American Journal of Mining and Metallurgy, 2017, Vol. 4, No. 1, 62-67
Available online at http://pubs.sciepub.com/ajmm/4/1/6

DOI:10.12691/ajmm-4-1-6

Prototype Model for Fire Safety System in Underground Mining

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Abstract As underground mines become deeper and larger with wide specifications it creates a diverse environment with multiple variables that make fire disasters difficult to manage. Therefore, developing an integrated fire safety system is of crucial importance in order to effectively deal with fire disasters and protect the life of every worker. The proposed prototype system in this study uses available technology that can integrate information about fire risk assessment, fire detection, safety situation awareness, and effective system for evacuation displayed on smartphone device to create an intelligent and two-way fire safety system. The proposed system uses sensors, detectors, smartphones, Internet of Things (IoT), cloud computing, application gateways, and application program interfaces for solving the problems of building the effective fire safety system. Two-way communication and 3D visualization with evacuation guidance are other possible functions of the proposed system for fire safety. Developing and implementing this prototype fire safety system can effectively provide information about fire risks, fire safety, fire detection, alarm responses, optimal evacuation routes, 3D visualization and simulation of evacuation routes, arrow and voice evacuation guidance from smartphone device and overall building fire safety with disaster response capabilities for every underground mine.

Keywords: *underground mines, fire, detection, alarm, evacuation, system*

Cite This Article: Vancho Adjiski, Zoran Despodov, and Dalibor Serafimovski, "Prototype Model for Fire Safety System in Underground Mining." *American Journal of Mining and Metallurgy*, vol. 4, no. 1 (2017): 62-67. doi: 10.12691/ajmm-4-1-6.

1. Introduction

Fire is still a major problem in the underground mining industry, especially if it is uncontrolled and constitutes a significant hazard that leads to catastrophic events. Many underground mining workers are not aware of how quickly and seriously mine fires can spread, they have little knowledge of their escape routes and they lack experience in using firefighting equipment [1].

Information on the latest strategies for fire risk assessment, fire detection, fire alarm, and evacuation may be difficult to obtain, and because of this there is the need for efficient fire safety system that uses the latest innovations in smart technologies that can provide continuous flow of information [2]. Such technologies and techniques could significantly improve fire safety and evacuation procedures in underground mines. An ideal fire safety system for underground mines would be low cost, reliable, fast, and able to warn underground workers and guide them all to safety, regardless of their location in the mine [3]. A fire safety system that is capable of alerting miners quickly would allow them to put on the self-rescue apparatus on time, which is crucial for safe evacuation. In order to ensure that the risks from underground fires are properly managed the latest technological developments should be implemented and used that can provide fire awareness and flow of crucial information for fire detection and safe evacuation [4].

The purpose of this paper is to develop a prototype model for fire safety system in underground mining to control the risks from fire events by providing continuous two-way flow of information for:

- fire risks
- fire detection
- fire alarms
- optimal routes for evacuation
- evacuation guidance

Fire safety systems have components of technology and people and they can work synergistically to bring the system back in balance. This paper is part of research aimed at improving fire safety and at obtaining a safer working environment in underground mines.

2. Literature Review

This section reviews the currently published studies on the application of smart technologies in mining industry for improvements in safety at work, fire management and evacuation planning.

Bhattacharjee et al. [5] proposed a system for detecting fire hazard in a Bord and Pillar coal mine panel that uses wireless sensor networks (WSNs) and can be used to detect the exact fire location and spreading direction.

Moridi et al. [6] proposed a system for the integration of Wireless Sensor Network (WSN) assisted with Geographic Information System (GIS) that enables monitoring and controlling underground mining applications from surface office and also to use ZigBee nodes to sense environmental attributes such as temperature, humidity and gases concentrations, switching ON and OFF ventilation fans and texting emergency messages.

Bandyopadhyay et al. [7] proposed work to showcase the impact of using real-time tracking, sensing and management system using active RFID, sensors and wireless mesh network for improving mine safety and underlay technology and system solutions for different mining applications.

Somov et al. [8] proposed wireless sensor–actuator system which aims at quick gas detection and immediate isolation of gas leak source.

Sun et al. [9] proposed tailings dam monitoring and pre-alarm system based on the Internet of Things (IoT) and cloud computing with the abilities of real-time monitoring of the saturated line, impounded water level and the dam deformation.

Zhang et al. [10] proposed a system that uses the existing Cable Monitoring System (CMS) as the main body and the Wireless Sensor Networks (WSN) with multi-parameter monitoring as the supplementary technique and the test results indicate that the proposed integrated environment monitoring system for underground coal mines is feasible and all designs performed well as expected.

Li and Liu [11] discuss the design of a Structure-Aware Self-Adaptive Wireless Sensor Networks system, that is able to rapidly detect structure variations caused by underground collapses.

Liu et al. [12] proposed a positioning system of non-complete coverage of the whole tunnel network by measuring point. This positioning system is made up of the monitoring center, gateways, underground base stations, reference nodes and mobile nodes that constantly compute their own locations and send them to the monitoring center for management.

Adjiski et al. [13] discusses the design of a system that by using available software, allows to work out complete evacuation plans that include analysis of fire scenarios and optimal routes for evacuation in underground mining.

Although most studies have similar objectives, no study focused on integrated smart fire safety system that constantly communicate with the user's smartphone and provide it with all the necessary information related to fire risk assessment, fire detection, fire alarm, personal localization, calculation of optimal routes for evacuation, and evacuation guidance with visualization on 3d model.

3. Proposed Methodology

3.1. System Structure for Wireless Network Setup

Installing an effective and reliable fire safety system in underground mines can allow people to reassess the procedures of structural fire protection required for safe evacuation. An automated underground mine communication and monitoring system based on the integration of new smart technologies is introduced to promote this prototype model for fire safety system. In response, to support the large data requirements of modern mines is enabled by the installation of an IEEE 802.11 compliant backbone [14]. This optical fiber infrastructure integrated with Wi-Fi nodes forms the backbone for this fire safety system that can also be used for other data hungry applications such as mine automation systems, remote control, video, etc. In the constantly changing topology of a mine, reliable and simplified communication backbone system is needed that can be capable of providing bilateral communications between the underground mine environment and the surface control center [15,16].

Figure 1 shows the architecture of this underground communication backbone composed of optical fiber infrastructure, gateways, routers, and end devices. The entire system is composed of different Wi-Fi nodes connected through gateway with the surface control center and the fire safety system. Routers with the ability of communicating with the fire safety system were employed to relay constant flow of information through the network.

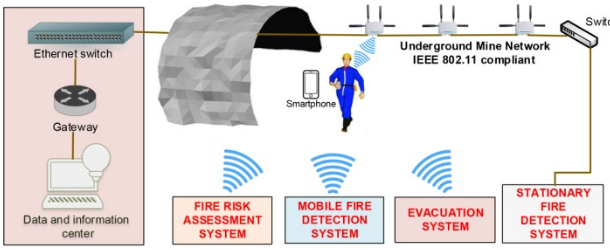

Figure 1. Proposed backbone for underground mine network

3.2. Prototype Model for Fire Safety System

Figure 2 shows the framework for the prototype model for fire safety system introduced in this research that uses smart technologies that can provide continuous flow of information and could significantly improve fire safety, detection and evacuation procedures in underground mines.

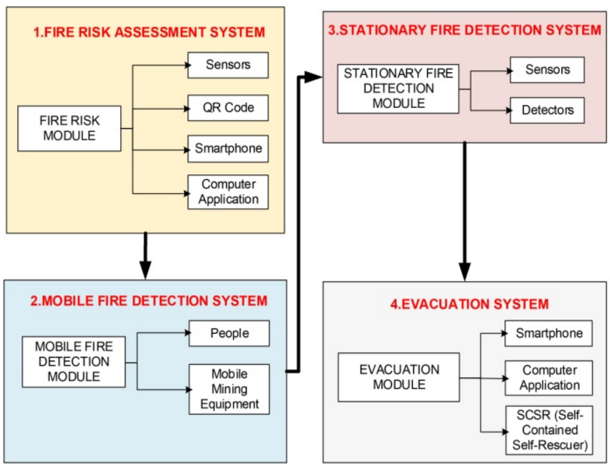

Figure 2. Framework of the prototype model for fire safety system

3.2.1. Fire risk assessment system

Fire risk assessment analysis in underground mining is a process of characterizing and understanding the fire hazards and the unwanted outcomes of fire occurrence. Fire risk assessment is defined as the product of the consequence to be expected from the fire and the probability of fire occurrence [17]. The fire risk assessment system presented in this paper uses available smart technology to estimate the fire risk from identified hazards in underground mining environment. This system comprises two steps of fire risk identification and fire risk analysis. The fire risk identification and fire risk analysis process in this system use QR codes to understand how and why fire could happen.

By placing the QR codes on highly flammable materials that are found in the underground mine along with magnitudes of consequence and probabilities from fire occurrence, by scanning the QR code with their smartphone each worker can obtain fire risk assessment expressed either in qualitative or quantitative terms depending on the type of risk and the information resources available (Figure 3).

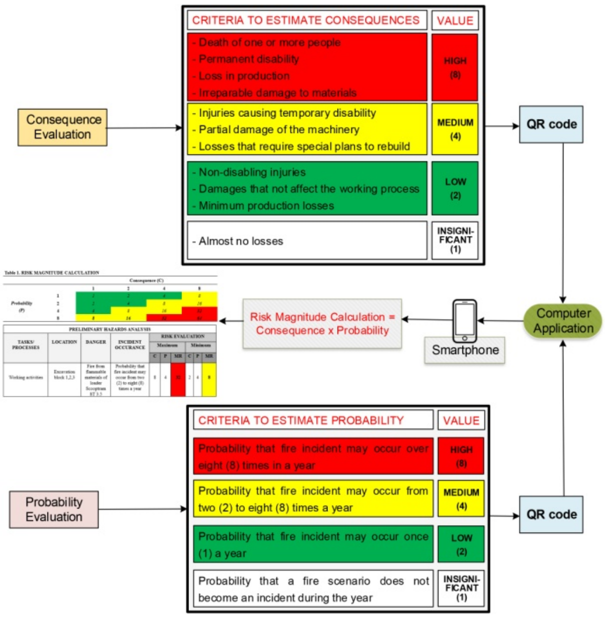

Figure 3. Fire risk assessment with QR codes and smartphone

Understanding the fire dangers, like the possible sources of ignition and the presence of dangerous substances, allows determination about the probability of a fire occurring. This methodology involves smart technology to establish the likelihood of fire occurrence and the personnel at risk.

Figure 4 shows the fire risk assessment system presented in this paper. This system consists of sensors attached to regular PPE clothing, which are connected with smartphone via energy-efficient Bluetooth sensors [18,19]. The sensors that are attached to the PPE can gather data points in real-time about smoke and heat exposure in underground mine environment, which data is then sent through Bluetooth to the local smartphone database from where it can notify the user about the presence of potential fire. With the help of a specially programmed computer application for this need that is installed on smartphone, the user can scan the QR codes that are put at high frequency work places and potential fire risk places and get automatic fire risk assessment from identified hazards in the underground mining environment. This data is then shown on the user's smartphone and when an internet connection is available it is sent via Wi-Fi to the networking device that enables the data to be viewed in the control center at the surface from where data and messages can be sand back to the user.

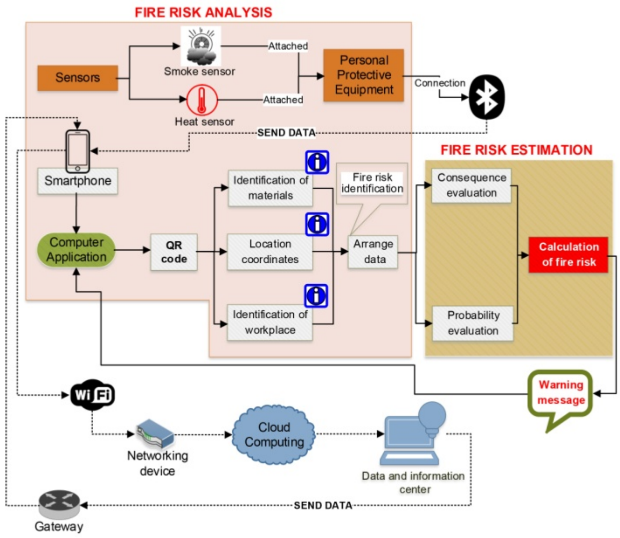

Figure 4. Framework of the fire risk assessment system

3.2.2. Mobile fire detection system

Accurate monitoring and constant flow of information about the underground mine environment is of crucial importance for miners' safety [20]. Early detection of fire and rapid response of miners for successful evacuation are key elements to survival.

An undetected fire could spread rapidly in underground mining facilities and, therefore, a combination of fire detection system is needed to overcome the difficult and hazardous environments of underground mines and to provide reliable early fire detection.

This combination of a fire detection system presented in this prototype model consists of sensors that are attached to the PPE of every miner and sensors attached to the working machinery which are capable of detecting fire (Figure 5).

Due to the constant movement of the mining workers and the working machinery through the mine, this system has the possibility of detecting fire at more locations within the mine, which shortens the time for detecting a fire with only stationary placed fire detectors.

The sensors that are attached to the PPE were mentioned in the previous section can gather data points in real-time that are sent through Bluetooth to the local smartphone database from where they can notify the user about the presence of potential fire (Figure 4).

In underground mines fuel and ignition sources are usually associated with infrastructure and mobile equipment. Most mining equipment is operated around the clock and virtually all of the working machinery used in mining operations contains large quantities of highly flammable fluids [21]. The material or fluids coming in contact with ignition sources can quickly erupt into a spreading fire that can have catastrophic consequences.

Rapid detection of this kind of fire caused by working machinery is crucial for quick suppression of fire and for safe evacuation.

This proposed versatile system that can be installed on every working machinery can provide detection, alarm and fire suppression system for mobile equipment such as haul trucks, hydraulic excavators, LHD, etc. The system offers linear and spot detection that can be used individually or in combination [22]. Thermal linear detection wire consists of conductors separated by a heat sensitive insulator which are melting at high temperature caused by fire. When the two conductors make contact they send a signal to the interface control module which signals the display module and the actuator device for the automatic fire suppression system. The thermal spot detectors used in this system are for higher reliability of fire detection. Thermal spot detectors signal the interface control module to initiate the fire suppression system when the temperature is over 150 °C and also to signal the display module. When the signal is sent from either of the two forms of detection, the display module then sends data about fire information through Bluetooth to the operator's smartphone so that the operator may evacuate to a safe distance from the detected fire.

This data is then automatically processed through the computer application installed on the operator's smartphone and then via Wi-Fi is sent through the installed backbone network of the mine to the surface control center (Figure 1). This mobile fire detection system can provide early fire detection that is connected with safe evacuation of miners before the underground passageways are filled with smoke.

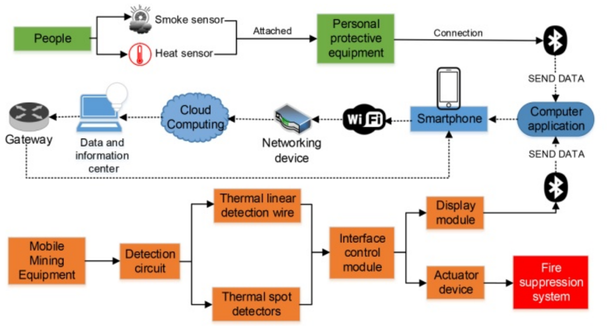

Figure 5. Framework of the mobile fire detection system

3.2.3 Stationary fire detection system

Fire detection system can be hindered by false fire alarms produced by smoke particulate and carbon monoxide (CO) emissions from diesel equipment and metal welding work activities. The constant generation of such false alarms can lead workers to ignore this repetitions of false alarms associated with these emissions and this can jeopardize their safety in the event of real fire.

This proposed stationary fire detection system uses combinations of different types of fire sensors for early fire detection and nuisance signal discrimination (Figure 6). Characterizing and identifying the signatures of interfering sources in underground mines using combinations of different types of sensors' arrays coupled with a rule decision system with alarm algorithms offer the possibility of generating an alarm according to the real situation.

Fire smoke detector, metal oxide semiconductor (MOS) sensors, CO sensors, optical and ionization smoke sensors were used in this proposed system to differentiate real combustion of fire products from emissions produced by diesel equipment and metal welding work activities. In the presence of emissions produced by diesel equipment and acetylene torch cutting an MOS sensor can respond with a signal which is sensitive to nitric oxides (NOx). Without the MOS sensor signal, the ionization smoke sensor and the CO sensor would identify these emissions as a fire [23]. An integrated system with a combination of fire smoke detector, MOS sensors, CO sensors, optical and ionization smoke sensors can reduce false fire alarms and provide early warning capability based on the real situation. This system integration with connection to the rule decision system can trigger an alarm and also send data through the installed backbone network of the mine to the workers' smartphones and also to the surface control center. This proposed stationary fire detection system can enhance the miners' safety by providing information about early fire detection and high emissions from diesel equipment and metal welding work activities.

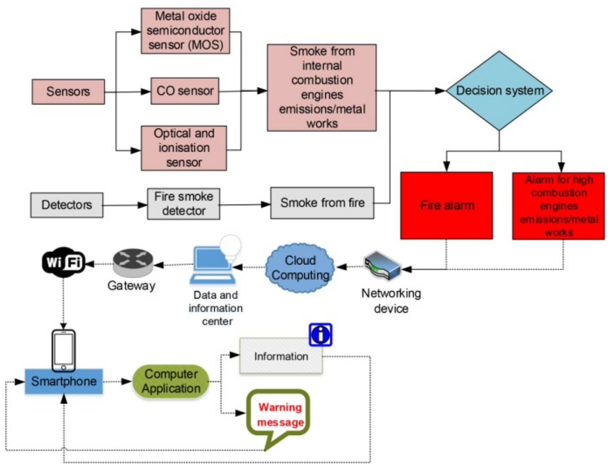

Figure 6. Framework of the stationary fire detection system

3.2.4. Evacuation system

Evacuation routes are commonly displayed in a two dimensional format (2D), and those charts usually cannot identify the location of the fire or recommend the ideal optimal evacuation route. Implementing evacuation system which can be displayed in a three dimensional format (3D) on smartphones can help users to visualize and understand the status of a fire or the evacuation plan [24].

The need to improve the traditional 2D fire evacuation systems encouraged the development of new systems to prevent and minimize fire disasters using smart technology. For instance, the information from the smart evacuation system may help workers to identify evacuation routes, effectively reduce disaster response time, locate field personnel and fire facilities [25].

This study proposes a prototype model for a fire evacuation system for underground mining industry that integrates and presents information on smartphone for SCSR (Self-Contained Self-Rescuer) capacity, evacuation and rescue routes, evacuation guide system and visualization on 3D model (Figure 7). When fire is detected, the mobile fire detection system and stationary fire detection system presented in the previous sections (Figure 5, Figure 6) send fire alarm data to the workers' smartphones. Once workers receive the fire alarm data, they start to install the SCSR apparatus on themselves. The SCSR apparatus is connected via Bluetooth with the smartphones where it is showing its capacity.

The smartphone with the computer application that contains 3D model of the underground mine is constantly sending packets of information about workers' location through the backbone network of the mine to the surface control center [26]. This system instantly shows in the 3D model the locations in the underground mine that are affected by the fire. This data then passes through the evacuation routes calculation module in the surface control center where this data is preprocessed and the results in the form of an evacuation guide system are sent through the gateway back to the workers' smartphones. The evacuation routes calculation module combines the received data from the mobile fire detection system, stationary fire detection system, unique location of workers and SCSR capacity in order to calculate the optimal evacuation routes for each worker and facilitate evacuation guidance. The smartphone computer application with voice/arrow functions provides assistance in evacuation guidance of the workers. This function works with the built-in gyroscope and accelerometer sensor in the smartphone which calculates the horizontal azimuth of the smartphone device and provides visual and sound direction guidance using an arrow shown on the smartphone screen that constantly points in the direction of the currently recommended optimal evacuation route [27]. The accelerometer sensor constantly calculates the workers' walking speed and this data, combined with the length of the evacuation routes and the remaining capacity of the SCSR apparatus, can significantly help in the calculation of an optimal evacuation route.

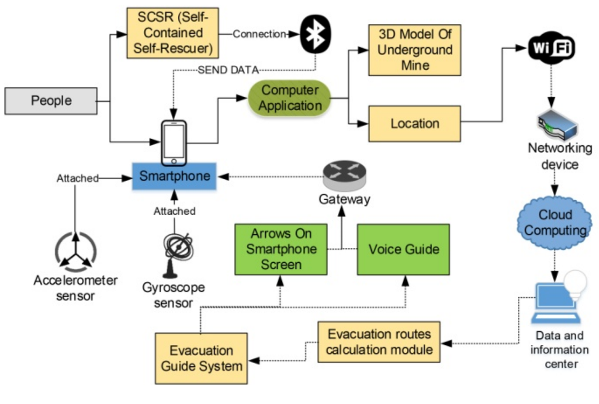

Figure 7. Framework of the evacuation system

3.2.5. Modelling of an Example Scenario

Based on the discussions in the previous sections, this research proposes a prototype model for fire safety system in underground mining that can provide fire risk assessment analysis, fire detection, safety situation-awareness and effective system for evacuation. Figure 8 shows an example scenario where some of the possibilities of the proposed fire safety system can be seen.

In this scenario the stationary fire detection system installed on specific workplaces in the underground mine detects fire with the help of the attached fire smoke detector. This data then passes through a decision system to differentiate it from emissions produced by diesel equipment and metal welding work activities. Once the data is processed as a real fire, the decision system triggers a fire alarm and also sends a warning message with fire location through the installed backbone network of the mine to the workers' smartphones and the surface control center.

The smartphone is constantly sending packets of information about the location of the workers and with the received data from all the parts of the fire safety system the evacuation routes module calculates the optimal evacuation routes for each individual worker based on their location in the mine. This data in the form of an evacuation guide system is sent through the gateway back to the workers' smartphones.

Moreover, this example scenario shows that this prototype model for fire safety system that combines information from multiple interconnected systems provides effective real-time evacuation in case of fire and also important information for fire rescue personnel.

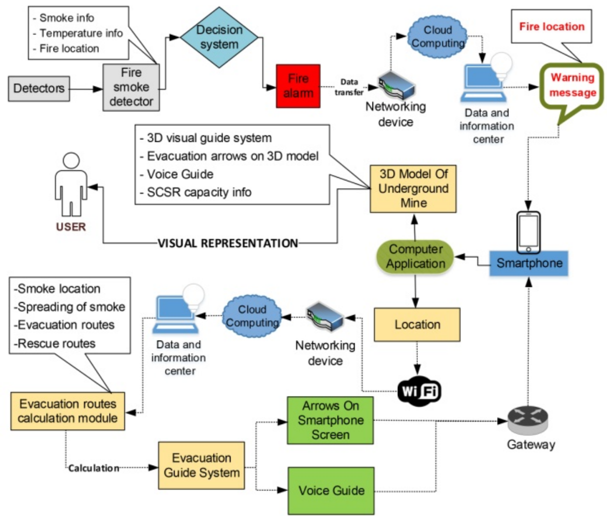

Figure 8. Modelling of example scenario

4. Conclusion

An underground fire is still a major problem in the mining industry that leads to catastrophic events such as loss of human life, injuries, damage to equipment, loss of property and production.

The presented paper investigates the potential of developing and implementing smart fire safety system that can be used in the underground mining industry. This proposed system is designed to solve current key problems about fire risk assessment, fire detection, safety situation awareness and effective system for evacuation. The crucial information that can be gathered from this prototype system that is connected with the backbone network of the mine can be sent and shown on smartphone devices. The potential of sharing this information with every worker is enormous, knowing the importance of giving the underground workers the earliest possible warning of potential fire.

The developing and implementing of this smart fire safety system in the underground mining industry offers benefits in many areas:

- quick calculation of fire risk assessment;
- early fire detection and generating extra time that allows opportunities to respond to the fire and extinguish it;
- location tracking of each underground mine worker;
- interconnected alarms with decision systems that can differentiate real combustion of fire products from emissions produced by diesel equipment and metal welding work activities that can reduce the false fire alarms and provide early warning capability based on a real situation;
- optimal evacuation and rescue route calculation and planning;
- solving of key evacuation problems that affect fire response efforts, including slow evacuations due to human errors and confusions;
- escape from the hazardous fire area on time;
- fire alarms to monitor the status of disaster areas in order to plan and show the optimal evacuation routes on the smartphone devices;
- reduce response times for fire accidents and minimize the time necessary to find trapped underground mine workers;
- 3D visual information presented on a smartphone device for optimal evacuation route for each worker;
- real-time evacuation arrow and voice guidance presented on smartphone devices to assist evacuees;

In this paper we introduced an initial effort towards an effective and efficient fire safety system. The benefits from the possible results of this study demonstrate that this smart fire safety system can significantly improve the fire safety management processes in underground mines.

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