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Intelligent Mining Technology for an Underground Metal Mine Based on Unmanned Equipment

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ABSTRACT

This article analyzes the current research status and development trend of intelligent technologies for underground metal mines in China, where such technologies are under development for use to develop mineral resources in a safe, efficient, and environmentally friendly manner. We analyze and summarize the research status of underground metal mining technology at home and abroad, including some specific examples of equipment, technology, and applications. We introduce the latest equipment and technologies with independent intellectual property rights for unmanned mining, including intelligent and unmanned control technologies for rock-drilling jumbos, down-the-hole (DTH) drills, underground scrapers, underground mining trucks, and underground charging vehicles. Three basic platforms are used for intelligent and unmanned mining: the positioning and navigation platform, information-acquisition and communication platform, and scheduling and control platform. Unmanned equipment was tested in the Fankou Lead-Zinc Mine in China, and industrial tests on the basic platforms of intelligent and unmanned mining were carried out in the mine. The experiment focused on the intelligent scraper, which can achieve autonomous intelligent driving by relying on a wireless communication system, location and navigation system, and data-acquisition system. These industrial experiments indicate that the technology is feasible. The results show that unmanned mining can promote mining technology in China to an intelligent level and can enhance the core competitive ability of China's mining industry.

1. Introduction

With the world's rapid economic development, the demand for mineral resources is increasing. It has been forecast that the depth of more than 33% of the metal mines in China will reach or exceed 1000 m within the next decade. Deep underground mining will become the trend of metal mining in China [1]. To overcome the disadvantages of traditional mining methods, such as excessive resource consumption, poor operating environments, low production efficiency, high safety risks, high production costs, and severe pollution, it is essential to develop an intelligent mining technology for underground metal mines that provides complete safety, environmental protection, and efficiency [2,3]. Some developed countries have done a great deal of work in the field of intelligent mining for underground metal mines over many years, and thus have considerable experience in this field. At the beginning of the 21st century, Canada, Finland, Sweden, and other developed countries made plans for intelligent and unmanned mining. At the Stobie Mine, an underground mine belonging to the International Nickel Company of Canada, Ltd. and a typical example of such an automated mine, mobile devices such as scrapers, rock drills, and underground mining trucks are operated remotely and workers can operate the equipment directly from the central control room on the surface [4]. According to the Canadian government's 2050 long-range plan, Canada intends to transform one of its underground mines in the northern part of the country into an unmanned mine. The plan states that all devices will be controlled from Sudbury via satellite in order to achieve intelligent and unmanned mining. Another intelligent mining program covering 28 topics—including the real-time process control of mining, real-time management of resources, construction of a mine information network, and application of new technology and automatic control—was carried out in Finland. Sweden has developed the Grountecknik 2000 strategic plan for mine automation [5–7], and veteran mining equipment companies such as Atlas Copco are actively developing a series of unmanned underground mining equipment and related control systems that can be used to

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implement the strategic plan. One of the most famous institutes in unmanned vehicles, the Commonwealth Scientific and Industrial Research Organization of Australia, is making great efforts to achieve the intelligent mining of underground mines, with a particular focus on the unmanned control of various types of equipment [8].

Although these developed countries have already invested a considerable amount of time and money into the study of intelligent mining, only a few related studies have been carried out in China, especially in the field of intelligent equipment and platforms. In order to rapidly advance its intelligent mining capabilities, China is supporting many intelligent mining projects, including the Key Technology and Software Development for Digital Mining project and the High-Precision Positioning for Underground Unmanned Mining Equipment and Intelligent Unmanned Scraper Model Research project. In particular, a project titled Intelligent Mining Technology for Underground Metal Mines was established during the 12th Five-Year Plan, in order to promote intelligent mining technology to a certain extent. This article introduces several research achievements and their applications in this project. Trackless mining equipment such as rock-drilling jumbos, down-the-hole (DTH) drills, underground scrapers, underground mining trucks, and underground charging vehicles have been developed using intelligent technologies. Suitable communication techniques, sensors, artificial intelligence, virtual reality, information technology, and computer technology for mining equipment and platforms have been implemented. The experimental results indicate that some of the system's functionalities are innovative and show good performance.

2. Intelligent mining

Mining is one of the oldest industries in the world. Mining production techniques have passed through a rapid change from artificial production, mechanized production, and on-site remote-control production, to intelligent and fully automated production. In order to move the mining industry forward, mechanization tools have been developed, single-equipment and independent systems have been automated, and the entire mining production process has been highly automated [9]. By integrating information technology with the industrialization of mining technology, intelligent mining technology has been rapidly developed, based on mechanized and automated mining, as shown in Fig. 1. This has resulted in the gradual upgrading of intelligent processes in mining equipment; unmanned and centralized mining equipment have now entered the stage of practical application, which will significantly advance the automation and information technology used in mining [10].

Integrated communication, sensors, artificial intelligence, virtual reality, information technologies, computer technologies, and unmanned control equipment were combined in order to achieve intelligent mining technologies, as shown in Fig. 2. Such technologies are based on precise, reliable, and accurate decision-making and production process management through real-time monitoring; they allow mine production to be maintained at the optimum level, and lead to improved mining efficiency and economic benefits. In this way, green, safe, and efficient mining can be achieved.

Taking a typical trackless mining technology as an example, intelligent mining technology can be divided into three layers—the control layer, transport layer, and executive layer [11].

As shown in Fig. 3, the executive layer mainly consists of trackless mining equipment such as rock-drilling jumbos, DTH drills, underground scrapers, underground mining trucks, or underground charging vehicles. The transport layer mainly includes a ubiquitous information-acquisition system, wireless communication system, and precise positioning and intelligent navigation

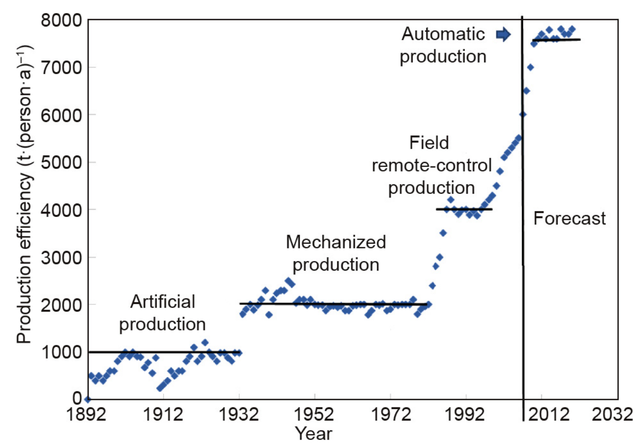

Fig. 1. A comparison of production efficiency and mining technology development.

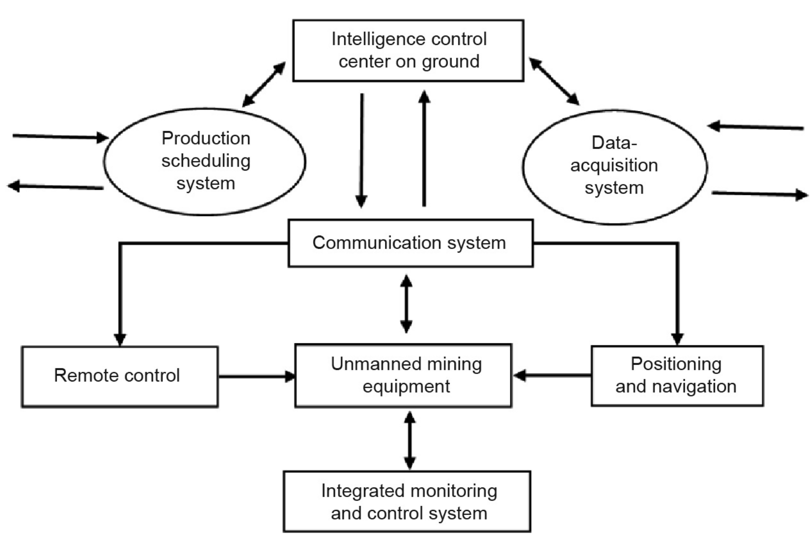

Fig. 2. The fundamentals of intelligent mining.

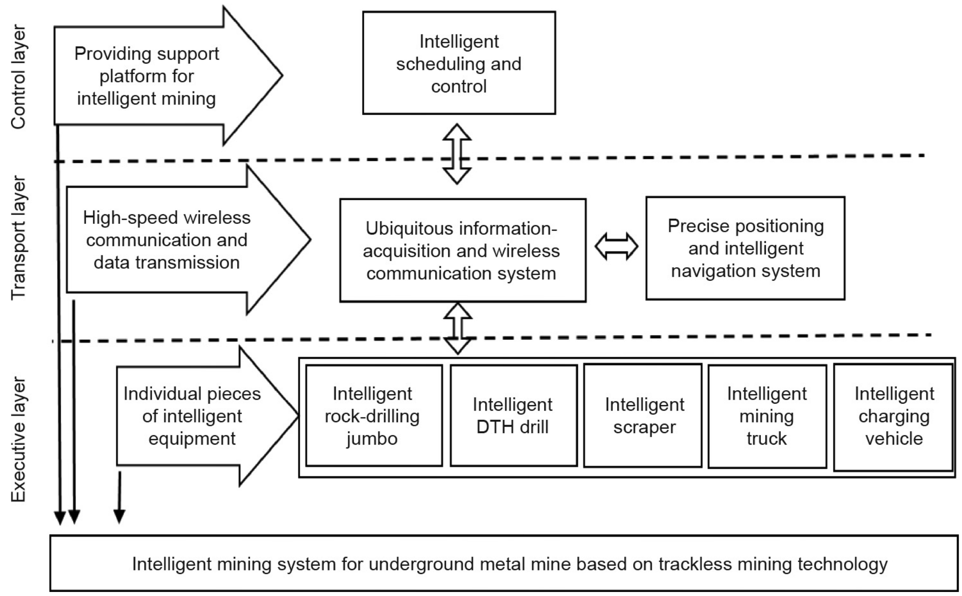

Fig. 3. A diagram of intelligent mining technology.

system. The control layer is designed as a system-level platform, and is responsible for intelligent mining process scheduling and control. This is the core of the entire system, because all intelligent mining-related functions and control ideas are implemented through this platform. First, a reasonable mining plan is designed by analyzing the reserves of mine resources and geological conditions in combination with the underground production schedule. Next, an intelligent scheduling and control platform is developed. Control instructions for the equipment are sent through the transport layer to a specific piece of equipment in order to perform a mining task at a specific position and time. Within the executive layer, the control layer collects current information on the tunnel and basic information about the vehicle in real time; this information can be used to determine the location of the equipment or adjust it at any time until that entire stage of the mining plan is successfully completed.

3. Unmanned equipment

Intelligent trackless mining technology is based on intelligent unmanned equipment at the executive layer, such as rock-drilling jumbos, DTH drills, underground scrapers, underground mining trucks, or underground charging vehicles. The functions of intelligent and unmanned mining equipment differ according to the different tasks each piece of equipment must carry out.

3.1. Intelligent rock-drilling jumbo

Rock drilling is the key process in mining, and plays a very important role in productivity, cost, and efficiency. Different geological conditions require different mining methods, and different methods require different types of rock drilling. A hydraulic rock-drilling jumbo is needed for medium-length hole drilling (i.e., depth of 20–30 m, diameter of 60–100 mm) [12]. An intelligent and unmanned rock-drilling jumbo has been designed to support intelligent mining technology and efficiently complete drilling work.

Remote control and a virtual-reality display were the first basic technologies implemented in the unmanned hydraulic rock-drilling jumbo. Fig. 4 shows the initial unmanned control platform for the jumbo on the surface. The virtual prototype display system,

Fig. 4. Remote control platform on the surface with on-site audio and video signals.

including on-site audio and video signals, is well-integrated in order to increase the feeling of immersion while performing remote-control operations.

Furthermore, the rock-drilling jumbo is autonomously controlled and operated in the tunnel under the guidance of a positioning and navigation system. By coordinating the positioning system and altitude control system, the jumbo can achieve autonomous driving to the location from the dispatch layer. This is a major step toward achieving continuous operation without interference. Given the coordinates of the drilling-hole position in the three-dimensional (3D) digital map of the mine, the identification of the stope top and floor and the accurate positioning of the rock-drilling system can be achieved independently. This provides a basis for unmanned operation. The intelligent control flow diagram is shown in Fig. 5.

The rock-drilling parameters are independently adjusted according to the rock conditions. The intelligent rock-drilling jumbo (shown in Fig. 6) is equipped with components for intelligent blockage prevention, rock-characteristic acquisition, and frequency matching; an automatic rod function; and a fully automatic drill-pipe bank. The hole-blasting parameters are specified independently, according to the scheduling system that is used, in order to ensure continuous drilling.

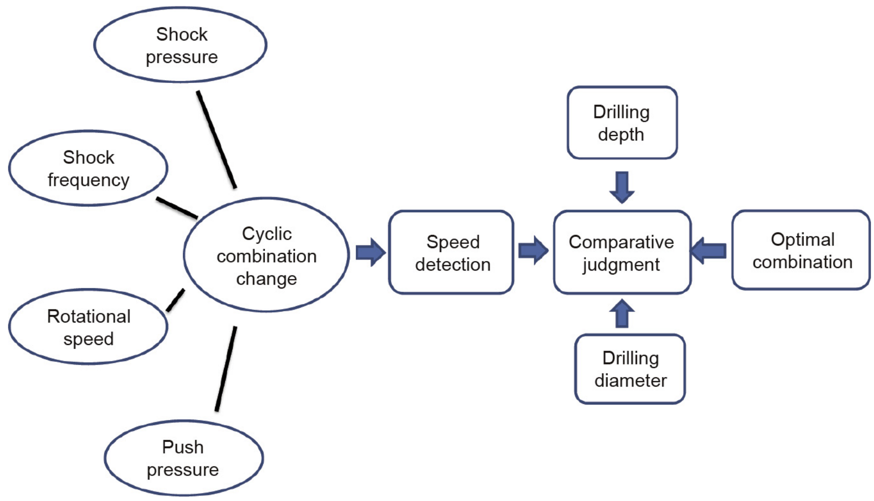

Fig. 5. Intelligent control flow diagram of hydraulic drilling.

Fig. 6. Intelligent rock-drilling jumbo.

3.2. Intelligent DTH drill

A DTH drill is needed when the rock-drilling jumbo cannot be used, such as in an ultrahigh section with large-bore deep-hole drilling (i.e., depth greater than 30 m, diameter of ϕ100–150 mm). The disadvantages of the DTH drill are its lack of safety, low ease-of-operation design considerations, insufficient matching of structure and parameters, oil leakage, and seepage. The existing DTH drill has low automation and is inefficient [13]. Therefore, an intelligent unmanned DTH drill was designed to support the intelligent mining technology.

The first features that were implemented in the new DTH drill were intelligent autonomous driving and a hole-positioning function. Like an intelligent rock-drilling jumbo, an intelligent DTH drilling machine should be capable of drilling holes in a predetermined position according to the requirements of the mining design. An autonomous driving function is needed for when the equipment is in drilling operation. The structure of a four-wheel independent steering system is shown in Fig. 7; this system was developed and applied to the new DTH drilling machine in order to ensure free turning in a narrow space.

Another feature to be applied was the automatic matching of the rock-drilling parameters with intelligent control technology.

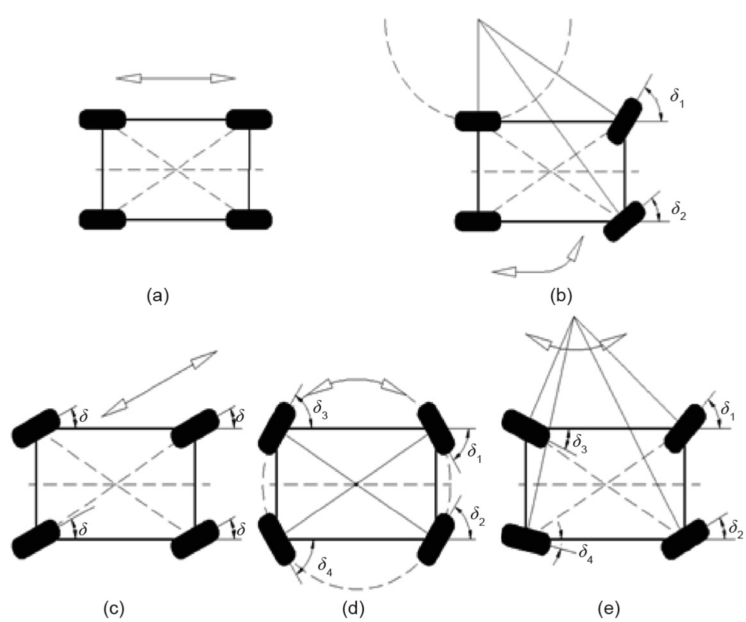

Fig. 7. The structure of a four-wheel independent steering system. (a) Straight driving; (b) front-wheel steering; (c) oblique driving; (d) point-turn motion; (e) four-wheel steering. δ: the angle of the four wheels; δ_1 and δ_2: the angles of the forward wheels; δ_3 and δ_4: the angles of the backward wheels.

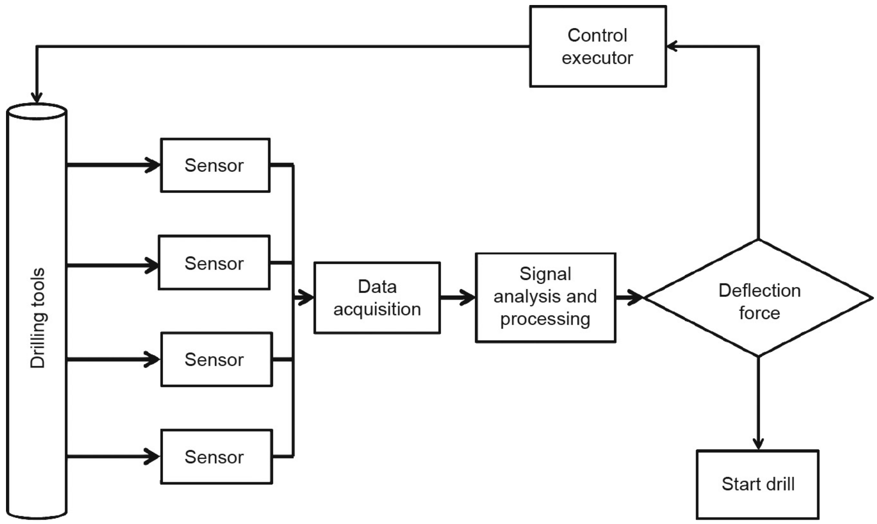

Fig. 8. Anti-deviation control flow diagram of the drilling rod.

The effect of the working parameters on drilling efficiency was analyzed by evaluating drilling parameters such as axial thrust, rotary speed, rotary torque, impact pressure, impact frequency, and rock-drilling pressure. A theoretical calculation model or empirical formula was deduced for each parameter selection, and the key parameters affecting drilling efficiency were determined. The optimal drilling parameters for the matching method were selected, including air pressure, gas volume, and propulsion force. The drilling efficiency was then optimized by intelligent control of the operation parameters.

The third feature was anti-deviation control technology, as shown in Fig. 8. Blasting can be directly affected by many factors, such as the positioning accuracy of the drill point, depth of the hole, and declination of the hole. An intelligent DTH drill should control the drill pipe in real time in order to avoid large errors that will affect the subsequent blasting [14].

The final features were multiple drill-pipe storage, automatic sorting, and anti-blocking resistance rod technology. Fig. 9 shows the operation of an intelligent DTH drilling machine. The characteristics of the DTH drill determine that if the hole is 60 m deep, then at least 40 drill pipes are needed every time. Therefore, multiple drill-pipe storage and automatic sequencing feed-rod technologies were designed in order to improve the operational efficiency of the equipment. By analyzing the mechanism of the drill rod, the parameters of the control function of the DTH drill rod can be established in order to avoid blocking of the rod during the automatic sorting process.

Fig. 9. Operation of the intelligent DTH drilling machine.

3.3. Intelligent underground scraper

Since the first successful testing of the ST-5 scraper by Wagner in the 1960s, scrapers have been widely used in underground mining because of their high efficiency, flexibility, maneuverability, and low cost. With the rapid development of electronic and information technology, intelligent control technologies for the underground scraper have been rapidly developed. The operation of the underground scraper has gradually changed from manual to remote control. At present, it is known as the fourth-generation autonomous scraper [15–18].

The main task of a scraper is the repeated transportation of ore between the loading point and the dumping point. Therefore, the first task of an intelligent scraper is to achieve unmanned driving during ore transportation. Recognition of the tunnel environment is achieved by a body-loading sensor, and a positioning and navigation system is used to assist in the operation of the scraper. Fig. 10 shows the driving algorithm of an unmanned scraper.

Another typical task of a scraper is shoveling ore, which may include automatic weighing. The main purpose of automatic weighing is to obtain real-time data and automatic statistics for the ore. Automatic weighing technology can obtain statistics for the class report, daily report, and monthly report, and can transfer this data to the central control room through the communication network. It can also enable managers to grasp the status of underground production in real time.

An intelligent underground scraper can automatically drive to a preset fixed point in order to dump ore, by relying on the positioning system, navigation system, and wireless communication system after the dispatch instruction has provided a specific dumping point. This is the basis for continuous unmanned mining with scrapers. An intelligent underground scraper does not operate within the view of its operator, and failure information cannot be observed in real time; therefore, it must be able to perform in an intelligent manner using the fault-diagnosis function [19,20]. The vehicle should be able to follow remote-control instructions from the surface such that the scraper can be controlled at any time. Fig. 11 shows the intelligent underground scraper and its remote-control platform.

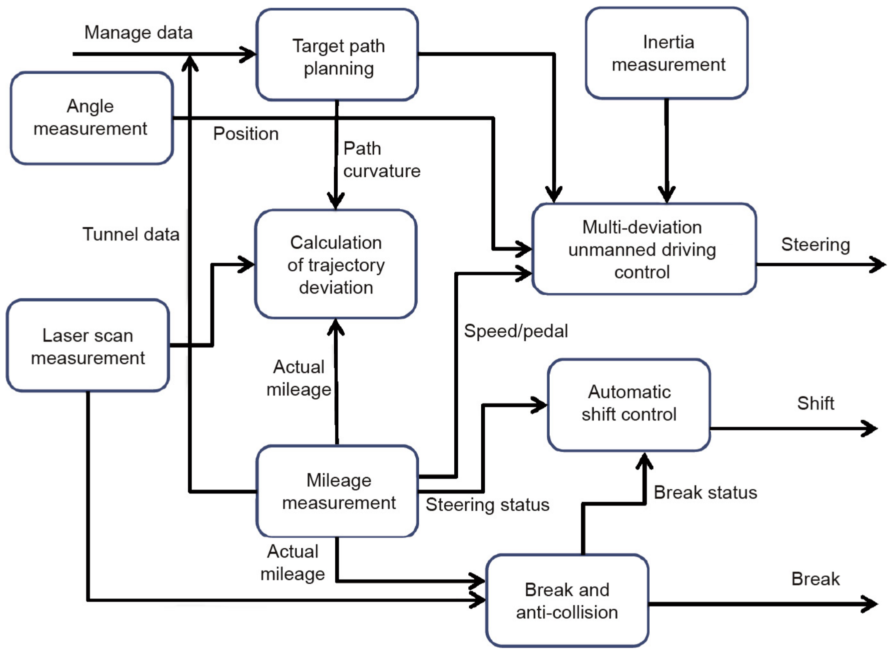

Fig. 10. The driving algorithm of an unmanned scraper.

Fig. 11. An intelligent underground scraper and its remote-control platform on the surface.

3.4. Intelligent underground mining truck

An underground mining truck is the main transport vehicle for underground trackless mining, and has the advantages of mobility, flexibility, high efficiency, and economy. Mining trucks have been widely used to transport ore in underground mines. Use of an underground mining truck can significantly improve the production capacity and labor productivity, increase the production scale, and improve the mining technology and transportation system. To conserve energy and protect the environment, a double-power transmission underground mining truck can obtain electric energy using a diesel engine driving generator. It can also obtain electric energy from the frame system through a bow collector. The vehicle has two braking systems—electric and mechanical—as shown in Fig. 12, which help to improve the degree of green mining and environmental protection.

A vehicle-control system combines the environmental information that is collected by various types of sensors. A machine-learning algorithm uses the vehicle state acquired by the articulated angle sensor to calculate the target output and control the actuator movement. Fig. 13 shows the distribution of sensors for unmanned driving. The system does not need the absolute coordinates of the vehicle; an unmanned driving function can still be achieved [21].

The first double-power transmission mining truck for use in an underground mine was designed in China for a full load of 35 t, a speed of 25 $km{\cdot}h^{-1}$, and a maximum climbing slope of 21.8%, as shown in Fig. 14. In addition to its unmanned driving function, the truck is capable of vehicle lane-space detection and intelligent auxiliary driving; it also has a remote-control function. The fully loaded autonomous operation speed is higher than 10 $km{\cdot}h^{-1}$.

3.5. Intelligent underground charging vehicle

In underground mining, the four main processes are drilling, blasting, loading, and transportation. As a charging vehicle is essential for blasting, it is very important to develop automation operation for a charging vehicle. An underground charging vehicle is an integrated mechanical and electrical product that performs raw-material transportation, explosive mixing, and gun-hole loading. It has the characteristics of a compact structure, a high degree of automation, and a wide application range.

An intelligent charging vehicle system is shown in Fig. 15. The pipe-reeling speed, pipe-feeding speed, and charging speed can be digitally controlled, and the reeling and feeding speeds are automatically matched with the charging speed and hole diameter. A fully coupled charge is achieved in order to improve the blasting effect. The safety protection system performs online monitoring and fault diagnosis of the charging system. Remote fault diagnosis, remote scheduling, remote management, and the upload and delivery of production tasks and data can be easily achieved using an intelligent scheduling system on the surface.

A charging vehicle uses wireless and intelligent control technology to achieve remote control and intelligent hole searching. The start and stop of a charging system, key process parameters,

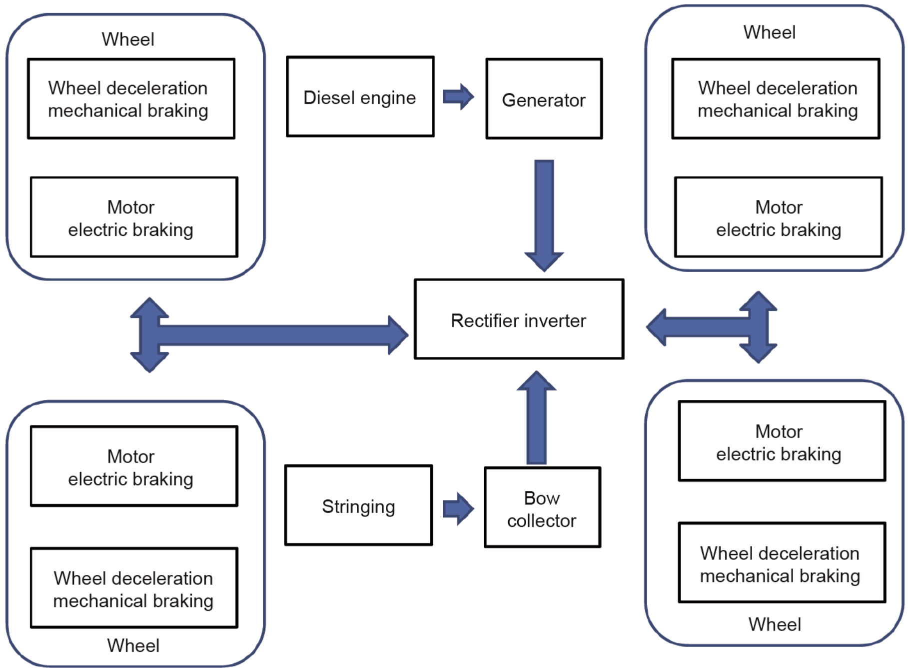

Fig. 12. A system block diagram of the double-power transmission underground mining truck.

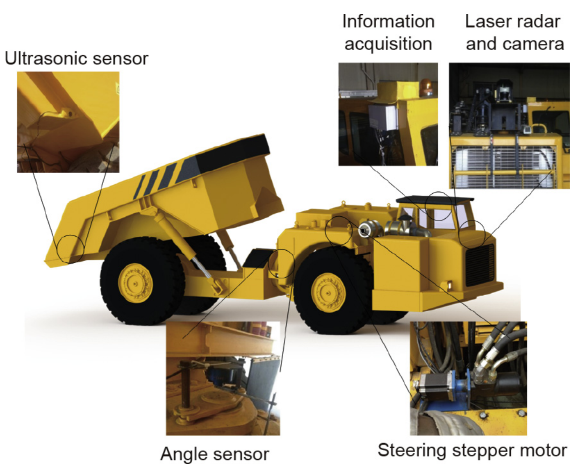

Fig. 13. Distribution of the sensors for unmanned driving.

Fig. 14. An intelligent underground mining truck.

temperature, pressure, and flow are displayed on the remote control. The automatic feeding and reeling system, automatic delivery, charging of hole depth, and single-hole charging during the delivery of pipeline are designed to support intelligent charging [22].

A wireless remote-control technology is used for the vehicle, and remote control and complete unmanned driving can be achieved using a positioning and navigation system and a wireless communication system. Coordinates can be accepted from a scheduling system, and the vehicle can then autonomously drive to the designated location point of the hole and complete the charge. Fig. 16 shows the operation of a charging vehicle in a tunnel.

4. Basic system platforms

4.1. Positioning and navigation platform

The positioning and navigation platform consists of a precise positioning system and an intelligent navigation system. The precise positioning system can provide position and altitude information to the underground mining vehicle. The intelligent navigation system consists of two key modules for path planning and path tracking. The path-planning module helps to find the navigation path of the mine vehicle according to the dispatch instructions, and the path-tracking module helps to automatically move the mine vehicle to the target position along the planning path.

Taking a point and line as the basic geometric representation, a two-dimensional (2D) navigation map was built, and accurate drawing of the underground map and detailed incorporation of the navigation information were achieved. This provides a basic map platform for the precise positioning and intelligent navigation of the mining equipment. Real-time high-precision positioning information was obtained by combining laser-positioning data with ultra-wide-band (UWB) auxiliary positioning data, as shown in Fig. 17. The positioning system consists of a high-precision laser-positioning base station system, a vehicle machine vision system, and UWB wireless positioning technology. The positioning accuracy can reach up to 100 mm. A reasonable and smooth planning path can be searched for on the electronic map using the path-planning module, based on the breadth of the first search, the dichotomy, and the symmetric polynomial curve-smoothing

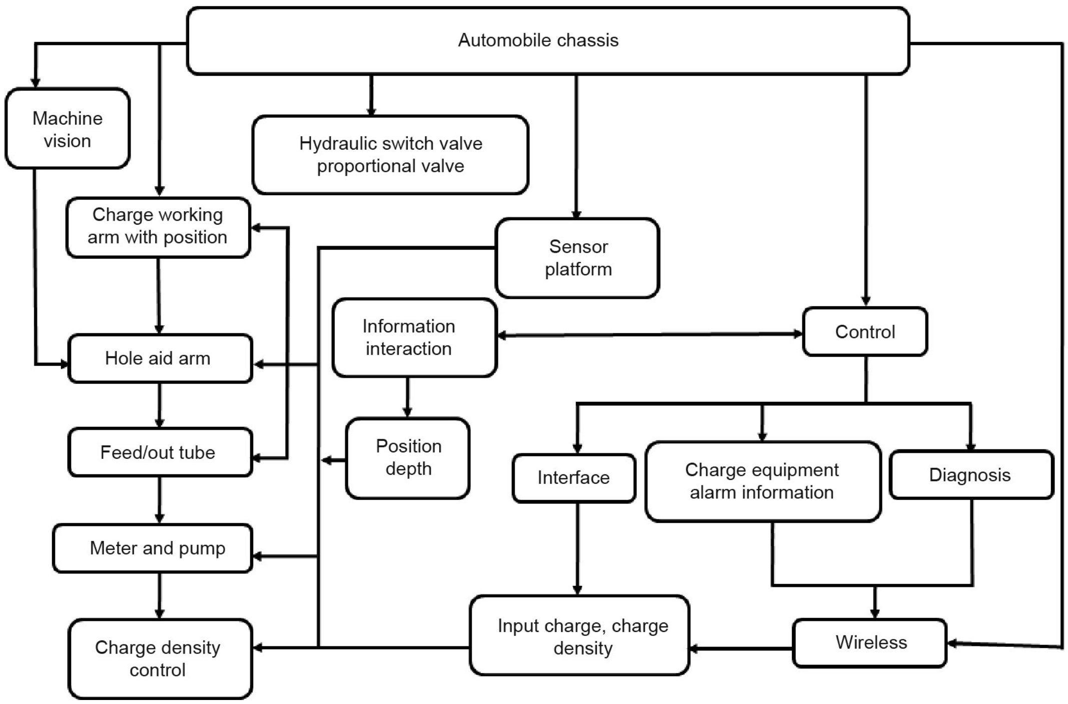

Fig. 15. Design of an intelligent charging vehicle system.

Fig. 16. An intelligent underground charging vehicle.

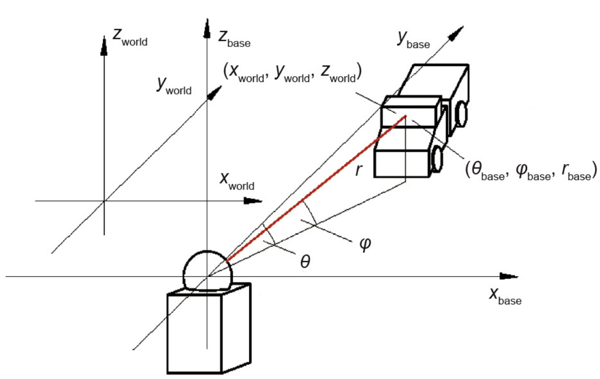

Fig. 17. Positioning information obtained by the laser system and UWB system. x_{world}-y_{world}-z_{world} is the world coordinate system; x_{base}-y_{base}-z_{base} is the local coordinate system; θ is the pitching angle and φ is the roll angle; r is the distance between the laser and the equipment; and (θ_{base}, φ_{base}, r_{base}) is the location of the equipment in the x_{base}-y_{base}-z_{base} coordinate system.

method. Hybrid architecture and a real-time reflection control system were used to achieve accurate tracking of the planning path using the positioning information [23,24].

4.2. Information-acquisition and communication platform

The main function of the information-acquisition and communication platform is to obtain intelligent mining data. The underground intelligent equipment, scheduling and control system, information-acquisition system, and data communication system work together using the same communication protocol within the framework of intelligent mining technology, as shown in Fig. 18. Thus, the extendibility, reusability, and standardization of intelligent mining technology have been achieved. Independent underground functions, geographically dispersed sensors, trackless equipment, production equipment, and local control systems were combined to form the basis of intelligent mining technology for an underground metal mine.

The basic functions are provided by a ubiquitous underground information-acquisition and control device. The real-time high-precision acquisition and rapid reliable transmission of analog, digital frequency, and video and audio frequency are achieved using a high-frequency embedded processor and distributed architecture, as shown in Fig. 18. The architecture can be configured with various pieces of underground equipment, a digital mine system, a mining production system, and an environmental monitoring system, and information can be uploaded efficiently. A non-differential data-transmission channel is established between the equipment and the communication system using CAN, RS485, Ethernet, and other data-transmission methods. A multilevel composite network architecture based on distributed technology permits the achievement of seamless roaming and redundant transmission technologies between the base stations during the movement of the underground vehicle. The underground wireless network has no blind area coverage, and has a high transmission rate and very reliable communication. This network provides a fast, efficient, and reliable data-supporting platform for the remote operation of mining equipment [25].

Fast mobile switching of underground wireless communication terminals is very important, as shown in Fig. 19. Multi-frequency cross-networking was used to overcome the communication

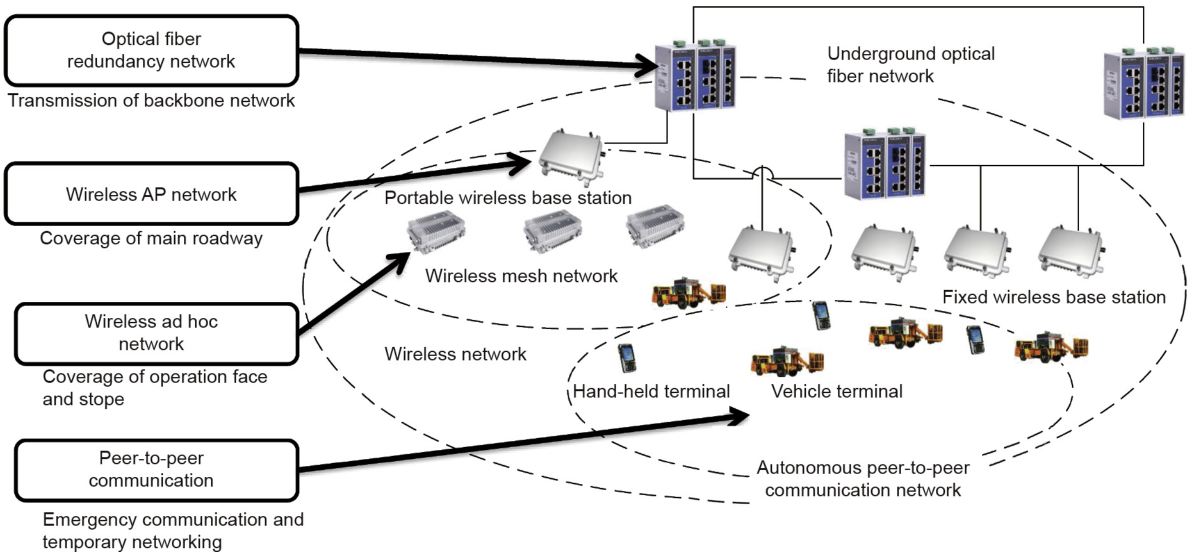

Fig. 18. Architecture of an underground wireless communication system. AP: access point.

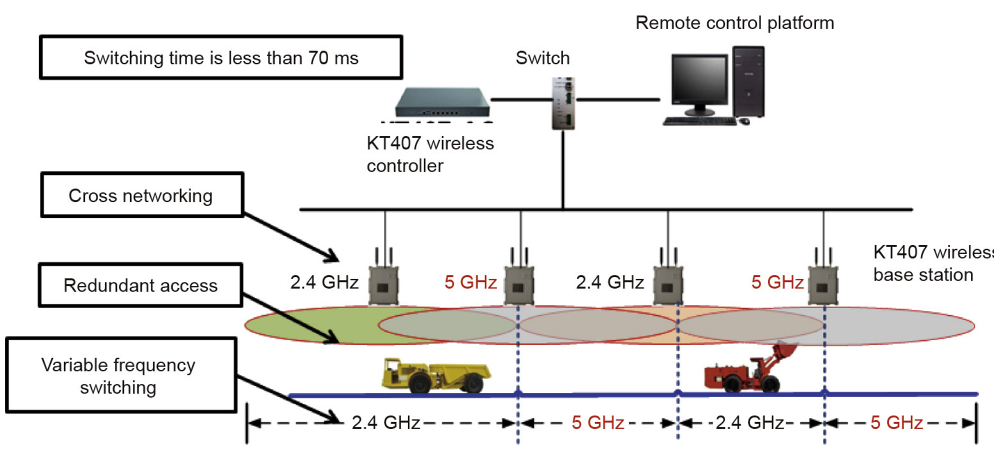

Fig. 19. Fast mobile switching of underground wireless communication terminals.

interruption problem for underground equipment in motion. Seamless mobile handover of the operation process of intelligent equipment was achieved. The communication system overcame the communication-rate bottleneck of traditional wireless devices and achieved a wireless link rate of up to 600 $\mathrm{Mbit \cdot s^{-1}}$ using 802.11n technology. The automatic identification, classification, and transmission of underground intelligent equipment business data were fully supported. A stable network communication platform was thus provided for the remote control and autonomous operation of the equipment.

4.3. Scheduling and control platform

The intelligent scheduling and control system plays an important role in the performance of mining. An intelligent software platform and management center are key features of an intelligent mining system. Based on the actual demand of underground metal mine production scheduling and process control, the intelligent dispatch of an underground metal mine based on a data warehouse was achieved by implementing key technologies such as the organization and management of multisource data, 3D visualization of resources and mining environment, dynamic simulation of production processes, and intelligent dispatch and control systems.

The scheduling and control system also performs the functions of organizing and managing mine data, modeling and updating resources, identifying the mining environment, automatically producing the mining plan, and intelligently dispatching the production process [26]. The platform can provide information on the 3D environment simulation, simulation of equipment condition, real-time status of equipment, intelligent scheduling of equipment, device real-time video, and location. An integrated intelligent scheduling and control platform for intelligent mining was built using this system, as shown in Fig. 20.

5. Experiment

An intelligent mining system was built in the middle part of the Fankou Lead-Zinc Mine in China. Centralized control, high-speed communication, autonomous driving, and the intelligent operations of an underground scraper, a mining truck, a rock-drilling jumbo, and a DTH drill were tested. The framework diagram is shown in Fig. 21.

The industrial field-test results show that the integrated technology of underground intelligent mining based on unmanned equipment is very useful. The intelligent dispatch and control system runs stably and can achieve the remote monitoring and

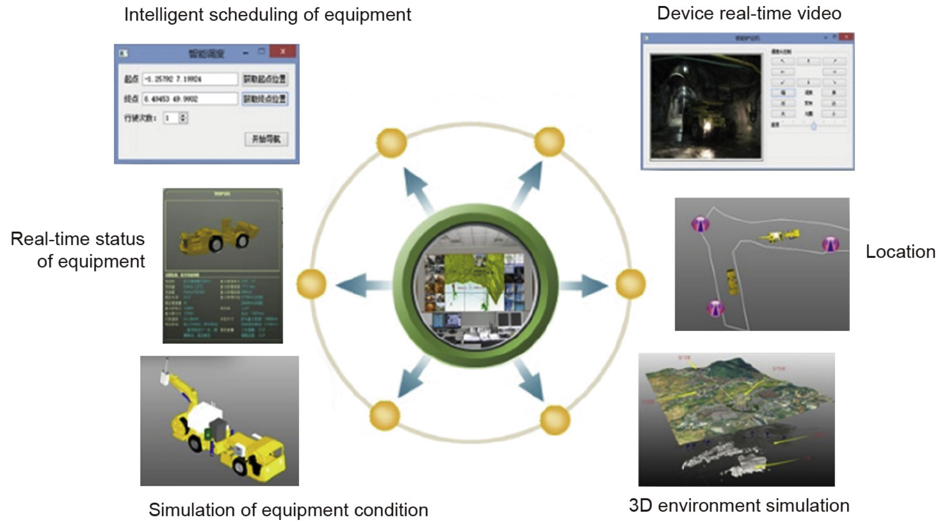

Fig. 20. Diagram of the intelligent scheduling and control platform.

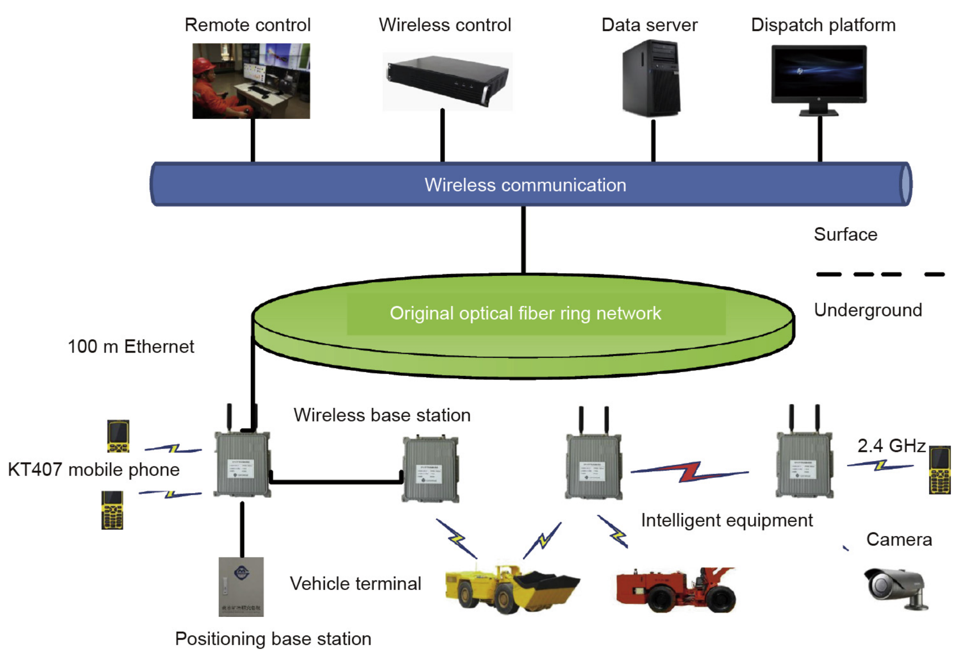

Fig. 21. A framework diagram of an intelligent mining system test in an underground metal mine.

synchronous 3D-operation display of the down-hole equipment. The positioning and navigation system is capable of navigating the underground environment and operating the equipment. The path planning is reasonable, and position tracking of the equipment was achieved with 100 mm accuracy. The performance of the ubiquitous information-acquisition and communication system was excellent.

The intelligent underground scraper had many operating modes including autonomous, remote, and manual driving, and carried out the functions of fixed-point unloading and autonomous weighing.

Autonomous driving and intelligent operation of the mining truck, charging vehicle, DTH drill, and rock-drilling jumbo were achieved. Thus, intelligent mining technology for an underground mine based on unmanned equipment was verified.

6. Conclusions

Intelligent mining technologies for underground metal mines are the concrete embodiment of China's national policy of upgrading traditional industries through modern and cutting-edge technologies. Intelligent mining technologies integrate the applications of high-end technologies based on automation, information technology, digital and artificial intelligence, and many other new technologies, through multidisciplinary and multiple technology integration. Intelligent mining not only improves the effectiveness of mining equipment and the intelligent monitoring of mining processes, but also significantly improves mining efficiency, thus reducing the mining cost and improving the competitive ability of mining enterprises. At the same time, intelligent mining can reduce the number of field operations and the risk of disasters. In addition, intelligent mining is an effective way to achieve cleaner production and sustainable development of mines. In intelligent mining, the loss and dilution of ore mining are effectively controlled, and the amount of waste ore produced by mining is minimized, while the recovery rate is maximized. Thus, intelligent mining can effectively reduce the discharge of mine solid waste and significantly improve the utilization rate of mineral resources. It can promote the efficient, safe, green, and sustainable development of mineral resources.

At the same time, intelligent mining will promote the development and enhance the core competitiveness of China's mining industry. The future application trend for underground intelligent mining is the economic, safe, and efficient mining of underground mines by relying on large-scale unmanned equipment, intelligent systems, and integrated optimal scheduling and production management. Potential for technology development lies in the combination of artificial intelligence and automatic mining. Of course, many shortcomings must still be remedied in the mining system; for example, the speed of unmanned equipment needs improvement. The reliability of the whole system needs to be verified by industrial experiments in order to meet the requirements of practical application.

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Compliance with ethics guidelines

Jian-guo Li and Kai Zhan declare that they have no conflict of interest or financial conflicts to disclose.

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