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Development and Application of Coal and as Outburst Monitoring and Early Warning System in Coal Mines

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Abstract: In view of the technical challenges faced by Pingmei No.13 Mine, such as frequent coal and gas outburst disasters, insufficient accuracy, and poor timeliness of traditional prediction methods, a coal and gas outburst monitoring and early warning system integrating multi-source data acquisition, intelligent algorithm analysis, and hierarchical early warning and response has been developed by considering the mines geological conditions and actual production conditions. This system adopts a hierarchical and distributed technical architecture, deeply integrating key influencing factors including gas geology, gas emission, daily prediction, outburst prevention measures, and mining disturbances. Based on big data mining and machine learning algorithms, an intelligent early warning model is constructed. A multi-level early warning mechanism coupling state early warning and trend early warning is innovatively established, and efficient interaction and display of early warning information are achieved through visualization technology. Field application results show that the system achieves an average state early warning accuracy of 95.94% and an average trend early warning accuracy of 97.09%. It significantly enhances the refinement and intelligence level of mine outburst prevention management, effectively reduces the risk of coal and gas outburst accidents, and provides reliable technical support for the safe production of high-gas outburst mines.

Keywords: Coal and gas outburst; Monitoring and early warning system; Multi-source information fusion; Intelligent early warning model; Multi-level early warning mechanism.

1. Introduction

Coal and gas outburst is a highly destructive dynamic disaster in coal mines. During its occurrence, a large amount of coal is instantaneously fragmented and ejected, accompanied by a dynamic outpouring of gas [1]. This easily triggers secondary disasters such as casualties, equipment damage, and gas explosions, and stands as a core bottleneck restricting the high-yield, high-efficiency, and safe sustainable development of coal mines in China [2]. The geological structure of coal mines in China is complex, and the mining depth increases year by year. As a result, coal and gas outburst accidents are becoming more frequent, especially in coal mines with high gas content and high ground stress, where the prevention and control of outburst disasters are extremely challenging [3].

Pingmei No.13 Mine is a large-scale modern coal mine with an annual production capacity of 2.1 million tons and serves as a core production unit of Pingmei Group. As the mining range expands and the mining depth increases, the coupling effect between the coal-rock stress field and the gas field intensifies, leading to a continuous rise in the risk of coal and gas outbursts. Since the mine went into operation, multiple coal and gas outburst accidents have occurred, resulting not only in heavy casualties and property losses but also seriously disrupting the normal production order of the mine and having a significantly negative impact on the enterprises economic benefits and social image.

Traditional prediction methods for coal and gas outbursts mostly rely on single indicators or empirical analogy methods, which have shortcomings such as one-sided monitoring dimensions, low prediction accuracy, and insufficient early warning timeliness [4-5]. These methods find it difficult to comprehensively characterize the dynamic evolution characteristics of the outburst hazard at the working face. Meanwhile, with the dynamic changes in mining conditions in coal mines, traditional methods can no longer meet the safety management requirements of high-yield and high-efficiency mines. Therefore, the development of a real-time, accurate, and intelligent coal and gas outburst monitoring and early warning system based on multi-source information fusion is of great theoretical and practical significance for improving the scientific level of outburst prevention management in mines and ensuring safe production. In recent years, the rapid iteration of new-generation information technologies such as the Internet of Things, big data, and artificial intelligence has provided new paths for the innovative breakthrough of coal and gas outburst early warning technologies [6-8]. By integrating multi-source heterogeneous monitoring data and constructing intelligent analysis models, real-time monitoring, dynamic assessment, and advanced early warning of outburst disasters can be achieved, providing quantitative bases for outburst prevention decision-making in mines. Based on this, Pingmei No.13 Mine has developed a coal and gas outburst monitoring and early warning system based on its own geological conditions, mining techniques, and outburst occurrence patterns. This paper systematically elaborates on the systems architectural design, key technologies, and application effects, aiming to provide technical references and practical insights for similar high-gas outburst coal mines.

2. System Development and Key Technologies

2.1. System Architecture and Characteristics

The system adopts a hierarchical and distributed technical architecture, which is divided from top to bottom into the data acquisition layer, data transmission layer, data processing layer, and application layer. Data flows efficiently and

functions are coordinated among these layers through standardized interfaces. Among them, the data acquisition layer is responsible for collecting multi-source information, including gas geology, gas emission, daily prediction, outburst prevention measures, and mining disturbances, providing basic data support for system analysis. The data transmission layer relies on industrial Ethernet and wireless sensor networks to achieve real-time and stable transmission of the acquired data to the data processing layer, ensuring the timeliness and integrity of the data. The data processing layer deeply analyzes the multi-source data through data cleaning, transformation, fusion, and intelligent mining algorithms, generating accurate early warning information. The application layer displays monitoring data and early warning results to users through a visual interactive interface, provides decision support functions, and achieves precise multi-terminal delivery of early warning information.

The core innovation points of this system are reflected in the organic integration of five aspects: It achieves comprehensive coverage monitoring of the influencing factors of coal and gas outbursts by integrating multi-source information such as gas geology, gas emission, daily prediction, outburst prevention measures, and mining impacts. It significantly improves the accuracy and timeliness of early warnings by constructing an intelligent early warning model based on big data analysis and machine learning algorithms. It tracks changes in working face parameters through real-time dynamic analysis technology, providing a scientific basis for taking timely outburst prevention measures. It innovatively constructs a multi-level early warning mechanism that combines state early warning and trend early warning, enabling precise matching of response measures according to different early warning levels. It significantly enhances the efficiency of information transmission and acquisition by achieving visual display of monitoring and early warning information through graphical interfaces and dynamic maps.

2.2. Key System Technologies and Implementation

The system adopts a diversified data acquisition mode of "real-time monitoring by sensor networks + connection to existing monitoring systems + supplementary manual entry". Sensor networks are deployed with sensors for gas concentration, wind speed, temperature, coal-rock stress, etc., to achieve real-time acquisition of environmental and mechanical parameters at the working face. Through interface development, it is connected to the mine mining scheduling system and outburst prevention measure management system to automatically obtain production management data such as mining progress, drilling construction parameters, and gas extraction volume. For unstructured data such as geological exploration reports and expert evaluation opinions, manual entry is used for supplementary completion to ensure the comprehensiveness and completeness of the data.

To address the issues of strong heterogeneity and varying data quality among multi-source data, the system employs data fusion technology. It cleans, denoises, and normalizes the acquired data, converting data in different formats and with different dimensions into a standardized format, and constructs a unified mine outburst prevention database, laying a solid data foundation for subsequent intelligent analysis. The intelligent early warning model is the core functional module of the system, and its construction process is divided into four key steps. First, a scientific and comprehensive early warning indicator system is constructed. Key indicators such as coal seam gas pressure, gas content, drill cuttings volume, and mining advancement speed are selected from five dimensions-gas geology, gas emission, daily prediction, outburst prevention measures, and mining disturbances-to ensure the representativeness, independence, and sensitivity of the indicators. Second, data preprocessing is carried out. Outliers are removed, missing values are filled, and normalization is performed on the acquired data to eliminate dimensional differences and noise interference and improve data quality. Third, model training and parameter optimization are conducted. Mature machine learning algorithms such as support vector machines and random forests are selected, and model training is carried out using historical outburst case data and real-time monitoring data from the mine. Model parameters are optimized through cross-validation and grid search methods to improve the generalization ability and prediction accuracy of the model. Fourth, an early warning rule library is formulated. Based on the model output results and the experience of coal mine outburst prevention experts, the indicator thresholds and response measures corresponding to different early warning levels are defined to effectively transform the model prediction results into engineering early warning information.

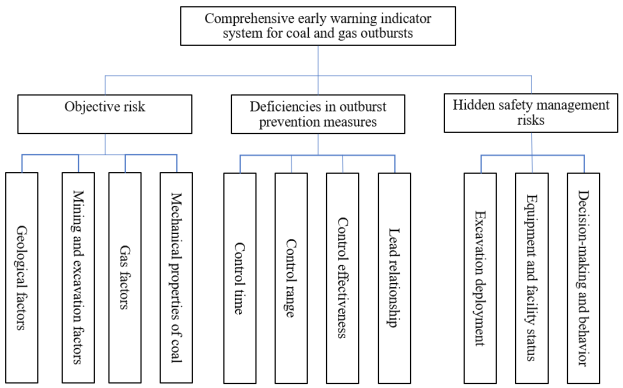

Figure 1. Framework of the Early Warning Indicator System for the No.13 Mine

The system relies on real-time monitoring data and employs sliding window and time series analysis methods to dynamically assess trends in working face parameter changes. When the monitored data exceed preset thresholds or exhibit abnormal fluctuations, the system automatically triggers an early warning mechanism. The system innovatively establishes a multi-level early warning mechanism combining "status-based early warning + trend-based early warning," enabling precise determination and proactive prediction of outburst risks. Status-based early warning categorizes the outburst risk of the working face into three levels—normal, threatening, and dangerous—based on real-time monitoring data, providing an intuitive reflection of the current safety status. Trend-based early warning classifies future outburst risks into three levels—green, orange, and red—based on data trends over a period of time, facilitating proactive anticipation of disaster risks. Different early warning levels correspond to differentiated emergency response measures, ensuring rapid and precise handling of early warning information.

Table 1 Classification of Early Warning Result Levels

Type	Level	Instructions
Status alert	Normal	All early warning indicators on the working face are normal, indicating that safe operations can be carried out.
	Threat	The prediction of outbursts in the working face poses no immediate danger or requires confirmation through prediction, but it warrants close attention and enhanced management.
	Danger	The working face poses a significant risk of outburst, necessitating the cessation of operations and the implementation of outburst prevention measures, or further confirmation of the risk of outburst.
Trend alert	Green	The prominent danger ahead tends to be safe.
	Orange	There may be a potential danger ahead at a certain distance, please pay attention.

3. System Application and Effectiveness Analysis

3.1. System Application

The system adopts a combined B/S (Browser/Server) and C/S (Client/Server) architecture to develop a visual interactive platform. Through dynamic electronic maps, real-time data curves, and early warning pop-up windows, it visually displays gas distribution, mining progress, and early warning status in working faces. Users can access early warning information through multiple channels, including PC clients, web browsers, and mobile terminals. Additionally, the system supports historical data query, statistical analysis, and automatic report generation functions, providing comprehensive and quantitative data support for mine outburst prevention management.

After its development, the system was fully deployed and applied across all major mining faces and key risk areas in Pingmei No.13 Mine. It achieves 24-hour continuous real-time monitoring of core parameters such as gas geology and gas emission. Early warning information is synchronously pushed to relevant positions, including the mine dispatching center and mining faces, through multiple terminals, establishing a closed-loop management process of "monitoring-analysis-early warning-disposal" and significantly enhancing the intelligent level of mine outburst prevention management.

3.2. Analysis of Early Warning Accuracy

To verify the systems reliability and effectiveness, field industrial tests were conducted in five typical mining faces, including the 11072 machine roadway, 11111 air roadway, 12072 machine roadway, 13031 supplementary cut, and 14020 air roadway. The systems early warning results were compared with actual underground conditions to calculate early warning accuracy. The test results showed that early warning accuracy rates ranged from 85.65% to 100% across all working faces, with the 12072 machine roadway and 13031 supplementary cut achieving 100% accuracy for both status-based and trend-based early warnings. The average status-based early warning accuracy rate across the entire mine reached 95.94%, while the average trend-based early warning accuracy rate reached 97.09%. This fully demonstrates that the system can accurately identify precursor information of coal and gas outbursts, providing a reliable technical basis for timely implementation of targeted outburst prevention measures underground.

3.3. Analysis of Outburst Prevention Management Effectiveness

The systems application has driven the transformation of outburst prevention management in Pingmei No.13 Mine towards "refinement, standardization, and intelligence." Firstly, the systems real-time monitoring function enables timely identification of weak links and potential hazards during the implementation of outburst prevention measures, effectively avoiding outburst risks caused by inadequate measure implementation. Secondly, the systems information-sharing function breaks down data barriers among geology, mining, ventilation, and other departments, promoting collaboration and efficient interaction among various specialties. Thirdly, the systems quantitative analysis function provides a scientific basis for optimizing outburst prevention plans and adjusting mining processes, facilitating a shift from "experience-based judgment" to "data-driven" outburst prevention work.

3.4. Economic and Social Benefits

The systems application has brought significant economic and social benefits. In terms of economic benefits, it reduces direct economic losses caused by equipment damage and production shutdowns by decreasing the frequency of coal and gas outburst accidents. Simultaneously, it optimizes the allocation of outburst prevention measures, reduces costs associated with gas extraction and drilling operations, and enhances mine production efficiency and resource utilization. In terms of social benefits, the system effectively safeguards the lives of underground workers and improves the mines safety production environment. Its successful application provides a replicable and scalable technical model for similar high-gas outburst mines, contributing significantly to advancing coal mine safety production technology in China.

4. Conclusion

This paper addresses the challenges of coal and gas outburst prevention in Pingmei No.13 Mine by developing an intelligent monitoring and early warning system based on multi-source information fusion. Through hierarchical and distributed architecture design, machine learning-based early warning model construction, and innovative multi-level early warning mechanisms, the system achieves real-time monitoring, precise early warning, and scientific prevention and control of coal and gas outbursts. Field application results demonstrate high early warning accuracy and strong practicality, significantly enhancing mine outburst prevention management levels and providing robust safeguards for safe production.

In the future, the system can be optimized and upgraded in three aspects. Firstly, deepen technological integration by introducing emerging technologies such as the Internet of Things (IoT), 5G, and digital twins to construct a digital twin system for mine gas prevention and control, enabling three-dimensional visual simulation and proactive prediction of outburst risks. Secondly, optimize model algorithms by incorporating deep learning algorithms to enhance the models ability to identify outburst disasters under complex geological conditions and introducing transfer learning

methods to facilitate rapid model adaptation across different mines. Thirdly, expand functional boundaries by extending system functions to areas such as gas extraction effectiveness evaluation and mining plan optimization, constructing an integrated coal mine gas comprehensive management platform. Through continuous technological innovation and functional enhancement, the system will drive coal and gas outburst early warning technology towards higher precision, broader coverage, and greater intelligence, providing solid technical support for the high-quality development of Chinas coal mine industry.

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