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Enhancing Coal Mining Efficiency: A Unified Platform for Intelligent Management and Control

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ABSTRACT

Coal is a prominent energy resource for several countries. Of late, exploring the automatic management and control of coal mining has been a significant task. This article presents a framework for a mine-wide integrated automation management and control platform with the goal of advancing coal mining through unified data, models, platforms, and plans. Utilizing cutting-edge technologies, the platform offers resource management, real-time monitoring, remote control, statistical analysis, and intelligent alarm systems. Data access design ensures standardized data collection and exchange, fostering interoperability. A big data storage center manages heterogeneous data sources. The platform interface design emphasizes flexibility and scalability through containerized applications and microservices frameworks, streamlining deployment. The functional design encompasses subsystem configuration access, real-time monitoring, remote access, etc. A detailed evaluation is presented to demonstrate the significance of the proposed platform in terms of functionality, performance, and scalability.

KEYWORDS

Automatic Management and Control, Big Data, Coal Mining, Collaborative Control, Integrated Automation, Intelligent Mining, Real-Time Monitoring, Security, Unified Data

Coal mining sites have limited space and are often harsh environments because of challenges such as gas explosions, roof falls, floods, and fires. These factors significantly impede the efficient development of the coal industry. However, with the continuous improvement of machinery and equipment reliability and stability in the coal industry in recent years, the implementation of environmental monitoring systems, production process automation control systems, and safety production information systems have further enhanced the level of mine mechanization, informatization, and digital management (Nepsha et al., 2021; Wu & Zhou, 2021).

However, the level of automation and informatization in mines is still relatively low, and the foundation for intelligent construction is weak. Currently, the subsystems within the information management system of coal mining enterprises remain separate entities with a single system and a single business model (Li et al., 2020). This results in serious information isolation, insufficient business interconnectivity, limited data value extraction and utilization, and a notable gap in achieving

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intelligent, distance, and unmanned objectives. Therefore, through scientific and technological innovation, it is imperative to drive the overall enhancement of coal mine intelligence. This entails devising and designing comprehensive objectives and a general technical framework for coal mines, defining the construction technology path, establishing a scientifically grounded design and construction paradigm, and realizing various disaster prevention and control scenarios. Such efforts hold theoretical and practical significance as they ensure and enhance the effectiveness of coal mine intelligent construction.

The mine-wide integrated automatic management and control platform applies new-generation information technologies such as the Internet of Things, big data, and intelligent control to the mining field. This platform is supported by the coal industry's big data center, which integrates and manages coal mine safety, production, and operational data. Model training establishes a digital foundation for coal mines, creating centralized and unified production scheduling, collaborative management and control, comprehensive risk prevention and control management, decision analysis, and other intelligent management and control business application centers based on the intelligent mine's fundamental information platform. This leads to comprehensive perception, real-time interconnection, and intelligent management of the mine. Decision-making and collaborative control ensure the safe, efficient, green, and intelligent production and operation of coal mines (Wang et al., 2022; Ding, 2020).

The major contributions of this article are as follows:

- proposing a novel framework for a mine-wide integrated automation management and control platform;
- presenting an effective functional design for the mine-wide integrated automatic management and control platform;
- demonstrating the proposed platform through evaluations using various parameters; and
- exploring the Practical Managerial Significance (PMS) and its applications.

Compared to previous works, the proposed work focuses on the construction of a mine-wide integrated automation management and control platform to accomplish four unifications from the top-level planning, namely "unified data, a unified model, unified platform, and a unified plan." This enhances the level of automation and informatization in mines. The unification of the proposed model eradicates the existing single system and a single business model in coal mining enterprises.

The article is structured as follows: the second section discusses state-of-the-art works related to the automatic management and control platform in an entire mine. The third section provides a brief overview of the research goals for the mine-wide integrated automation management and control platform. The fourth section presents the overall framework of the mine-wide integrated automation management and control platform. The fifth section covers the functional design of the mine-wide integrated automatic management and control platform. The sixth section evaluates the proposed platform by considering various parameters. The seventh section introduces the Practical Managerial Significance (PMS) and its applications. The eight section discusses scenario-based and practical applications. The ninth section elucidates the significance of the proposed platform, its implications, and future research. Finally, the 10th section concludes the research work and outlines future directions.

RELATED WORK

Intelligent mining combines informatization and industrialization and is rooted in mechanized and automated mining methods. It has revolutionized the coal industry (Wang et al., 2016). This new technology enables automatic mining through intelligent environmental perception at the work

face, intelligent control of each mining machine, and automatic direction of mining equipment. Recently, many countries have witnessed the technological development and application of intelligent mining.

Domestic coal mines encounter safety monitoring challenges. Zhang (2012) proposed a computer-controlled coal mine safety monitoring system comprising three subsystems: monitoring, communication, and control. The monitoring subsystem consists of gas, wind speed, negative pressure, temperature, and other sensors distributed throughout the mine for real-time monitoring. The communication subsystem, consisting of coordinators, routers, and end nodes, is responsible for wireless communication. CAN buses connect these two subsystems to the central control computer, which is located on the surface.

The transformation of the coal industry, in alignment with the national level of productive forces development, indicates a growing trend towards automation in coal mining. The utilization of innovative automated technologies, energy-efficient equipment, and computer-aided technology facilitates the automation of coal mine production. Research and development, as well as production and automation systems technology, play a pivotal role in the transformation of the coal industry. Han (2012) conducted an analysis of coal production automation systems to explore coal mine safety in high-yield, efficient mining, and automated production.

In Xueping and Xingquan (2014), the authors examined the system configuration and characteristics of a coal mine based on the Internet of Things, elaborated on the realization and structure of coal mine automation technology based on the Internet of Things, and explained the main functions of the platform for coal mine automation technology based on the Internet of Things.

Underground coal mining requires advanced instrumentation to ensure long-term growth and miner safety. Multiple parameters such as gas emissions, strata conditions, temperature, air velocity, humidity, and more must be simultaneously monitored using appropriate sensors. In Mandal et al. (2016), the authors presented the applications of a programmable logic controller (PLC) for key activities in underground automatic mining operations. PLCs are the preferred option for increasing output while maintaining safety in gassy underground mines. They can switch off the power supply when the concentration of flammable gases exceeds the permissible limit and simultaneously raise an alarm to save miners' lives and mine property. Additionally, PLCs can be used to monitor strata conditions.

In China, Longwall automation technology was proposed by the Longwall Automation Steering Committee during the 12th Five-Year Plan (2011–2015), signifying significant technological progress. Jinhua and Zenghua (2017) recapitulated this achievement, which included advancements in intelligent equipment for hydraulic-powered supports, dynamic decision-making, performance coordination, information transfers, and achieving a high level of consistency under challenging conditions.

The mining industry's unique characteristics have garnered considerable attention since they limit the use of automation and sometimes even mechanization in specific processes. Bołoz and Biały (2020) studied the automation and robotization of underground mining in Poland and presented the status of underground mining automation and robotization in Poland through selected examples.

Over the past 30 years, coalfield geology and mine geology IT applications have achieved notable milestones. In Shanjun (2020), the author illuminated the growth of geological and surveying spatial management information systems. Leveraging recent advances in computer and spatial information technologies, this study presented the development trend, system structure, function design, and sub-systems of the next generation of geological and surveying spatial management information systems.

Kexue et al. (2022) deliberated and studied intelligent unmanned mining from the perspective of key technologies and engineering applications, with a focus on 5G + intelligent mines and intelligent equipment. This work introduced the fundamental concepts and features of intelligent unmanned mining and established a research structure with four detailed layers, including basic theory, key technology, mining mode, and overall design system theory and technology.

Guofa et al. (2022) focused on coal's role as China's primary energy source and examined the development of the coal industry. They explored intelligent coal mine development and introduced the "Chinese mode" of intelligent mining in underground coal mines, which employs comprehensive technical equipment to propose classification and grading standards. The authors developed a digital logic model and proposed a method for building information entities and knowledge maps. This entails an active information push strategy based on a knowledge demand model, as well as an intelligent portfolio modeling and distribution method for collaborative coal mine control.

Intelligent applications such as autonomous intelligent mining, human-machine collaborative rapid tunneling, unmanned auxiliary transportation, closed-loop safety control, lean collaborative operation, and intelligent ecology are integrated into the top-level architecture of 5G+ intelligent coal mine systems. These systems incorporate elements such as a dynamic modified geological model, an underground 5G network with positioning technology, intelligent control of mining height and straightness of the longwall working face, and intelligent mining.

In Yuan et al. (2022), an evolutionary algorithm-based approach is employed to establish a fully mechanized mining face in coal mining. This approach eliminates the loading phase of the sixth-order input-output equal-length and unequal-length cavity filter. The coal mining security system proposed by Guhe et al. (2012) utilizes a data acquisition system, communication, automatic detection, and embedded controllers, offering high reliability and accuracy.

Zrelli and Ezzedine (2018) introduced a new technology for monitoring mining operations using wireless sensor networks and optical sensors. They established sensor setups in underground tunnels, and the data were processed by the underground mining monitoring system (UMMS). The architecture also detects changes in humidity, temperature, and strain vibration. Moridi et al. (2018) elucidated a detailed communication scheme and monitoring system for mining tasks using ZigBee technology. They evaluated manageable and unmanageable factors of the network and underground environment for the ZigBee network setup. Experimental results demonstrate reliable functionality and application in mining tasks.

Wu et al. (2019) proposed an IoT-based dynamic information platform for underground coal mining tasks, addressing several problems through subsystems like transmission, analysis, data acquisition, and application. Six functional layers were designed to address these issues, and big data and cloud computing technologies were used for coal mining task analysis. Wang et al. (2019) elaborated on the modern trends in the China Coal Industry 4.0 and analyzed scenarios for China Coal Industry 5.0, providing valuable insights into the transition from coal to clean energy. Hao et al. (2022) proposed an IoT-based ground control system for monitoring coal mining tasks and investigated developments in Non-destructive Testing (NDT) with IoT-based ground control for intelligent mining.

Hao et al. (2022) developed a data mining-based method for dust removal in coal mining, utilizing various sensors and mathematical measures to ensure dust removal and employee health and safety. The construction of coal mining enterprises was accomplished using the Moran process stochastic evolutionary game model, as detailed by Tian et al. (2022), resulting in improved cost-effectiveness of coal mining operations. Zhang et al. (2022) investigated factors influencing mining performance by developing a triangulation method and a fuzzy Bayesian network (FBN) model, providing valuable insights for human error analysis.

Brodny and Tutak (2022) studied the challenges faced by the Polish mining industry and developed a novel model for innovative development and sustainability in the coal mining industry, identifying connections between stakeholders and the coal mining sector. Bai et al. (2022) proposed a method to mitigate water hazard risks in coal mining under the Neogene aquifer, focusing on the utilization of waste heat during coal mining tasks. Jiang et al. (2022) introduced a deep learning-based method called Multiscale Feature Pyramids and Attention Network (MFPA-Net) to detect ground fissures in Unmanned Aerial Vehicles (UAVs). Their

Table 1. Summary of the existing works related to the coal mine task

Author(s)	Approach	Description	Level of Automation	Level of Informatization	System and Application Type	Business model	Limitation
Fedor et al. (2021)	Control system for coal mine based on a digital platform	A two-level architecture is proposed for a coal mine control system that utilizes IoT devices.	Moderate	Low	Single	Single	Lack of effective use of intelligent methods for implementing unmanned mining.
Li et al. (2020)	Intelligent safety system of coal mine	An intelligent method for coal mine tasks is proposed to accurately perceive coal mines, identify risks, enhance safety, and provide early warnings.	Moderate	High	Single	Single	Mining tasks face issues with insufficient business interconnection.
Wang et al. (2022)	Digital Logic Model and 5G+ Intelligent coal mines	Adopted the "Chinese mode" for mining in underground coal mines by utilizing a collection of equipment to establish organizational and grading standards.	Moderate	Moderate	Single	Unified	The development mode of intelligent coal mines and the resource allocation of coal mine enterprises are not addressed.
Zhang et al. (2022)	Sensor-based safety monitoring system for coal mine	A safety monitoring system for coal mining is proposed by making use of three sub-systems such as monitoring, control, and communication.	Low	Low	Single	Single	The focus is solely on safety monitoring.
Han et al. (2012)	Automation of coal mine production system design	Presented a coal mine automation system that includes a mechanized mining face control system, a subversive air waybill belt control system, a main shaft hoist control system, and a ground coal washing system.	Moderate	Low	Single	Single	Mining task faces insufficient business interconnection and this work did not address intelligence in coal mines.
Xueping and Xingquan (2014)	Automation of coal mine using IoT	This work examines and establishes the characteristics and system configuration of a coal mine based on IoT.	Moderate	Moderate	Single	Single	The focus is solely on safety monitoring.
Mandal et al. (2016)	Automation of coal mines using programmable logic controller (PLC)	This work focuses on performing mining operations such as excavation, loading, blasting, and transportation automatically using PLC.	Moderate	Low	Single	Single	The work lacks safety monitoring and does not address the intelligence aspect in coal mines.
Jinhua and Zenghua (2017)	Intelligent Mining Technology for coal mines	This work proposed a model to enable unmanned processes and single-person inspections for mining tasks, significantly reducing the number of miners on the work face.	Moderate	Low	Single	Single	This work primarily focuses on intelligent decision-making for production and does not cover other aspects of mining operations.
Bołoz, Ł, and Biały (2020)	Study on robotization and automation in underground mining	This work investigates several underground mining tasks adopted in Poland and discusses intelligent machines for breaking rocks, research works, and prototypes.	Moderate	Low	Single	Single	This work deals with the automation and robotization of coal mining production process.
Shanjun (2020)	"One Map" online collaborative (2D-GIS) management platform	This work elucidates a modern geological and surveying spatial information management system for coal mine tasks.	Moderate	High	Single	Single	This work discusses the modernization of coal mining management, primarily focusing on production aspects.
Kexue et al. (2022)	Intelligent unmanned mining technology	This work investigates intelligent unmanned mining, considering the relationship between technologies and engineering applications, with a particular emphasis on 5G+ intelligent mines.	Moderate	High	Single	Unified	The degree of intelligence in unmanned mining tasks is relatively low.

research constructed the Ground Fissures of the Coal Mining Area (GFCMA) using UAV images from the coal mining region, and performance analysis showed the superiority of MFPA-Net over existing techniques.

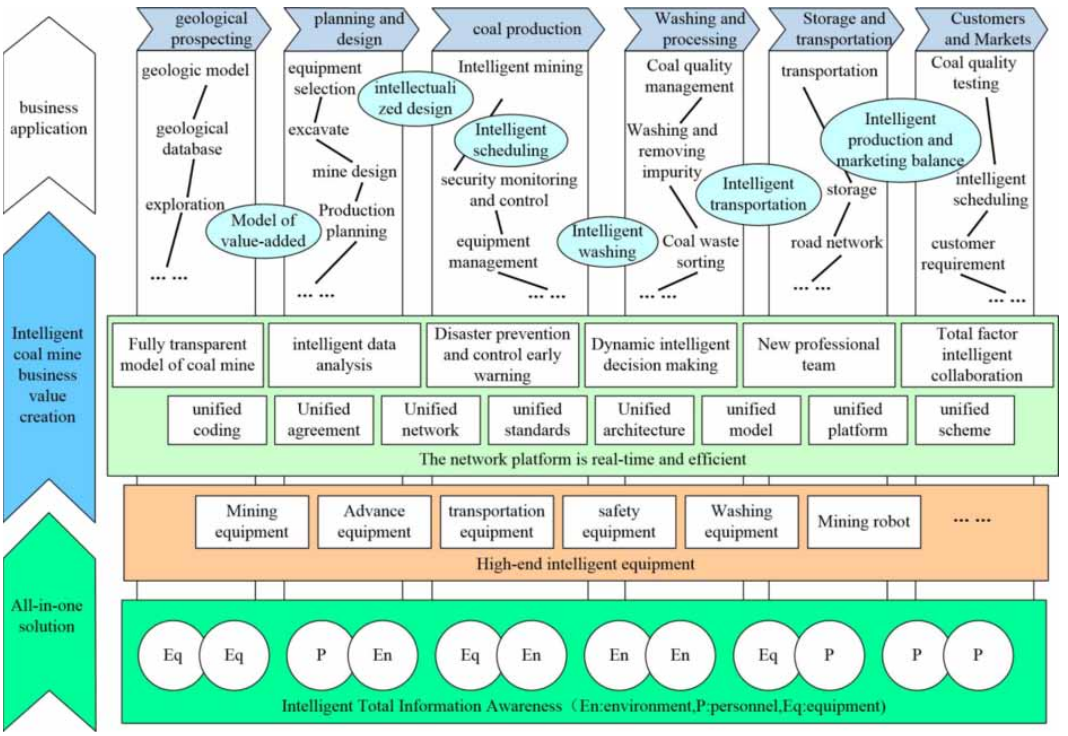
One of the significant hazards in coal mining production is methane. Brodny et al. (2022) presented a new approach for detecting and predicting methane hazards, utilizing a neural-fuzzy model for short-term methane content prediction. Du et al. (2022) introduced a 3D model-based image analysis method for constructing intelligent coal mines. This approach employs image segmentation, image registration, image diffusion, image fusion, and 3D model construction. A swarm intelligence optimization algorithm is used to improve the image registration process.

Analysis of hidden dangers and early warning systems is essential in coal mining operations. Miao et al. (2023) developed a Natural Language Processing (NLP) and Bidirectional-Long Short-Term Memory (Bi-LSTM) method for classifying hidden dangers during coal mining operations. They also proposed a new method for data analysis of a visual screen and information processing for applications.

THE OVERALL GOAL OF THE MINE-WIDE INTEGRATED AUTOMATION MANAGEMENT AND CONTROL PLATFORM

The overall objective of constructing the mine-wide integrated automation management and control platform is to accomplish four unifications at the top-level planning, which include "unified data, a unified model, a unified platform, and a unified plan." Figure 1 illustrates the overall platform architecture diagram, and the individual components of this architecture are discussed below.

Figure 1. Overall platform architecture diagram



Unified Data

This refers to the unification of mine codes, protocols, semantics, networks, and other elements within the management and control platform. The primary objective is to enable heterogeneous applications and intelligent mining systems to 'understand' each other at the data level, facilitating data interoperability and information integration. To achieve this, a unified protocol is adopted as the foundation. An industrial Internet information model description paradigm is employed, establishing a specification for the semantic model of the mine information system. This leads to the establishment of a unified data standard, providing the necessary technical support for interaction and collaboration among various intelligent mine application systems.

Unified Model

This is the fundamental approach to achieving information fusion and system coordination in the development of intelligent mines. It enables the digital representation of mining resources, the environment, and mining engineering objects, leading to the digital reconstruction of the entire life cycle of mine business processes. It facilitates information sharing and collaborative work, effectively addressing industry-wide challenges. This model helps resolve the issue of information isolation in the mining sector, promotes information interconnectivity among various business entities, and enhances the efficiency and quality of mining resource management.

Unified Platform

This platform is utilized to establish an industrial Internet platform for intelligent mines. It forms a comprehensive solution package that encompasses the entire ecological landscape of the mine, empowering the creation of integrated solutions for intelligent mining. The intelligent system and platform will transition from the traditional "single application" approach to a "cloud, edge, terminal" three-layer architecture based on the industrial Internet platform architecture. This industrial Internet platform will reconfigure the development mode and deployment method of the original business system, gradually achieving the seamless integration of the mine information system and business processes.

Unified Plan

Centered on integrated comprehensive solutions, a collaborative service model is established with mines as the focal point, aiming to assist mines in achieving the maximum return on investment value. Built upon four unified standard systems, the intelligent mine industrial Internet platform develops a unified data access platform, establishes a unified data center, offers a unified application development platform, and provides a unified application deployment platform. To deliver on-demand services for various business systems, the core components include intelligent comprehensive management, a control platform, and a data center. Within the context of coal mine safety production, the objective is to create a closed-loop system encompassing state perception, real-time analysis, scientific decision-making, and precise execution.

By employing a unified data access platform and utilizing data extraction, transformation, and loading processes in conjunction with a data lake, unified querying, and computing engines, we achieve the seamless integration of multi-source and heterogeneous data from various business subsystems. Grounded in data governance theory and technology, which ensures data quality from the source, we transform data into valuable assets. Furthermore, we construct visual and intelligent analysis platforms and services, leveraging machine learning and data analysis technologies.

Through the unified data access platform and the data middle platform, we facilitate the downward access of various perception data, eliminate information silos, and establish robust big data analysis capabilities. The development and deployment of these capabilities provide mining enterprises with flexible resource management and allocation options. The platform ensures network security, is

Figure 2. The framework of mine-wide integrated automation management and control platform

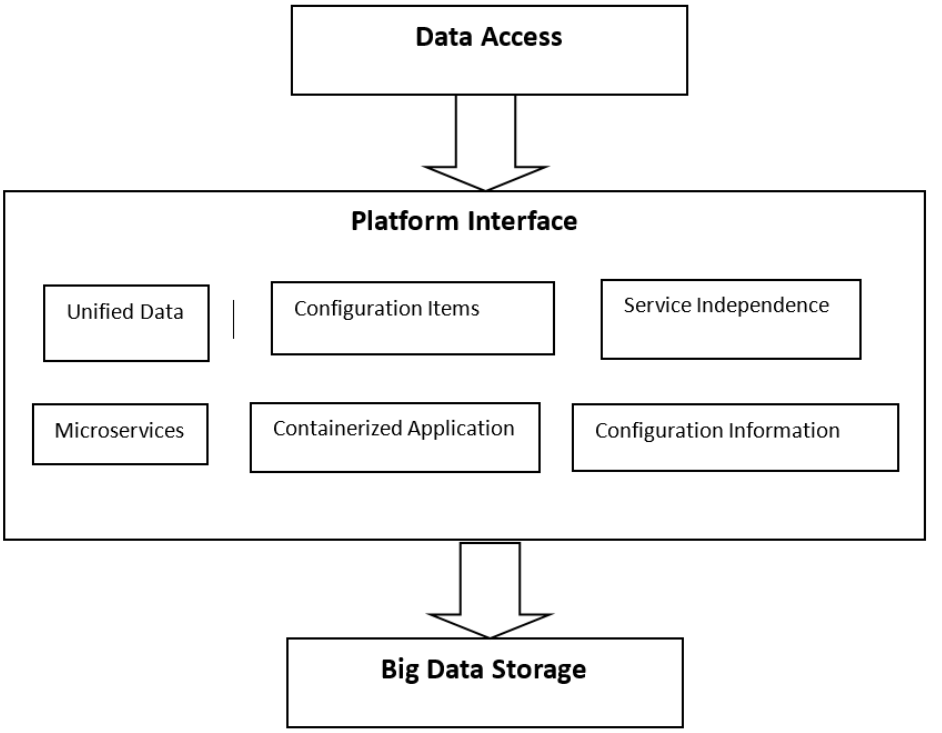
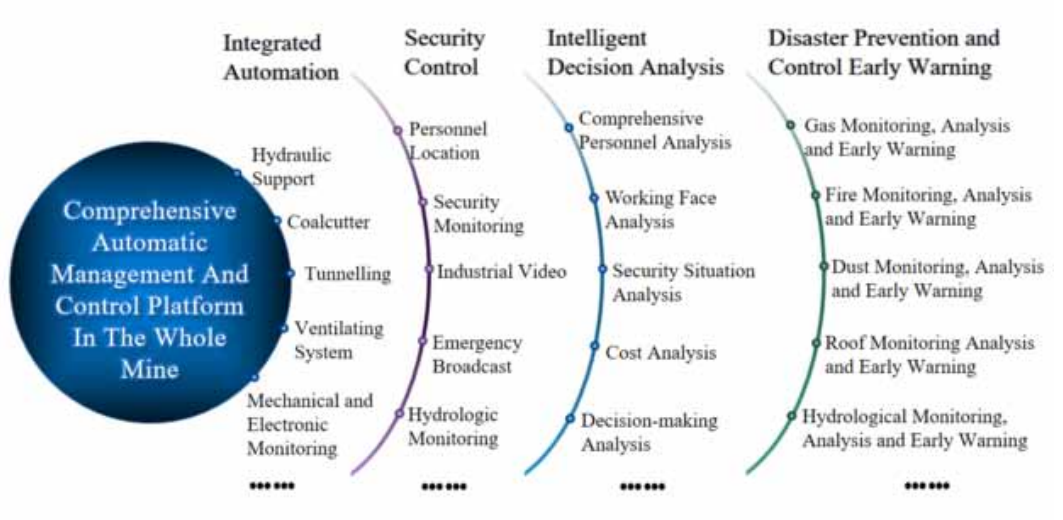


Figure 3. Platform function diagram



supported by the data platform, and encompasses key business modules such as geological assurance, mining systems, auxiliary production systems, mine safety, and intelligent construction. These modules collectively enable the comprehensive perception of all elements and processes within the

mine, facilitating real-time interconnection, analysis, decision-making, autonomous learning, dynamic prediction, and collaborative control.

OVERALL FRAMEWORK OF THE MINE-WIDE INTEGRATED AUTOMATION MANAGEMENT AND CONTROL PLATFORM

Figure 2 illustrates the framework of the mine-wide integrated automation management and control platform. This framework comprises three layers: data access design, platform interface design, and the big data storage center. Each of these layers will be elaborated in detail.

Data Access Design

Adhering to national and industry-related standards for infrastructure, data resources, communication networks, and more, and using a unified architecture, unified standards, unified certification, and a unified operation and maintenance system, we establish intelligent mine data and application standards. These standards encompass the standardization of data exchange and transmission, thus achieving standardized mine data collection and effective sharing of platform information. We design a unified data gateway interface according to the standardized access method for intelligent mines, enabling the normalization, standardization, and comprehensive coverage of data access. Integrated embedded equipment serves as the unified interface gateway, effectively separating data collection from business logic. This equipment operates independently of other platforms.

Big Data Storage Center

Taking into account the characteristics of multi-source heterogeneous data within the industry, we have developed hybrid data storage technical solutions to establish a data pool capable of supporting the storage of time series data, structured data, and audio and video files. We have created a big data-level mine, incorporating a data governance system built on data governance theories and technologies. This system transforms data into valuable assets and offers data asset-sharing services, fostering data interconnection. Through big data modeling, data analysis, and visualization technologies, we have constructed a visual data analysis platform. This platform effectively eliminates information silos and enhances our big data analysis and service capabilities.

Platform Interface Design

1. For existing applications or application systems developed in traditional ways, containerized applications are better, and the design process is explored as follows:
    - Unified persistent data: Store all output data in the same directory. This facilitates containerized version deployment and ensures data retention between containers.
    - Environment-related configuration items: Identify and manage configuration items related to the environment. Reset configuration values each time the container is started to adapt to different environments.
    - Service independence: If an application relies on other services, ensure these services are highly independent and easy to migrate.
2. For newly developed application design, the design process is explored as follows:
    - Microservices framework: Divide applications into functional components using a microservices framework. These components should be independent and capable of using familiar frameworks.
    - Containerized application: Encapsulate applications within containers to isolate them from the runtime environment. This allows for easy application mobility across different environments while preserving functionality and scalability.

- Data and application separation: If a service component requires persistent data storage, specify separate directory storage for data, keeping it distinct from the application logic.
- Configuration information is stored in environment variables: Simplify service configuration by defining commonly used configurations as environment variables. Adjust these variables for personalized configuration when deploying in different environments.

FUNCTIONAL DESIGN OF THE MINE-WIDE INTEGRATED AUTOMATIC MANAGEMENT AND CONTROL PLATFORM

This section explores the proposed functional design of the mine-wide integrated automatic management and control platform and its components. Figure 3 provides a visual representation of the platform's functions.

Subsystem Configuration Access

Each screen in the system can display real-time data for process variables and the operational status of equipment. These data and statuses are updated in real time. The displayed colors or graphics vary based on the process status. Bar graphs and trend graphs can be shown on any part of the screen. Images of production equipment, process flowcharts, equipment diagrams, single-line diagrams, and more can all be displayed on the terminal. Each screen can include alphanumeric characters and graphic symbols. Typically, variable colors, graphics, and flashing are used to represent process variables. Different states and values of all process variables can be dynamically refreshed. Operators can manipulate and adjust relevant process variables on this screen. Function keys and soft switches can be placed anywhere on the screen, allowing for cursor-based operation of various processes. All process points can be displayed, including analog inputs, analog outputs, digital inputs, digital outputs, intermediate variables, and calculated values.

Access Method

In mine production sites, there are numerous commonly used automation systems and monitoring subsystems, often provided by different manufacturers. Based on the technical characteristics of each subsystem, the mine-wide integrated automation management and control platform typically employs three access methods: the upper computer access method, the PLC access method, and the embedded controller access method.

Data Exchange Method

Real-time and dynamic data interaction is one of the basic functions of the coal mine integrated automation system. Currently, there are several standard data-driven interaction methods. Supported by data interface standard protocols and specifications built on the physical link layer, there are several typical data interaction methods in use, including the OPC method, the DDE/NetDDE method, the ODBC method, and the FTP file method.

Subsystem Access Scheme

The establishment of a comprehensive coal mine automation system requires the system's software and hardware platform, as well as various professional subsystems, to engage in reliable, real-time, and efficient information exchange. To achieve this, two conditions must be met. Firstly, it is essential to establish the physical link connections between the subsystem equipment and the data collection server, defining the content and format of the interactive information. Simultaneously, a range of flexible, standard, and robust data interaction methods should be made available.

Regarding physical link connections, the system should support various access methods with lower entry thresholds to enable the seamless integration of automation subsystems from

different technologies and manufacturers. This approach ensures that both existing systems and those developed in the foreseeable future can choose access methods that are suitable and easy to implement.

Configure Real-Time Monitoring

For subsystems that require remote monitoring, real-time configuration screen monitoring is provided. The graphics also support a partial zoom function. The system allows for the definition of fault conditions. When any piece of system equipment experiences a fault condition, an alarm window will promptly appear in real time. This alarm window requires manual confirmation before it can be closed. Additionally, the system integrates with the industrial video and alarm system, enabling users to access remote video feeds.

The comprehensive automation management and control platform can be directly published as a web page. It utilizes the latest HTML5 technology, provides cross-platform support, and can run on Android, Linux, and other systems. This platform realizes real-time data monitoring of key production scenarios and offers animated displays of equipment operations. It aims to provide users with a seamless and scalable operating experience.

Remote Control Function

For equipment with remote control capabilities, authorized personnel can remotely initiate and stop the equipment through the management and control platform using interfaces and communication protocols. Using the management authority within the platform software, control commands can be transmitted to the relevant automation system. Based on the pre-defined control logic, this enables remote centralized control of mining production equipment, allowing for unattended operation under specific conditions.

Statistical Query Analysis

This function is employed to summarize production information into reports on the automation platform. The mine production equipment monitors real-time operating parameters and economic performance indicators, presenting the results through flowcharts, trend charts, bar charts, and tables. This allows operators and managers to have a comprehensive understanding of the entire mine subsystem's performance. Automatic data statistics are performed based on various conditions, such as equipment type, alarm type, and fault type. This automatic data analysis generates various styles of reports and charts, including columnar, pie-shaped, and curve graphs. These reports and charts aid the management center in conducting statistical analyses of diverse data.

Intelligent Alarm Analysis

When a fault or alarm is triggered within the system, an automatic fault display window or alarm bar will appear. The system categorizes alarms based on user-defined severity levels, providing a hierarchy of alarms. Beyond the typical text and voice alarms for equipment start/stop and various parameters, the system employs a hierarchical warning and alarm system, ranging from low to high priority, to assist in production scheduling and decision-making.

The system also automatically counts the number of alarm faults for yesterday, today, and the current period. Users can click to view relevant information, including accident location and cause. Historical alarms or faults can be queried and categorized by subsystems, types, severity levels, and dates. Additional features include voice alarms, real-time fault displays, and printing functions.

The system establishes a hierarchical priority structure, classifies deliveries, and integrates intelligent linkage alarm mechanisms based on accident or hazard levels, categories, and response methods. It creates a unified database for managing data collected by each system. Early warning messages offer options for dead zones, delays, and alarm suppression to prevent redundant alarms

within a specified period and to suppress unnecessary alarms during communication interruptions, maintenance, and testing.

In addition to the conventional text and voice alarms for equipment operations and parameters, the system employs a hierarchical early warning and alarm system, providing support for production scheduling and command decisions.

The monitoring center can issue alarms simultaneously based on relevant measured values and display the related systems and equipment visually. Intelligent alarm features include:

1. Guiding personnel in hazardous areas to safety using personnel positioning information;
2. Triggering alarms for exceedance of standards, such as harmful gas levels, prolonged underground time, high water levels, low water pressure, and excessive temperatures;
3. Providing alarms for extended stays or entry into dangerous areas, sent to underground personnel through positioning cards or communication equipment;
4. Identifying false alarms by evaluating alarm content and cross-referencing with real-time systems, such as personnel positioning; and
5. Collaborative alarms that allow for querying related measurement values and obtaining real-time analysis data by clicking on alarm information.

System Extension Function

The comprehensive automation management and control platform collects data from each subsystem through standardized data interfaces, ensuring the accuracy and real-time nature of the collected data. Both the hardware and software components have sufficient capacity, making expansion convenient and meeting the future construction requirements of the mine. The system platform is constructed on an open foundation, making it easier for other subsystems to integrate at later stages.

EVALUATION

In this section, we provide a comprehensive evaluation of the proposed mine-wide integrated automation management and control platform. The evaluation encompasses various aspects, including its functionality, performance, scalability, and potential impact on the coal mining industry. This is illustrated in Figure 4.

FUNCTIONALITY ASSESSMENT

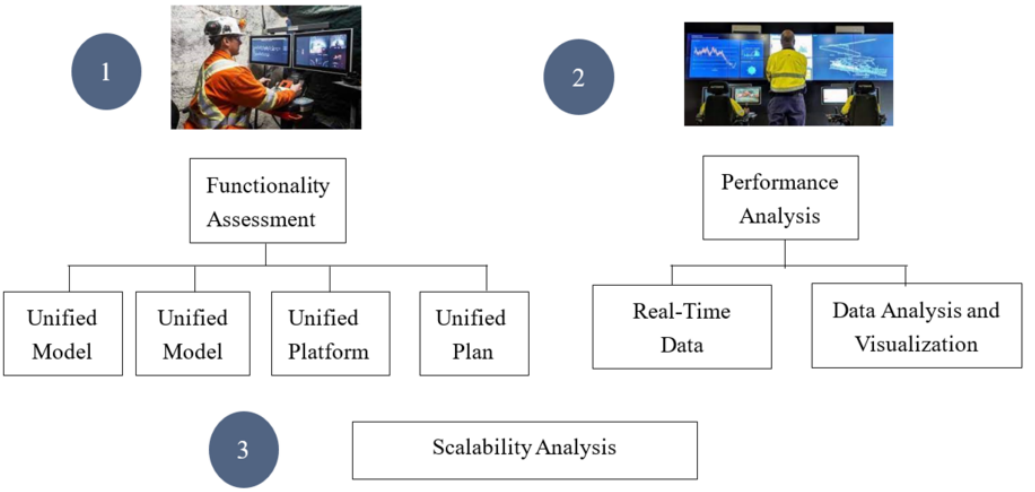
Unified Data

The unification of mine codes, protocols, semantics, and networks within the management and control platform is a significant achievement. Our evaluation demonstrates that this unified data approach successfully allows for seamless data interoperability and integration across intelligent mining applications. Data exchange between heterogeneous systems and applications is achieved, marking a substantial improvement in data accessibility and utilization.

Unified Model

The establishment of a unified model for the digital representation of mining resources and business processes proves to be highly effective. The evaluation reveals that this model successfully addresses the problem of information islands, enabling efficient information interconnection and improving the overall quality of mining resource management.

Figure 4. Flow of experimental evaluation



Unified Platform

The transition from a traditional "single application" approach to a cloud-based, three-layer architecture demonstrates notable progress. Through our assessment, it is evident that this unified platform offers comprehensive solution service capabilities for various mining scenarios. The platform's adaptability and scalability allow for the construction of integrated solutions tailored to the needs of intelligent mines.

Unified Plan

The collaborative service model centered on mines, based on four unified standard systems, is a valuable contribution. It facilitates on-demand services for different business systems, emphasizing intelligent comprehensive management, control, and data analysis. Our evaluation confirms the effectiveness of this approach in optimizing coal mine safety production processes.

PERFORMANCE ANALYSIS

Real-Time Data Integration

One of the critical aspects of the platform's performance is its real-time data integration capabilities. The evaluation demonstrates that the platform successfully integrates and processes data from various business subsystems. The use of a data lake and data governance techniques ensures the quality and reliability of integrated data.

Data Analysis and Visualization

The platform's data analysis and visualization tools, based on machine learning and data analysis technologies, are evaluated positively. They provide valuable insights for decision-makers by enabling dynamic prediction, collaborative control, and autonomous learning. The platform's support for machine learning contributes to enhanced data-driven decision-making.

Scalability

The platform's architecture and design demonstrate scalability, accommodating both current and future needs. The platform allows for the flexible expansion of resources and integration of additional subsystems, ensuring its sustainability and technological advancement.

Practical Managerial Significance (PMS) and Application

In this section, the practical managerial significance of the mine-wide integrated automation management and control platform is investigated by elucidating how this technology can be applied in real-world mining operations. The tangible benefits of the platform for mine managers, operators, and stakeholders are highlighted, showcasing the platform's potential to revolutionize coal mining management.

Enhanced Decision-Making

The primary practical managerial significance of our platform lies in its capacity to empower decision-makers within coal mines. By providing real-time data and comprehensive insights into mining operations, the platform equips managers with the information necessary to make informed decisions.

SCENARIO ANALYSIS

Mine managers can use the platform to conduct scenario analysis. They can simulate various production scenarios, adjust parameters, and evaluate potential outcomes. For example, they can assess the impact of altering drilling techniques, resource allocation, or equipment maintenance schedules. This capability facilitates proactive decision-making based on data-driven insights.

RESOURCE ALLOCATION OPTIMIZATION

Effective resource allocation is essential to mine management. The platform enables managers to optimize resource allocation based on real-time data. This includes personnel deployment, equipment utilization, and material distribution. By identifying bottlenecks and underutilized assets, managers can ensure efficient resource utilization, reducing operational costs and enhancing profitability.

SAFETY AND COMPLIANCE

The practical managerial significance of the platform extends to safety and compliance management. The coal mining industry is subject to stringent safety regulations, and compliance is paramount to avoid fines and accidents.

Safety Monitoring and Enforcement

Mine managers can use the platform to monitor safety compliance in real-time. Sensors can detect safety violations such as unauthorized personnel in restricted areas or equipment operating beyond safety thresholds. Immediate alerts and automated responses ensure that safety protocols are rigorously enforced.

Regulatory Compliance Reporting

Compliance with regulatory standards is streamlined through automated reporting. The platform generates comprehensive reports on safety measures, emissions, and operational practices. These reports can be submitted to regulatory authorities to demonstrate adherence to environmental and safety regulations.

OPERATIONAL EFFICIENCY

Efficiency is the essence of any successful mining operation. The platform offers practical managerial significance by optimizing operational efficiency in several key ways.

PREDICTIVE MAINTENANCE

Equipment downtime is a significant cost factor in mining. The platform's predictive maintenance capabilities allow managers to schedule maintenance proactively. By identifying equipment issues before they lead to failures, managers in mines can minimize downtime, reduce maintenance costs, and maximize equipment lifespan.

REAL-TIME PERFORMANCE MONITORING

Real-time performance monitoring ensures that mining operations are continually optimized. Managers can track equipment performance, material flow, and energy consumption in real-time. Any deviations from optimal performance trigger immediate responses, preserving operational efficiency.

STAKEHOLDER ENGAGEMENT

Effective stakeholder engagement is essential for the success of any mining project. The platform enhances stakeholder communication and collaboration.

TRANSPARENT REPORTING

The platform facilitates transparent reporting to stakeholders, including investors, regulators, and local communities. Access to real-time data and performance metrics fosters trust and demonstrates a commitment to responsible mining practices.

COLLABORATIVE DECISION-MAKING

Stakeholders can actively participate in decision-making through the platform. They can access relevant data, participate in scenario analysis, and provide input on operational strategies. This collaborative approach enhances stakeholder satisfaction and minimizes conflicts.

SCALABILITY AND FUTURE-PROOFING

Another critical aspect of the platform's practical managerial significance is its scalability and future-proofing. Mines are dynamic environments, and the platform is designed to adapt to evolving needs.

Scalability

The platform can accommodate the growth of mining operations. As mines expand or new sites are developed, additional sensors, equipment, and data sources can be seamlessly integrated into the platform. This scalability ensures that the platform remains effective in both small-scale and large-scale mining operations.

Future-Proofing

The platform's architecture is designed for future technologies. It can incorporate emerging technologies such as artificial intelligence, advanced robotics, and renewable energy integration.

This future-proofing ensures that mines remain competitive and sustainable in an ever-changing industry landscape.

SCENARIO-BASED AND PRACTICAL APPLICATION

A scenario-based and practical application of the mine-wide integrated automation management and control platform can provide a clearer understanding of its real-world benefits. Below, a scenario to illustrate how this platform could be applied is outlined:

Scenario: Real-Time Safety Monitoring and Emergency Response

In a coal mining operation, ensuring the safety of workers and mitigating potential disasters is of paramount importance. The unified automatic management and control platform can be applied in a scenario focused on real-time safety monitoring and emergency response.

Key Components and Functionality

- Sensor Network: Deploy a network of sensors throughout the mine to monitor crucial parameters such as gas concentrations (e.g. methane levels), temperature, humidity, air quality, and equipment status. These sensors continuously collect data in real time.
- Data Integration: The platform integrates data from various sensors into a unified data stream. It uses standardized protocols to ensure data consistency and compatibility.
- Unified Control Center: This platform is used to establish a centralized control center equipped with the platform. This control center acts as the nerve center for monitoring and managing safety in the mine.
- Continuous Monitoring: The platform continuously monitors sensor data in real time. For instance, if methane levels exceed safety thresholds, the system detects this immediately.
- Early Warning System: Implement an early warning system that triggers alarms and alerts relevant personnel and stakeholders when unsafe conditions are detected. These warnings can be in the form of visual indicators, audible alarms, or automated notifications to mobile devices.
- Emergency Response Protocols: Define automated emergency response protocols within the platform. For example, in the event of a sudden increase in methane levels, the system can trigger the shutdown of specific mining equipment, initiate ventilation adjustments, and activate emergency evacuation procedures.
- Communication: The platform includes robust communication capabilities, enabling seamless communication between underground workers, supervisors, and the surface control center. Two-way communication allows for immediate response to emergencies.

Practical Application

Imagine a coal mining operation deep underground where miners are working in different sections of the mine. Suddenly, one of the methane sensors detects a dangerous increase in methane levels in a specific area. The following elements demonstrate how the unified platform practically applies in this scenario:

- Real-time Detection: The sensors in a platform detect the elevated methane levels immediately.
- Early Warning: Alarms and alerts are triggered both underground and at the control center. Miners in the affected area receive immediate alerts on their wearable devices, while the control center is notified simultaneously.

- Emergency Response: The platform automatically initiates predefined emergency response protocols. This includes shutting down equipment in the affected area to prevent sparks, adjusting ventilation to disperse the gas, and activating evacuation signals.
- Communication: Miners in the affected zone receive real-time communication instructions on their devices, directing them to evacuate to a designated safe zone.
- Control Center Oversight: The control center has a real-time visual representation of the mine's layout, showing the affected area and the locations of all miners. They can monitor the evacuation progress and guide as needed.
- Data Logging: Throughout the incident, the platform logs all data, including sensor readings, emergency response actions, and communication logs.
- Post-Incident Analysis: After the incident is resolved, the platform supports post-incident analysis. The data collected during the emergency can be used to identify the root cause, assess the effectiveness of the response, and make improvements to prevent similar incidents in the future.

This scenario demonstrates how the unified automatic management and control platform enhances safety in coal mining by providing real-time monitoring, immediate alerts, automated emergency responses, and effective communication, ultimately protecting the lives of miners and preventing disasters.

DISCUSSION

The proposed unified automatic management and control platform for coal mining holds huge potential for the coal mining industry. Its practical implications encompass safety enhancement, operational efficiency, data-driven decision-making, improved communication, scalability, cost-effective solutions, and alignment with the evolving mining landscape. As coal mining organizations continue to face challenges and seek ways to improve their operations, this platform stands as a valuable tool for achieving these goals. This section explores the significance of this study's findings, its implications for the coal mining industry, and potential future directions for this technology.

Significance of the Platform

The development and implementation of the mine-wide integrated automation management and control platform represent a pivotal step towards realizing a safer, more efficient, and technologically advanced coal mining industry. The unification of data, models, platforms, and plans lays the groundwork for holistic automation and informatization in mines. This achievement not only addresses the existing challenges in coal mining but also positions the industry for sustainable growth and innovation.

Implications for the Coal Mining Industry

Safety Enhancement

One of the paramount implications of the proposed platform is the substantial improvement in safety within coal mines. The real-time monitoring, intelligent alarms, and remote control functionalities of the platform contribute significantly to accident prevention and rapid response. By reducing the incidence of equipment failures and hazardous conditions, the platform safeguards the well-being of miners and minimizes potential production disruptions.

Production Efficiency

The proposed research demonstrates that the platform has a profound impact on production efficiency. The ability to monitor, analyze, and optimize various aspects of mining operations translates into reduced downtime, enhanced resource allocation, and ultimately increased production

output. The platform permits mine managers to make data-driven decisions that maximize efficiency and profitability.

Technological Advancement

By integrating emerging technologies such as the Internet of Things, big data, and intelligent control, the proposed platform drives the coal mining industry into the digital age. The adoption of a three-layer architecture, including cloud, edge, and terminal components, represents a significant leap in modernizing mine management systems. This technological advancement not only improves current operations but also positions coal mines for future innovation and competitiveness.

Future Directions

While our research has made substantial progress in the field of intelligent coal mining, several avenues for future exploration and development exist.

Resource Allocation

Efficient resource allocation remains a critical challenge in coal mining. Future research should focus on advanced algorithms and models for optimizing resource distribution, minimizing waste, and maximizing productivity.

Ecological Environment

As the coal mining industry evolves, a greater emphasis on environmental sustainability is imperative. Future efforts should address how intelligent mining can coexist with ecological conservation, minimizing its ecological footprint and contributing to cleaner, greener mining practices.

IoT Data Security

With the increasing reliance on the Internet of Things for data collection, securing IoT data becomes paramount. Future work should explore robust data security measures to protect sensitive information gathered from connected devices.

CONCLUSION

The overall level of intelligent construction in coal mines is currently in its initial stage. The intelligence level of each production link is relatively low, the intelligent control platform is immature, the development and application of massive multi-source heterogeneous data is insufficient, the use of robots has not yet been popularized, and there is still significant potential for development in intelligent construction.

The intelligent mine comprehensive management and control platform is based on the intelligent mine fundamental information platform. The whole mine's comprehensive automatic management and control platform facilitates the aggregation, management, storage, and analysis of various safety, production, and operational data from the mine, empowering upper-level safety, production, and operational management business applications.

This work adopts a unified plan for the overall construction, employing unified data and a unified model to develop a comprehensive automatic management and control platform for the entire mine. This approach realizes the development and management of various business application centers, meeting the application needs for intelligent comprehensive management and control in mines and achieving the integration of business management and control. It promotes the construction of the safety production management system with "horizontal coordination and vertical connection" in mines, which plays a positive role in optimizing coal mine organizational structures and labor production organization and achieving unmanned and less labor-intensive operations in fixed places.

The platform reduces the cost of overall development and deployment, subsequent operation, and iterative upgrades, ensuring the sustainability and technological advancement of intelligent construction in coal mines. However, this work does not address the optimal allocation of resources in coal mining organizations or the establishment of an ecological environment for intelligent coal mining. It also does not address the security of sensor data gathered by the IoT. In the future, efforts will focus on resource allocation, creating an ecological environment, and enhancing IoT security for intelligent coal mining. Additionally, there will be an effort to propose 3D modeling for intelligent mining to perform target detection and production monitoring.

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