sensor data and process it with algorithms to provide meaningful analysis of a situation that would help in deciding the best course of action in emergency response. A brief review of the underground mine communication system and AMS is outlined in the article. This section discusses the features, including the sensors and algorithm, that are used in the development of the software development.

2.2. Communication in underground mines

Underground mines have two types of communication systems, including wire based and wireless. Wireless communication systems are used for sending and receiving information wirelessly. Different kinds of wireless communication systems are used for communication in underground mines depending on their utility. The wireless communication systems can further be categorized into two types: ones that require physical infrastructures such as wireless local area network (IEEE 802.11b) and others that do not require any infrastructure for operation. Infrastructure is not required in ad hoc networks, and their coverage in mines can extend up to 1800 ft for straight tunnels (IEEE 802.15.4) operating at 900 MHz. The mine communication system in the underground mine includes a hard-wired system wherein the wire forms the communication link in the network. The wireless system consists of four communication technologies, including leaky feeder, node based, medium frequency, and through the earth systems. The miner positioning system is installed in underground mines and consists of a radiofrequency identification system. The operating principle is based on the fact that when an RFID tag reader of a miner is in the vicinity of a fixed reader, the information is relayed to a central command center, specifying the location of the miner. Furthermore, a node-based system based on the operating principle when a radiofrequency device with a unique identification comes in contact with a fixed node, the location of the miners is established and relayed to the command center. The communication system in underground mines is well established, and several research studies and existing mines have pointed out that obtaining real-time atmospheric monitoring information, including gas concentration, temperature and humidity, and miner's positional information is possible [21,22]. In addition, a technology review was conducted by National Institute for Occupational Safety and Health (NIOSH) to investigate the use of sensors in a hazardous environment. Different types of sensing techniques, such as body sensors, smart environment, and wearable digital displays were discussed. Wireless transmission of data from these sensors and environments is discussed in detail in respect of underground mines. Wearable sensors can help in monitoring the physiological state of miners working in the mine. Safety can also be enhanced by using wireless proximity detection installed on heavy equipment such that the machine stops when it is dangerously close to miners [23].

2.3. Atmospheric monitoring system

30 CFR § 75.351 designates detailed provision for installation, location, functioning, examination, testing and calibration, record-keeping, and communication of AMS. Among notable provisions are

the requirements to monitor the functional status of sensors, installing audiovisual alarms at the designated levels in surface and underground levels that should function in case the concentration of methane and CO exceeds the prescribed limit. Furthermore, detailed requirements are mentioned regarding the location for installation of these sensors in working sections, belt-air course, primary escape-way, return air-splits, and electrical installations [6]. Rowland et al conducted a survey of the AMS, highlighting a steady increase in the utilization of these systems from the year 2003 to 2018. Two hundred thirty-five operating coal mines were surveyed, and it was found that 14% of the surveyed mines used AMS, and the remaining used the CO systems [24]. CO systems consist of a network of CO sensors located at fixed places to monitor and generate warning signals when the concentration exceeds the prescribed limit. CO systems could be defined as a subset of AMS systems that have fewer regulatory requirements than AMS systems, which could be attributed as the reason for their utilization by most of the mines [24]. NIOSH conducted a research study to evaluate the efficacy of ultrasonic velocity instruments in determining the airflow quantity and direction and concluded that these sensors correlated well with the standard measurement techniques. In addition, the effectiveness of sensors, including CO sensor, smoke sensors, and flame sensor, was evaluated under simulated conditions to ascertain their performance in a fire situation [25].

2.4. Arduino microcontrollers

Arduino microcontrollers and sensors are used to simulate an underground AMS. These microcontrollers are inexpensive tools to emulate the communication system existing in underground mines and accomplish collecting and relaying the real-time sensor information. Arduino microcontrollers are used in the development of projects for a variety of purposes. Arduino boards are equipped with sets of digital and analog pins that can be interfaced with different breadboards. The connection of sensors to the microcontrollers was accomplished using breadboard and jumper wires. The sensors require three different kinds of connection, including ground, power supply, and digital or analog output, depending on the type of sensor. DHT11 (temperature and humidity), MFRC-522 (RFID), and MQ-7 (CO) were used for this study. Furthermore, the Arduino microcontroller was connected to the computer using a universal service bus drive. These sensors were selected to demonstrate the process of collecting and transferring the data in real time. Several innovative projects were developed using Arduino microcontrollers, which were used in real-life applications,

including the mining industry [26–28]. Arduino microcontrollers and sensors were successfully used in developing a GIS-based AMS [29]. Real-time data transfer and processing were accomplished such that data obtained from the sensors were stored in feature class with a timestamp. Furthermore, a risk-based warning system, ventilation on demand, and data analytics feature was developed using the real-time sensor feed [29]. Fig. 1 shows the Arduino microcontroller, temperature and humidity, CO, and RFID sensors.

3. Results

GUI software development was accomplished using the python programming language. Python is an interpreted programming language with vast library support for software development, including GUI, data analysis, and machine learning to name a few. In addition, simultaneous real-time data collection, storage, and display of sensor information can be accomplished without latency from the sensor feed. The software is designed to import AutoCAD-based mine maps on the GUI featuring points and connecting lines. The lines represent working sections, haulage ramp, ventilation shaft, and drifts within underground operations such that they are labeled to highlight the specific utility. The points are characterized as junctions that connect two or more lines, and few points could be regarded as a fixed sensor location based on the user's input. In actuality, the drifts, working sections, haulage ramps, and shafts could have varying dimensions and shapes; however, that is not relevant for emergency response. These points are described in x, y, and z coordinates, usually based on a local coordinate system used by the mine. When a mine map, an AutoCAD file, is imported, it requires conversion of the coordinate system such that the map can fit the window/screen. This conversion is accomplished by normalizing the actual coordinates to fit the screen of the software. However, algorithms and calculations are based on the actual coordinates such that the screen coordinates are only for visualization purposes. The visualization capabilities of software have functionality, including translation, rotation, and perspective projection. All these functionalities enhance the user's capabilities to observe specific areas of the map by moving, rotating, and panning the map across the screen. The specifics of the algorithms used to implement the visualization functionality are acquired from the discipline of computer graphics [30,31]. The details of these algorithms and their implementation within the software are beyond the scope of this article. Furthermore, the Dijkstra algorithm is used to calculate the shortest path between two nodes in the software [32].

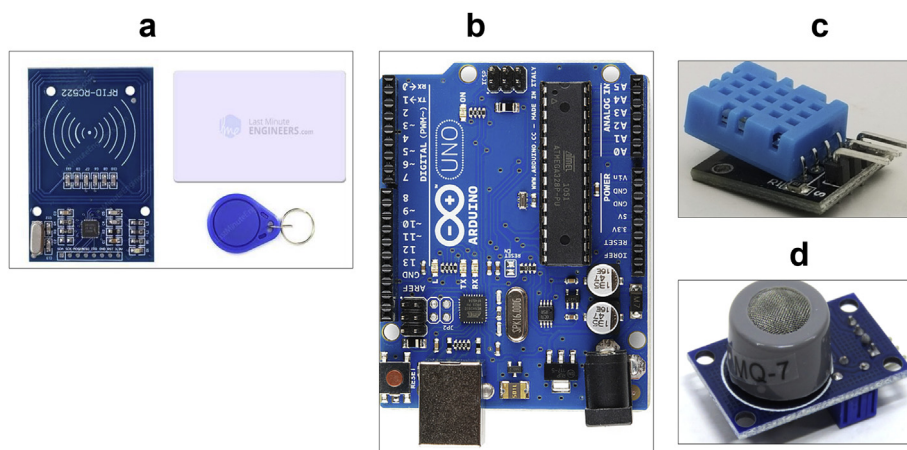


Fig. 1. (a) RFID sensor, (b) Arduino microcontroller, (c) temperature and humidity sensor, and (d) carbon monoxide sensor.

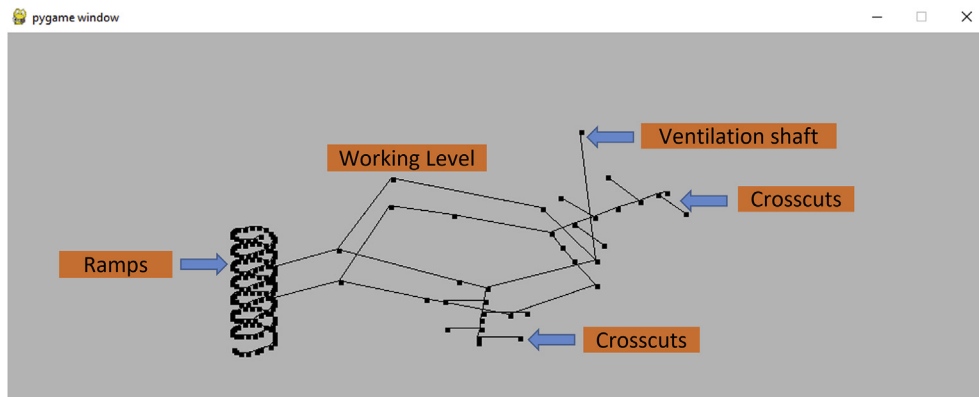


Fig. 2. Imported mine map—A screenshot of GUI-based software.

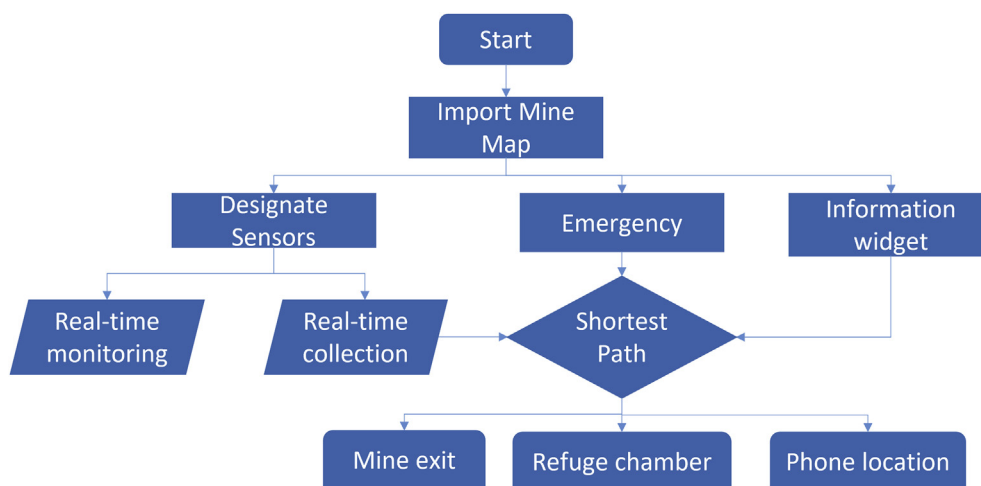


Fig. 3. Flowchart showing the functionality of the software.

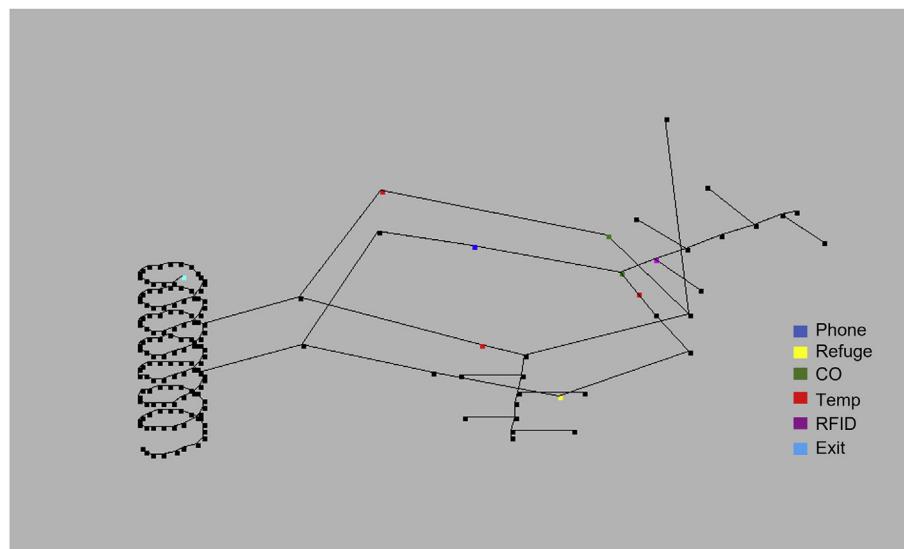


Fig. 4. Location of the sensor in the underground mine map.

A case study of block caving operation is presented in this study such that the detailed mine map is developed using AutoCAD. Fig. 2 shows the imported mine map on the GUI screen with labeled features, including ramps, working levels, ventilation shaft, and

crosscuts. The ramps are the main access to the mine, and as such, they provide means of ingress and egress to the miners. Furthermore, fresh air for ventilation enters the mine through these ramps and exits through the ventilation shaft. The working levels are

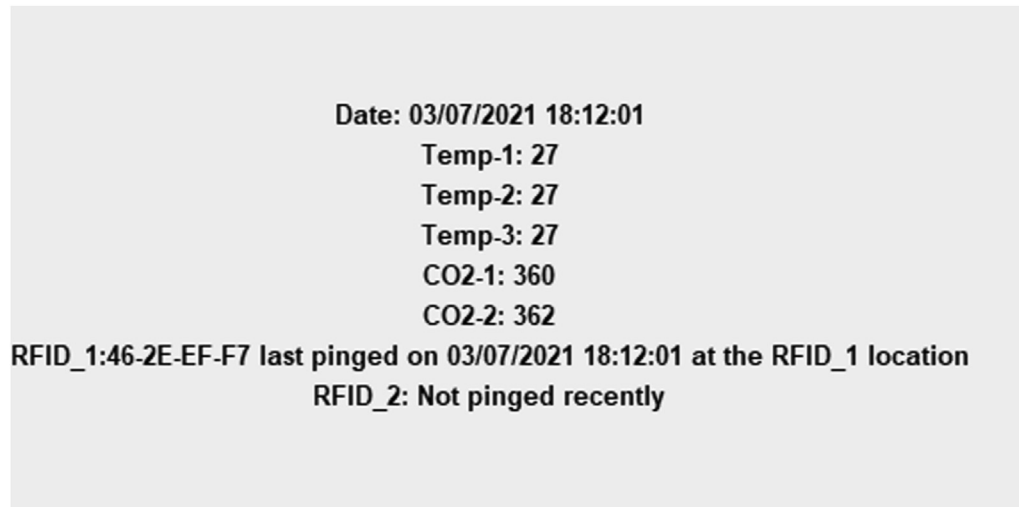


Fig. 5. Live data from the atmospheric monitoring system.

where the mining activities are carried out that connects to the crosscuts where the actual ore is being excavated using load haul dumpers. The user can designate the location of sensors on the mine map such that the position of CO, RFID, and temperature and humidity sensors are shown on the map. The RFID sensor on the mine map specifies the location of the RFID tag reader, which is fixed such that when the miners are in the vicinity of the RFID tag reader, the positional information is displayed to the surface.

3.1. Detailed functionality of software

This software requires an AutoCAD-based mine map imported using functionality available in the GUI. The fixed sensor locations, including the CO, temperature, and humidity, and RFID sensors, are designated by the user at the specific location in the map. These sensors are connected to the Arduino microcontrollers such that real-time sensor feed is displayed on the GUI. The CO and temperature and humidity sensors are programmed to relay data at a frequency of 1 second, which could be altered by the user as required. The RFID sensor is activated when a key is in close proximity to the sensor, thereby demonstrating an actual mine

condition when the miner's positional information is relayed to the surface on sensing the location of the miner in the vicinity of the beacon. The data relayed by all the sensors are collected and stored in a comma-separated value (CSV) file to could be recalled at a later stage. The sensors are designated with a color scheme to distinguish them visually and avoid confusion while dealing with an emergency. Moreover, in a typical emergency scenario, information is received from sources within and outside the mine. This information is crucial in deciding and varying the course of action in emergency response and is required to be stored and recalled such that they are included in the decision-making process. Functionality to store information via a text box is created within the software, which stores information in a separate CSV file. Furthermore, the stored information could be recalled by another functionality and displayed on a new window in the GUI. The functioning of this software is demonstrated using a case study to cover the entire range of usages. This case study entails an emergency in an underground metal mine involving miners working in different sections. The sensors used for this study include three temperature and humidity, two CO, and one RFID sensor. These sensors are located at specific locations within the mine map such that they

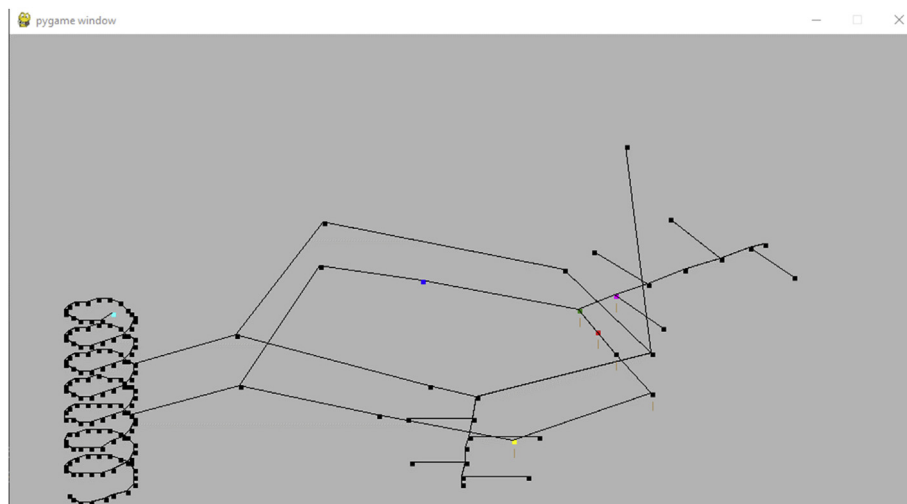


Fig. 6. Route from RFID_1 to refuge chamber in tan color.

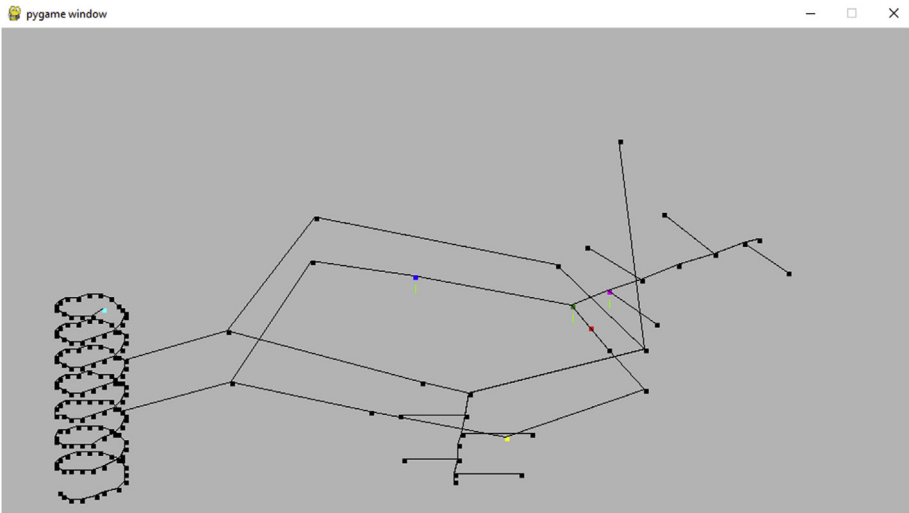


Fig. 7. Route from RFID_1 to phone location in lime green color.

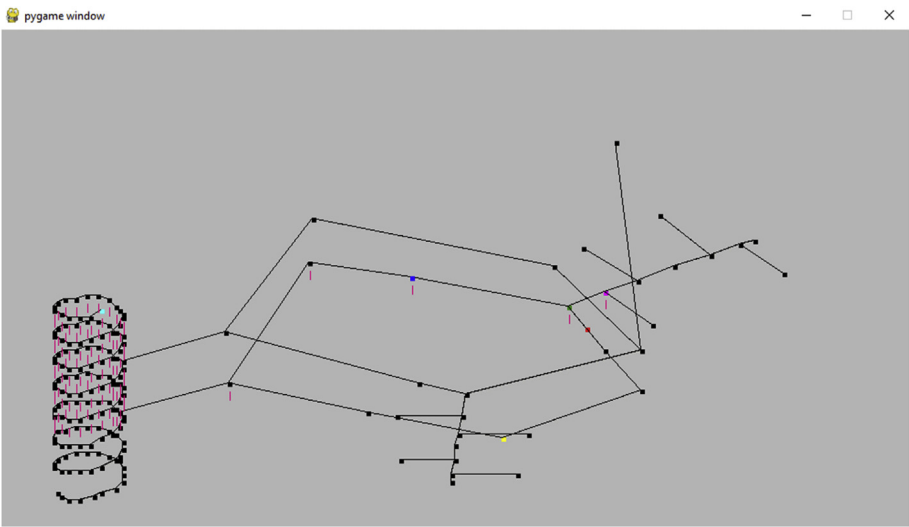


Fig. 8. Route from RFID_1 to mine exit in red color.

could be distinguishable using the color scheme. Fig. 3 shows the functionality of the software using a flowchart.

The software indicates the miner's positional information and the shortest path that should be undertaken to exit the mine safely

Shortest distance and time to refuge chamber, exit, and phone

The time to the nearest phone location is 2.64 minutes and the distance is 222.06 meters from RFID-1

The time to the nearest refuge chamber is 3.58 minutes and the distance is 300.86 meter from RFID-1

The time to the nearest exit is 16.2 minutes and the distance is 1360.4 meters from RFID-1

OK

Fig. 9. Shortest distance from the RFID location to phone location, refuge chamber, and exit.

in case of an emergency. Furthermore, the shortest path to the nearest refuge chamber, phone location, and additional self-contained self-rescuers are also calculated and displayed by the program. The real-time positional information of miners and the shortest route to the nearest safe destination is essential in planning the course of action for a rescue operation. In addition, the rescue teams can be apprised of the recent situation while communicating with the command center, which would help them in devising the action plan. Two cases involving working of the software are discussed in the section below, which necessitates the evacuation of miners on sensing of the emergency. The software calculates the shortest path route for miners to the nearest phone location, respirator location, and mine exit. These routes can be observed on the mine map such that the command center can monitor and act to expedite the safe exit of the miners. In addition, these routes could be conveyed to miners and relayed over the communication systems to be displayed on neon displays installed for the purpose. Also, smart devices such as smartphones or tablets could be used by miners to obtain this information and follow the route to safety. In addition, navigation indicators consisting of

The figure shows a window titled "Information Widget" with a standard Windows-style title bar (minimize, maximize, close buttons). Inside the window, there are three input fields stacked vertically, labeled "Name", "Location", and "Information". To the right of these fields are two buttons labeled "OK" and "Cancel".

Fig. 10. Information widget to store information obtained from different sources.

green/red lights should be installed in the underground mines to guide miners to safe exist. These lights are of particular importance in rescue situations involving smoke when reading of screen and other indicators within the underground premise is impractical.

3.2. Case study 1

This section illustrates a case study on using this software in real-time emergency response in an underground metal mine. Fig. 4 shows the location of the sensor on the mine map; such unique color represents each different sensor type to distinguish them clearly on the mine map. Furthermore, three temperature sensors (red), two CO sensors (green), and one RFID sensor (magenta) are shown on the mine map. In addition, refuge chamber (yellow), phone location (blue), and exit location (cyan) are also delineated on the mine map (Fig. 4). The data relayed from the AMS is updated live on another widget as shown in Fig. 5. These data are updated every second on the screen, and the user can choose to observe the data or close off the widget. A CSV file also records all the data in the background as they are relayed by the sensors such

that the recorded data can be recalled later if required. The temperature readings are recorded in degrees Celsius, CO in parts per million (PPM), and the RFID sensor records the value of the key sense in the desired range of the RFID sensor and the time. All the miners are provided with a key identification, which allows the command center to ascertain the identity of a specific miner. In this case, the number "46-2E-EF-F7" represents a specific miner who was in proximity of the RFID sensor at the time mentioned in the window. This case study entails an emergency involving an increased level of CO due to a potential fire situation. Fig. 5 shows the elevated CO concentration with 360, 362 PPM and represents a situation that requires evacuation. The CO concentration is much approaching the short-term exposure limit value of 400 PPM prescribed by the MSHA (Cauda, 2012). The miners are required to evacuate the mine such that the command center can visualize the time required by the miner at the RFID_1 location to reach the refuge chamber, phone location, and exit location. Figs. 6–8 represent the shortest route from the miner location to the refuge chamber, phone location, and exit of the mine. Fig. 9 shows the shortest distance from the RFID location to the refuge chamber,

The figure shows a window titled "Python - Import CSV File To Tkinter Table". Inside the window is a table with the following data:

Date	Time	Name	Information	Location
2021-06-25	21:10:39	Miner 2	Elevated Gas Concentration	2nd Level 7th crosscut
2021-06-25	21:06:23	Miner 1	Miner Injured	2nd Level, 4th crosscut

Fig. 11. Information retrieval widget to read all the recorded information.

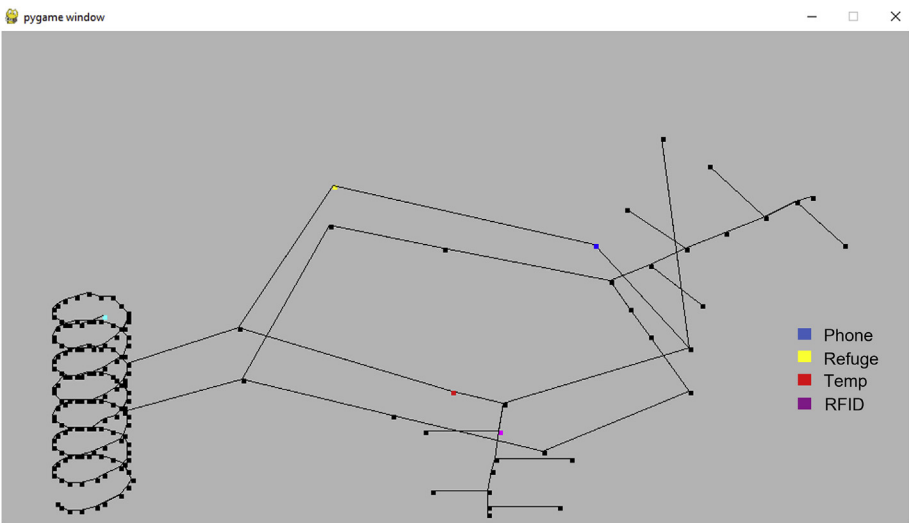


Fig. 12. Sensor locations for case study 2.

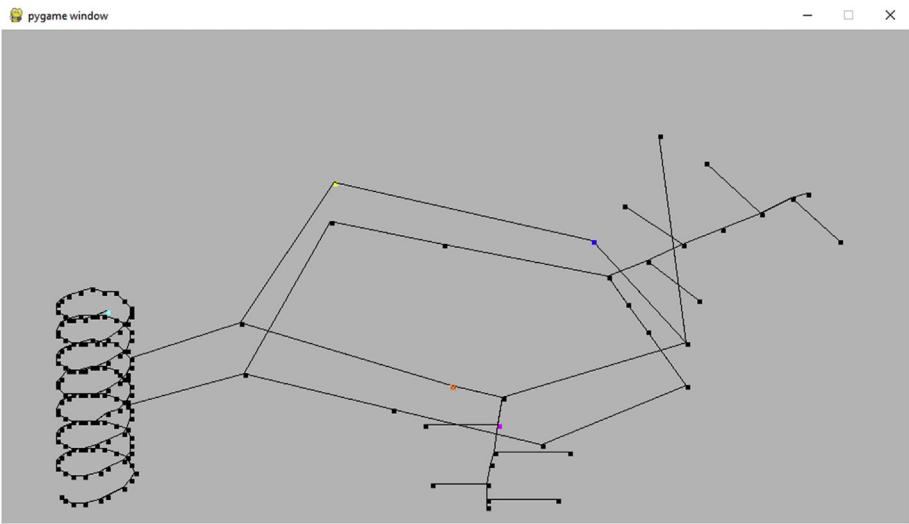


Fig. 13. Inaccessible path due to elevated temperature shown by a cross mark.

phone location, and the exit of the mines. In addition, the time required to reach these destinations are also mentioned in the wizard. On receiving this information, the command center can decide the course of action in terms of whether to send a rescue

team or otherwise to monitor the rescue such that the miners can exit on their own with the underlying situation.

Fig. 10 shows an information storage wizard that can store information from different sources in a CSV file. Furthermore, another functionality allows the retrieval of the stored information by members of the command center as shown in Fig. 11.

3.3. Case study 2

This case study illustrates a different condition where one of the temperature sensors records elevated reading (63oC), indicating a fire scenario. On sensing the condition, the miners have decided to evacuate and exit the mine. However, the route indicating the fire could not be accessed under these conditions such that miners have to evacuate through alternate routes. The software has the functionality wherein a particular route could be blocked from being used in the shortest path algorithm in case of its inaccessibility. In that case, the algorithm search for alternate routes and suggests other paths that miner could take to reach the refuge chamber, phone location, or exit the mine. Fig. 12 shows the locations of the designated sensors for this

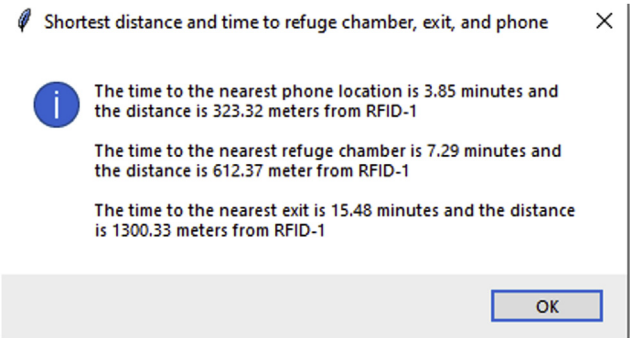


Fig. 14. The shortest distance and time for miner to reach the refuge chamber, phone location, and exit of the mine.

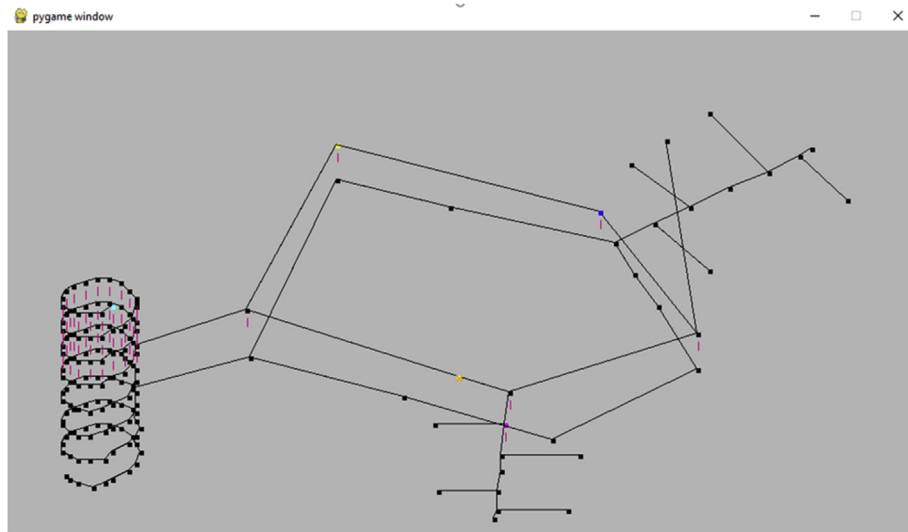


Fig. 15. Alternate path suggested by the program in red color.

study, which comprises RFID and temperature sensors. In addition, the mine exit, refuge chamber, and phone locations are depicted on the mine map. Fig. 13 shows the capability of the software to label a route as inaccessible, as shown with a cross mark. The path with cross mark could not be accessed on account of elevated temperature and as such miners have to take an alternate path to exit the mine. Fig. 14 shows the shortest distance and time taken to exit the mine, reach the phone location, or the refuge chamber. Fig. 15 shows the route to be taken by the miners to exit the mine using the alternative route. This route was the second-best shortest route to exit the mine when the shortest route was inaccessible.

4. Discussion and conclusions

A GUI-based integrated command center was developed to manage emergency response in underground mining operations in real time. The real-time sensor feed from the AMS and the miner's positional information was collected and processed by the software such that emergency response could be monitored and planned. Furthermore, the software calculated the shortest path for the miners to reach the nearest refuge chamber, phone location, respirator location, and the mine exit. The functionality developed in the software applies to all the underground mines to develop additional customized features. Furthermore, additional sensors can be connected to the GUI software that could provide enhanced monitoring capabilities to the rescue operation. The software has the capability of finding alternate routes in case any of the shortest route is inaccessible to miners on account of emergency. There can be scenarios wherein the normal functioning of sensors could be impeded on account of damages to the sensor due to the emergency. These types of situations could be sensed by the central command center when the real-time sensor feed is not received such that alternate rescue strategies could be devised. The real-time information obtained from the AMS in an underground operation is crucial in deciding the course of action in a rescue situation. This GUI-based software aids in decision-making at the central command center to make an informed decision and expedite the rescue operation.

Conflicts of interest

The authors disclose no conflict of interest.

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