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Design and Key Technology Research of Coal Mine Safety Comprehensive Monitoring System based on AHP Analysis Method

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Abstract:

With the continuous deepening of coal mining activities, the importance of coal mine safety has become increasingly prominent and has become a widely concerned focus of society. In order to improve the efficiency and accuracy of coal mine safety management, we adopted the Analytic Hierarchy Process (AHP) to design and implement a comprehensive monitoring system for coal mine safety. This system not only combines the actual situation of coal mining, but also fully utilizes modern technological means to ensure the safety and stability of coal mining operations. Firstly, we conducted an in-depth analysis and statistical analysis of the causes of 45 coal mine gas explosion accidents that have occurred in the past 5 years. Through detailed accident investigation and data analysis, we identified the key factors leading to gas explosions and constructed a dishonesty model for gas explosion accidents based on the Analytic Hierarchy Process. Based on the current situation of coal mine safety monitoring system and the development trend of wireless sensor network technology, a design scheme of coal mine comprehensive monitoring system based on wireless sensor network is proposed. Based on the CC2430/CC2431 node design, a security monitoring system in wireless sensor networks has been implemented. This system adopts advanced wireless communication technology to ensure stable data transmission and real-time processing. At the same time, we also conducted strict testing on the system to ensure its reliability and stability in practical applications. The test results in a simulated mine show that when the distance between wireless nodes is 10m, the system can meet communication requirements, achieve accurate data transmission and real-time monitoring.

Keywords: Coal mine safety; Integrated monitoring system; AHP analysis; Risk assessment; Early warning mechanism

1. INTRODUCTION

Coal is the foundation of our national economy and social development. Our country belongs to a country poor in oil but rich in coal [1]. Despite the continuous rise of new energy sources such as solar and wind energy with technological progress and diversification of energy structure, the position of coal as the dominant energy source will not waver in the foreseeable future. This is mainly due to China's huge energy demand and abundant coal resources. Coal not only has a relatively stable price, but also its mining and utilization technology is quite mature, which gives it an irreplaceable advantage in the energy market. More importantly, the coal industry plays a crucial role in the sustainable development of the national economy. It is the fundamental raw material for many industrial sectors, including electricity, steel, chemical industry, etc., all of which are pillar industries of the national economy. The stable supply of coal is not only related to the normal operation of these industries, but also has a profound impact on the economic stability and social development of the country. Safety is very important for coal production. At present, the production of coal mines in our country is mainly using the method of well drilling, and the production environment is complex, so it is essential [3]. After years of development, the security situation of China's coal industry has been significantly improved [4]. However, underground casualty accidents are still very serious, and major accidents occur sometimes, which has become a "bottleneck" problem that constrains the development [5]. The coal seam conditions and geological structures in our country are quite complex, which is not only reflected in the diversity of coal seam types, such as spontaneous combustion coal seams, high gas coal seams, and coal and gas outburst coal seams, but also in the safety challenges brought by various coal seam characteristics. This complexity makes safety issues particularly prominent in coal mine production [6]. Firstly, the spontaneous combustion of coal seams increases the risk of fire due to their tendency towards spontaneous combustion. High gas coal seams face the threat of gas accumulation and explosion, which poses a huge challenge to the safety production of coal mines. And coal and gas outburst coal seams may cause serious safety accidents due to the sudden release of coal and gas pressure during the mining process. Secondly, as the depth of coal mining continues to increase, we are facing more complex geological environments and higher mining difficulties. This not only includes changes in physical conditions such as increased ground pressure and geothermal rise, but also involves the interactive effects of various factors such as groundwater and geological structures. These changes have further increased the safety risks in coal mine production [7]. Therefore, it is an inevitable trend of loss of historical development and the urgent problem in the coal industry safety needs to be solved to take scientific, systematic, and complete measures to change the coal security situation in our country and the backwardness and to strengthen the research and application of the safety management and safety science and technology. In addition, it is quite urgent to effectively prevent and control all kinds of accidents, and reduce the casualties and economic loss caused by all kinds of accidents [8]. In recent years, coal mine accidents have occurred frequently in China. Through in-depth analysis of the causes of accidents, we have found that the vast majority of coal mine accidents are caused by negligence and improper management, rather than just technical reasons [9]. This means that relying solely on improving coal mine safety control technology to reduce accidents is far from enough. Therefore, we must start from a broader perspective and comprehensively and systematically examine the root causes of coal mine accidents. Firstly, we need to conduct a thorough root cause analysis of coal mine accidents. This is not only about analyzing the direct cause of the accident, but also tracing back to the management loopholes, lack of responsibility, and cultural issues behind it. By establishing an effective accident model, we can more accurately identify the potential factors and triggering conditions of accidents [10]. This article will start with studying the dishonest factors in coal mine safety accidents and use Analytic Hierarchy Process (AHP) to construct a coal mine safety accident dishonest model [11]. This model aims to reveal the human factors behind the accident, such as weak safety awareness, illegal operation, management negligence, etc., and quantify the impact of these factors on the accident. Through this model, we can more clearly understand that the occurrence of coal mine safety accidents is often closely related to human factors, not just technical issues. After analyzing the dishonest factors of coal mine safety accidents, we need to further explore how to take effective measures to prevent and reduce the occurrence of accidents [12]. This involves countermeasures in both technical and management aspects. In terms of technology, we need to continuously promote innovation and development of coal mine safety control technology, improve the reliability and safety of equipment. At the same time, we also need to pay attention to the application of wireless sensor network technology in coal mine safety monitoring, and timely discover and warn potential safety hazards through real-time monitoring and data analysis [13].

2. VIDEO MONITORING SYSTEM AND COAL MINE SAFETY SYSTEM

As an emerging industrial country, the demand for coal in China's industrial production is very large. China's vast territory provides abundant coal reserves for China. However, most of China's coal mines are underground, and open-pit coal mines are very scarce, so about 90% of China's coal production is underground mining [14]. The underground mining process needs to go through the drift to the underground mining area. There is a huge risk in the production process due to the special production environment [15]. Therefore, production safety has become a top priority.

Fig.1 Coal mine accident scene

However, although China's coal production has been generally mechanized, the level of automation in coal mines is not high [16]. The information exchange between various links of production is not smooth, which seriously restricts the application of safety monitoring systems in China's coal mine production process [17]. At present, China's coal mine monitoring system mainly consists of three parts: mine monitoring, underground monitoring and alarm management, and communication. Among the three systems, the well-monitoring system is mainly used for fire prevention and suspicious information detection [18]. Downhole monitoring and alarm system is used for monitoring and alarm. Communication is used to communicate between different parts of the job. These three parts operate as separate systems. Due to the independent operation of the three major systems, there are great hidden dangers and vulnerabilities in China's coal mine production safety monitoring system [19]. These risks and vulnerabilities are mainly for underground monitoring, with only monitoring and recording functions, and no communication functions. When there are risks in the mine, it is impossible to identify and warn the risk behaviour of the mine [20]. The existence of these hidden dangers and loopholes leads to a large number of safety accidents in China's coal mine production every year, resulting in a large number of casualties and economic losses. The statistics of coal mine accident casualties in the past 6 years from 2010 to 2015 are shown in Table 1.

Table 1 Coal casualty statistics in China over the years

Particular year	2010	2011	2012	2013	2014	2015
Death toll (person)	2433	1973	1384	1067	931	588
Million tons mortality (person / million tons)	0.803	0.564	0.374	0.293	0.257	0.159

At present, with the rapid development of network video monitoring technology, the coal mine safety monitoring system can use the network video monitoring technology to upgrade the existing safety monitoring system in the mine. Powerful image and information processing capabilities of computer systems in the network video monitoring system are used to improve the ability to identify and monitor early warning systems, improve the monitoring efficiency of the underground monitoring system, and reduce the loss of personnel and property in the safety accidents in coal mine production.

2.1 Video monitoring system

Video surveillance originated from simulation monitoring in the 1980s. After the hot development of digital monitoring, it has become today's network video monitoring. It is an integrated system which is composed of a real-time control system, a monitoring system and an information management system. First of all, according to the necessary conditions of the controllable gas explosion, we make a classification statistics of the direct causes of the 45 accidents: the fire source causing the occurrence of accidents and the reason for the gas concentration overrun, and the data in Figure 2 are obtained.

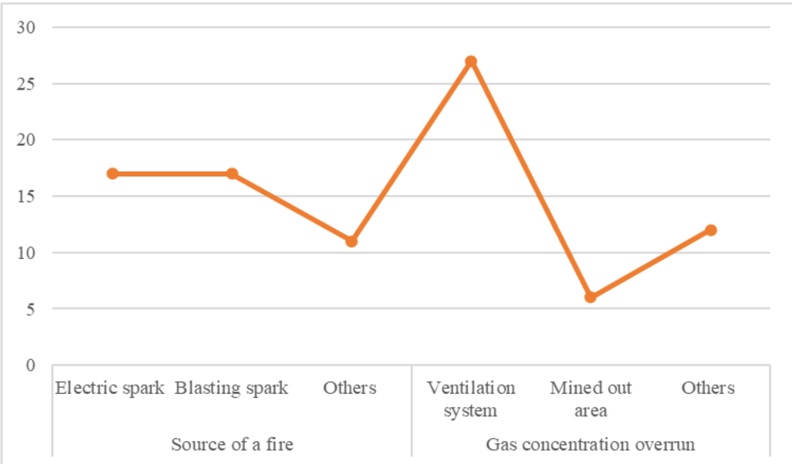

Figure 2 Statistical analysis of gas explosion accident

2.3 Establishment of the hierarchy model of dishonesty factors

Through the investigation report of the 45 cases of heavy gas explosion accidents, we can see that these accidents are all responsibility accidents, so they can be attributed to the personnel dishonesty factors and the equipment dishonesty factors. For the personnel dishonesty factors, they include managers' dishonesty and staff dishonesty. Equipment dishonesty factors include production equipment dishonesty and monitoring equipment dishonesty. Through the dishonesty analysis of the gas accident, the dishonest factors in the gas accident are decomposed into several sub-factors, and the hierarchical structure model is constructed according to the relationship among these factors, as shown in Figure 3.

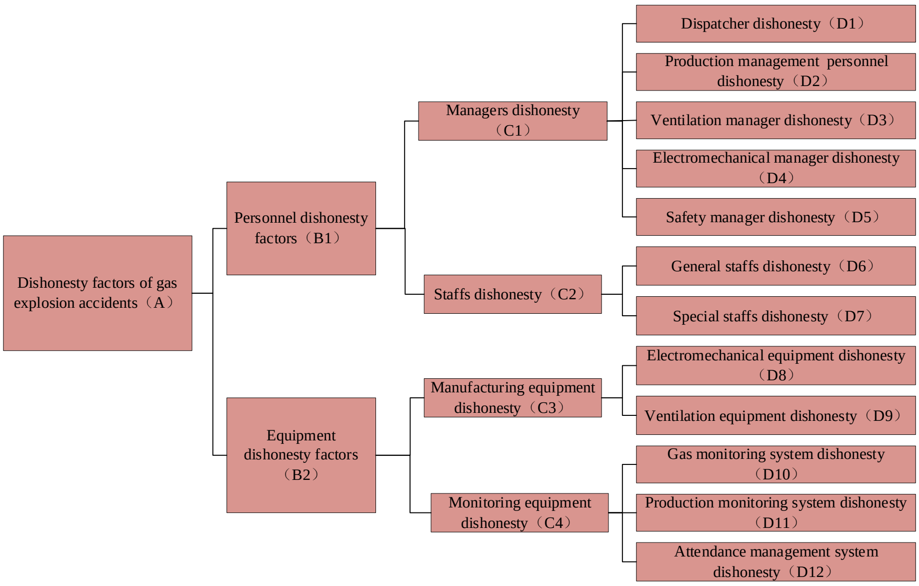

Figure 3. The hierarchy structure model of dishonest factors in a gas explosion accident

2.3 Construction of judgment matrix

The analytic hierarchy process uses 1~9 scaling to assign the importance degree of various factors, and the value of each factor we get is the number of them appearing in the accident. In consequence, the differences between various factors are used as the basis for determining 1~9 scaling. Set the difference of each factor value to be $a_x = u_i - u_j (x = 1,2,...,n)$, where n indicates the number of lower indicators. For the lower level indicators u_i and u_j corresponding to the higher level indicators, the meaning of the corresponding 1~9 scales is shown in Table 3. According to the meaning of scales in Table 2, the comparison judgment matrix under different criteria can be obtained.

Table 2. Meaning of 1~9 scaling

Scaling	Difference (a_x)	Meaning
1	0~4	It represents that u_i and u_j have the same importance.
3	6~9	u_i is slightly important than u_j.
5	11~14	u_i is more important than u_j.
7	16~19	u_i is quite important u_j.
9	Above 20	u_i is extremely important u_j.
2,4,6,8	5,10,15,20	The adjacent intermediate values of the above judgments.
1,1/2,1/3,…,1/9	The negative values	The importance ratio of u_i to u_j is a_{ij}, then the importance ratio of u_j to u_i is $\frac{1}{a_{ij}}$.

According to the Table, we can obtain the judgment matrix between managers and subordinate personnel:

C_1	D_1	D_2	D_3	D_4	D_5

D_1	1	9	1	1/5	1/7
D_2	1/9	1	5	3	2
D_3	1	1/5	1	1/5	1/7
D_4	5	1/3	5	1	1/2
D_5	7	1/2	7	2	1

The characteristics value of the matrix is W=(0.0426，0.4285，0.05，0.1823，0.2965).

W refers to the weights of four kinds of personnel dishonesty, including dispatchers, production managers, ventilation managers, electromechanical managers, and safe managers. Similarly, we can get the various judgment matrixes under other criteria. We calculate and obtain the comprehensive weights of various dishonesty factors, and thus get the dishonesty model of gas accidents.

According to the dishonesty model of gas accidents, the weight of personnel dishonesty accounted for 0.9, while the weight of equipment dishonesty is only 0.1. And in the staff's dishonesty, what accounted for the larger weight are the special personnel dishonesty, production management personnel dishonesty and safety management personnel dishonesty.

3. DESIGN OF COAL MINE SAFETY MONITORING SYSTEM BASED ON WIRELESS SENSOR NETWORK

This system is the core of the coal mine safety monitoring system, which collects real-time data on key environmental parameters such as gas concentration, temperature, humidity, pressure, and wind speed through various sensors deployed underground. At the same time, multimedia sensors can also capture video and audio information, providing more intuitive and comprehensive underground environmental information for monitoring personnel. This system is responsible for real-time transmission of data collected by the sensing and detection system to the ground monitoring center. The network architecture based on wireless communication technology ensures the stability and reliability of data transmission, and can maintain efficient communication even in complex underground environments. As shown in Figure 3.

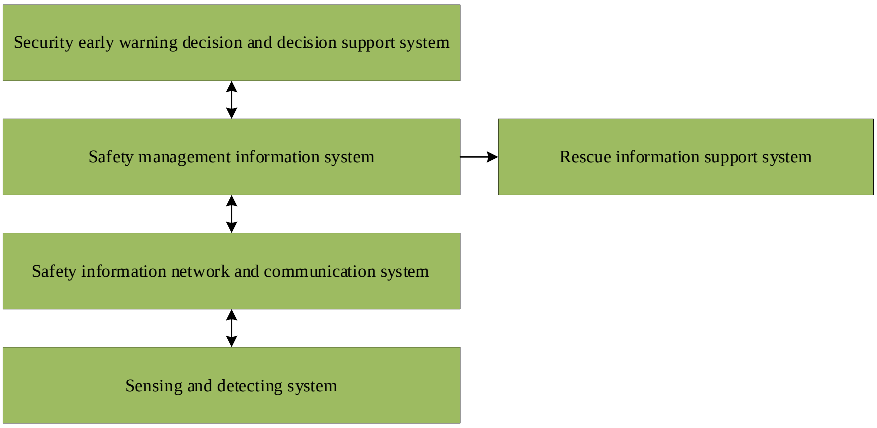

Figure 3. Structure of coal mine safety monitoring system

3.1 Sensing and detection system

The sensing and detection system is the bottom support system of a coal mine safety comprehensive monitoring system. It is composed of a large number of sensors underground and wireless sensor network nodes, to realize the collection of underground basic data, and to upload it to the upper system for processing. The sensor is the terminal equipment for underground data acquisition, which can acquire the underground environment and equipment data. To the needs of underground production safety monitoring, sensors usually include environmental sensors, equipment sensors, video sensors, audio sensors and vital signs sensors. Each sensor is connected with the underground wireless sensor network nodes through the interface. Each underground sensor node has the function of calculation, storage, and wireless communication, with an embedded operating system inside. According to the monitoring needs, write the monitoring program. Each sensor node has an intelligent interface identification function. It can automatically identify the connected sensor types and models, and automatically call the corresponding monitoring program to drive the sensor to work.

3.2 Safety information network and communication system

The sensor detection system, as the cornerstone of the comprehensive monitoring system for coal mine safety, carries the key task of underground data collection. This system is constructed from a large number of underground sensors and wireless sensor network nodes, which together weave a vast and sophisticated data collection network. These sensors are like the "eyes" and "ears" of coal mine safety monitoring, constantly collecting and transmitting real-time data about the underground environment and equipment status. Specifically, sensors play the role of terminal devices in underground data collection. They can accurately capture and convert various physical signals into digital information, thereby achieving comprehensive monitoring of the underground environment and equipment. According to the actual needs of coal mine production, sensors are usually divided into several categories: environmental sensors are used to monitor environmental parameters such as gas concentration, temperature, humidity, pressure, etc; Device sensors focus on the operational status and performance of the device; Video and audio sensors provide intuitive visual and auditory information, helping monitoring personnel to have a more intuitive understanding of the underground situation; Vital sign sensors are used to monitor the safety status of miners in real-time. Each sensor is connected to an underground wireless sensor network node and transmits data through an interface. These nodes not only have data transmission capabilities, but also have powerful computing and storage capabilities built-in. They are equipped with embedded operating systems and can flexibly write monitoring programs according to monitoring needs, achieving intelligent processing and analysis of data.

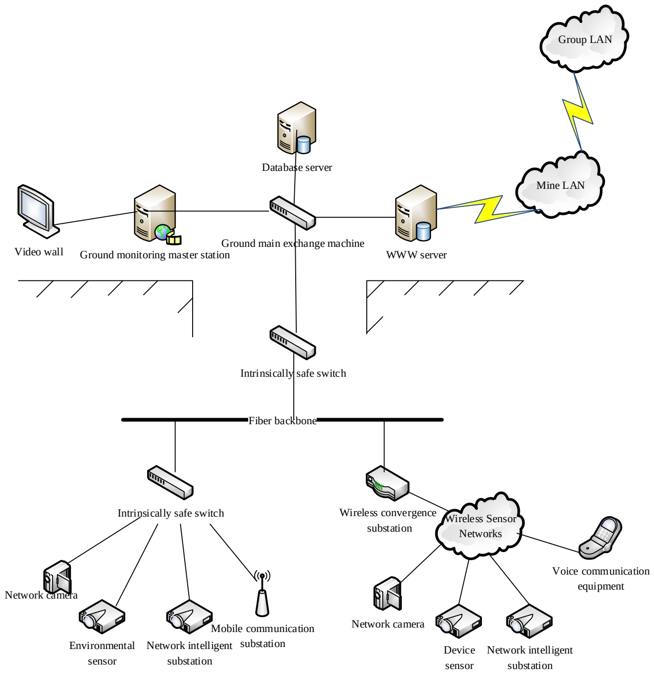

Figure 4. The overall structure of the system

3.3 Security early warning Decision and decision support system

Each sensor is connected to an underground wireless sensor network node and transmits data through an interface. These nodes not only have data transmission capabilities, but also have powerful computing and storage capabilities built-in. They are equipped with embedded operating systems and can flexibly write monitoring programs according to monitoring needs, achieving intelligent processing and analysis of data. In addition, each sensor node also has intelligent interface recognition function, which enables the system to automatically recognize the type and model of connected sensors, and automatically call the corresponding monitoring program to drive the sensor to work. This intelligent design greatly improves the flexibility and adaptability of the system, enabling it to cope with various complex monitoring needs. At the same time, it can be used to evaluate the changing process of the hazard degree of high-risk sources in real-time and to continuously change the level of the early warning, to adapt to the complex coal mine production environment. The decision support system shall carry out uninterrupted continuous monitoring of all kinds of underground dangerous sources. According to the enterprise development, the critical value or the critical environmental parameters Approved by industry authorities make dynamic monitoring of the dangerous source. As long as there is a danger source reaching the set value, enterprises have entered into an early warning management period.

3.4. Rescue information support system

The rescue information security system plays a crucial role in emergency response to coal mine accidents. After a mining accident, it can quickly extract critical rescue information from the safety information management system, providing real-time and accurate data support for rescue decision-makers, thereby ensuring the timeliness and effectiveness of rescue operations. Specifically, the rescue information security system first extracts information on the number of underground personnel. This information is crucial for determining the priority and resource allocation of rescue efforts. At the same time, when an accident occurs, the system can quickly link with the underground personnel positioning system to send emergency notifications and rescue guidance to trapped personnel, ensuring that they can receive timely assistance.

In addition, the rescue information security system can also obtain various environmental data from the underground mining environmental information system, such as gas concentration, temperature, humidity, wind speed, etc. These environmental data are of great significance for evaluating the safety status of accident sites and formulating rescue plans. By analyzing these data, rescue personnel can more accurately determine the development trend and potential risks of accidents, and thus take corresponding response measures. At the same time, the system can also extract the status of various device information from the device information system. This includes the operating status of the equipment, fault information, maintenance records, etc. These pieces of information are of great significance for assessing the reliability and safety of equipment, as well as evaluating the impact of accidents on equipment. Rescue personnel can conduct targeted inspections and repairs on equipment based on this information to ensure equipment support during rescue operations.What's more, it can analyze the possible personnel moving track and distribution after the mine accidents occurred, and based on virtual reality technology, simulate the effects of various rescue schemes, to determine the best rescue plan.

3.5. Verification of enhancement algorithms

To verify the effectiveness of the enhancement algorithm in a video surveillance image, two methods are used to evaluate the image enhancement effect. One is to randomly extract two images from the video surveillance images of the mine for enhanced verification, Another method is to use quantitative evaluation to compare the enhancement effect and the details before and after the enhancement, which can be seen in. The contrast of the image enhancement effect is defined as:

$$c=\left(g_t-g_b\right)/\left(g_t+g_b\right) \tag{1}$$

The above formula g_t represents the average grey of the video image and g_b represents the average grey of the background in the video image. The quantitative evaluation of the image before and after enhancement is realized by the Range function. This method can be used to calculate the grey of the image histogram, that is, the difference between the maximum and the minimum values of the grey band:

$$F=\max\left(kH_k>0\right)-\min(kH_k<0) \tag{2}$$

The above formula H_k represents the value of the grey level k . The greater the value F , the more abundant the details of the image. On the contrary, there are fewer image details.

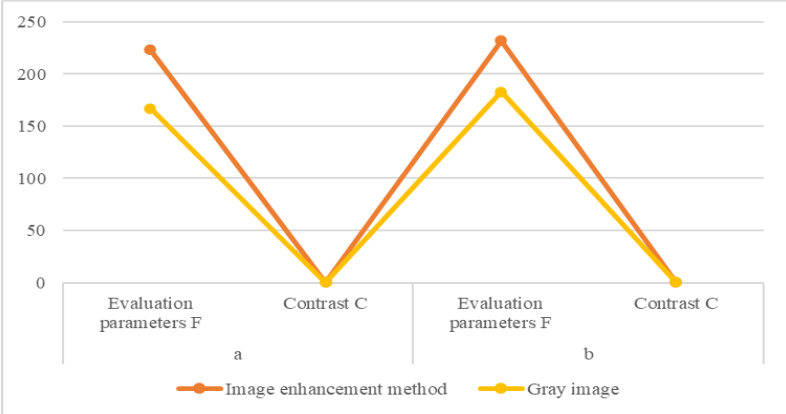

Figure .5 Image a, B enhancement before and after evaluation parameters

By contrast in Figure 5, after monitoring image enhancement in effect and details, the original image is clearer and richer, and the image enhancement method proposed in this paper is feasible.

4. EXPERIMENTAL RESULTS AND ANALYSIS

The accidents of safety production that happen in the coal mine have a contingency. The production management of coal mines is very strict, and non-relevant personnel cannot enter the mine. Therefore, it is impossible to identify the method proposed in this paper through the actual situation of the accident, and the method is verified by simulation in the laboratory. The specific method is to use video to monitor and identify people's throwing objects in the dim light of the laboratory. Specific steps are. After the processing of the enhanced parabolic image with two values, the parabolic two-valued image can be obtained. Then find out the very white spots in four directions. Assuming that the very white spot in the up direction is A with the coordinates of (x_A, y_A); the very white spot in the down direction is B with the coordinates of (x_B, y_B); the very white spot in the left direction is C with the coordinates of (x_C, y_C) ; the very white spot in the right direction is D with the coordinates of (x_D, y_D); the centre is set to with the coordinates of E (x_E, y_E).

The coordinates of centre point E of the rectangular can be obtained by the coordinates of four very white spots, the formula is as follows:

$$x_E = \frac{(x_D - x_C)}{2} \tag{3}$$

$$y_E = \frac{(y_A - y_B)}{2} \tag{4}$$

With the formulas (3) and (4), we can get the coordinate value of the moving object in the two graphs. According to the change of the coordinate value of the object, we can know the change of the position of the parabola in unit time. Unit time is Δ_t, and the height change of the parabolic in unit time is $\Delta_h = y_E - y_E$. The position changes from left to right $\Delta_l = x_E - x_E$, and the value is L. Then the comprehensive identification of parabolic is carried out. When Δ_h is always positive $\Delta_l < L$, it means that there is an object falling from above, and personnel can be excluded from moving or personnel parabolic. The identification results of the experiment of parabolic in the laboratory are shown in Figure 6.

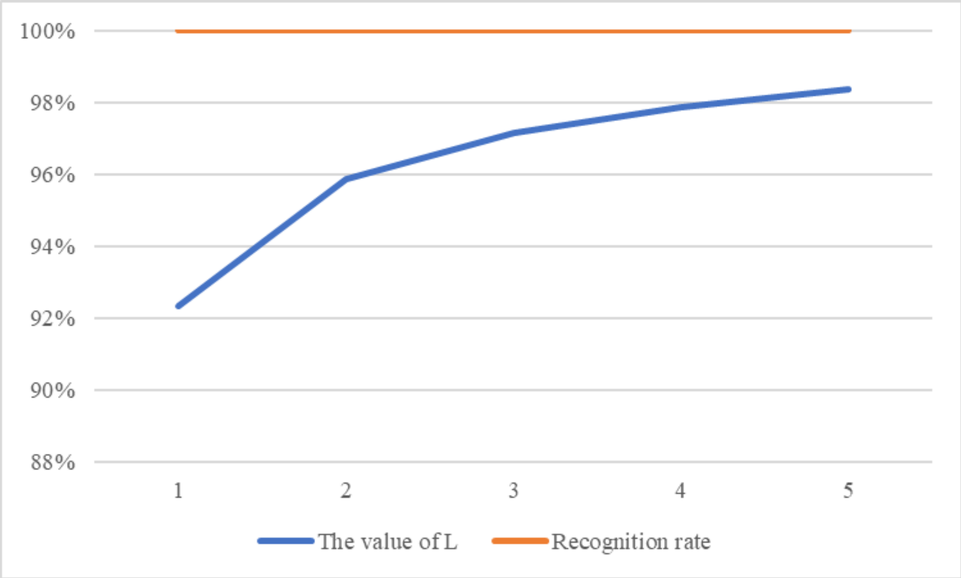

Figure .6 Statistics of laboratory parabolic identification

From Table 3 we can get the following results. When the value L is too large or too small, the recognition rate of video surveillance is lower. The main reason is that when the L is set too low, the object moves downward, and the distance between the left and the right is larger than the set value, which is recognized as normal behaviour, and it can lead to inaccurate recognition. On the whole, when the setting value is too large or too small, the recognition rate of the video surveillance system is higher than 80%, but less than 85%. When the set value is appropriate, the recognition rate is higher than 85%. Therefore, the accuracy of coal mine safety behaviour identification combined with video monitoring has a great relationship with the setting value of abnormal behaviour. The key to improving the recognition rate of video surveillance is to set up a more accurate identification value. Whether the setting value is too large or too small, the overall recognition rate of video monitoring is more than 80%, which shows that it is feasible to identify the behaviour of coal mines in video monitoring.

5. RESULTS AND DISCUSSION

The beacon node of the wireless sensor network node of the system uses the CC2430 node, the unknown node uses the CC2431 node, and the sink node uses the C51RF-CC2431-ZDK network expansion board. The software development environment of the CC2430/CC2431 node is composed of IAR Embedded Workbench and C51RF-CC2431-ZDK emulator. PC control software is running on the PC control computer, and making data exchange with the sink node through the RS232 interface. It is mainly responsible for the deployment of nodes in the wireless sensor network, network data receiving, storage and graphical display. To verify the change of network signal of the coal mine safety monitoring system based on the wireless sensor network with the distance, we design the experiments that the underground signal intensity changes with the distance. First of all, according to the wireless sensor network test platform constructed, the acquisition and test of the RSSI value between the nodes with the distance in the tunnel is carried out. The two nodes are deployed in the underground roadway and the transportation lane, one is the transmitter, and the other is the receiving end. Continuously change the distance between the nodes and record the RSSI value of the communication between the two nodes.

The results of the experiments are shown in Figure 7 and Figure 8.

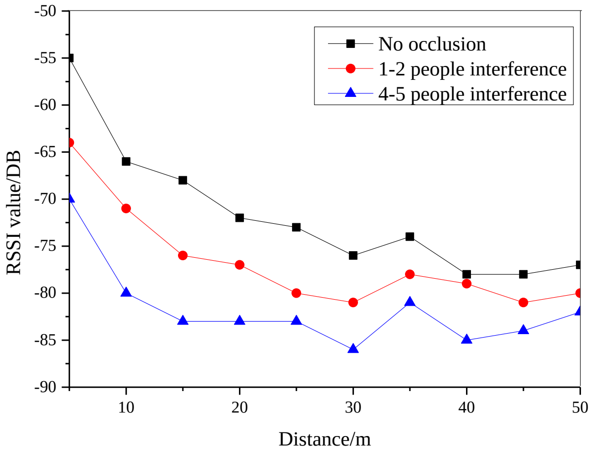

Figure 7. RSSI test data in the main lane

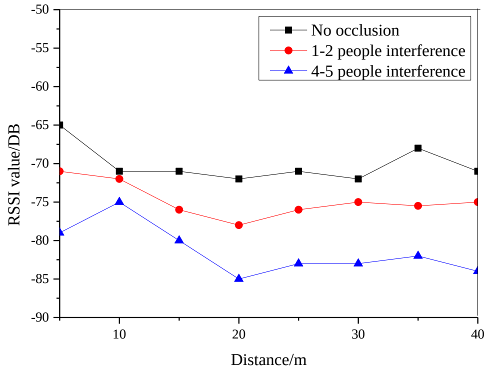

Figure 8. RSSI test data in the transport lane

As can be seen from the results, with the increase of distance between the transmitter node and the receiving end node, the change of distance will result in the RSSI values between nodes producing greater change. The closer the two nodes distance, the stronger the received signal strength, and the greater the RSSI value; the farther the distance, the weaker the received signal strength, and the smaller the RSSI value. In the case of the same distance, with the narrowing of the tunnel width, the attenuation degree of the wireless signal increases, and the narrower the roadway is, the smaller the RSSI value received at the same distance will be. Because the width of the roadway is larger than the width of the lane, the signal attenuation in the traffic lane is worse than that in the lane. When there is no barrier between the nodes, the change of RSSI value with the distance is relatively smooth; when the nodes are shielded, the change curve of RSSI value with the distance is relatively fast, and with the increase of disturbance, the degree of signal attenuation increases. The experimental results showed that when the distance between nodes is 10m, the intensity of the signal meets the needs of the system.

6.CONCLUSION

In the field of coal mine safety, building an efficient and comprehensive safety comprehensive monitoring system is the key to ensuring the safety of miners and the smooth progress of coal mine production. In order to scientifically and reasonably design such a system, we adopted the Analytic Hierarchy Process (AHP) for in-depth research. The Analytic Hierarchy Process provides us with a structured decision-making framework that enables us to systematically evaluate the relative importance of various factors in coal mine safety monitoring systems. This method not only considers technical factors such as monitoring accuracy and scope, but also takes into account various aspects such as management and economy, ensuring the comprehensiveness and practicality of system design. Based on the results of the Analytic Hierarchy Process, we propose a systematic design scheme. Firstly, we established a hierarchical model to clarify the main components of the system, such as sensing and detection systems, security information networks and communication systems, and security management information systems. Next, we weighted the key indicators based on the functionality and importance of each part to ensure the scientific and targeted design of the system. In the design process, we paid special attention to typical coal mine safety accidents that have occurred in recent years. Through statistical analysis of these accidents, we analyzed the causes of the accidents from a holistic perspective and identified the dishonest factors involved. In response to these issues, we have established a dishonesty model for typical gas explosion accidents using the Analytic Hierarchy Process, providing a basis for preventing and reducing similar accidents.

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