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Synergizing AI and Industrial IoT for Intelligent Ecosystem Evolution in Underground Coal Mining Systems

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Abstract: Intelligent mining has become an inevitable choice for the sustainable development of the coal industry. Intelligent fully mechanized mining faces have demonstrated significant advantages, including comprehensive monitoring, optimized equipment maintenance, energy efficiency enhancement, improved personnel safety, and data interoperability with remote control capabilities. However, several challenges persist, such as immature gangue recognition technology, imperfect automatic leveling systems, insufficient system stability, high maintenance costs, and low levels of intelligence in remote fluid supply systems. The intelligentization of coal mining areas requires full-process linkage, involving six key technologies: positioning and navigation of mining equipment, underground environmental monitoring, data extraction and analysis, real-time communication, intelligent decision-making, and underground robotics. The core technologies of intelligent coal mines focus on data monitoring and analysis, real-time intelligent decision-making, optimization of safety production management systems, and research and development of critical equipment. Currently, coal intelligentization remains in its infancy. It is essential to promote the deep integration of geological exploration, communication, information processing, and equipment technologies to achieve safe, efficient, and green mining, thereby driving the transformation and upgrading of the industry.

Keywords: Intelligent Fully Mechanized Mining Face; Intelligent Sensor; Intelligent Decision; Intelligent Mining.

1. Introduction

China occupies a significant position in the global coal industry pattern. It is not only the world's largest coal producer, but also the largest coal consumer. In 2024, coal accounted for 55% of China's energy consumption, with a total output of 4.78 billion tons. With the rise of disruptive technologies such as materials science, information technology, artificial intelligence and big data, intelligent manufacturing, intelligent equipment and intelligent production have ushered in new development opportunities. In this context, the construction of intelligent coal mines and the development of intelligent mining are not only in line with the development orientation of the times, but also the inevitable choice for the sustainable development of the coal industry. Wang et al.[1] proposed eight intelligent system management platforms for the construction of smart coal mines, emphasized the realization of safe and efficient coal mining through multi-source data fusion, equipment group collaborative control and intelligent decision-making technology, and defined the three basic theories and key technology directions of intelligent mining. Lv et al.[2] redefined the smart mine as a "smart system with multi link automatic control", and proposed a systematic construction plan covering the formulation of technical standards, the research and development of intelligent equipment and the application of intelligent decision-making, aiming to solve the problem of mine informatization island. Chen et.al[3] have built a five-tier architecture system of smart mines (data acquisition, transmission, storage, decision control, and display), and pointed out that the key technologies include 3D geological modeling, cloud network integration, and big data-driven intelligent decision-making, providing a technical path for the lack of mine informatization standards. Ren[4] systematically sorted out the research framework of intelligent decision support system (IDSS), emphasized that the integration of knowledge base and expert system was the key to break through the unstructured decision-making, and pointed out that the challenges of cognitive model construction and multi-source knowledge fusion need to be solved in the future. Xia et al.[5] developed an auxiliary system for treatment of diseased slopes based on expert system and multi-objective decision-making method, which realized intelligent decision support from qualitative generation to quantitative optimization of treatment scheme.

2. Intelligent Fully Mechanized Mining Face

2.1. Advantages of Intelligent Chemical Industry

Some coal mines have taken the lead in adopting intelligent fully mechanized mining face with many significant advantages. In terms of monitoring, it can realize the comprehensive monitoring of the working face and belt conveyor, provide real-time monitoring images for the dispatching center, provide detailed information for the operation of remote monitoring equipment, and help the dispatching center operate the equipment more accurately[6].

Intelligent is applied to equipment maintenance. The hydraulic support of intelligent fully mechanized mining face has strict requirements on the quality of emulsion at the working face. The emulsion that has reached a higher standard after several times of purification is used to reduce the loss of the hydraulic support, so as to effectively extend the service life of the hydraulic support.

Intellectualization is applied to energy conservation and equipment performance. Taking the belt conveyor inverter

control as an example, it can carry out heavy load startup and operation control functions, and has the advantages of stable startup, large initial torque, reliable performance and long operation life[7].

Intelligent application in personnel safety and management, intelligent working face can significantly reduce the number of production shifts, and with the help of real-time monitoring images, the control center can timely detect risks and reduce the injury to operators[8].

In terms of data management and remote control, the intelligent fully mechanized mining face equipment collects and analyzes data in real time through sensors and video real-time monitoring systems, so as to realize the data exchange between the underground and the well, so as to realize the remote control of the intelligent working face.

2.2. Issues to Be Addressed in Intelligent Fully Mechanized Mining Faces

Although certain progress has been made in intelligent fully mechanized mining faces, numerous challenges remain. First, the issue of gangue recognition: accurate gangue identification is crucial for adjusting the height of shearers when the roof of the mining face changes, reducing equipment wear. Currently, no mature technology exists, requiring manual intervention by production personnel[9].

Second, automatic leveling systems are not yet perfect. A key specification for fully mechanized mining faces is that the coal wall, conveyor, and supports must be on the same plane. During long-term production operations, the absence of manual intervention can lead to unsafe and inefficient production.

Furthermore, system stability cannot be guaranteed. There is still a probability of system crashes, blue screens, and other issues in data transmission and system operation, requiring operations such as system restarts, which pose safety hazards.

Additionally, the maintenance costs of intelligent fully mechanized mining faces are relatively high. The spare parts and maintenance costs for intelligent fully mechanized mining equipment are prohibitively expensive, making it difficult for ordinary enterprises to bear, with only large enterprises able to adopt such systems.

Finally, remote fluid supply cannot yet be fully automated. It still requires remote video monitoring, and the function of remote fluid supply can only be achieved through optimizing filtration systems and remote coordination between the surface and the monitoring center.

3. Challenges in Intelligent Coal Mining Areas

The intelligentization of coal mining extends beyond individual fully mechanized mining faces to require integrated intelligent linkage across entire mines and mining areas. It is necessary to organically combine the Internet, artificial intelligence, big data, and intelligent equipment to build a complete system for real-time information monitoring, analytical prediction, autonomous analysis, and multi-faceted coordination in mines, integrating intelligence into processes such as roadway development, mining face operations, coal transportation, coal washing, gangue disposal, and safety production management[10].

Constrained by current technological levels and the complexity of coal mining conditions, while some enterprises have applied intelligent fully mechanized mining faces in production, the current level of intelligentization has not yet met expectations, with many challenges remaining. To achieve true intelligent mining, the following six issues need to be addressed: equipment positioning and navigation technology, underground environmental monitoring systems, data extraction and analysis systems, real-time data transmission systems, intelligent decision-making systems, and underground robotics technology[11].

3.1. Equipment Positioning and Navigation Technology

To ensure that mining equipment operates along predetermined trajectories, it is necessary to record and feedback equipment position information in real time. Limited by the mine environment, conventional satellite navigation technologies cannot be used. The mainstream technology is a GIS (Geographic Information System)-based navigation technology system, with the most commonly used being inertial navigation systems. By fixing inertial measurement instruments on equipment, measuring axial linear acceleration and angles, and performing matrix calculations through real-time data transmission to computers, navigation calculations are achieved.

3.2. Underground Environmental Monitoring Systems

Sensors serve as the foundation for intelligent mining areas to acquire accurate and comprehensive information, which is critical for intelligent operations[12]. However, due to factors such as narrow underground spaces, harsh air conditions, and complex electromagnetic environments, detection technologies cannot fully realize their effectiveness. Currently, although intelligent sensor technologies such as ground-penetrating radar detection, laser scanners, visible light analysis equipment, infrared monitoring equipment, pressure sensors, acceleration sensors, and displacement sensors exist, these technologies still cannot fully meet the special requirements of coal mines. Technologies that still need to be researched include gangue detection technology for the front section of mining operations, used to automatically identify and adjust the height of shearers to reduce equipment wear, and equipment condition sensors in harsh conditions that enable the control center to monitor machine posture information in real time.

3.3. Data Extraction and Analysis Systems

Extracting key information from large volumes of data is a critical point for intelligent mines, where the role of artificial intelligence will be pivotal. The key technology lies in analyzing and extracting data information of different types and levels, establishing matching and pushing mechanisms based on the information required by intelligent mines, and analyzing and pushing data such as sensor information, real-time monitoring videos, surrounding rock monitoring, and production information.

3.4. Real-Time Data Transmission Systems

The role of underground communication technology is to establish efficient data transmission between underground and surface operations, enabling real-time and accurate transmission of intelligent safety monitoring systems, sensor data, and surface operation commands. Currently, data transmission is divided into wired and wireless. Wired transmission includes fiber optics and cables, which have the

advantages of good stability and long transmission distances but are difficult to deploy and vulnerable. Wireless transmission commonly includes Bluetooth, WiFi, and LTE, which are mobile and convenient but severely affected by environmental factors. It is necessary to further improve transmission quality and coverage to meet the information transmission needs of mines.

3.5. Intelligent Decision-Making Systems

To achieve efficient extraction of coal resources, it is necessary to enhance the adaptability and intelligence level of coal mining equipment. However, complex underground coal seam conditions, such as faults and collapse columns, pose challenges to automatic cutting. The data from sensors, real-time monitoring videos, surrounding rock monitoring, and production information are complex, making it difficult for humans to make rapid decisions. Intelligent judgment can quickly make decisions under complex conditions and propose optimal solutions.

3.6. Underground Robotics Technology

Underground robotics is one of the current research hotspots. Due to the complex and changeable underground environment, manual exploration is impossible in some areas with poor air quality and narrow spaces. In such cases, robots can operate in harsh and complex environments, reducing risks to personnel. Robots equipped with infrared scanning, acoustic emission, and vision equipment can be used to detect narrow spaces and surrounding rock fragmentation, providing data support for subsequent operations. Robots with heat preservation and navigation functions can automatically deliver meals to workers at meal times, enhancing the well-being of underground workers. Robots carrying gas monitoring instruments and dust monitoring devices can patrol roadways, simultaneously detecting air concentration and roadway surrounding rock deformation to provide early warnings of dangers.

4. Key Technologies for Intelligent Coal Mines

To achieve intelligent mining, address the diversity of coal seam occurrence conditions, and ensure the urgency of safe production, significant investments are needed in core technologies for intelligent mining. Currently, the key technologies for intelligent coal mines mainly focus on four aspects: data monitoring and analysis, real-time intelligent decision-making, intelligent safety production management, and research and development of key technical equipment[13][14].

4.1. Data Acquisition and Utilization

The level of data acquisition determines the accuracy of decision-making in the mining process. Developing higher-precision geological condition detection technologies and equipment to construct accurate and reliable numerical models of coal seams in working faces provides accurate geological information support for mining operations. Developing more reliable and lower-cost positioning and navigation systems ensures accurate tracking of equipment positioning under complex working face conditions, reducing uncertainties in the mining process and improving production efficiency.

4.2. Real-Time Intelligent Decision-Making

Deeply researching machine learning algorithms to improve the intelligence level of intelligent fully mechanized mining systems and thereby enhance mining efficiency. Intelligent decision-making systems analyze and judge various situations encountered in the mining process based on real-time data collected by sensors and other devices, making optimal decisions to achieve efficient extraction of coal resources.[15]

4.3. Intelligent Safety Production Management

Optimize coal resource management and capacity layout: establish safe, efficient and green coal mining as the basic industrial policy for China's coal resource development, resolutely eliminate backward mining methods and capacity equipment, and promote the transformation and upgrading of the coal industry. The implementation of intelligent coal mine and intelligent mining system integration solutions, including system maintenance cloud service, the establishment of intelligent mining professional team and market-oriented services, to solve the problem of coal mine talent shortage and unbalanced management and operation level. Speed up the establishment of technical standard system, operation management specification and safety regulation system for intelligent coal mine and intelligent mining, eliminate the restriction of existing safety regulations on intelligent unmanned mining, and encourage the innovative development of intelligent unmanned mining technology and equipment.

4.4. Research and Development of Key Technical Equipment

Study the key components of the equipment under the special conditions of the working face to make it work normally under complex and diverse geological conditions. Remote real-time monitoring and efficient and reliable equipment are combined to realize intelligent diagnosis and feedback system. The research and development of technical equipment will effectively improve the intelligent level of coal mining, reduce manual intervention, and improve production efficiency and safety[16].

5. Conclusion

Intelligent technology of coal mining equipment is the core of intelligent coal mining. Through real-time and accurate collection of coal mine environmental status and equipment operation status data, the intelligent technology of coal mine equipment uses advanced data analysis technology to conduct in-depth correlation analysis on the collected data, and uses the analysis results to guide the independent decision-making system, so as to issue accurate control instructions to coal mine equipment. At the same time, the intelligent control system carries out in-depth learning according to the running state of the equipment, and constantly optimizes its own algorithm to achieve more efficient and intelligent mining operations.

The development of the coal industry has always been closely linked with scientific and technological progress. From early manual mining to today's large-scale machine mining, and then to the future intelligent mining, many key technologies need to be continuously optimized and improved. Given that the coal industry is currently in the initial stage of intelligent development, intelligent coal mining should be

carried out in an all-round way around geological exploration and mapping, electronic communication, information processing and analysis, and intelligent equipment, so as to promote the in-depth integration of relevant technologies and the needs of the coal field, provide strong support for safe, efficient and intelligent mining of enterprises, and promote the sustainable development of the coal industry.

References

[1] GF Wang, GR Zhao, HW Ren. Analysis on key technologies of intelligent coal mine and intelligent mining. Journal of China Coal Society, 2019,44(01):34-41.(in Chinese).

[2] PF Lv, M He, XJ Chen, et al. Development and prospect of wisdom mine. Journal of Mine Automation, 2018,44(09):84-88.(in Chinese).

[3] XJ Chen, M He. Framework system and key technology of intelligent mine construction. Coal Science and Technology, 2018,46(02):208-212+236.(in Chinese).

[4] ML Ren,SL Yang,WD Zhu. Intelligent decision support system: State of art and challenges, Journal of Systems Engineering, 2002, 17 (05): 430-440 (in Chinese).

[5] YY Xia, RG Zhu. An intelligent aided decision-making system of choosing control plans for unstable slope,1998(04):105-110.(in Chinese).

[6] HW Ren,GF Wang, GR Zhao, et al. Smart coal mine logic model and decision control method of mining system. Journal of China Coal Society, 2019,44(09):2923-2935.(in Chinese).

[7] ZH Huang, F Wang, SX Zhang. Research on the architecture and key technologies of intelligent coalmining system. Journal of China Coal Society, 2020,45(06):1959-1972.(in Chinese).

[8] GF Wang,YJ Xu, JH Zhang, et al. New development of intelligent mining in coal mines. Coal Science and Technology, 2021,49(01):1-10.(in Chinese).

[9] JL Que. Construction and implementation of platform for intelligent mine. Journal of Mine Automation,2018,44(04):90-94.(in Chinese).

[10] GF Wang, DS Zhang. Innovation practice and development prospect of intelligent fully mechanized technology for coal mining. Journal of China University of Mining & Technology,2018,47(03):459-467.(in Chinese).

[11] CJ Tian. Research of intelligentized coal mining mode and key technologies. Journal of Mine Automation, 2016,42(11):28-32.(in Chinese).

[12] EX T, YL Z, P M. Research status and development prospect of intelligent mining technology in coal mine. Coal Science and Technology, 2019,47(10):111-115.(in Chinese).

[13] KX Z, SB L, MC H, et al. Study on key technologies of intelligent unmanned coal mining series I : study on diagonal adjustment control technology of intelligent fully-mechanized coal mining face. Coal Science and Technology, 2018, 46(01):139-149. (in Chinese).

[14] KX Z. Study on intelligent mining technology of fully-mechanized heading face. Coal Science and Technology. 2017,45(07):106-111. (in Chinese).

[15] QY W, L J, GF W, et al. Top-level architecture design and key technologies of smart mine. Coal Science and Technology, 2022,48(07):80-91.(in Chinese).

[16] XQ G, FY D, AG C. Study on load characteristic and intelligent speed control strategy of VFD scraper conveyor. Mining & Processing Equipment,2011,39(11):12-16.(in Chinese).