Design of intelligent comprehensive management and control system for mine auxiliary safety risks based on RFID technology

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ABSTRACT

In addition to the numerous safety risks, such gas leaks and earthquakes, which can cause injuries and fatalities, the working environment in mines is complicated and unpredictable. An intelligent comprehensive management and control system for mine auxiliary safety concerns based on RFID (radio frequency identification) technology is designed to assist managers in precisely monitoring mine seismic hazards and ensuring operational safety. The hardware component of the system employs RFID electronic tags, which are affixed to important locations for seismic monitoring, workers, and mining equipment, using the detected objects as carriers. These sensors are used to collect information about the detected objects. Data transmission to the data layer occurs after the RFID reader receives the data. Following a series of processing steps, such as data cleansing, it is saved for quick access by the application layer. Among them, the LANDMARC algorithm is used to obtain the signal reception strength values of the reference and to-be-located electronic tags in real time, and to locate and track the positions of the objects to be monitored in coalmines in real time. The earthquake risk-monitoring module can obtain the earthquake risk area and the corresponding earthquake risk level, and issue warnings in time through the alarm module, providing decisions for mine safety management and risk avoidance and rescue, and presenting them through the display layer. The experimental results show that the system can realize intelligent monitoring and early warning of the mine environment, obtain real-time location information of personnel and earthquake risk areas, and effectively assist in comprehensive mine management and control.

Keywords: RFID technology, mine safety, seismic risk, integrated management and control system, environmental monitoring, electronic tags

1. INTRODUCTION

The growing demand for minerals in China has increased the depth of mining and the load of production activities, putting further strain on mine safety production[1-3]. The safety risk management approach has become unable to satisfy the demands of safety management and control owing to its decentralized structure[4-6]. As a result, it is critical to develop a mine auxiliary safety intelligence comprehensive management and control system in order to increase administration efforts and extend the scope. To improve mine production safety and lower the likelihood of accidents by examining and addressing safety risk management concerns from a methodical, comprehensive perspective.

Many academics has recently undertaken significant study on the safety intelligent integrated management and control system. For example, Tan et al.[7] studied an intelligent coalmine management and control system, which effectively combined information technology, database technology and other system structures to realize coalmine safety risk monitoring, early warning, management and control and other system functions to ensure the safe operation of coalmines. However, the system may face the problem of high complexity of data fusion and processing. Zhao et al.[8] constructed a hierarchical safety status management and control system for coalmines, which calculated coalmine safety risks by selecting indicators such as environmental risks, personnel risks, and accident risks, and proposed management and control measures to control coalmine risks based on the evaluation results. However, this method mainly focuses on risk assessment, and its real-time monitoring and early warning functions for risks are relatively weak. Fu et al.[9] studied an intelligent safety-monitoring robot for coalmine shaft construction, which went deep into the mine to collect images and gas concentration data in real time through a robot equipped with high-definition cameras, gas sensors and other sensing equipment. Through advanced data processing and analysis technology, the system can automatically identify anomalies and potential hazards, and immediately send early warning information to the ground control center. However, the

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development and deployment costs of robots can be high, especially in complex and harsh mine environments, and the stability and reliability of robots may be challenging.

Yang et al.[10] studied a coalmine safety management system based on text classification mining algorithms and hazard source association rules. During the coalmine production process, a significant quantity of text data was gathered and analyzed. This allowed the text classification-mining algorithm to automatically categories and extract safety-related information as well as identify and extract important information about the cause of the danger. The association rule algorithm should then be used to identify possible relationships and rules between these danger sources. By building a hazard source association rule library, the safety status of the coalmine production process is monitored in real time. However, since the safety status of the coalmine production process is constantly changing, the system combined with historical data analysis may not be able to capture these changes in time, resulting in a lag in early warning and response measures.

An intelligent, all-encompassing RFID-based monitoring and control solution for auxiliary hazards in mines is developed to address the aforementioned issues. RFID technology is used for early warning systems in the event of external forces such as earthquakes, equipment management, transmission positioning and tracking, and relevant information collection. A detailed investigation is conducted to achieve a comprehensive understanding and real-time tracking of mine safety risks.

2. INTELLIGENT COMPREHENSIVE MANAGEMENT AND CONTROL SYSTEM FOR MINE AUXILIARY SAFETY RISKS

2.1 Design the overall architecture of RFID-based system

The intelligent mine auxiliary safety risk integrated control system based on RFID is a hierarchical structure, as shown in Figure 1.

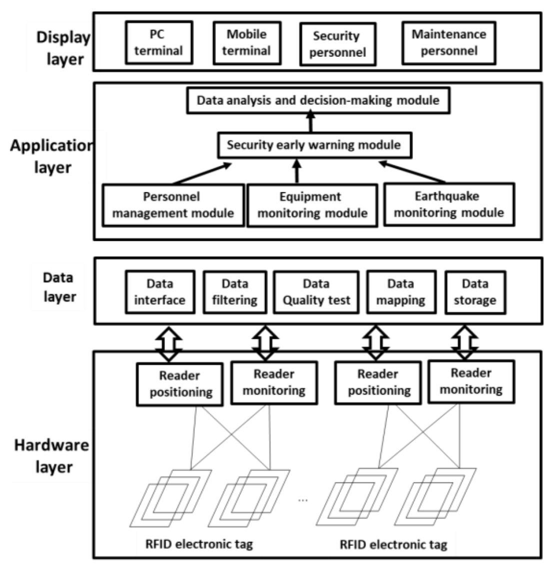

Figure 1. Overall structure of the system.

2.1.1 Hardware layer. It is mainly composed of RFID readers and electronic tags, in which RFID readers can realize information interaction with electronic tags. The system has a strong signal processing function, which can receive radio frequency signals from electronic tags and translate them into a format that can be read by a computer. The electronic tag is based on the object to be detected and attached to the mining equipment, personnel and key locations with high risk. Each transponder has a unique code that identifies the object to which it is attached. When the electronic tag enters the signal range of the RFID reader, it will actively send its own identification code and related data to the reader. These data include the status information of equipment, personnel location information, seismic wave vibration, etc., which provide data sources for the system to carry out mine seismic risk control. The data layer is responsible for receiving the collected data at the hardware layer, and storing it after preprocessing such as data cleaning, which is convenient for the application layer to call.

2.1.2 Application layer. It contains various functional modules. Personnel management module uses RFID technology to locate and track mine personnel in real time. The real-time location of personnel is obtained to prevent them from entering dangerous areas by mistake and ensure the safety of personnel.

2.1.3 Equipment monitoring module. By installing RFID electronic tags on mining equipment, the system can collect data such as the operating status and location information of the equipment in real time. By comparing with the inherent information of the equipment[11,12], the system can judge the health status of the equipment and automatically set the corresponding maintenance level. When the equipment fails or is abnormal, it can alarm in time and remind the manager to take measures in time. The earthquake monitoring module uses RFID technology to collect the vibration acceleration of the monitoring area in real time, and compares the collection results with the standard value. Once the standard value is deviated, a risk warning will be issued, and the monitoring point where the vibration acceleration exceeds the standard value will be regarded as the center point, and the circular area with a radius of r will be regarded as the risk area. The total risk area is obtained by integrating all risk areas, and the risk of mine instability is calculated to guide the safety-warning module to issue a risk warning.

2.1.4 Safety warning module. Combined with RFID data, the system can monitor the safety status of the mine in real time. When abnormal conditions are detected (such as excessive gas concentration, equipment failure, earthquake risk, etc.), the system can immediately trigger the early warning mechanism and remind the management personnel and on-site personnel to take emergency measures through sound and light alarms, SMS notifications, etc. The data analysis and decision-making module can provide decision-making support for the safety management of mines. The total risk area obtained during earthquake monitoring can be combined with the personnel management module and the equipment-monitoring module to obtain the positioning results of equipment and personnel, effectively guiding managers to make correct risk avoidance and rescue decisions for comprehensive safety management of mine areas, such as notifying personnel and large mobile equipment to evacuate.

2.1.5 Display layer. Real-time data and operation interface are provided to various types of users through a visual interface.

2.2 RFID technology hardware design

The hardware layer of the system uses RFID readers and tags to realize real-time positioning and information collection of mine personnel, equipment and key locations. RFID mainly includes electronic tags and readers; wherein electronic tags are selected in this article as shown in Figure 2.

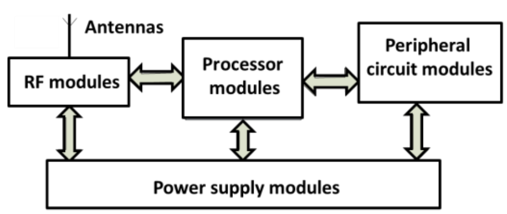

Figure 2. Structure of electronic tags.

As the core of the electronic tag, the processor module is used to ensure the smooth completion of the electronic tag, which is designed with CC2530 as the chip, which can effectively process the collected data and control the wireless radio frequency module to transmit the collected data to the reader through the antenna. The power module is responsible for supplying power to the processor module, because the electronic tag is installed on the mine staff or equipment, so it provides power for the electronic tag through the power supply mode of two dry batteries. The radio frequency module is responsible for sending the collected data through the transmitting antenna. There are three main peripheral interface circuits: serial, emulation, and I/O interfaces, which are used for online debugging and transponder integration[13] to achieve better serial communication functions for transponders.

Given the complexity of the mine environment[14], the number of monitored objects is proportional to the requirements, cost, and maintenance difficulty of the control system. Therefore, in order to minimize the number of monitoring devices, the system integrates a variety of sensor devices in the design of the reader, so that RFID not only has positioning and identification functions, but also adds a variety of sensor perception functions to it, which better assists the intelligent integrated management of my risks. The structure of the reader is shown in Figure 3.

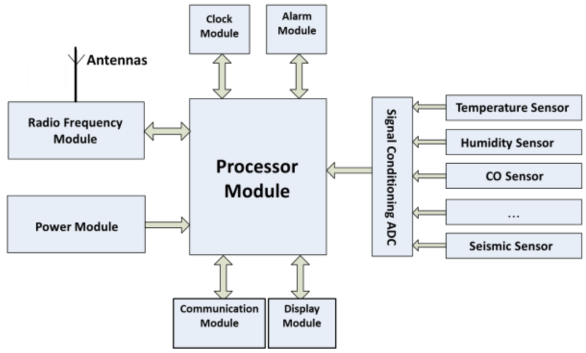

Figure 3. Structure of the reader.

The processor module of the reader is similar to the electronic tag and designed with CC2530 as the core chip. It is mainly accountable for organizing the different modules to accomplish their assigned responsibilities and serves as control hub of the reader. Similar to the electronic tag, the reader's processor module is built using the CC2530 core chip, which serves as the control center and mainly responsible for coordinating each module to accomplish a distinct function. The radio frequency module is responsible for receiving the data signal collected by the electronic tag and demodulating the signal. There are two types of sensor modules: one is temperature, humidity and seismic sensors, which integrate sensitive components into the chip, and the processor module completes information acquisition through a direct control chip[15]. Another type of sensor is a gas sensor, which is used to collect harmful gases in coalmines, mainly carbon monoxide sensors, methane sensors, hydrogen sulfide sensors, which cannot be integrated into the chip like temperature and humidity sensors. The display module adopts 12864LCD liquid crystal display, which presents the temperature and humidity of the mine environment, seismic waves, harmful gases, and relevant information of personnel and equipment. The clock module can effectively record the time when the data is transmitted from the electronic tag to the reader. The alarm module can send out an alarm in time when there is an abnormality, and prompt the abnormal information. The communication module is responsible for transmitting the information obtained by the reader to the data layer for subsequent applications.

2.3 RFID-based positioning software design

The system application layer uses RFID positioning algorithms to track the locations of monitored objects in real time, including coal mine personnel, mobile equipment, and various earthquake risk key points. When safety risks occur, timely positioning can provide decisions for comprehensive management and control. To enable prompt risk management, for instance, the location of personnel and equipment will be used to determine whether they are in the risk area. If the positioning of a monitoring point results in the identification of an excessive vibration acceleration, that point will be considered the earthquake risk center point. Numerous RFID positioning techniques are available for identifying purposes. This paper thoroughly examines variables such the intricate mining environment, positioning accuracy, cost, and technical implementation complexity. In order to effectively manage and regulate system auxiliary safety hazards in mines and maximize the safety of mine operations, it utilizes the RFID positioning technique based on RSSI (signal receiving intensity) to finish the positioning software design.

The electronic tag is usually based on the monitored object in the mine as the carrier, and the RSSI positioning method calculates the distance between the two according to the power loss between the electronic tag and the reader, and completes the positioning. The LANDMARC algorithm is a positioning algorithm based on RSSI (Signal Reception Strength), and the process of locating the target to be monitored is as follows:

The number of existing readers, reference transponders, and transponders to be measured is set to *U*, *H*, *M* respectively, and the RSSI value of the reference transponder *RTj* in each reader is:

$$S_R^j = (S_{R_1}^j, S_{R_2}^j, \ldots, S_{R_U}^j) \tag{1}$$

where $S_{R_U}^j$ is used to describe the RSSI value of the reference electronic tag RT_j read by the reader ξ_u. The RSSI value of the electronic tag LT_i under test at each reader is:

$$S_L^i = (S_{L_1}^i, S_{L_2}^i, ..., S_{L_U}^i) \tag{2}$$

where $S_{L_U}^i$ is used to describe the RSSI value read by the reader ξ_u for the measured electronic tag LT_i. Then the expression of the Euclidean distance E_{LR}^{ij} of the signal strength between RT_j and LT_i is:

$$\begin{cases} E_{LR}^{ij} = \sqrt{\sum_{u=1}^{U} \phi_u^{ij}} \\ \phi_u^{ij} = (S_L^i - S_R^j)^2 \end{cases} \tag{3}$$

where $i \in (1, M)$, $j \in (1, H)$. The lower the value of E_{LR}^{ij}, the closer the RSSI value of the reference and the tag to be measured on the reader

According to equation (3), the Euclidean distance between LT_i and all RT_j is calculated, the distance vector $E_{LR}^i = (E_{LR}^{i_1}, E_{LR}^{i_2}, ..., E_{LR}^{i_H})$ is established, and the distance values with the smallest distance are composed of the distance vector $EP_{LR}^i = (EP_{LR}^{i_1}, EP_{LR}^{i_2}, ..., EP_{LR}^{i_k})$ after sorting, and the corresponding k reference electronic tags are regarded as the neighbors of LT_i.

According to EP_{LR}^i, the differential weight is set for the reference electronic tag, and the calculation formula of the coordinate (x_{LT}^i, y_{LT}^i) of the electronic tag to be measured is as follows:

$$\begin{cases} (x_{LT}^i, y_{LT}^i) = \sum_{j=1}^{k} w_j^i (x_{RT_j}^i, y_{RT_j}^i) \\ w_j^i = (EP_{LR}^{ij})^{-2}, j \in (1, k) \end{cases} \tag{4}$$

Among them, w_j^i is used to describe the weight of the j th neighborhood reference electronic tag; $(x_{RT_j}^i, y_{RT_j}^i)$ is used to describe the coordinates of the j th neighborhood reference electronic tag of LT_i. That is, when positioning, the location of the personnel or equipment or each earthquake risk key point is

2.4 Earthquake risk monitoring software

The RFID electronic tag is installed on the earthquake monitoring point, we collect its vibration acceleration data Q, and compare the collected data with the set standard value J to obtain the quantitative value Δ of the difference between the two. The calculations are derived by following equation:

$$\Delta = \frac{|J - Q|}{J} \times 100\% \quad \text{v} \tag{5}$$

The vibration amplitude of the monitoring point is considered to be in normal condition when the difference between the two is within the range of [0%, 15%]. When the difference between the two exceeds 15%, there is an earthquake danger, and an alert must be activated promptly. In addition, the circular region with a radius of r is considered the danger area, and any places with a difference quantization value more than 15% are deemed the center point. The seismic risk level is calculated and sent to the safety-warning module alongside the danger region for warning purposes.

The risk level calculation process is as follows:

(1) Calculating the force exerted by earthquake on the mine soil based on the collected vibration acceleration:

$$F = \frac{\xi \alpha \chi W}{g} \tag{6}$$

Among them, α, χ, ξ, W and g are used to describe the vibration acceleration, dynamic distribution coefficient, reduction coefficient, coal mine soil gravity, and gravity acceleration collected by the seismic sensor in RFID, respectively.

(2) Calculating the probability of instability under earthquake action as the earthquake risk probability:

$$p_f = \sum_j p_f(F < S | I_j) \cdot p(I_j) \tag{7}$$

Among them p_f, I_j, $p(\cdot)$, and S are used to describe the instability probability, earthquake intensity, earthquake probability, and earthquake action response, respectively.

According to the earthquake risk probability value, the earthquake risk level is set, as shown in Table 1.

Table 1. Earthquake risk levels.

Earthquake risk probability	**Seismic risk level**
<0.0001	Level 1 (very low)
0.0001-0.001	Level 2 (low)
0.001-0.01	Level 3 (lower)
0.01-0.1	Level 4 (moderate)
0.1-0.5	Level 5 (higher)
>0.5	Level 6 (high)

3. EXPERIMENTAL ANALYSIS

Taking a mine located in northeast China as the research area, the mine has huge iron ore resource reserves and excellent quality, and the ore types are mainly magnetite and hematite. The mine is also associated with other metal minerals, such as copper, lead, zinc, etc., but on a relatively small scale. In terms of non-metallic minerals, limestone, talc, clay and other resources are also abundant, as shown in Table 2.

Table 2. Details of the mine.

Parameter	**Details**
Iron ore reserves	More than 3 billion tons
Ore grade	25%-65%
Associated mineral resources	Copper, lead, zinc and other metal minerals; Non-metallic minerals such as limestone, talc, and clay
Ore body size	Extra-large
Ore body morphology	Deep ore body and steep inclination
Mining method	Combination of open pit and underground mining
Production equipment	Mining machines, transportation equipment, drilling and blasting equipment, ventilation equipment, etc.

In order to improve the mining of the mine, the intelligent comprehensive management and control system of mine auxiliary safety risk based on RFID technology designed in this paper was applied to the mine, and the practical application effect of the system in this paper was analyzed from multiple perspectives. The core function of the intelligent management and control system of mine auxiliary safety risks designed in this paper is to realize comprehensive monitoring and intelligent management of the mine production process through RFID hardware equipment. In view of the key role of RFID in the system, its selection process is particularly important. RFID technology has multiple working frequency bands, including low frequency, high frequency, ultra-high frequency and microwave, and each frequency band has different performance. The comparison of the application performance of RFID in different working frequency bands is shown in Table 3.

Table 3. Applicability of RFID in different operating frequency bands.

Operating frequency	**Working frequency**	**Transmission speed**	**Maximum recognition speed**	**Collision avoidance**	**Maximum recognition distance**
Low frequency	120-130 kHz	8.5 kbps	1 m/s	limited	0.6 m
High frequency	13.45 MHz	65 kbps	5 m/s	Better	1.5 m
UHF	850-950 MHz	65 kbps	50 m/s	Better	6 m
Microwave	2.45 GHz	65 kbps	10 m/s	Better	60 m

Table 3 shows that the working frequency band has a bigger influence on the identification distance. Low-frequency and high-frequency RFID have maximum identification ranges of only 1.5 m and are most suitable suited to smaller ranges. However, in a large, open and complex production environment such as a mine, this recognition distance is obviously unable to meet the needs for precise positioning of personnel and equipment. In contrast, RFID in the microwave frequency band has an identification distance of up to tens of meters, showing significant advantages. This characteristic makes microwave RFID have broad application prospects in personnel positioning and equipment management in mining environments. For this system, microwave RFID with an operating frequency band of 2.45 GHz is selected as the hardware device for system application. This choice not only fully considers the particularity of the mining environment, but also ensures the effectiveness and reliability of RFID technology in the system. This system integrates multiple sensors in the RFID reader, which can collect environmental data such as harmful gas concentration, humidity, temperature, etc. in each tunnel and working area of the mine in real time, and pre-process and store the collected data. If a certain data exceeds the standard, it will immediately alarm and display the exceeded area and item. Taking the 0002-working area of the 0001 tunnel of the mine as an example, the various environmental data monitored by the system at 8:35:00 are shown in Figure 4.

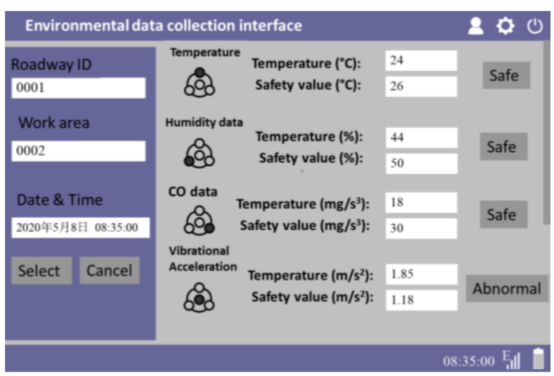

Figure 4. Monitoring results of various environmental data.

The system uses a variety of sensors integrated in the RFID reader to monitor important environmental parameters like harmful gas concentration, humidity, temperature, and vibration acceleration in the 0002-work area of the 0001 tunnel of the mine at 8:35:00 in real time, according to an analysis of the environmental data collection results shown in Figure 4. The vibration acceleration temperature data is higher than the established safety value, but the temperature, humidity, and dangerous gas monitoring findings are all within the predetermined safety limits, as shown in Figure 5. At this time, the system immediately issued an abnormal alarm and notified the management personnel to take emergency measures in time. The experimental results show that the system has played an important role in environmental monitoring and early warning, and has provided effective technical support for the safe production of mines.

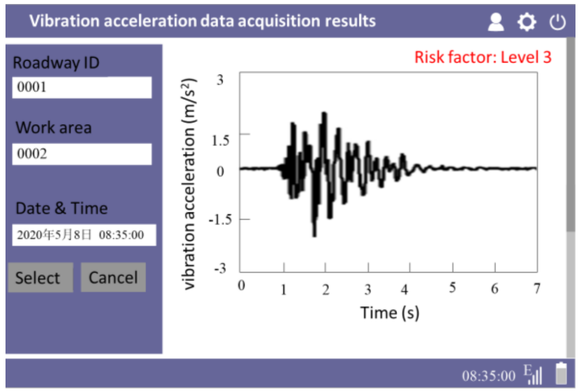

Figure 5. Vibration acceleration acquisition results.

At this time, the specific location of the staff with the number 006 in the 0002-operation area of the 0001 roadway of the mine and the results of the risk area are shown in Figure 6

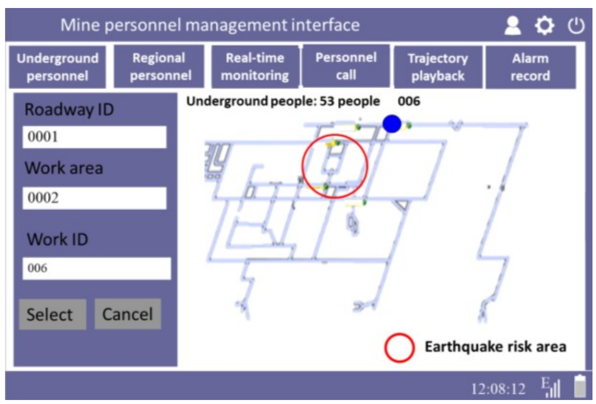

Figure 6. Personnel positioning results.

The staff positioning function in this study could be effectively realized by the system, as demonstrated by the analysis of the outcomes of personnel positioning in Figure 6. It is evident from the image where the staff member with the number 006 is positioned in the mine operation area. With the use of RFID technology, the system precisely locates the employees, and it instantly presents the location data on the interface. This positioning function not only helps managers understand the distribution of people in the work area but can also be used to monitor whether workers are entering seismic risk areas or following safe operating procedures. In this example, the system location results show that the worker with the number 006 is near the seismic risk area. This means that the person might be exposed to potential safety risks, and managers can take necessary safety measures in a timely manner based on this information, such as reminding the person to pay attention to safety, adjusting their work tasks, or increasing safety supervision to prevent potential safety accidents. To sum up, this paper systematically demonstrates its effectiveness and practicability for personnel positioning and safety management in mine safety production. This feature helps to improve the safety of mine operations and reduce safety risks.

4. CONCLUSION

Through the research on the intelligent integrated management and control system of mine auxiliary safety risks, the following conclusions are obtained:

(1) This paper presents an intelligent comprehensive management and control system for mine safety risks using RFID technology. The system monitors the mine production process and collects real-time data, detecting potential safety risks

and proposing early warnings. This system reduces production accidents and ensures personnel safety. The analysis of production data optimizes the mine's mining plan, improves resource utilization efficiency, promotes sustainable development, and coordinates the development of economic and social benefits. The system has been proven to effectively reduce production accidents and ensure personnel safety. The application system in mining operations is expected to enhance overall efficiency and safety in the mine industry.

(2) Introducing artificial intelligence algorithms to improve mining equipment maintenance efficiency. The steady operation of mining equipment is critical for sustaining production efficiency and safety. The primary intelligent integrated management and control system of mine auxiliary safety hazards based on RFID technology can have AI algorithms included in it in order to further increase the dependability and efficiency of maintenance of mining equipment. The system employs RFID technology to capture real-time equipment operation data such as operating time, load conditions, temperature, and so on, which is transmitted into the AI algorithm for deep learning and analysis. The AI algorithm can predict potential equipment failures and intelligently formulate equipment maintenance plans based on the actual operation conditions and historical data of the equipment.

(3) The gauge function of the mine network is immovable because of the short construction period and long blasting interval of the mine network, which limits the blasting sample size that can be recorded by the network. This work intends to keep improving the gauge function of the local seismic magnitude of the mine network based on this study as monitoring time and sample size increase. The objective is to further enhance the empirical formula that links the local magnitude (ML) and the quantity of explosives (Y).

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