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Smart Mines and Intelligent Mining

Hang Li

Henan Polytechnic University College of Energy Science and Engineering, Henan Jiaozuo 454000, China

ABSTRACT

As a crucial energy resource, coal plays a pivotal role in the global energy mix. This is particularly evident in China. Endowed with abundant reserves, the country relies on coal as its primary energy source. However, traditional extraction methods are fraught with challenges, including resource depletion, environmental degradation, and significant safety hazards. Consequently, the advancement of intelligent mining technologies is of paramount importance. These innovations enhance resource utilization efficiency, mitigate environmental impacts, and safeguard the well-being of miners. Intelligent coal mining leverages modern information systems, automation, and artificial intelligence to achieve a fully automated, informatized, and smart extraction process. In this context, "intelligence" denotes a comprehensive system capability. It encompasses the real-time, precise perception of data objects, alongside rapid and accurate decision-making support. Furthermore, it involves efficient execution coordination and the autonomous ability to analyze, judge, and act upon external stimuli, coupled with the capacity for independent learning and process optimization. Recent years have witnessed remarkable technological breakthroughs in this domain. These advancements are primarily driven by the integration of big data, artificial intelligence, the Internet of Things (IoT), advanced sensor technologies, and 5G+ networks. By systematically aggregating mine production data, big data and AI have substantially elevated the sophistication of production management. Concurrently, IoT and sensor technologies facilitate the real-time monitoring of mine environments and equipment operational status, thereby ensuring absolute data accuracy and immediacy.

KEYWORDS

Intelligent mining, Unmanned mining, Sensor technology, Identification.

1. INTRODUCTION

Intelligent information systems must possess three fundamental capabilities. First is the capacity for real-time smart perception and the proactive collection of valuable external data. Second is a comprehensive ability to acquire, analyze, and process the information necessary for judgment, self-learning, and decision-making activities. Finally, it requires the analytical prowess to execute autonomous learning and practical decision-making based on real-world conditions.

Intelligent extraction refers to the comprehensive automation, informatization, and smart operation of coal mining processes driven by cutting-edge technologies. These include modern IT, automation, and artificial intelligence. At its core, this approach utilizes advanced sensors, robust data processing techniques, and smart control systems. Together, they enable the intelligent monitoring, management, and continuous optimization of the entire mining lifecycle.

The evolution of this technology has progressed sequentially through three phases: automation, informatization, and ultimately, intelligentization. Initially, automation technologies primarily addressed the manual operation and control of machinery, utilizing devices like Programmable Logic

Controllers (PLCs) to achieve basic autonomous equipment functionality. Subsequently, informatization facilitated the digitization and networking of critical operations, including production management, resource allocation, and environmental monitoring. Today, propelled by the rapid expansion of AI, big data, and the Internet of Things, coal extraction has officially entered the intelligent era. A defining characteristic of this new paradigm is that mining equipment is inherently equipped with capabilities for smart perception, decision-making, and control.

Intelligent automated coal mining [1] is fundamentally achieved by integrating autonomous learning and decision-making functionalities into existing automated monitoring systems. This vital upgrade empowers conventional mining machinery to perceive, collect, and track dynamic shifts in underground environmental parameters and the conditions of the surrounding rock in real time. Consequently, the machinery can automatically adjust extraction control parameters, thereby realizing true intelligent perception. Ultimately, smart decision-making and intelligent execution control serve as the indispensable pillars of modern automated mining operations.

The hallmark of an intelligent automated mining machine [2] is its robust capacity for self-learning, self-management, and autonomous decision adjustment. These machines boast a suite of advanced functionalities—including self-awareness, self-analysis, process self-control, and defect self-correction—that enable seamless automatic adaptation. In this context, "self-awareness" relies on the real-time aggregation of conditional data. "Self-analysis" involves the continuous evaluation of this instantaneously gathered information. Furthermore, "self-process control" represents an autonomous, real-time correction and decision-making protocol derived from that analysis, functioning as an ongoing feedback loop. Ultimately, a fully realized intelligent mine system builds upon basic automation by applying modern smart concepts. It delivers comprehensive intelligent services, seamlessly integrating real-time data acquisition, network transmission, standardized data fusion, visualization, and autonomous operation.

2. UNMANNED INTELLIGENT MINING

2.1. Unmanned Intelligent Mining

Unmanned intelligent mining is a highly innovative technology. It integrates advanced fields such as artificial intelligence (AI), automated control, and machine learning to achieve fully automated coal extraction. Supported by this technology, mining equipment operates autonomously across all operational stages, including drilling, extraction, and transportation. This autonomy significantly enhances both production efficiency and safety. Furthermore, these intelligent systems continuously collect and analyze mining data in real time. This capability allows for the ongoing optimization of extraction strategies, thereby minimizing resource waste and reducing environmental impact.

Within the framework of unmanned intelligent mining [3], a fundamental approach involves deploying automated equipment throughout every phase of the operation. These machines execute tasks autonomously based on pre-programmed protocols. Consequently, the necessity for manual intervention is drastically reduced, effectively mitigating the occupational risks faced by underground personnel. Beyond basic automation, these systems heavily leverage AI and machine learning. This empowers the equipment not only to operate independently but also to learn and optimize its performance using real-time data feedback. By analyzing geological information, the machinery can automatically adjust its mining strategies. It minimizes direct human control while simultaneously boosting extraction efficiency. Ultimately, this ensures the working face operates continuously, stably, and efficiently. It transforms the traditional mine into a sophisticated production system capable of autonomous perception, analysis, and decision-making.

2.2. Development History of Unmanned Intelligent Mining

The development of unmanned intelligent mining technology has traversed several distinct stages [4]. Initially, the industry focused on achieving partial automation through specialized equipment. Engineers developed and applied video surveillance, automated tracking of hydraulic supports, shearer memory cutting, and remote control systems. These critical innovations liberated miners from the hazardous working face. Instead, personnel could oversee and manage normal coal extraction tasks from the safety of roadway monitoring centers.

Subsequently, the focus shifted toward enhancing multi-machine coordination. To realize continuous automated production at the working face, several advanced technologies were integrated into the mining process. These included inertial navigation, personnel positioning systems, and multi-machine collaborative controls. The application of these technologies established the necessary foundation for the continuous, mechanized advancement of the mining face.

In the next phase, engineers began utilizing geological detection data in combination with inertial navigation and 3D laser scanning. This fusion of technology allows the system to accurately perceive the specific conditions of the working face and subsequently construct detailed 3D mining models. Such modeling approaches enable a far more precise understanding and prediction of extraction scenarios, thereby further elevating both operational efficiency and safety.

As technology continued to evolve, the integration of AI and machine learning became more profound. This shift allowed machinery to function with greater autonomy, constantly refining its operations based on instantaneous data collection. Today, the technology has advanced into a transformative new phase: comprehensive unmanned extraction. In this current stage, every facet of the mining process is executed by automated equipment. Driven by AI and machine learning, these systems work entirely autonomously, continuously learning and optimizing their operations through rigorous real-time data analysis.

3. INTERNET OF THINGS AND SENSOR TECHNOLOGY

The architecture of IoT platforms in coal mines primarily comprises four hierarchical layers: the perception layer, the communication and transmission layer, the information service layer, and the application layer. Perception Layer: This tier is fundamentally responsible for aggregating diverse downhole data, including temperature, humidity, gas concentration, and equipment status. These metrics are typically collected by an array of sensors and devices before being transmitted across the network to the subsequent layer. Communication and Transmission Layer: Dedicated to data routing, this layer transfers the information gathered by the perception layer to the information service layer via wired or wireless networks. Crucially, it must guarantee the real-time delivery, reliability, and security of the transmitted data. Information Service Layer: This level focuses on data processing and storage. It processes the incoming data from the transmission layer through operations such as data cleaning and analytics. Subsequently, the refined data is archived securely for utilization by the application layer. Application Layer: Serving as the uppermost tier of the IoT architecture, this is the layer most accessible to end-users. It delivers a variety of application services, such as data querying, visualization, and early warning alerts. These services are typically provided to users through web interfaces or mobile applications.

Sensors developed utilizing optical fiber sensing technology feature a compact footprint, cost-effectiveness, intrinsic safety, high sensitivity, electromagnetic interference resistance, and corrosion endurance. Consequently, they have been widely adopted in the field of engineering monitoring [5]. However, given the delicate and fragile nature of fiber Bragg gratings (FBG), robust protective measures are imperative. These measures ensure sensing accuracy and facilitate the sensors' long-term, stable operation within the harsh and complex environments of coal extraction. Beyond offering high precision and exceptional anti-interference capabilities, properly packaged optical fiber sensors exhibit formidable environmental tolerance, and their network multiplexing configurations are highly versatile. To effectively navigate the dynamic application scenarios inherent in underground mining, these sensors must possess intrinsic safety, stable performance, high precision, strong interference resistance, and ease of both installation and maintenance [6].

3.1. Environmental Perception Sensors

The primary targets for intelligent environmental perception in underground coal mining include the stress of the surrounding roadway rock, the force conditions of the anchor bolt bodies, the load-bearing status of the anchor support structures, roadway roof displacement, and the temperature within the goaf. To address these monitoring needs, several critical devices have been developed. These include fiber grating borehole stress sensors, fiber grating anchor bolt stress sensors, fiber grating anchor bolt dynamometers, and fiber grating roof separation sensors.

Figure 1. Fiber grating borehole stress sensor

The fiber grating borehole stress sensor represents an advanced sensing technology designed specifically to monitor internal stress variations within boreholes. It leverages fiber grating technology, utilizing the reflection and diffraction characteristics of light waves within the optical fiber to precisely measure fluctuations in both stress and temperature. Typically, this type of sensor comprises several integral components: the fiber grating sensing unit, the light source and demodulation equipment, a robust protective casing, and a comprehensive data transmission and processing system.

3.2. Equipment Posture Perception Sensors

An intelligent coal mining face is a sophisticated system grounded in sensing capabilities, driven by autonomous decision-making techniques, and aimed at automated control. Its ultimate objective is to achieve the highly coordinated execution of operational processes across the working face. The intelligent and precise perception of the equipment's operational status serves as the foundational link of this entire system. To satisfy the rigorous demands of constructing intelligent mining faces, a specialized suite of sensors has been engineered based on optical fiber sensing technology. This suite includes fiber grating bracket tilt sensors for detecting the posture of hydraulic supports, fiber grating bracket pressure sensors for monitoring support load, and fiber grating curvature sensors for assessing the straightness of the scraper conveyor. Collectively, these devices furnish a comprehensive set of smart perception equipment tailored to enable the true intelligentization of the coal mining face.

Figure 2. Fiber grating bracket pressure sensor

4. EFFICIENT COAL-ROCK RECOGNITION TECHNOLOGY

Resolving the challenges associated with coal-rock recognition is a critical step in the intelligent development of mines. It remains an urgent issue demanding immediate attention. Since the 1960s, major coal-producing nations—including the UK, the US, Australia, Germany, Russia, and China—have actively researched this technology, proposing nearly 20 different methods to date. However, the complex and diverse geological conditions of coal mines, coupled with varying coal and rock types, severely limit the universal applicability of these recognition techniques. Furthermore, the intricate stress conditions encountered during extraction make sensors highly susceptible to damage, resulting in poor reliability. Recognition performance is also heavily influenced by harsh underground environmental factors, leading to a significant margin of error. These compounding challenges explain the limited practical application of coal-rock recognition technologies in actual engineering scenarios. Therefore, researching efficient recognition methods tailored to complex and variable geological conditions constitutes a vital scientific imperative for the current coal industry [7].

At present, the primary coal-rock recognition technologies include process signal monitoring, infrared thermography, image feature recognition, ultrasonic detection, and electromagnetic wave detection.

Process signal monitoring involves extracting characteristic signals during the mining operation. Because coal and rock exhibit distinct mechanical and physical properties, the shearer displays different behavioral characteristics during the cutting process. Based on this principle, it is possible to monitor the characteristic parameters of the cutting state to accurately determine the cutting status of the coal or rock. Commonly utilized characteristic parameters include vibration signals, acoustic emission signals, electrical circuit signals, and cutting torque.

Active infrared thermography builds upon passive infrared techniques. It utilizes an external energy radiation source to heat the surface or interior of the target object, causing a rapid temperature increase. Due to inherent differences in material properties and structures, the diffusion of heat varies significantly between coal and rock. By measuring the intensity of the outward infrared radiation emitted by the inspected object, an infrared thermal imager can calculate the surface temperature without requiring direct physical contact.

Image recognition is the process of conducting comprehensive visual analysis to identify a desired target. This technology relies heavily on specific image features. Because coal and rock undergo distinct geological formation processes, they exhibit substantial differences in brightness, color, texture, and shape. Notably, color brightness maintains a degree of independence. This allows the analytical model to effectively account for both the macroscopic properties and the microscopic structures of the image.

Ultrasound is a mechanical wave characterized by an extremely short wavelength. Typically measuring less than 2 centimeters in air, these waves strictly require a physical medium for propagation. As ultrasonic waves travel through the coal mass, they undergo phenomena such as reflection, refraction, diffraction, and scattering. Whenever these waves encounter media with differing densities, physical parameters like penetration rate and refraction angle change accordingly.

Coal and rock act as lossy media. Consequently, electromagnetic waves experience attenuation when propagating through them, with the loss factor varying depending on the specific geological conditions. When a broadband electromagnetic wave reaches the surface of a coal seam, reflection and refraction occur. A portion of the wave is reflected back into the original medium from the seam surface, while another portion penetrates the interior of the coal seam via refraction. As this penetrating wave reaches the interface between the coal and an adjacent medium, it undergoes a subsequent round of reflection and refraction. By meticulously analyzing parameters such as the echo time delay and the frequency of these electromagnetic waves, the thickness of the coal seam can be estimated. Ultimately, this mechanism enables the effective identification of coal and rock.

5. INTELLIGENTIZATION AND 5G TECHNOLOGY

The intelligent development of coal mines serves as a crucial technical support and a powerful driving force for achieving high-quality development in the coal industry. Its core lies in deep integration with new-generation information technologies such as 5G, big data, and artificial intelligence. Most coal mines in China utilize underground mining methods, where geological conditions are highly complex. Due to imperfect surface-to-underground communication systems, information exchange between equipment and systems remains challenging. The ultra-high-density connectivity of 5G presents a viable solution to dismantle information silos across various mine systems and departments. It enables seamless interconnection between systems and mobile devices, eliminates spatial barriers, and optimizes operational workflows.

Supported by technologies like cloud computing and big data, massive volumes of equipment and environmental data undergo multi-dimensional integration. Through advanced data analysis, intelligent applications are realized to synergistically control multiple systems, thereby providing scientific decision-making support to enhance safe and efficient mine production. These intelligent measures not only reduce human labor and boost efficiency but also enable dynamic risk prevention and monitoring via faster, more precise data analysis, steering the coal mining industry toward a safer, more efficient, and smarter future.

Consequently, the application scenarios of 5G extend beyond traditional remote control and high-definition video transmission; they encompass a profound integration and transformation driven by new-generation information technologies. Examples include remote mining and expert-supported maintenance integrated with virtual reality; concurrent multi-sensor access and low-level collaborative decision-making integrated with the Internet of Things (IoT); as well as mobile inspections and multi-terminal collaboration integrated with positioning and navigation systems.

6. CONCLUSION AND PROSPECTS

Intelligent coal mining represents a further elevation of traditional mechanization and automation. It marks a transformative new stage in the revolution of coal production methods and productive forces. Serving as the crucial technical support for the high-quality advancement of the sector, the construction of intelligent coal mines is now widely regarded as an inevitable path forward.

In recent years, innovative research and development in intelligent mining technologies and equipment have yielded breakthroughs in numerous core technologies. Significant achievements have been realized across a variety of complex operational scenarios. These successes include fully mechanized intelligent extraction in thin and relatively thin coal seams, operations featuring large and ultra-large mining heights, as well as intelligent fully mechanized top-coal caving technologies and equipment designed for extra-thick seams.

However, we must objectively recognize the current reality. The development of intelligent coal mining in China remains in its primary stage, leaving substantial room for improvement. Moving forward, we must promote this evolution comprehensively, systematically, and steadily. It is imperative to deeply integrate cutting-edge innovations—such as artificial intelligence, blockchain, big data, cloud computing, the Internet of Things (IoT), and smart machinery—with foundational coal extraction techniques. Only through this profound technological integration can we ultimately secure victory in the critical endeavor to build fully intelligent coal mines.

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