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Prospect of Cluster Control Technology for Automatic Gas Extraction Drilling Rig in Coal Mine

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Abstract: *Coal mine gas disasters pose a great threat to the safety of people and property. Pre-extraction through drilling construction is the main means of gas management. On the premise of realizing the automatic construction of single gas extraction drilling rig, the cluster control of automatic gas extraction drilling rig to realize the cooperative operation of multiple drilling rigs is an effective way to further improve the automation level of downhole drilling construction and consolidate the effect of automatic drilling rig in reducing manpower and increasing efficiency. Based on the brief description of the current application status and scientific research progress of automatic gas extraction drilling rig cluster control technology, four key technologies are proposed to realize cluster control: automatic drilling rig downhole precise positioning and automatic navigation and obstacle avoidance technology; automatic drilling rig intelligent drilling technology; automatic drilling rig cluster intelligent sensing and multi-rig collaborative control technology; automatic drilling rig group multi-system integrated management operation platform. To realize unmanned downhole disaster, it lays the technical foundation for the realization of unmanned downhole disaster management. The development trend of automatic gas extraction drilling rig cluster control is foreseen, which provides the possibility to promote the construction of intelligent mine in China.*

Keywords: *Gas control; Automatic drilling rig; Cluster control; Intelligent drilling; Intelligent perception; Intelligent mine*

1. Introduction

China's coal mines have abundant reserves, but the mining process is accompanied by numerous associated hazards, primarily including six types: fire hazards, water hazards, roof accidents, rock bursts, gas outbursts, and coal dust explosions. Gas disasters are the "number one killer" affecting coal mine safety production, posing a significant threat to personnel safety and property. In recent years, coal mining in China has rapidly shifted to deeper levels at a rate of 10 to 25 meters per year, with most of the original key state-owned coal mines now engaged in deep mining. As the depth and intensity of coal mining continue to increase, ground stress and gas pressure rise, mining structures become more complex, and the intensity and frequency of outburst disasters increase, posing a greater threat and easily triggering major accidents[1-5]. The primary method of preventing gas disasters in China is through the construction of gas drainage boreholes using gas extraction drilling rigs, focusing mainly on underground extraction. The volume of borehole engineering is large, and there are many construction personnel. For instance, in coal mines like Henan Pingmei and Shanxi Jincheng, drilling personnel account for about 50% of the gas control personnel. During borehole construction, disasters such as water hazards, rock bursts, and gas outbursts are still unavoidable. Due to the extremely low automation and intelligence levels of the drilling equipment used domestically, drilling rig operation requires many personnel, involves high labor intensity, and relies entirely on personnel experience, making it difficult to ensure fundamental safety. Therefore, automated and intelligent gas extraction drilling equipment and technology will be crucial to achieving "reducing personnel and increasing efficiency, ensuring safety" and will be one of the key technologies and equipment for realizing "intelligent mines"[5-10].

In 2020, eight ministries, including the National Development and Reform Commission and the National Energy Administration, jointly issued the "Guiding Opinions on Accelerating the Intelligent Development of Coal Mines," clearly requiring the acceleration of unmanned coal mining. As a key link, underground disaster management should also achieve unmanned operation[11-12]. To achieve "unmanned, efficient, safe, and green" gas disaster management, the key lies in solving the automation and intelligence problems of conventional drilling equipment, that is, replacing manual control with intelligent gas extraction equipment groups. Currently, the ZYWL series drilling equipment developed by Chongqing Research Institute Co., Ltd. (hereinafter referred to as "Chongqing Research Institute") of China Coal Technology & Engineering Group is at the leading domestic level. It has realized automated construction with features such as automatic loading and unloading of drill rods at large angles, fully automatic drilling, intelligent anti-sticking drilling, and automatic adjustment of drilling posture, and has been promoted and applied in multiple coal mines in China[13-16]. Automation is only the foundation of intelligence; unmanned operation is the advanced stage and development trend of intelligence. The "13th Five-Year Plan for the Development of the Coal Industry" clearly pointed out the need to break through key technologies such as intelligent coal drilling, improve the digital control, automated production, and remote operation capabilities of coal machinery equipment. To achieve intelligent drilling and coordinated underground operation of multiple automated gas extraction drilling rigs, it is necessary to solve the cluster control technology of automated gas extraction drilling rigs.

2. Research Status of Cluster Control Technology for Automated Gas Extraction Drilling Rigs

There are no relevant reports on intelligent drilling equipment for underground coal mines abroad, and even less on cluster control technology for automated gas extraction drilling rigs. However, in the research field of mining construction robots, the automation of single-machine equipment has been realized, capable of automatic drilling, anti-sticking drilling, automatic loading and unloading of drill rods, automatic movement, positioning, and remote control. Drilling construction robots produced by companies such as Sweden's Atlas Copco, SANDVIK, France's FLANDERS, Finland's Tamrock, and Norway's BEVER are representative worldwide and have reached practical levels[8].

In China, the research and development of intelligent control drilling technology and equipment started relatively late. Chongqing Research Institute began researching long-distance anti-outburst drilling technology and equipment in 2006 and successfully developed a long-distance anti-outburst drilling rig in 2008. This rig features automatic loading and unloading of drill rods and can operate the drilling rig from a safe area 150 meters away from the working face. During the "11th Five-Year Plan" period, Chongqing Research Institute developed an underground gas extraction drilling rig controlled from the surface, which achieved underground drilling construction through remote video monitoring and control systems. During the "12th Five-Year Plan" period, based on the research results of the "11th Five-Year Plan," Chongqing Research Institute successfully developed a long-distance automatic control drilling rig from the surface, featuring one-key fully automatic drilling. During the "13th Five-Year Plan" period, Chongqing Research Institute led the key research and development project "Underground Gas Extraction Drilling Robot in Coal Mines," which has achieved automatic path planning and autonomous walking positioning of the drilling robot.

In summary, although advanced drilling equipment developed domestically and abroad has certain automated functions, they still use single-machine control, and multi-machine collaborative control is just beginning. Therefore, in the pursuit of unmanned disaster management underground, the cluster control technology of automated gas extraction drilling rigs will be a future research hotspot and trend[17].

3. Key Technologies for Realizing Cluster Control of Automated Gas Extraction Drilling Rigs

Automated gas extraction drilling rigs have achieved some stage-specific results in terms of intelligence, realizing functions such as automatic loading and unloading of drill rods, automated drilling, and wireless remote control, thereby achieving certain successes in "reducing personnel and increasing efficiency, ensuring safety." However, due to the diversity and complexity of gas extraction conditions, achieving the goal of cluster control technology for automated gas extraction drilling rigs still requires addressing four core technological shortcomings: 1. Precise underground positioning and automatic navigation with obstacle avoidance for automated drilling rigs; 2. Single-machine intelligent drilling technology for automated drilling rigs; 3. Intelligent perception and multi-machine collaborative control technology for automated drilling systems; 4. Integrated management and operation platform for multiple systems within automated drilling rig groups.

3.1 Precise Underground Positioning and Automatic Navigation with Obstacle Avoidance Technology for Automated Drilling Rigs

Precise underground positioning and navigation are fundamental to the accurate control of automated drilling rigs and essential for achieving coordinated multi-machine operations. Currently available underground positioning methods are limited to traditional technologies such as radio frequency positioning, inertial positioning, and video monitoring, which suffer from limitations in range, low accuracy, poor stability, and discontinuous positioning results. Additionally, coal mine operations are conducted in environments with explosive gas, and currently, there are no high-performance explosion-proof UWB devices or laser scanners, and related key sensors lack adequate explosion-proof capabilities.

Therefore, to solve the challenges of autonomous navigation and positioning for automated drilling rigs, technological innovations can be pursued in several areas:

(1) Use multiple sensors and 3D laser scanning to collect multidimensional data on tunnel dimensions and obstacle sizes. Employ efficient strategies and algorithms to process this data, achieving real-time, high-precision 3D modeling and dynamic updating of the tunnel environment.

(2) Conduct in-depth research on UWB wireless sensor networks and SLAM (Simultaneous Localization and Mapping) for adaptive multi-sensor combination positioning, achieving precise positioning in complex and dynamic underground environments.

(3) Develop explosion-proof multi-source sensor networks and signal equipment to fill the gap in explosion-proof devices and systems for underground navigation systems, providing hardware support for the navigation system.

(4) Combine 3D models and motion and dynamic parameters of drilling equipment to develop feature point tracking, precise control, and deviation correction technologies for walking mechanisms, achieving autonomous walking strategy control for automated drilling rigs.

(5) Through research on target data processing algorithms, evaluate tunnel terrain mechanisms and formulate path planning, obstacle avoidance, and optimization strategies aimed at complex extraction points in drilling fields.

3.2 Single-Machine Intelligent Drilling Technology for Automated Drilling Rigs

As the core unit of cluster control technology for automated drilling rigs, automated drilling rigs have achieved high levels of automation with functions such as automatic loading and unloading of drill rods, automated drilling, and wireless remote control. However, achieving intelligent drilling still requires overcoming several challenges, including intelligent sensing of drilling conditions, intelligent control of the drilling process, intelligent design of gas control boreholes, and fault diagnosis technology.

3.2.1 Intelligent Sensing of Drilling Conditions

Intelligent sensing of drilling conditions refers to the ability of gas extraction drilling equipment to autonomously sense and feedback information about the geological characteristics of the coal and rock, drillability grade, gas pressure and content, and the working status of the equipment during the drilling process, providing control basis for intelligent drilling[18]. Intelligent sensing of drilling conditions includes real-time identification of coal and rock layers, addressing the issue of delay in coal and rock identification technology, and eliminating the difficulty of corresponding drilling feedback parameters with coal and rock and structural formations. Based on the extraction of a large amount of drilling data from automated drilling rigs, a sample feature database (including physical and mechanical properties of rock layers, energy consumption characteristics of coal and rock drill bits, and cutting slag parameters) is established. This allows for online database recognition of rock layer drillability, matching drillability grades. Additionally, a coupled analysis of multiple factors such as gas pressure and content, drilling status parameters, formation conditions, and the working status of the automated drilling rig itself is performed to obtain a composite drilling condition evaluation mechanism. This mechanism generates a series of drilling parameters to achieve efficient, low-energy intelligent drilling.

3.2.2 Intelligent Control of the Drilling Process

The existing drilling process has achieved automated control, which involves controlling actuators to perform procedural actions according to predetermined programs but lacks intelligence and autonomy. The drilling process is a nonlinear time-varying process, and intelligent control of the drilling process for automated drilling rigs should quickly and timely adjust and optimize control vectors based on changes in formations, geological parameters, and real-time working conditions. Through gradient-level classification and autonomous learning, adaptive control of the drilling process can be realized, reducing fault rates and improving drilling efficiency.

3.2.3 Intelligent Design of Gas Control Boreholes

Currently, the design of gas control boreholes has the defect that manual drilling cannot dynamically correct the design in real time, making it difficult to achieve the expected results, and posing safety hazards in coal mining. Therefore, it is urgently necessary to develop an intelligent drilling design system with self-learning and self-optimization functions. The intelligent design system for boreholes constructs a three-dimensional gas geological model based on geological characteristics of coal and rock layers, permeability, and gas parameters. It combines the dynamic evolution law of gas-containing coal and rock bodies under active disturbance in gas control boreholes and multi-field coupling theory to guide borehole design. Drilling construction is carried out according to the design results, and the intelligent recognition unit provides real-time feedback on multiple parameters of coal and rock layers, achieving real-time updates of the three-dimensional geological model and optimizing the design to achieve the best gas extraction borehole design results.

3.2.4 Fault Diagnosis Technology

Faults occurring during the drilling process can severely impact drilling efficiency and adversely affect construction progress. Ensuring continuous, reliable, and automated operation of underground gas extraction is a core requirement for achieving intelligent extraction. To ensure the reliability and safety of long-term operation of automated gas extraction drilling rigs, it is necessary to detect the operational status of the equipment and automatically handle faults. Automated gas extraction drilling rigs can integrate big data computation and various fault diagnosis technologies, such as fault tree analysis, rule-based reasoning, case-based reasoning, neural network diagnosis, grey relational analysis, and fuzzy theory diagnosis. By integrating two or more of these diagnosis technologies, an expert system for fault diagnosis can be established. This system can handle drilling faults (e.g., stuck drill, bit jamming, unscrewing) and mechanical faults (e.g., component failures) urgently or provide early warnings. Additionally, visualizing fault handling can form a fault handling method demonstration system.

3.3 Intelligent Perception and Multi-Machine Collaborative Control Technology for Automated Drilling Systems

In coal mines, the underground environment is characterized by poor lighting, high humidity, and significant dust, making it complex and demanding for operations. Collaborative operation of multiple machines is essential to meet the dynamic and complex application requirements underground. For instance, during the operation of the automatic loading and unloading system of the drilling rig, it is necessary to perceive the surrounding environment in real-time, detect collisions, and match and track the relative positions of the automatic drilling rigs. During the drilling process, the automated drilling rig needs to intelligently sense its operational status, confirm whether the drill rod is loaded or unloaded correctly, whether the robotic arm has retracted to a safe position, and whether there are any faults, thereby achieving mutual perception and precise collaboration with the loading and unloading system and other automated gas extraction drilling rigs. Currently, existing robot intelligent perception technologies and multi-machine collaborative control methods are mostly based on simple or specific application environments. There is a lack of robust intelligent perception and multi-machine collaborative control methods for complex underground coal mine environments. The integration of multi-sensor information and intelligent algorithms is crucial for achieving intelligent perception and multi-machine collaborative control of automated gas extraction drilling systems in such complex environments.

3.3.1 Dynamic Adaptive Technology for Automated Gas Extraction Drilling Rig Clusters

With accurate underground positioning and real-time updating of 3D models, adaptive cluster control technology is a new approach to achieving optimal overall performance by studying the dynamic adaptive formation of the underground automated gas extraction drilling rig cluster network. By addressing issues such as limited underground communication and asynchronous information transmission between individual drilling rigs, analyzing the actual overall performance of the automated gas extraction drilling rig system, and establishing online planning objective functions, the Hamiltonian function is constructed using the minimum principle for optimal path calculation. This enables functions such as collision avoidance, obstacle avoidance, target tracking, and formation maintenance.

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3.3.2 Distributed Formation Control Technology for Automated Gas Extraction Drilling Rig Clusters

The formation control of automated gas extraction drilling rig clusters is similar to the multi-agent collaborative control in artificial intelligence. The control of automated gas extraction drilling rig clusters can draw on multi-agent collaborative control, viewing each automatic drilling rig as a relatively independent agent. By solving distributed control problems, each agent completes its sub-tasks independently to achieve cooperation, focusing on how multiple agents coordinate and use their respective knowledge, objectives, skills, and construction plans to act together to achieve construction goals. For example, based on fault diagnosis technology for handling faults and predicting mechanical fatigue life in automatic drilling rigs, predictive control can be performed through appropriate design algorithms, allowing a single automated gas extraction drilling rig to seamlessly exit or join the entire cluster formation, maintaining consistency, integrity, and topology of the entire formation. Thus, based on distributed control technology, it is possible to achieve group behavior control and collaborative decision-making and management of multiple individual units, thereby completing collaborative operational tasks.

3.4 Comprehensive Management and Operation Platform for Automated Drilling Rig Clusters

The comprehensive management and operation platform for automated drilling rig clusters integrates various application modules such as geological condition management, production planning and task management, energy consumption analysis, equipment and personnel management, and accident warning management. It is an information perception, display, and application platform based on big data, cloud computing, the Internet of Things (IoT), and mobile internet technologies. This platform allows for comprehensive perception, real-time interconnection, analysis and decision-making, collaborative control, remote human intervention, and multi-system access for the automated gas extraction drilling rig cluster system. It effectively integrates and centrally controls the various subsystems of the automated gas extraction drilling rig system, enabling timely handling, guidance, and adjustment of production systems and operational processes. Currently, establishing a comprehensive management and operation platform involves solving two major issues: data transmission and processing, and customization of the visualization platform.

3.4.1 Data Transmission and Processing

Data is the foundation and core for controlling the automated gas extraction drilling rig system. Therefore, it is essential to establish a unified format standard to ensure that all data entering the operating system is in a uniform format, facilitating seamless data communication. Additionally, the system should intelligently filter the vast amounts of data generated and adopt a unified storage solution to address data resource disorganization. Enhancing the anti-interference capability of data communication and improving stability, while also increasing the real-time performance of data transmission, is crucial. Furthermore, the platform should be capable of high-performance interfacing with big data analysis platforms, enhancing data openness, and supporting flexible integration of multiple software systems and intelligent systems.

3.4.2 Customization of the Visualization Platform

Developing an application interface tailored to the characteristics of coal mine extraction is essential. Utilizing virtual reality display technology, the platform can provide real-time visualization of true 3D geological models that include parameters such as porosity, permeability, gas content, and various mechanical properties. It should offer comprehensive evaluation of extraction production tasks and track the progress of task completion. The platform should also enable intuitive display of energy consumption analysis, real-time prediction of system lifespan, intelligent warnings, demonstration of equipment and drilling fault diagnosis methods, and multi-level, multi-angle visualization of the operational status of the automated gas extraction drilling rig system. This enhances human-machine interaction capabilities.

4. Prospects for Automated Gas Extraction Drilling Rig Cluster Control

The technology for cluster control of automated gas extraction drilling rigs holds significant strategic importance for enhancing disaster management capabilities in Chinese mines and advancing the construction of intelligent mines in the country. Given the technical challenges and opportunities faced by automated gas extraction drilling rig cluster control:

(1) Advanced technologies from high-intelligence fields such as robotics, autonomous driving,

intelligent manufacturing, and smart missiles, both domestically and internationally should be assimilated and adapted. Based on the analysis of multi-agent cooperative control technologies such as UAV group, multi-autonomous underwater vehicles and intelligent logistics, a set of mature automatic gas extraction drilling rig cluster control technology adapted to complex geological environment and working conditions is transformed and upgraded. This will accelerate the process of unmanned disaster management in mines.

(2) A comprehensive large database should be created, including establishing common standards for data acquisition, storage, and transmission. It is necessary to establish data quality evaluation standards, standardize data algorithms, and evaluate the accuracy, completeness, and timeliness of data. It is also necessary to establish a coal formation parameter database, a mechanical parts failure database, a drilling failure database, an energy consumption database, etc. Through deep learning, a deep model is constructed to realize automatic feature extraction and complex mapping relationship fitting, which lays a data foundation for real-time perception, dynamic analysis, fault control and management decision of the automatic gas drainage rig cluster control system.

(3) The state shall formulate special plans for the research and development and application of intelligent equipment and robots in coal mines, establish and improve industrial standards and certification systems for cluster control of coal mine gas drainage rigs, and strengthen basic cutting-edge science and key technology research. In terms of funds, taxes and product sales subsidies, it is necessary to formulate corresponding support policies to improve the enthusiasm of coal mining enterprises, scientific research institutions and colleges and universities for the R & D and application of automatic gas drainage drilling rig group control system. It is necessary to support the construction of functional equipment demonstration projects in the coal industry, and include intelligent unmanned coal mine underground disaster control demonstration mines into national pilot demonstration projects.

5. Conclusion

(1) This paper briefly outlines the development status of automated gas extraction drilling rigs both domestically and internationally. It emphasizes that achieving cluster control technology for automated gas extraction drilling rigs is crucial for realizing unmanned disaster management underground.

(2) Under the condition that some phased achievements have been made in the intelligentization of gas drainage drilling rigs, four technical shortcomings need to be solved urgently to fully realize the cluster control technology of automatic gas drainage drilling rigs: accurate positioning and automatic navigation and obstacle avoidance technology of automatic drilling rigs; intelligent drilling technology of single automatic drilling rig; intelligent sensing and multi-machine cooperative control technology of automatic drilling rig system; and multi-system comprehensive management operation platform of automatic drilling rigs. By solving the above four core technologies, the gas drainage height can be realized intelligently and the whole process of gas drainage can be "transparent", laying a foundation for realizing unmanned underground disaster management.

(3) The development trends of cluster control for automated gas extraction drilling rigs were discussed, suggesting the assimilation, absorption, and enhancement of mature cluster control technologies from other intelligent fields. It was proposed to establish a comprehensive database for gas extraction systems and to drive the engineering application of automated gas extraction drilling rig cluster control technology under national policies and planning.

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