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XU LIU[1,2*], KAI ZHAN[2], YUAN SHENG ZHANG[2]

RESEARCH AND APPLICATION OF MULTI-EQUIPMENT AUTONOMOUS MINING SYSTEM IN THE DEEP OF SANSHANDAO GOLD MINE

This paper presents a comprehensive study on the development and implementation of an unmanned mining system for deep underground metal mines, focusing on the Sanshandao Gold Mine as a case study. The research addresses the challenges associated with mining in deep, challenging environments characterized by high temperatures and humidity. To address these challenges, the paper explores the theoretical foundations and key technologies of intelligent mining, aiming to minimize the underground workforce while ensuring safe and efficient operations. An unmanned mining system is designed, comprising four layers: comprehensive control, remote centralized control, mobile control center, and intelligent operation. The system integrates smart equipment, autonomous vehicle management, multi-equipment coordination, and real-time production optimization. Technologies such as image recognition, automatic control, and LiDAR are utilized in the remote control systems for rock drilling trolley, scrapers, and fixed rockbreakers. A multimodal integration network, including a fiber optic ring network, fixed wireless base stations, and WiFi base station coverage, ensures comprehensive and redundant communication services. A production and operation scheduling system is developed to provide remote control, real-time monitoring, and job statistical analysis, enhancing scheduling efficiency and production stability. The application of these innovations at the Sanshandao Gold Mine demonstrates their practical feasibility and potential to transform mining technology towards greater informatization, digitization, and intelligence. However, the study reveals that unmanned multi-equipment collaboration still lags behind manned or remotely controlled operations, with an efficiency rate of 61%. Ongoing research and development are needed to improve autonomous capabilities, enhance communication systems, and optimize system workflows to bridge this efficiency gap and promote the widespread adoption of intelligent mining technologies in the industry.

Keywords: Intelligent mining technologies; Multi-equipment management; Unmanned mining equipment; Real-time production scheduling

1 UNIVERSITY OF SCIENCE AND TECHNOLOGY BEIJING, CHINA
2 BBGRIMM TECHNOLOGY GROUP, CHINA

* Corresponding author: liuxu@bgrimm.com

1. Introduction

The number of mines involved in deep mining activities is steadily increasing both at home and abroad, with mining depths also rising consistently. Many domestic deep mines are situated in challenging conditions characterized by high temperatures and humidity. However, a significant number of deep metal mining operations lag in terms of automation and technological advancement, requiring a large workforce. This reliance on manual labor has resulted in insufficient protection for essential domestic strategic resources and an overdependence on the global market, which presents serious risks to the stable growth of the national economy and security [1].

In recent years, as superficial resources have been nearly depleted, the extraction of subsurface resources at depths ranging from –1000 to –1500 meters has become essential for advancing gold mining in Shandong Province. This represents a significant challenge to the development of metallic mineral resources in China. The endeavor to explore deep resources is beset with substantial difficulties, such as extreme mining conditions, increased safety risks, intensified labor demands underground, reduced operational efficiency, and escalating production expenditures. Therefore, the research and deployment of advanced intelligent mining technologies and equipment for subterranean metallic mines, aimed at minimizing underground workforce requirements and ensuring safe operational practices, has emerged as the foremost objective in addressing the complexities of secure and efficient deep resource extraction [2-3].

Utilizing the Sanshandao Gold Mine as a case study, this research comprehensively investigates the theoretical underpinnings and essential technologies associated with intelligent mining in underground metal extraction. It focuses on advanced intelligent mining apparatus, autonomous vehicle operation, and optimized production scheduling. The investigation successfully addresses critical technologies vital for intelligent mining in deep subterranean metal mines, including smart equipment, autonomous vehicle management, multi-equipment coordination, and real-time production optimization. Furthermore, it tackles significant technical hurdles such as high-precision localization and intelligent navigation for mobile units, pervasive data acquisition, and high-bandwidth, reliable wireless communication. These innovations have led to the development of a robust theoretical and technical framework for intelligent mining of deeply embedded metallic mineral resources in coastal regions. The effective application of these groundbreaking innovations at the Sanshandao Gold Mine underscores its crucial contribution to the evolution of mining technologies in China towards greater informatization, digitization, and intelligence. Additionally, it serves as a noteworthy model for sustainable, intelligent, safe, and efficient mining methodologies for solid mineral resources nationwide [4-6].

2. Design Framework for Unmanned Mining Demonstration Sites

The unmanned operational system in Sanshandao Gold Mine's –645 middle section achieves seamless coordination among three core automated components: rock drilling trolleys, intelligent scraper systems, and stationary rockbreakers. At the –630 level, these drilling trolleys demonstrate particularly efficient performance in completing tunneling operations. Once blasting has occurred and the ore has fallen, the intelligent scraper transformation, located in the –645 middle section, scoops up the ore from the mine room and transports it to the 10# ore pass position. In the event that large chunks of ore obstruct the sluice separating screen, the the fixed rockbreakersystem automatically detects these obstructions and efficiently clears them away. The synchronized operation of these three process equipment – rock drilling trolley, the intelligent scraper transformation, and the fixed rockbreakersystem – forms the intelligent "rock drilling-shoveling-crushing" operational process.The system architecture for this unmanned mining demonstration project is illustrated in Fig. 1.

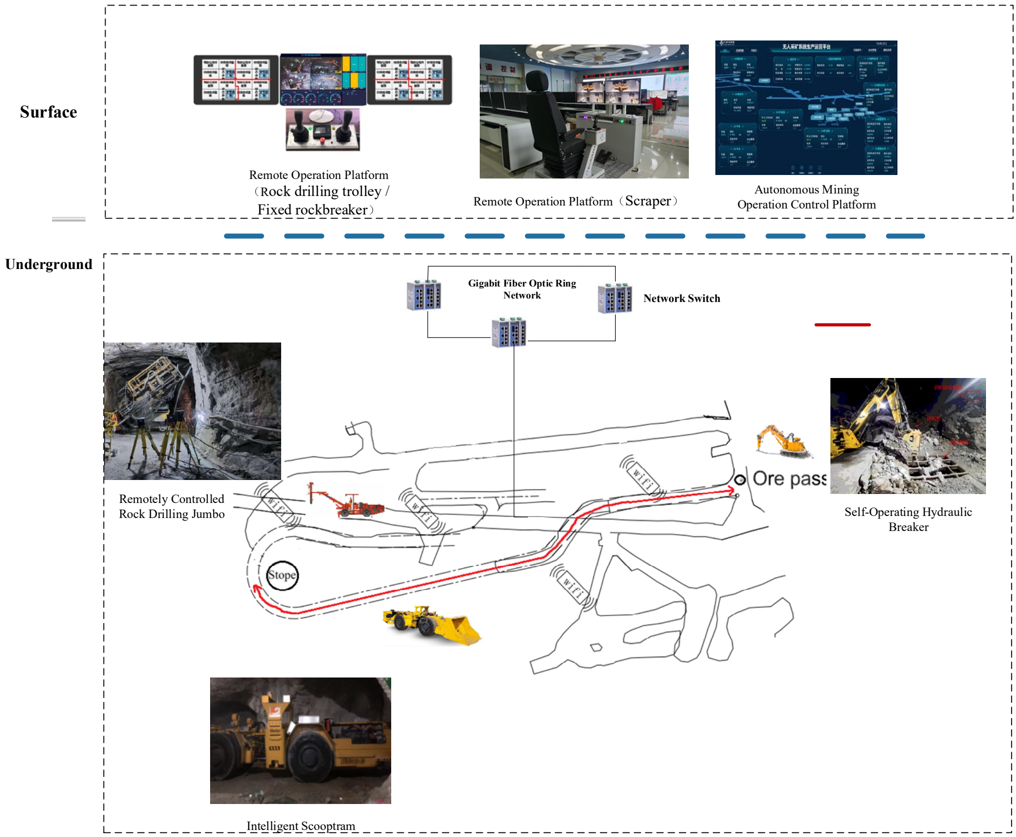

Fig. 1. System Architecture for an Unmanned Mining Demonstration Project

2.1. Continuous Mining Scheme Design

The unmanned mining site of the Sanshandao Gold Mine is located in the southwestern wing of the XinShan Mining Area at levels –630 m to –645 m, with the exploration lines between 1440 and 1520. The unmanned mining site at –645 m uses a downward medium-deep hole drop mining method followed by backfilling [7-8].

The drilling level is located at –630 m, and a fan-shaped hole is drilled in the excavation tunnel. The mining level is situated at –645 m. A flat-bottomed structure of the loader is used for ore extraction at the end.

Main Mining Procedures:

(1) Drilling and Blasting:
The mining operation involves downward fan-shaped deep hole drilling for ore drop, requiring a drilling rig and an explosives loading vehicle.

(2) Ventilation in the Workface:
Forced ventilation is implemented using a local fan system. The local fan connects the ventilation shaft at –615 m to the –630 m level. Fresh air flows into the –630 m level from the –615 m level, creating a system of air intake through the ventilation shaft and return airflow through the decline.

(3) Inspection of Loose Rock:
After the smoke from blasting is cleared, a rock pick-up vehicle is used to inspect and remove loose rock.

(4) Support:
After the inspection of the roof is completed, support is provided using a Mercary-B type bolt rig.

(5) Ore Extraction:
The modified Atlas ST3.5 loader is used for ore extraction in the lower drilling area. For ore blocks larger than 1 m^3, a mobile rock breaker crushes them on site, or they are concentrated and crushed at the mining site or a designated location. For ore blocks smaller than 1 m^3, they are transported to the #10 ore chute, where they are crushed by a remotely operated fixed rock breaker before entering the chute.

(6) Backfilling the Workface:
Backfilling operations commence immediately after the workface is completed.

2.2. The scheduling module for unmanned mining equipment

The medium-deep hole blasting process in ore extraction involves four distinct stages: rock drilling, explosive charging, ventilation, and ore extraction. These stages are supported by corresponding unmanned mining equipment, namely an unmanned rock drilling trolley, an unmanned charging vehicle, and an unmanned scraper. To meet the production capacity requirements of mines, unmanned mining operations require the concurrent deployment of multiple types and units of equipment across various mining sites.

2.3. Construction of a scheduling module for unmanned mining equipment

A multi-equipment scheduling model based on time windows translates the real-world challenge of managing unmanned mining operations across a mining area into a mathematical framework for resolution. This model addresses the scheduling of various types and sets of unmanned mining equipment operating in parallel at multiple mining sites. It is built upon the complexities of cross-sequential task operations within the mining process, factoring in both the operational duration of mining tasks and the production capabilities of the unmanned equipment.

3. Design of a Four-Tiered Approach for Intelligent Production and Operations

To fulfill the operational needs for stripping and ore transportation in the –645 m middle section, and to establish a showcase for underground unmanned mining operations, we plan to deploy an intelligent stripping trolley, an intelligent mining cart, and a mobile control center within the –645 m middle section. This deployment will form an integrated intelligent operation system encompassing rock drilling rigs, scrapers, fixed crushers, an augmented reality centralized control system for intelligent equipment, and a comprehensive control platform for mining production and operations [9].

The unmanned mining system at Sanshandao Gold Mine encompasses the core aspects of mining production and operation. It is a comprehensive production and operation control system that leverages digitization, informatization, virtualization, intelligence, and integration. This system is supported by intelligent operational equipment and managed through computer networks, which supports both surface remote control and unmanned operation functions. Building upon Sanshandao Gold Mine's existing information system and equipment deployment, a novel unmanned mining system will be established, structured into four distinct levels: the first level is the comprehensive control layer, followed by the remote centralized control layer, then the mobile control center layer, and finally the intelligent operation layer,as shown in the Fig. 2.

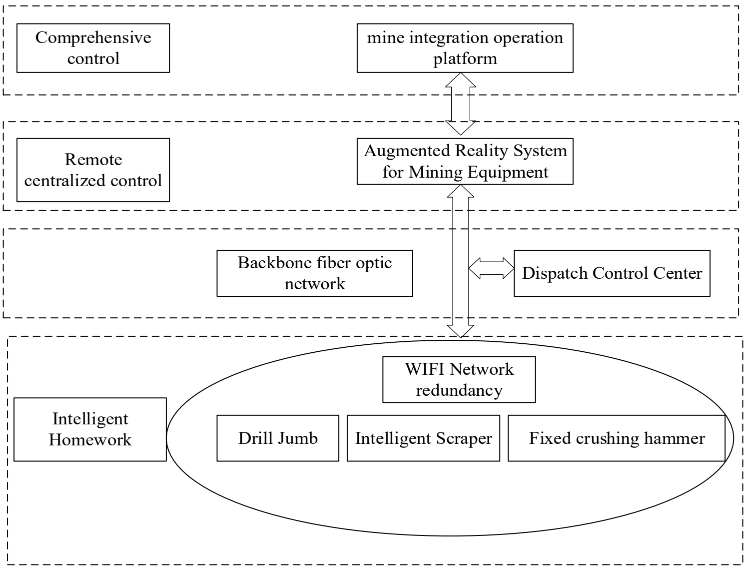

Fig. 2. System overall structure diagram

(1) Comprehensive Control Layer:
By developing a visual integrated platform for comprehensive mine production control, we can achieve real-time scheduling and short-interval control of mining equipment, while simultaneously monitoring production operations and safety status.

(2) Remote Control Layer:
Utilizing an augmented reality centralized control platform, we can remotely control production equipment such as underground scrapers, drilling machines, and transport trucks. Additionally, this layer enables fault diagnosis and safety monitoring of underground equipment operation status.

(3) Mobile Control Center Layer:
The mobile control center integrates remote control platform software and offers scalable communication methods, including point-to-point and network access. This allows for rapid, flexible, and cost-effective deployment and centralized control of intelligent mining equipment.

(4) Intelligent Operation Layer:
As the operation execution layer of the unmanned mining system, the intelligent operation layer is the core of the system. It consists of intelligent mining equipment and production systems, such as underground intelligent scrapers, intelligent drilling machines, and transport trucks, forming the backbone of mining operations.

Based on these four layers of the unmanned mining system, our focus will be on researching and applying an integrated control platform for mining production and operation, an augmented reality centralized control system for intelligent equipment, a vehicle remote control system, a line-of-sight vehicle remote control system, a vehicle autonomous driving system, and a mobile control center platform. Through comprehensive monitoring of equipment operation status across various stages of mining production, we aim to achieve intelligent and clustered control of operating equipment. In combination with the comprehensive production control system, we will realize intelligent and unmanned mining and transportation in the deep areas of Sanshandao Gold Mine, thereby enhancing the mine's level of safe and efficient production.

3.1. Design of the remote control system for rock drilling trolley

The Sanshandao gold mine utilizes DL330 rock drilling trolley, which have undergone renovation and transformation to achieve intelligent functionality. The centralized operation platform of the remote automation control system for these trolleys is connected to the mining area's local area network via wired connections. Wireless base stations are strategically placed on the underground working face of the rigs, and these base stations are linked to underground fiber optic switches through wired means, facilitating seamless integration with the mining area's local area network. The rock drilling trolley was intelligently upgraded through the integration of multiple sensors, including displacement sensors, pressure sensors, encoders, and angle sensors, as illustrated in Fig. 3.

During rig operations, the onboard wireless transmitters capture and transmit real-time videos of vehicle operations and status information. These transmissions are received by the base stations and subsequently relayed to the monitoring center through fiber optic cables. Conversely, control information from the monitoring center is transmitted via fiber optic cables to the base stations located in the underground tunnels. The base stations then transmit this information to the onboard receivers, enabling operators to remotely manage and control the rigs' working status with precision and efficiency [10-11].

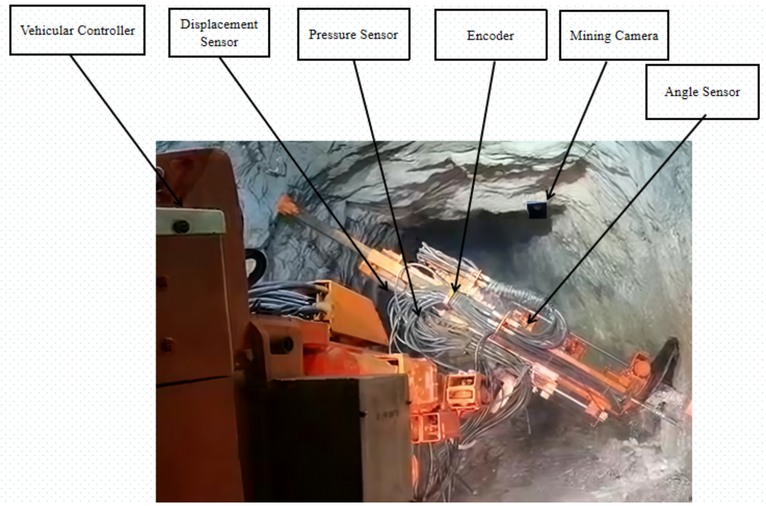

Fig. 3. The design of the remote control system for rock drilling trolley

(1) Remote control function
The central control operation platform serves as the operating unit of the entire remote control system, mainly completing functions such as wireless remote control of equipment, video monitoring, and recording of equipment working status. It includes an operation platform, a large-sized curved liquid crystal display screen, video processing and display software, and status information processing and display software;

(2) Video display function
To achieve remote control of the device and real-time video monitoring, this vehicle-mounted video system includes a high-definition infrared camera for mining, a high-performance wireless bridge, and a joystick controller for the pan-tilt camera;

(3) Single-hole automatic control system
The rock drilling platform has achieved fully automatic drilling for a single hole. The automated rod-changing mechanism is specifically engineered to accommodate the requirement for seamlessly advancing to the next drill rod during the geological drilling operation. The initiation timing of this automated process is contingent upon the positional status of the drilling apparatus. Furthermore, at the onset of the automated rod exchange sequence, to enhance the capabilities of fully automated and intelligent drilling operations, the existing operational data is independently transmitted and stored, thus enabling logical processing of this data by the intelligent drilling system.

During the automatic rod connection process, the system must not only connect and disconnect threads, retrieve and place drill rods, and operate the robotic arm, but also verify the success of each action using status information from various drill rod storage types. Appropriate prompts or actions should follow based on these verifications. The client updates action details and statuses in real-time, allowing users to promptly intervene in any abnormalities. The interaction between the automatic rod connection program and the drill rod storage status accurately reflects the storage conditions and causes of any issues, providing users with valuable information for quick fault diagnosis and drill rod storage assessment.

The automatic rod connection program stores action information in the database, enabling users to easily access historical data. This allows for analysis of drill rod storage usage based on execution status. By thoroughly analyzing the causes of abnormal conditions, fault points in the structural, hydraulic, and electrical systems can be pinpointed, facilitating a targeted examination of hardware failures. By improving the relevant structures, we can enhance the success rate of automatic rod connection actions,which is shown in Fig. 4.

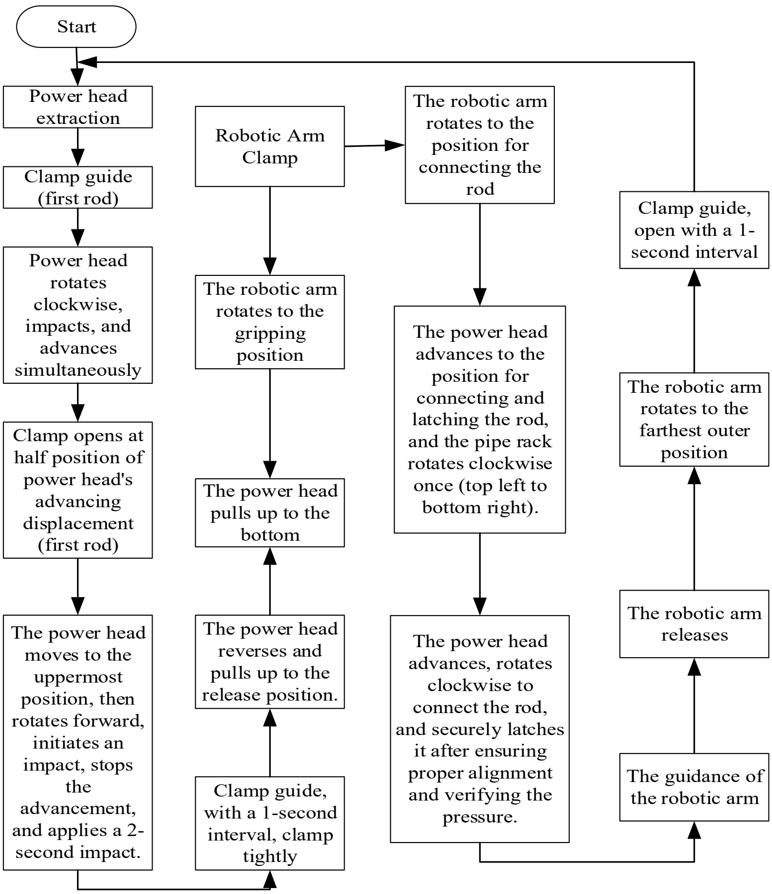

Fig. 4. Flowchart of Single-Hole Drilling for Rock Drilling Jumbo

(4) Intelligent Monitoring System

The system provides operational monitoring, execution process monitoring, fault diagnosis display, and emergency handling modules. It offers comprehensive monitoring and parameter adjustment during the intelligent operation process, as well as command issuance and emergency response capabilities.

3.2. Design of the remote control system for Scraper

The Sanshandao Gold Mine employs the Scooptram ST3.5 scraper, which has been upgraded and modified to incorporate intelligent capabilities. This enhanced scraper is now equipped with features such as remote operation, automated loading assistance, real-time status monitoring, and video surveillance, as depicted in Fig. 5.

The intelligent optimization of the scrapers lays the foundation for the future deployment of remote and autonomous scraper operations. This extensive enhancement involves the seamless integration of various subsystems, including embedded computing, sensor arrays, weighing mechanisms, monitoring frameworks, safety guard systems, installation components etc. [12-15].

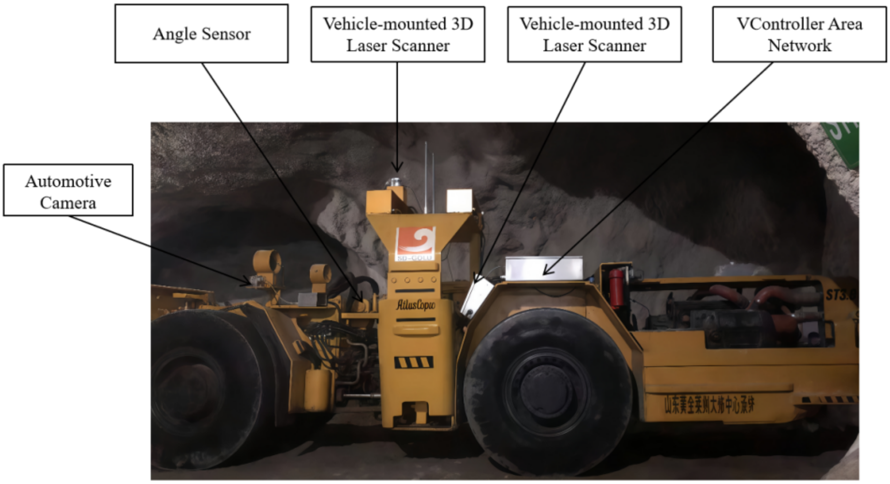

Fig. 5. Intelligent Scraper Transformation

The remote control system for Scraper has the following functions:

(1) Remote control function
The intelligent cockpit issues commands and remotely operates the scraper to execute diverse tasks, encompassing all functionalities of line-of-sight remote control;

(2) Video display function
The vehicle is equipped with a dust-proof network camera for remote surveillance of the working environment. The camera's video data is seamlessly uploaded to the monitoring center via a wireless network;

(3) Automatic driving function
The scraper is fitted with a LiDAR system that provides real-time monitoring of the surrounding spatial information. Utilizing our proprietary positioning navigation and intelligent control algorithm, the scraper is capable of autonomous navigation;
The autonomous driving and remote control technology of the scraper involve the research on control and positioning algorithms based on LiDAR and wireless communication information processing technology, and have promoted on-site engineering

demonstration work. The underground scraper achieves autonomous driving functionality by equipping various sensors. The navigation system includes components such as an onboard controller, laser scanner, microwave radar, and angle sensor,which is shown in Fig. 6.

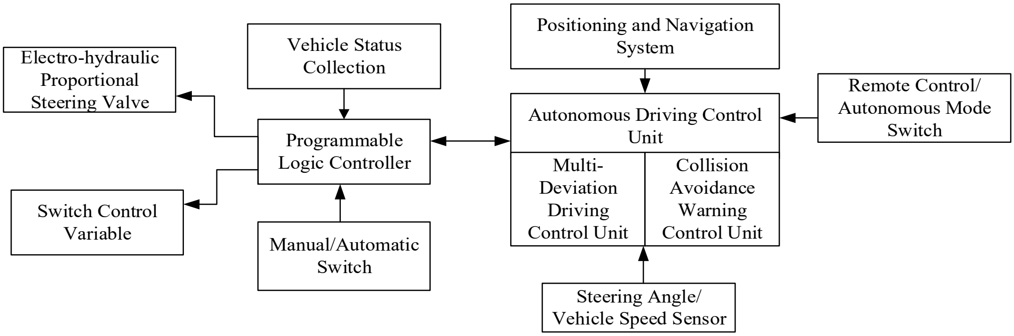

Fig. 6. Autonomous Driving and Remote Control Framework

(4) Operation status monitoring and recording function
The intelligent control unit onboard the scraper monitors the vehicle's operational status in real-time and displays this information instantly at the control center's operational interface. The status information encompasses driving duration, engine operational status, braking status, neutral gear status, forward and reverse movements, throttle position, left and right turns, boom lifting, bucket retraction, braking engagement, fire extinguisher activation, and engine start indication, among others.

(5) Scraper remote control management software
This platform integrates a video display system, which obtains monitoring video signals from the vehicle's operating environment from the onboard camera, and displays them at the corresponding positions on the software interface for monitoring. Equipped with auxiliary remote control function: By visualizing the vehicle's operating parameters such as vehicle speed and engine speed through the video screen of the onboard camera, the driver's operation is more intuitive.

3.3. Design of the remote control system for fixed rockbreaker

The unmanned fixed rockbreakersystem is designed to enhance the mining operational efficiency of Sanshandao Gold Mine. It incorporates advanced technologies like image recognition and automatic control. By capturing real-time depth images of the ore on the chute's screen, the system extracts image features using onboard computers. Through multiple information fusion and pattern recognition techniques, it performs ore block size analysis and position recognition. Ultimately, the system controls the rockbreakerto autonomously complete the crushing of large ore blocks and the management of ore piles,as illustrated in the Fig. 7.

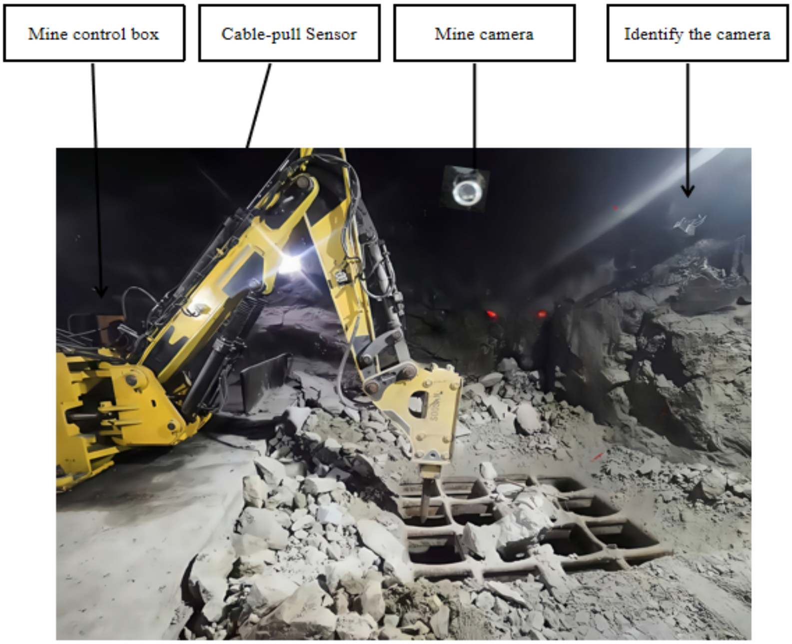

Fig. 7. The system of the remote control system for fixed rockbreaker

The technical framework of the automatic control system for the fixed rockbreaker's robotic arm is illustrated in the Fig. 8. The impact point of the hydraulic breaker is dynamically adjusted based on the size and height information of the ore blocks. During the movement of the robotic arm, displacement and angle sensors are used to collect the offset of each joint, allowing for the calculation of the robotic arm's trajectory. Based on the deviation between the target and actual positions, the joint movements are dynamically adjusted, forming a closed-loop control system.

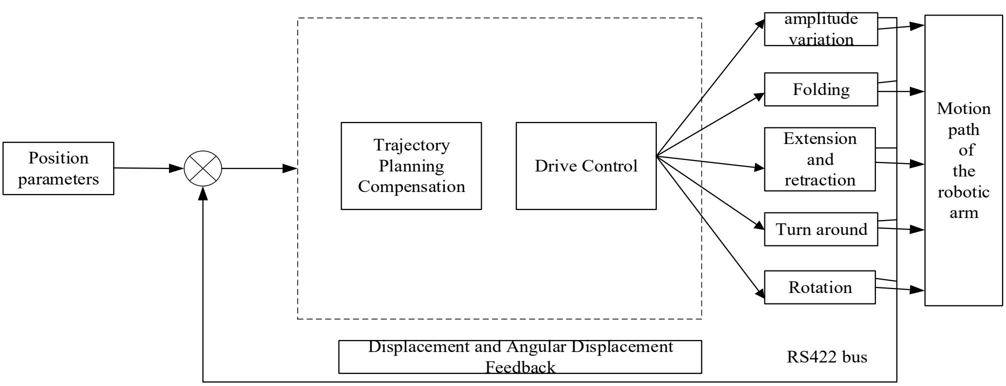

Fig. 8. The technical framework of the automatic fixed rockbreaker control system

The autonomous breaking hammer has the following functions:

(1) Identification of large ore blocks
Utilizing image recognition and pattern recognition, we establish an ore block size analysis model that precisely identifies large blocks of ore, thereby preventing screen blockages and enhancing resource utilization.
Collect three-dimensional point cloud data of the ore piled up in the chute using a TOF camera, and acquire two-dimensional intensity image information of the ore using an infrared band camera. Perform edge detection, block segmentation, feature extraction, and other overlay processing on the two-dimensional and three-dimensional data to achieve precise positioning of ore heaps and blocks.

(2) Accurate crushing of large blocks
Establish both a screening coordinate system and a crushing hammer coordinate system, and achieve accurate localization of large ore blocks through the coupling and mapping of these dual coordinate systems. The precise positioning of the robotic arm is attained using displacement sensors and angle sensors, allowing the driving system to control the crushing hammer for effective multiple crushing operations.

(3) Mobile target recognition
To guarantee the safety of production operations, the system continuously monitors the wellhead's operational status in real-time. Upon detecting any moving targets within the operational area, it automatically engages a safety lock on the crushing hammer to prevent accidents..

(4) Pushing and dispersing ore piles to assist in falling
Once the large block crushing operation is complete, the ore pile is carefully pushed to prevent the accumulation of small ore pieces, which could disrupt the normal flow of ore through the pass.

(5) Fault diagnosis and alarm
The system automatically conducts fault diagnosis. Upon detecting any abnormal operational information or feedback on working conditions, it immediately locks the device and sends alarm notifications to the control room, thereby enhancing the system's safety operation level[16].

4. Design of Multivariate Fusion Network

The mining environment at the -645 m level of the Sanshandao Gold Mine poses considerable challenges. The narrow roadways often lead to damage of communication cables from rockfalls and equipment collisions, complicating efforts to maintain cable connectivity. Additionally, high humidity, irregular rock formations, and poor visibility underground further hinder the establishment of reliable and stable wireless communication.

Following a comprehensive on-site environmental assessment, testing, data collection, and network data simulation analysis using the NS2 network simulator, we have optimized and redesigned the existing underground wireless communication system. Our solution involves a two-tier composite architecture, which incorporates a fiber optic ring network, fixed wireless base stations, and 5G base station coverage. This approach ensures comprehensive network coverage and provides multi-level redundant communication services for underground metal mines. The multivariate fusion network consists of fiber optic ring network, fixed base station, 5G communication base station, portable base station, etc., as shown in Fig. 9.

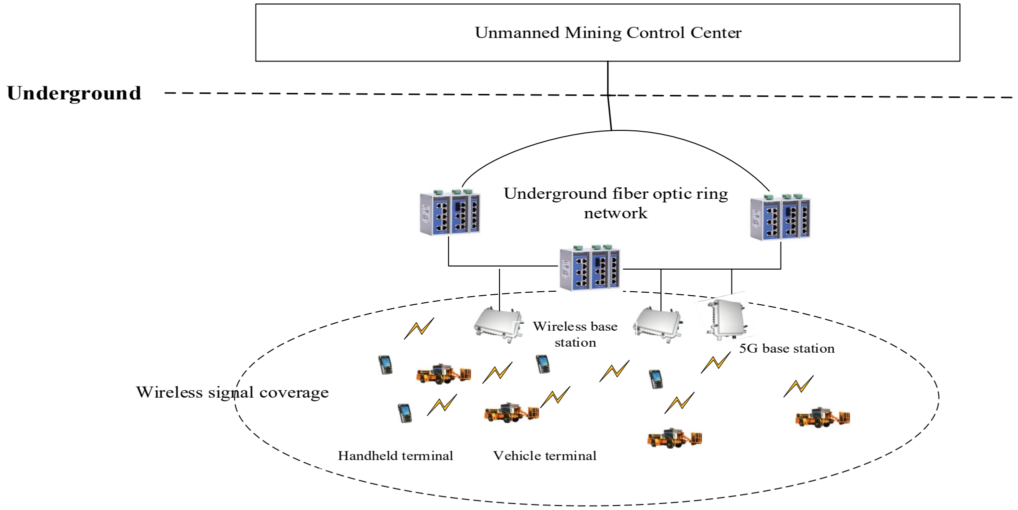

Fig. 9. Multimodal Integration Network Design Diagram

The wireless communication system is built upon an underground gigabit fiber optic ring network, which provides not only substantial bandwidth but also incorporates loop redundancy technology. This ensures continuous data transmission within the backbone network, even in the event of node or cable failures. Consequently, this guarantees stable physical connectivity and reliable data exchange among the network's core nodes (ring network switches) [17-18].

The core structure of the wireless communication system encompasses fixed wireless communication base stations and portable intelligent base stations. A wide array of vehicle communication terminals, handheld communication devices, and Wi-Fi6 appliances compatible with IEEE 802.11AC standards can seamlessly interconnect and exchange data within the system's effective coverage area.

Fixed intelligent base stations are strategically placed in various main alleys and expandable wired network alleys. Their primary function is to facilitate direct interconnection between local wireless and wired networks. Within the wired network's reach, wireless signal coverage spans the 2.4 GHz to 2.483 GHz frequency band. This enables wireless data access for vehicle terminals, handheld devices, and IEEE 802.11AC-compliant Wi-Fi appliances in main alleys and surrounding areas, ensuring swift and reliable data communication.

To further enhance the system, 5G base stations are deployed to ensure low-latency transmission of wireless and high-definition video, as well as intelligent control signals. These base stations leverage Huawei's 5G solutions, while leakage cables are used for wireless private network signal coverage in challenging areas such as turns and uncovered sections within tunnels.

During deployment, meticulous and scientifically sound network planning is imperative. This ensures maximum wireless coverage at the right times and locations within the service area, while also meeting the required communication success probability. It's crucial to minimize interference within the base station's coverage area, given the limited bandwidth. This allows for the largest possible system capacity while maintaining the desired quality of service (QoS).

Data transmission for unmanned underground scraper equipment during operation requires seamless and rapid switching between different network base stations as the position changes. Achieving seamless and fast switching is crucial for monitoring, controlling, and managing the equipment throughout its operation. This paper aims to adopt multi-radio heterogeneous network fast switching technology to develop equipment for switching between heterogeneous networks. This equipment will support parallel connections with multiple radio heterogeneous networks while preventing network storms, thereby enabling rapid and seamless roaming of the device across different networks. It will ensure stable and uninterrupted online transmission of key data such as streaming media data, control information, and warning information from the underground equipment. Ultimately, a high-performance data acquisition and transmission device will be developed, which will undergo laboratory platform testing and field industrial trials to ensure high-quality and reliable data transmission throughout the equipment's operation.

Through a wireless network redundancy switching transmission mechanism, stable and reliable data transmission can be ensured. When deploying the network, the wireless coverage areas of the two networks overlap to some extent, ensuring that at any given moment, at least one wireless link has excellent signal strength and signal transmission quality. This reduces the likelihood of link switching or unstable signal transmission in areas with weak signal strength. As shown in the diagram, at Point A, the 2.4G network signal is the strongest, while the 5.8G network signal is the weakest, yet the overall network transmission remains stable. At Point B, the 5.8G network signal is the strongest, and the first heterogeneous network WiFi Customer Premises Equipment (CPE) is in the process of roaming and switching, but the overall network transmission still remains stable. This means that heterogeneous networks can achieve "seamless switching". When the terminal CPE is operating within the wireless network coverage area, the overall average delay of the wireless network can be controlled to around tens of milliseconds [19], which is shown in Fig. 10.

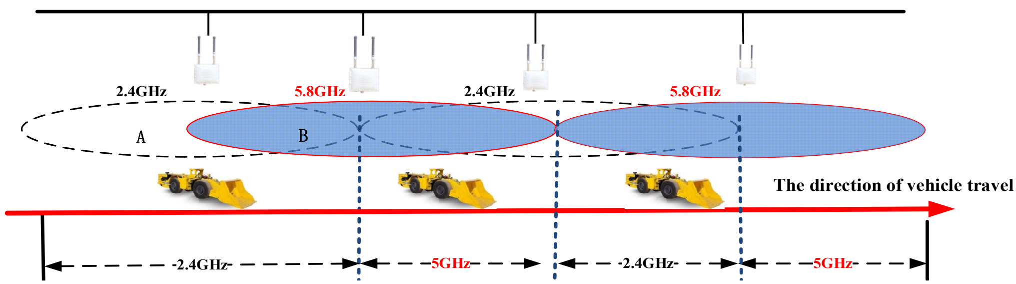

Fig. 10. The principle of rapid switching in 2.4G & 5G dual-frequency redundant networks

5. Design of The Unmanned Mining System Production and Operation Platform

The production and operation scheduling system primarily enables remote control of critical production equipment, including rock drilling trolleys, charging trolley, scraper, and fixed breaking hammer, while also providing real-time monitoring and job statistical analysis to facilitate rational scheduling and production balancing, as shown in Fig. 11. Additionally, through effective scheduling task management, it enhances scheduling efficiency and ensures production stability.

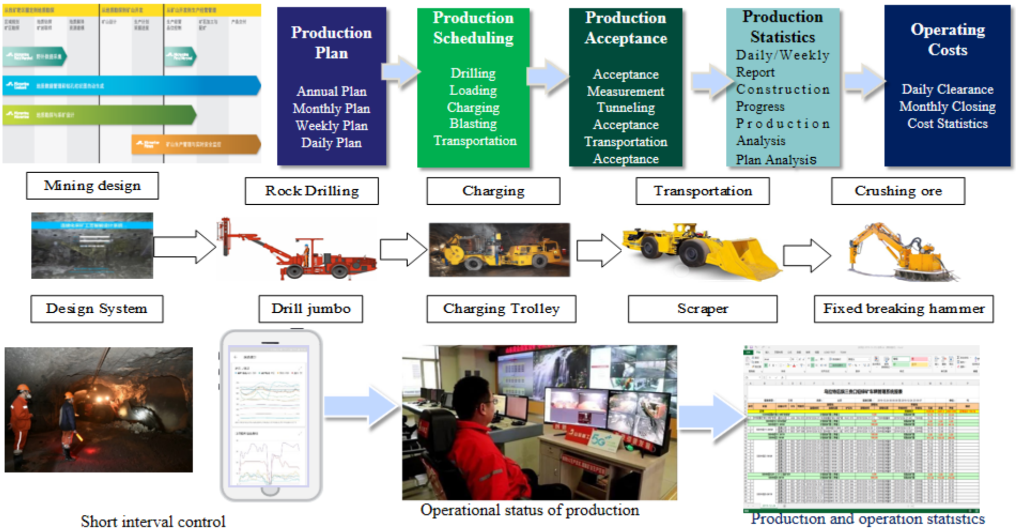

Fig. 11. The Operating diagram of the Unmanned Mining System Production and Operation Platform

Developed using the B/S architecture, this system leverages Java as the primary development language, alongside Web front-end and back-end frameworks. It employs a MySQL database and WebGL as the 3D rendering engine. The system architecture is structured into four distinct layers: the model layer, control layer, business layer, and view layer.

The model layer, also referred to as the data layer, organizes data collected from various sources such as interface inputs, manual entries, diverse sensors, and other monitoring subsystems by designing an appropriate data structure. The control layer is responsible for data updates, reorganizations, and the communication of data messages between the view and model layers.

The business layer encompasses specific operational tasks related to the analysis of the mining operation process and the implementation of multi-source information monitoring and management throughout the mining operation. Lastly, the view layer serves as the user interface, displaying software interface elements, managing information input and output, and facilitating centralized control and scheduling operations during mining activities.

The specific approach for the integrated control platform for unmanned mining production operations is as follows:

(1) Based on the unmanned mining process workflow and operational control requirements, establish a data model and integrated control service model that encompasses the unmanned mining operations. This will be combined with backend server technology based on Software as a Service (SaaS) to create rapid and accurate data processing and analysis capabilities for integrated control.

(2) Research the integration mechanism for the unmanned mining production operation integrated control platform, establish design and construction standards for the hardware and software of the unmanned mining production operation control system, and develop an unmanned mining production operation data analysis system, ultimately leading to the creation of a big data system for unmanned mining production operation control.
(3) Using real-time production data from specific unmanned mining operations, simulate the operational status of the mining process to test the system's analytical capabilities, thereby better serving the unmanned mining operations in underground metal mines, as shown in Fig. 12.

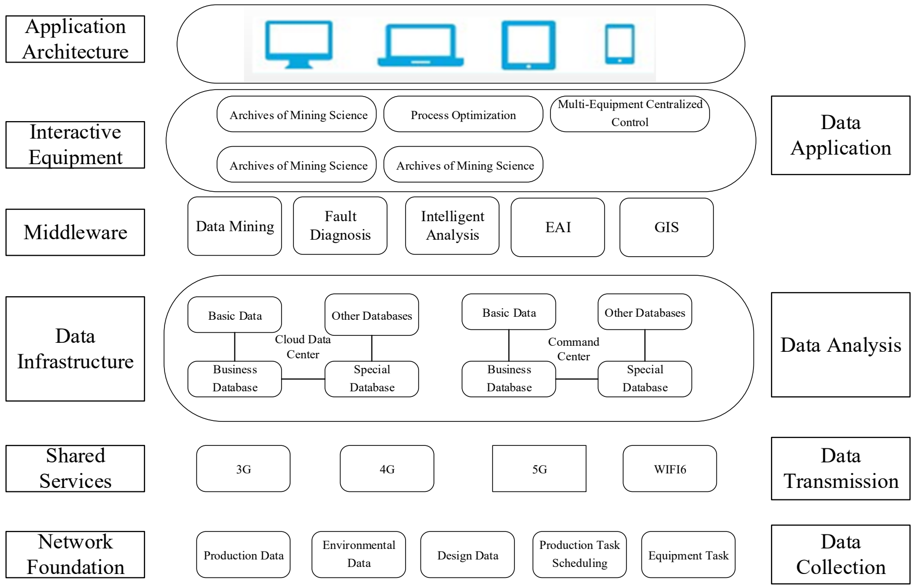

Fig. 12. Architecture diagram of production scheduling system

The production and operation scheduling system realizes the maintenance and update of the current mining situation in a three-dimensional environment, interfaces with the real-time data of the mining truck scheduling system, and displays the position, working conditions, and real-time production data of the shovel and loading equipment in the three-dimensional environment [20-23].

(1) Production resource scheduling
The production and operation scheduling system enables the maintenance and updating of the current mining status within a three-dimensional environment. It interfaces seamlessly with real-time data from the mining truck scheduling system, and vividly displays the position, operating status, and real-time production data of shovel and loading equipment in this immersive 3D setting.

(2) Tracking of abnormal production events
Offer functionalities for reporting, inquiring, modifying, and visualizing abnormal events, while also ensuring comprehensive recording and tracking of the entire process

of managing abnormal events (encompassing request submissions and instructional communications) that arise during the production cycle.

(3) Temporary production task scheduling
For ad-hoc task scheduling that arises during the production process, incorporate a scheduling process trace management feature to document the sequence of events, including personnel requesting instructions from supervisors and the subsequent communication of those instructions to subordinates.

(4) Dispatch Record Table
Mainly record information such as underground ore output and ore grade.

(5) Dispatch handover log
Each shift is required to summarize the safety production status, detail any encountered issues, outline the handling measures taken, and list any pending matters, all of which are compiled into a production log. The system facilitates statistical queries of these logs by date, shift, personnel, location, and information importance, with support for fuzzy searches based on content.

The production scheduling system integrates two-dimensional and three-dimensional visualizations to provide a centralized display of the mining production and operation status, enabling seamless display, browsing, and interaction. It features functions for 3D model roaming, resetting, quick viewpoint access, and browsing mode customization. The quick viewpoint function allows users to rapidly focus on a specified destination by simply clicking on a specific mine roadway location or equipment name, ensuring precise positioning and display of the mine's production and operation status. The browsing mode function enables users to show or hide corresponding 3D models within the centralized control platform by clicking on specific ore body, midsection, roadway, or ramp model names, optimizing the visibility of specific details within the model. The roaming function displays the entire ore body model in a surround view upon clicking. The reset function, meanwhile, returns the browsing perspective to its initial state each time the page is loaded after a conversion [24-25]. The specific situation is illustrated in the following Fig. 13.

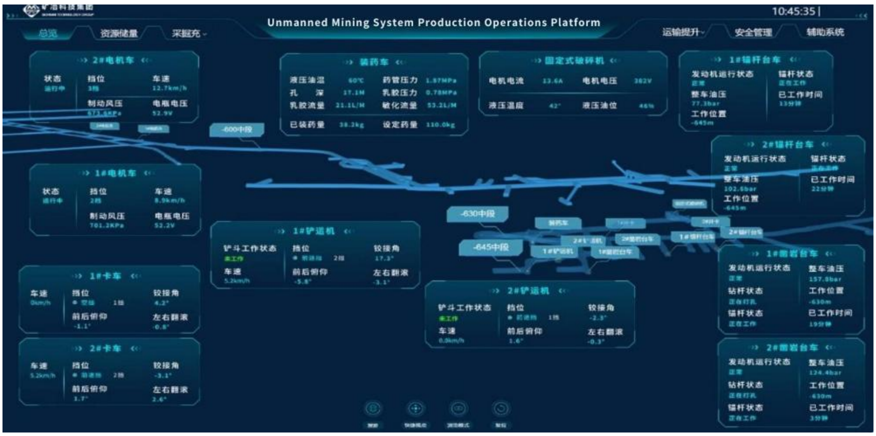

Fig. 13. Roaming display of the overall ore body model in the production scheduling system framework

The operational status of equipment such as drilling rigs, scraper loaders, and fixed rock-breakers at the Sanshandao Gold Mine is illustrated in Fig. 14.

Fig. 14. The operational status of equipmen

6. Result analysis and discussion

Based on the development and composition of the aforementioned equipment and software system modules, an application study was conducted on the multi-equipment collaborative intelligent mining system for the -645 m level underground mining area at the SanShanDaoGold gold mine.

3D scanning result of the autonomous scraper technology based on LiDAR technology is shown in the Fig. 15.

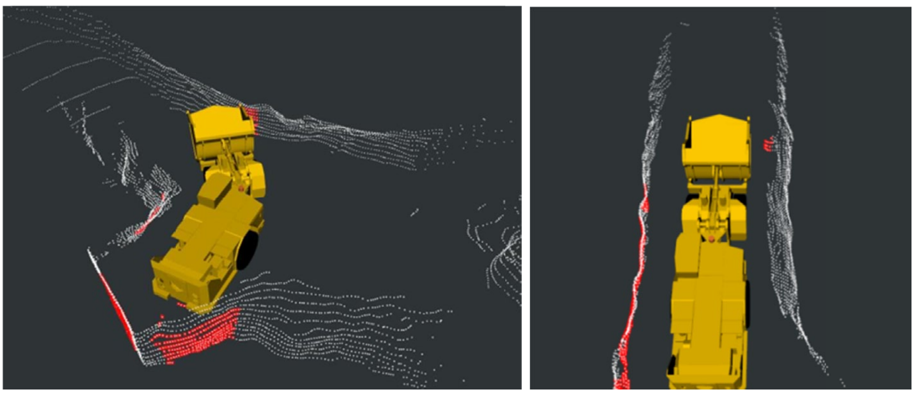

Fig. 15. 3D Laser Autonomous Scraper Driving Technology

The diagram of edge detection for crushed stone of the unmanned fixed rockbreakersystem is shown in Fig. 16.

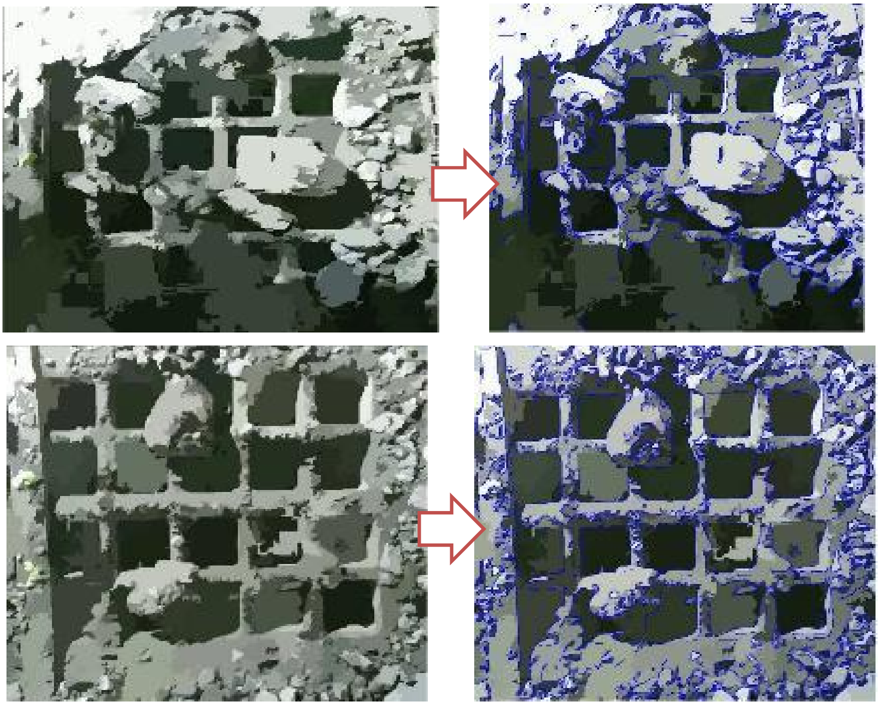

Fig. 16. Diagram of Edge Detection for Crushed Stone

After conducting multiple tests and optimizations underground at the Sanshandao Gold Mine, and gradually comparing the efficiency local manual control, surface remote control and unmanned operation, the results are presented in TABLES 1-3.

TABLE 1

Statistics of local manual control Time

No.	Rock Drill Time minutes (70 m depth)	Scraper working time minutes	Fixed rockbreaker minutes
1	480	3.5	5.2
2	479	3.8	5.4
3	475	3.4	5.3
4	485	3.9	5.2
5	482	4	4.5
6	480	3	5.6
7	485	3.8	5.8
Average	**480.86**	**3.63**	**5.29**

TABLE2

Statistics of surface remote control Time

No.	Rock Drill Time minutes (70 m depth)	Scraper working time minutes	Fixed rockbreaker minutes
1	483	3.7	5.3
2	485	3.9	5.5
3	482	3.5	5.2
4	481	3.8	5.1
5	485	4.2	5.2
6	482	3.6	5.3
7	486	3.7	5.6
Average	**483.42**	**3.77**	**5.31**

TABLE3

Statistics of Unmanned Operation Time

No.	Rock Drill Time (autonomous rod changing and handling) minutes	Scraper working time (autonomous driving) minutes	Fixed rockbreaker (autonomous operation) minutes
1	523	5.9	8.2
2	510	6.4	8.5
3	533	6.3	8.0
4	530	6.6	8.8
5	520	7.1	8.5
6	532	6.8	8.2
7	528	5.2	8.3
Average	**525.14**	**6.33**	**8.36**

After completing the preliminary preparations for the underground drilling jumbo, such as the connection of air, water, and electricity. The manual operation time, remote control operation time from the surface, and autonomous rod changing and handling time for the drilling jumbo underground are 480.86 minutes, 483.42 minutes, and 525.14 minutes respectively. The comparison between the remote control and manned operation revealed that both achieved similar efficiencies, with remote control taking 483.42 minutes and manual operation taking approximately the same amount of time. This suggests that the remote control system has reached a level of maturity and reliability comparable to traditional manual operation in terms of execution speed. But the working time of the drilling jumbo that supports autonomous rod changing and handling is 525.14 minutes. This shows that the efficiency of the rock drilling carriage is not as high as that of the manual control, so it is necessary to further improve the stability of the autonomous rod encoder sensors and so on [26]. At the same time, it is also necessary to further realize the matching of rock drilling parameters and rock characteristics in the drilling process, and to reasonably select the optimal rock drilling parameters according to the results of rock characteristics identification, so as to achieve the purpose of fast, accurate and stable drilling.

Assuming that the working hours of the rock jumbo is not taken into account, the working time of the manual control and remote control of the fixed rock breaker of the scraper is similar, which is 8.92 minutes and 9.08 minutes. However, the unmanned operating working time of the scraper and fixed rock breaker is 14.69 minutes. This indicates that, while unmanned systems provide numerous advantages – such as enhanced safety, reduced labor costs, and consistent performance – they still encounter challenges in matching the efficiency of manned or remotely controlled operations. Unmanned control of a scraper and fixed rock breaker is about 61% as efficient as local manned control or remote control from the surface.

Several factors may contribute to the efficiency gap between unmanned and manned or remote operations. These factors include the current limitations of autonomous navigation and decision-making algorithms, potential communication delays or disruptions between equipment, and the need for further optimization of the overall system workflow.

To bridge this efficiency gap, future research and development efforts should focus on improving the autonomous capabilities of the equipment, enhancing communication systems, and refining the system's workflow to better accommodate unmanned operations. Additionally, continuous monitoring and data collection can help identify bottlenecks and areas for improvement, allowing for iterative optimization of the system.

7. Conclusion

This study presents designing a comprehensive intelligent approach mining to system for deep underground metal mines, using the Sanshandao Gold Mine as a practical case study. The proposed multi-layered intelligent mining system encompasses advanced technologies such as autonomous vehicle operation, remote control modules for production equipment, a robust wireless communication network, and a web-based monitoring system.

The multi-layered architecture of our intelligent mining system, which integrates smart equipment, autonomous vehicle management, multi-equipment coordination, and real-time production optimization, provides a robust framework for achieving safe and efficient mining operations. The successful application of these technologies at the Sanshandao Gold Mine underscores their potential to transform mining technology towards greater informatization, digitization, and intelligence.

The results of our tests comparing local manual operation, remote control, and unmanned operation reveal that the remote control system performs similarly to traditional manual methods, demonstrating its reliability and feasibility. However, unmanned operation was found to be slightly slower than manual control, highlighting the need for further optimization and refinement of autonomous capabilities.

Despite the progress achieved, our study also identifies key bottlenecks in unmanned operation, particularly in terms of time cost and efficiency. These findings point to areas for future research and development, such as improving autonomous navigation and decision-making algorithms, enhancing communication systems, and optimizing system workflows.

In conclusion, this work contributes significantly to the advancement of intelligent mining in deep underground metal mines. The proposed system offers numerous new automatic functions and demonstrates the potential for minimizing the underground workforce while ensuring safe and efficient operations. We believe that our findings and insights will serve as a valuable reference for researchers and practitioners in the field, guiding future efforts towards the widespread adoption of intelligent mining technologies.

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