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Research on the Intelligent System Architecture and Control Strategy of Mining Robot Crowds

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Abstract: Despite the pressure of carbon emissions and clean energy, coal remains the economic backbone of many developing countries due to its abundant resources and widespread distribution. The stable supply of coal is also vital for the global economy and remains irreplaceable in the future global energy structure. China has been a major contributor to annual coal output, accounting for nearly 50% worldwide since 2014. However, despite implementing intelligent coal mining technology, China's coal mining industry still employs over 1.5 million underground miners, posing significant safety risks associated with underground mining operations. Therefore, the introduction of coal mining robots in underground mines is an urgently needed scientific and technological solution for upgrading China's and even the world's coal energy industry. The working face needs a shearer, hydraulic support, a scraper conveyor, and other equipment for coordination. The deep integration of intelligent technology with factors such as "humans, machines, the environment, and management" in the workplace is the core content of intelligent coal mines. This paper puts forward an advanced framework for robot technology systems in coal mining, including single robots, robotized equipment, robot crowds, and unmanned systems. The framework clarifies the common key technologies of coal mining robot research and development and the cross-integration with new technologies such as 5G, the industrial internet, big data, artificial intelligence, and digital twins to improve the autonomous and intelligent application of coal mining robots. By establishing a scientific and complete standard system for coal mining robots, we aim to achieve the customized research and development and standardized production of various types of robot. A specific analysis is conducted on the research progress of common key technologies such as the explosion-proof design, mechanical system innovation, power drive, intelligent sensing, positioning and navigation, and underground communication of coal mining robots. The current research and application status of various types of coal mining robots in China are summarized. A new direction for future coal mining robot research and development is proposed. Robotic mining systems should be promoted to enhance the overall intelligence level and efficiency of mining equipment. To develop human–machine environment-integrated robots to improve the autonomy and collaboration level of coal mining robots, the digital twinning of the entire mine robot system should be accelerated; the normalized operation level of coal mine robots should be improved; research on coal mining robots, shield support robots, and transportation robots should be performed; intelligence should be achieved in fully mechanized mining faces; and equipment shield support for fully mechanized mining faces should be provided. The practical process of implementing coal mining robotization is summarized in this paper, and the technical and engineering feasibility of the coal mining machine population is verified.

Keywords: coal mining; robot crowds; intelligent system architecture; control strategy

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1. Introduction

As an important part of the global energy supply, coal's status is still difficult to be replaced in the short term. According to a report of the International Energy Agency (IEA), although the use of renewable energy is growing rapidly, coal still accounts for a considerable share in the global energy structure, especially in some developing countries in Asia. Due to the limitations of economic and technological conditions in these countries, coal is still the main source of energy, supporting the process of industrialization and urbanization. As shown in Figure 1, by 2050 global coal production will still exceed 3.5 billion tons. In addition, coal is closely related to energy-intensive industries such as the steel and chemical industries, which use coal as a raw material and a fuel in large quantities in the production process. Therefore, the relevance of coal to the global energy structure cannot be ignored [1]. In the transition to clean fuels, carbon dioxide emissions from the use of coal is an important issue. In order to reduce the impact of these emissions on the environment, carbon capture and storage (CCS) technology has become an important solution. According to the report of the Intergovernmental Panel on Climate Change (IPCC), CCS technology can significantly reduce carbon dioxide emissions from the use of coal, which is of great significance for achieving the global greenhouse gas emission reduction targets [2]. With CCS technology, the carbon dioxide generated by coal combustion can be captured and stored to avoid its emission into the atmosphere. This technology has been applied in some countries and regions with positive results. In the context of net zero emissions, mining automation technology has broad application potential. With the development of clean energy, the demand for key raw materials such as lithium and cobalt is increasing. The mining process of these raw materials can be optimized by automation technology to improve mining efficiency, reduce energy consumption, and reduce environmental impact. According to a report of the mining research institutions, automation technology has been applied in some mines with significant results [3]. Through automation technology, the intelligent management of mines, the optimization of production processes, and the improvement of resource utilization can be achieved. In addition, automation technology can also be applied in the process of coal mining to improve the safety and environmental protection of coal mining. Therefore, mining automation technology has broad application prospects worldwide. In summary, coal still plays an important role in the global energy structure and also plays an important role in the transition to clean fuels and mining automation technology.

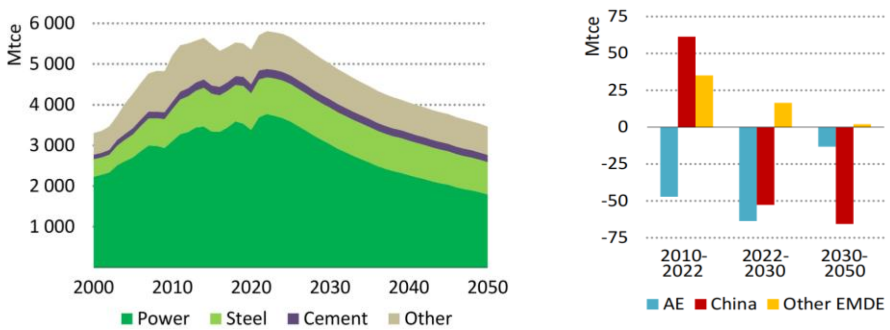

Figure 1. Global coal demand by sector and annual average change by region in the STEPS, 2000–2050 [1].

Since 2014, fully mechanized mining equipment automation and information technology have been adopted in the Huangling Coal Mine No.1 in China. The Shaanxi Coal and Chemical Industry Group coal mine in Shaanxi Province, China, uses the "unmanned operation and patrol" visual remote intervention mining mode. There are more than 500 intelligent mining faces in China [3]. The development process of intelligent mining in China's mining industry is shown in Figure 2.

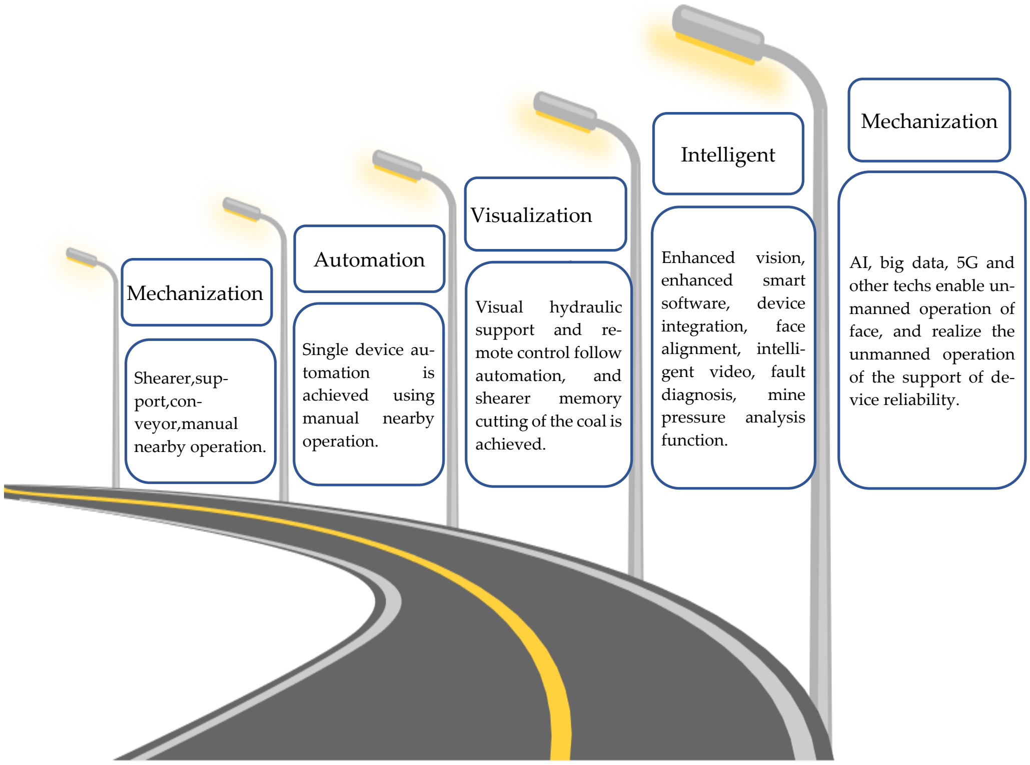

Figure 2. Development path of an intelligent mine in China.

Most of these fully mechanized working faces have good geological conditions. When encountering complex geological conditions, various equipment companies have begun to try to use robot technology to solve the adaptability problem in mining environments. Although inspection robots have been used to monitor the production process of fully mechanized mining faces, they have not yet been integrated into the fully mechanized mining automation control system. The three machines used at the coal face can be rotated to form a group of mining robots, including mining robots, shield support robots, transportation robots, and inspection robots; this approach is a future solution suitable for the complex giant systems of mining production in most coal mines in China. Based on an analysis of the problems that arise in the current intelligent process of fully mechanized mining, this article proposes the building of a machine crowd system with a coal mining robot group at the core, and studies the cooperative control strategy of machine crowds. This includes using inertial navigation devices to solve the straightness problem of the working face and conducting research on the sliding control of scraper conveyors and on inspection robots to achieve the goals of coal mining machines. This paper discusses the autonomous operation and multi-machines cooperative linkage operation of mining production equipment, such as hydraulic supports and conveyors, and provides a summary of the practical process of implementing coal mining robotization. The development process of China's coal mine robot industry is shown in Figure 3.

China has been stepping up the use of robots in coal mines to improve mining efficiency and safety. According to the classification of the Key R&D Catalogue of Coal Mine Robots issued by the National Coal Mine Safety Administration, coal mine robots are currently categorized into five groups: tunneling, coal mining, transportation, security control, and rescue, as shown in Figure 4 [4].

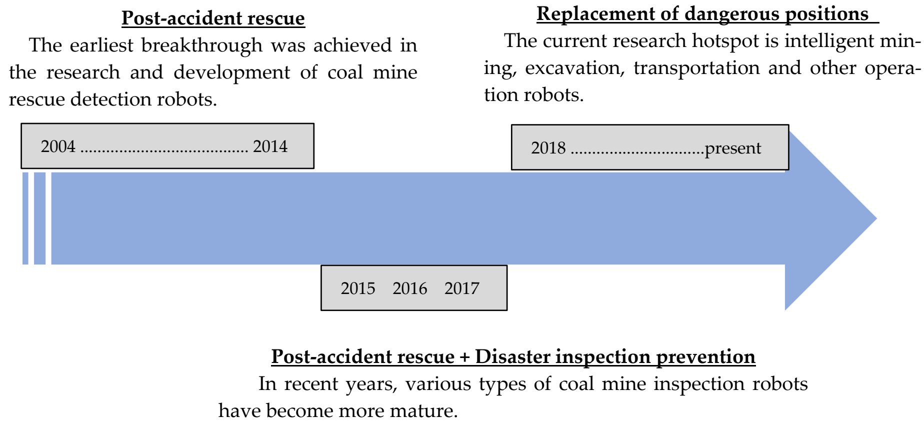

Figure 3. The development process of China's coal mine robot industry.

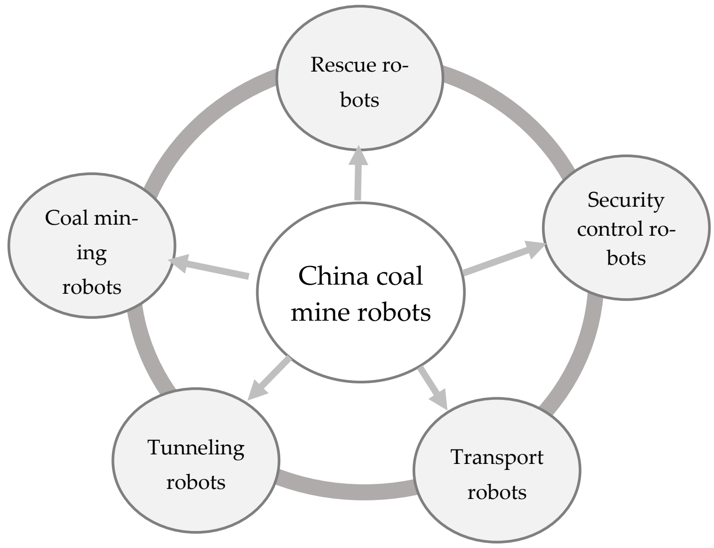

Figure 4. Classification of coal mine robots according to operation area and functions in China.

The robots have been used in patrolling, picking refuse, and nine other situations, while nineteen other applications are under development. These robots are used in numerous subsystems, such as geology, tunneling, coal mining, main and auxiliary transportation, power supply, and drainage in intelligent coal mines, as shown in Table 1. The traditional method of control for coal mine robots mostly consists of independent supporting control systems for each robot. These systems are activated using manual instructions to perform regular tasks. However, there is a lack of unified scheduling between robots and there is no effective interaction with the intelligent coal mine's main system. Consequently, it becomes difficult to fully utilize the potential of these robots.

The research on coal mining robots in China has centered around the China University of Mining and Technology and the China Coal Science and Engineering Group. Video monitoring technology is used in the fully mechanized mining of working faces to "extend" human vision to the working face, freeing operators from harsh working faces by using monitoring centers or ground control centers [4]. Based on real-time monitoring videos, the equipment at the fully mechanized working face is centrally controlled, thus providing the mining face with robot features. The intelligent adaptive mining mode is based on visual remote intervention technology and further enhances the intelligence of mining control systems through transparent mining by enhancing the capabilities of mining environment perception, intelligent decision making, and adaptive equipment control.

Table 1. China's 38 kinds of robot for coal mines.

Robot Groups	Robot Names	Order
Tunneling robot	Excavating working face machine crowd	1
	Driving robot	2
	Full-section vertical shaft shield robot	3
	Temporary shield support robot	4
	Anchor robot	5
	Spraying robot	6
	Water exploration drilling robot	7
	Anti-process drilling robot	8
	Anti-impact drilling robot	9
Coal mining robot	Coal mining robot crowds	10
	Shearer robot	11
	Advance roof support robot	12
	Filling and roof support robot	13
	Open-pit mine perforated blasting robot	14
Transportation robot	Handling robot	15
	Broken robot	16
	Car yard cart robot	17
	Tunneling cleaning robot	18
	Coal bunker cleaning robot	19
	Water warehouse cleaning robot	20
	Choose rock robot	21
	Tunneling dust-washing robot	22
	Underground unmanned transport vehicle	23
	Automatic loading system for open pit electric shovel	24
	Open-pit mine truck unmanned system	25
Security control robot	Working face inspection robot	26
	Pipeline inspection robot	27
	Ventilation-monitoring robot	28
	Dangerous gas inspection robot	29
	Automatic drainage robot	30
	Closed masonry robot	31
	Pipe-mounting robot	32
	Belt conveyor inspection robot	33
	Well safety intelligent inspection robot	34
	Tunneling inspection robot	35
Rescue robot	Underground emergency rescue operation robot	36
	Mine rescue robot	37
	Post-disaster search and rescue of an amphibious robot	38

With the application of more types of robots underground, the system will implement the intelligentization of robot operation and charging according to the formulated task strategy and charging scheduling strategy, effectively improving the operation management level and the collaborative operation efficiency of the robot crowds. At the same time, by using the massive basic mine data provided by the underlying equipment, the platform layer uses artificial intelligence technology to build a data model, realizing the intelligent control of robots driven by data. In addition, 5G network data access is supported, using its high-speed, low delay, and high reliability characteristics, with the latter realizing the remote control of robot crowds and the simulation of the entire process, further improving the production equipment security control under the intelligent mine architecture.

The coal mine robot is an important branch of the special robot field. It is an important technological innovation in coal mine intelligence and is also a new development direction in the cross-integration of traditional coal machinery equipment and modern robot technology. In recent years, with widespread policy promotion, scientific and technological traction, and engineering applications, the development of coal mine robots has made significant progress: its concept definition is clearer, the coverage is expanding, and an increasing number of robot products and pieces of intelligent equipment are being applied in the coal mining field. The underground coal mine robot has multi-variety, multi-scene, multi-mode, and multi-functional characteristics [5]. Due to the complex process of coal mining operations and the fact that multi-seam and multi-face mining modes exist in individual mines, a large number of single-robot installations and applications are employed in different operational scenarios and processes, leading to considerable difficulties in the management and normal operation of coal mine robots, including the following:

(1) Each single robot is relatively independent. There are many types of robots, and the data communication interface and protocol are not unified.
(2) There is a lack of interaction regarding information between the surrounding environment and personnel, meaning there is no data fusion or analysis.
(3) The robot's operation is isolated, and the robot is not included in the coal mine safety production management system. The cooperative operation ability between homogeneous and heterogeneous robots lack a unified scheduling and management, and the overall operation efficiency is low [3].

For these reasons, it is necessary to carry out the crowd-coordinated scheduling of heterogeneous robots for different operation scenarios and processes in coal mines, to give full play to the advantages of robot crowds, to shield support intelligent businesses involved in coal mine production processes and fixed scenarios, and to realize the all-round perception and fusion monitoring, task scheduling, crowd management, and collaborative control of single-robot and robot swarm operation processes.

2. Current Situation of Intelligent Mining Robots in China and Abroad

2.1. Current Status of Foreign Coal Mine Robot Technology

After the realization of mechanization and digitization, coal mining will enter a new stage of robotization. The global mining industry has developed a variety of mining robots to achieve coal mining, shield support, anchor protection, rescue functions, and other production safety functions. Consequently, the transformation of traditional mining models into intelligent mining models should be promoted.

The research on coal mining robots abroad has mainly focused on developed countries, such as the United States, Germany, and Japan, and the representative research results are as follows:

(1) ACARP (The Australian Coal Industry's Research Program) is a unique and highly successful mining research program that has been running in Australia since it was established in 1992. The project was undertaken by CSIRO (Sydney, Australia) Exploration & Mining and the Cooperative Research Centre for Mining Equipment and Technology CMTE and had the support of the major longwall equipment manufacturers. It is 100% owned and funded by all Australian black coal producers through a five cents per ton levy paid on saleable coal. Most development operations in Australia utilize manual line-of-sight, radio-controlled miners to cut roadways, and operator-driven shuttle cars to transfer coal from the working face. These levels of technology are not able to achieve the goal of the safe remote operation of roadway development. Two issues have been identified that inhibit progress in the domain of remote development: ① Continuous miner self-steering technology to maintain desired roadway headings has not yet reached the required level of performance required for sustained remote operation. ② No automated options currently exist to guide shuttle cars while tramming through roadway systems and whilst avoiding ribs, cut-through corners, and other infrastructure. A system based on CSIRO's ExScan technology along with SLAM techniques has been developed to address these issues. A bracket that mounts two ExScans on the shuttle car operator cab has been designed so that the ExScans provide both forward and reverse views along with the distance to the ribs during operation. The bracket is currently being fabricated. The system electronics have also been operated for several days inside an enclosure to ensure the system does not overheat when running in production conditions, which was successful. Once the mounting bracket and components have been fabricated,

the system will be assembled and tested at CSIRO to confirm the ExScan mounting configuration is stable. Once that is deemed suitable, the system will be transported to the host site for installation on a shuttle car so that a production trial can be conducted with UPEE approval.

LASC is an English abbreviation for the Longwall Automation Steering Committee. It is managed by CRC Mining, a subsidiary of CSIRO. The LASC's longwall automation technology has been developed as a significant milestone project funded by the Australian Coal Association (ACA) through ACARP. Launched in 2001, this technology has been widely adopted, with approximately 70% of longwall working faces in Australia currently utilizing it. The latest iteration of this technology is known as LASC2.0. Notably, DBT, JOY, Eickhoff, Neapen, and other OEMs are authorized manufacturers of LASC technology and must adhere to established protocols, interfaces, and standards when implementing it.

(2) The White Oak Coal Mine(Illinois Basin, US) has developed a planned shearer, significantly improving the work efficiency and programmable operation capabilities. The coal mining robot adopts a wheeled walking and robotic arm mining method, which can complete the entire coal mining process [6], as shown in Figure 5. The robot also has the functions of autonomous control and navigation; it can independently plan coal mining routes based on the situation of the mine and improve coal mining efficiency.

Figure 5. Realistic view of the working face in the White Oak Coal Mine of the US.

(3) German coal mining robot: The German Bosch company(Stuttgart, Germany) developed a coal mining robot that uses wheeled walking and mechanical arm mining and can complete the entire mining process. The robot also has the functions of autonomous control and autonomous navigation and can independently plan the coal mining route according to the situation of the mine to improve the mining efficiency. In addition, the robot uses advanced sensing technologies such as LIDAR and infrared cameras to measure and detect the internal environment of the mine with high precision [7].

(4) Japanese coal mining robot: The Robotics Institute of the University of Tokyo(Tokyo, Japanese) in Japan developed a coal mining robot that adopts the methods of caterpillar walking and mechanical arm mining and can complete the entire coal mining process. The robot also has the functions of autonomous control and navigation, and can independently plan the coal mining route according to the situation of the mine to improve efficiency [8]. In addition, the robot uses ultrasonic sensing technology, which can measure and detect the internal environment of the mine with high precision.

2.2. Current Status of China's Domestic Coal Mine Robot Technology

The following are representative research findings from a selection of institutions:

(1) China University of Mining and Technology (Xuzhou, China): A group of robotized coal mining machines was developed, among which a robotized shearer controls the coal mining drum speed, traction speed, and adaptive height. Robotized shield support can help regulate the shield support force, posture, roof support group arrangement, etc. [9]. Robotized transportation can control the speed of the scraper conveyor, the tension of the scraper chain, and the straightness. Robotized transportation integrates intelligent transfer machines, intelligent crushers, and intelligent belt conveyors for control.
(2) Shandong University(Jinan, China): A coal mining robot was developed that uses wheeled walking and hydraulic drive to complete the entire coal mining process. The robot also has the functions of autonomous control and navigation; it can independently plan coal mining routes based on the situation of the mine and improve coal mining efficiency [10].
(3) Beijing University of Science and Technology(Beijing, China): A coal mining robot was developed that adopts the methods of wheeled walking and mechanical arm coal mining and can complete the entire coal mining process. The robot also has the functions of autonomous control and navigation; it can independently plan coal mining routes based on the situation of the mine and improve coal mining efficiency.
(4) Henan University of Science and Technology(Jiaozuo, China): A coal mining robot was developed that uses track walking and hydraulic drive to complete the entire coal mining process. The robot also has the functions of autonomous control and navigation; it can independently plan coal mining routes based on the situation of the mine and improve coal mining efficiency.
(5) China Coal Science and Technology Group(Beijing China): The research and development of two sub-projects of the National Key Research and Development Plan project "Research and Development of Intelligent Mining Safety Technology and Equipment in Coal Mines", namely, the "Intelligent Mining Control Technology and Equipment" the and "Unmanned Working Face Inspection Robot", were implemented [11], as shown in Figure 6. We conducted industrial experiments on coal mining inspection robots at Shaanxi Huangling Mining Company (Yan'an, China) and undertook the development of inspection robots in Project 6 of the National Key Research and Development Plan. To achieve the production goal of intelligent working faces from "unmanned operation and manned inspection" to "unmanned operation and unmanned inspection", the Tianma Company (Beijing, China) proposed a plan to use automatic inspection robots on working faces to replace inspection personnel and proposed mining equipment suitable for long, narrow underground mining spaces and dangerous and harsh working environments [12].

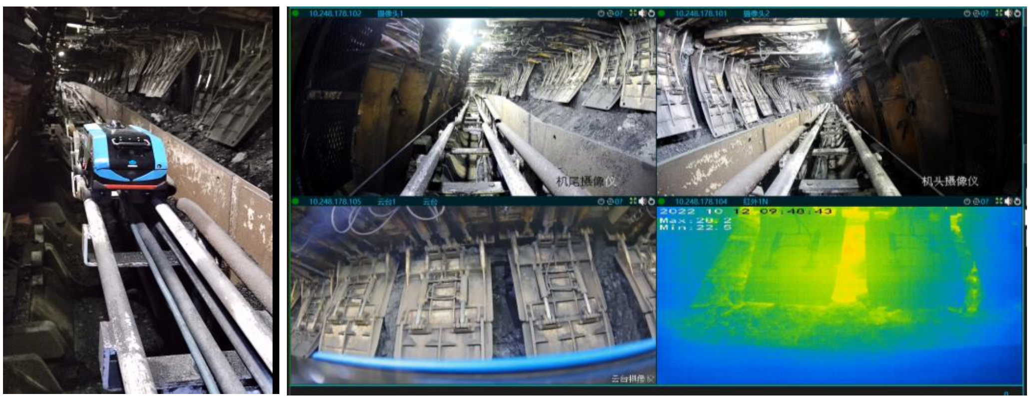

Figure 6. Operation of the inspection robot in the Huangling Mining No. 1 Mine (Yan'an, China) and the Shendong Mining Yujialiang Mine (Yuling, China).

3. Construction of Mining Robot Crowds

3.1. Layer Levels of Mining Robots

The current coal mine robots primarily function as inspection robots due to the limitations imposed by complex operational environments and special requirements such as explosion prevention. As a result, there is a scarcity of mature operational robots for various auxiliary operation posts [13]. To address this demand for crowd control in coal mine robotics applications, a robot crowd control and scheduling platform was developed along with key technologies for collaborative robots crowd control.

(1) Method for target position recognition in complex application scenarios within coal mines: A multi-dimensional information-splicing algorithm based on multi-visual sensors was developed specifically for tunneling scenarios in coal mines. This algorithm enables the automatic differentiation of position information regarding target objects through external parameter calculations that facilitate multi-dimensional information splicing and fusion using RGB images and point clouds. This approach establishes a multi-dimensional feature space to describe the global features of targets, while identifying key points based on the projection mapping relationship, and realizes the accurate operation of the robot.

(2) Standardized access technology for coal mine robots: In order to ensure the standardization of the data access of the robot and the objectification of the data model, the unified robot communication protocol and middleware based on OPC UA were used for development. The data standardization process of the coal mine robot is shown in Figure 7. OPC UA uses service-oriented architecture to realize the data exchange. Based on the TCP/IP protocol, the three-handshake principle is adopted to send messages through the communication stack to ensure the reliability of the data transmission [14]. When OPC UA is applied to the information interaction of the coal mine robot, on the one hand, the mining robot swarm and auxiliary robot swarm that have already transmitted data through the OPC are upgraded and the objectified information model is constructed to form a rapidly expanding object that includes the basic information, attitude information, and control information of the robot; on the other hand, a protocol-adaptive conversion is realized by building the protocol middleware.

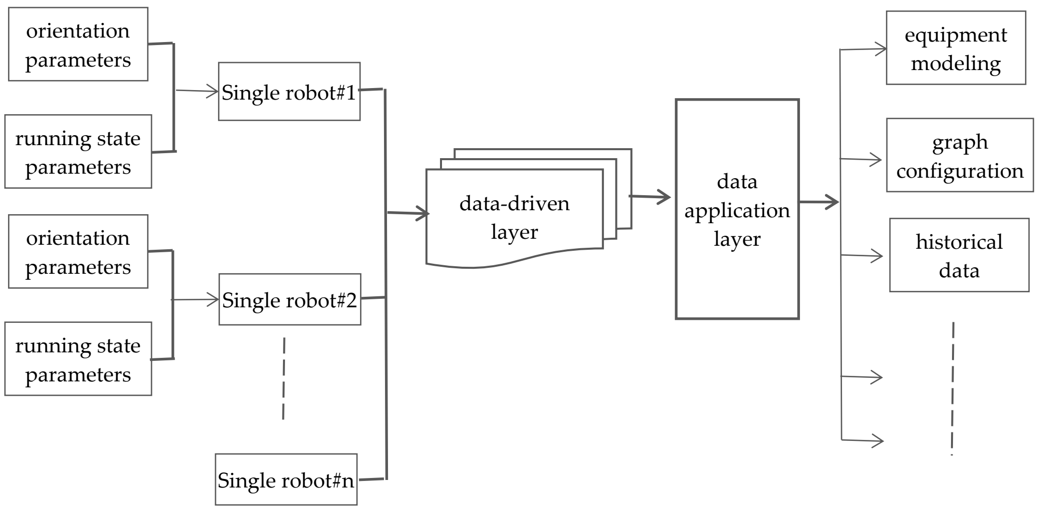

Figure 7. Data standardization process of coal mine robot.

(3) Robot job scheduling strategy: In order to respond to emergencies and complete normal inspection tasks within the region at the same time, the same kind of job scheduling strategy is proposed. Grid management is adopted to divide the application scenarios of similar robots into several regions, and the robots are assigned according to these regions to ensure a normal inspection in each scenario. The grid

management is subject to the scheduling time, which is the main indicator used to measure the speed of a robot's response. Under the limited robot resource configuration, reasonable deployment can ensure the shortest response time of the robots in the region. In the daily scheduling command, although the independent scheduling of a single robot and the coverage scheduling of similar robots are two different types of resource deployment methods, they are often combined with each other in practical applications. First, the task is assigned to the key emergency scenarios, and then the deployment of regional mobile inspection operations is carried out.

(4) Robot crowds management and collaborative scheduling platform: This scheduling platform is divided into a robot swarm layer, a communication access layer, an application service layer, a data release layer, and a data interaction layer at the technical architecture level.

Robot swarm layer: This includes tunneling robots, coal mining robots, transportation robots, and other types of robot devices and sensor monitoring information, including robot ontology data, position data, action attitude data, and video information.

Communication access layer: This layer mainly uses WiFi/4G/5G/Industrial Ethernet to build the network link for robot data transmission, achieving the data acquisition, object-oriented modeling, data processing, and storage management of field robots.

Application service layer: This is the base of the robot crowd control platform, used to analyze and process the massive data required by the upper specific business.

Data release layer: This layer applies data sharing services to obtain object-oriented data from various robots and from professional algorithm models and transfers the calculation results based on Restful, WebAPI, OPC, and other methods of data sharing and release.

Data interaction layer: This layer is combined with the needs of front-end robots in data twinning, simulation interaction, and collaborative control, and applies HTML5, GIS mapping, U3D, charts, graphics, and other modes of business application interaction.

On the basis of the research on single-machine equipment technology and equipment development, a group of coal mining robots was constructed that is composed of auxiliary systems such as a power supply, a liquid supply, and lighting to collaborate with a group of machines [15], as shown in Figure 8.

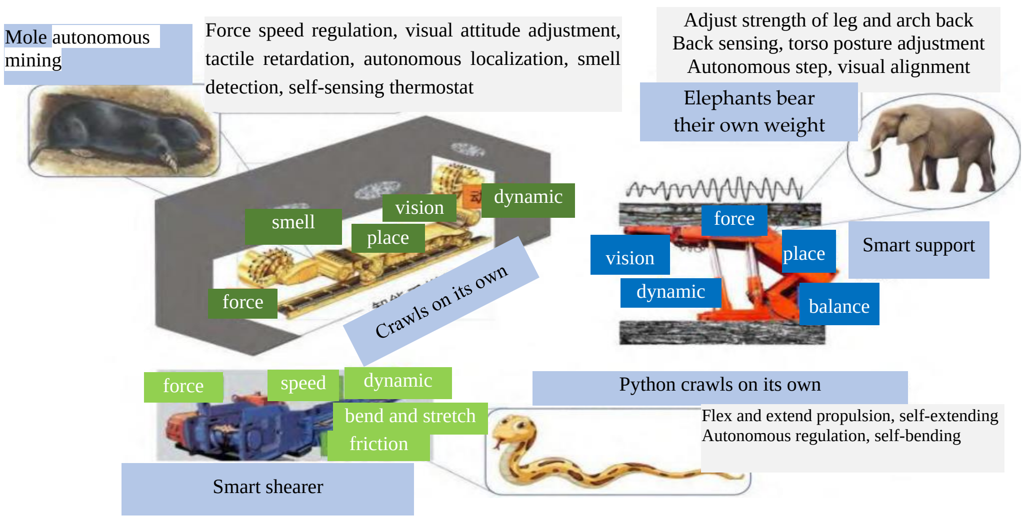

Figure 8. The development of intelligent functionalities for fully mechanized mining face equipment in China.

The cooperative control platform at one end of the working face is the central link for achieving the intelligent mining of the working face. In mining work, the coal mining robot can autonomously and adaptively predict coal cutting, and the hydraulic support robot collaborates with the coal mining robot to achieve automatic machining following operations on the entire working face [16]. The coal mining machine and the other three machines have dual closed-loop cooperative control, significantly improving the level of intelligence. Undercover and mining height data can be dynamically optimized by analyzing the historical data from multiple sources [17].

3.2. Mining Robot

For the mining robot to achieve the local control of the operator, the technology must be very mature, with a focus on improving the reliability of the shaft encoder of the mining machine, enhancing the detection accuracy of the height of the rocker arm, and improving the control accuracy as the breakthrough point in order to carry out the research of the mining robot, as shown in Figure 9.

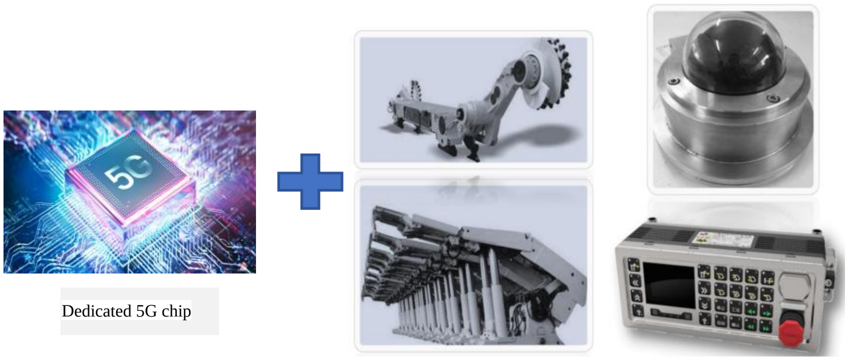

Figure 9. Mining equipment for a coal mining machine crowd.

Various methods, such as a central follow-up, a triangular follow-up, and cutting processes, are used for coal mining machines and hydraulic supports to achieve automated coal cutting control [18]. Through touch operation, the real-time online modification of the mining height and undulation settings is achieved, the planning and cutting of the local mining height are achieved, and various undulation adjustment strategies are supported. The offline editing of coal mining processes should be supported, and multiple mining process configurations should be developed.

The online monitoring and control of coal mining stages and tasks should also be supported. The coal cutting process of the coal mining machine and the following roof support process can be switched according to the coal mining process. Intelligent image recognition was performed for four scenarios: the position of the shearer drum, the position of the personnel on the working face, the large amount of coal in the upstream drum of the coal flow, and the working conditions of the tail scraper conveyor, as shown in Figure 10. Active alarms that sound alerts to abnormal working conditions on the working face should be developed, and remote monitoring by personnel should be supported [19].

(1) The operation and control accuracy of robots needs to be continuously improved to meet the needs of coal mining. The autonomy and intelligence of the robots also need to be continuously improved to meet the operational requirements in complex environments [20]. Specifically, these improvements can be achieved by improving the robot's sensors, control systems, and computing capabilities [21]. For example, the use of high-precision inertial navigation systems, multi-sensor fusion technology, and high-performance computing platforms enables robots to perceive and control their motion and posture more accurately.

(2) An intelligent coal mining robot crowd control system based on the integration of production, safety, and environmental protection information throughout the entire process should be developed. Moreover, a hierarchical scheduling planning strategy and process knowledge graph for coal mining machine populations should be constructed; human–machine collaboration, cloud–edge collaboration, and robot–group collaboration should be achieved; and an intelligent coal mining robot group control mode should be created that integrates the horizontal business collaboration and vertical processes, forming a crowd effect [21]. Robotization refers to endowing traditional

machinery with robot functions, providing it with semi-autonomous or autonomous operation capabilities in specific environments [22]. Traditional machinery can be replaced with robots to complete production tasks such as mining, transportation, and selection; an adaptive flexible production process can be formed through autonomous collaboration among robot groups; and a highly productive, reliable, and safe robotic mining system can be constructed.

(3) The robotized mining system embodies the characteristics of "integration of networking, intelligence, and robotization" [23]. Networking helps robotization to "go hand in hand", and intelligence empowers robotization, much like "adding wings to a tiger", greatly improving the level of mining autonomy and achieving the goals of robotization.

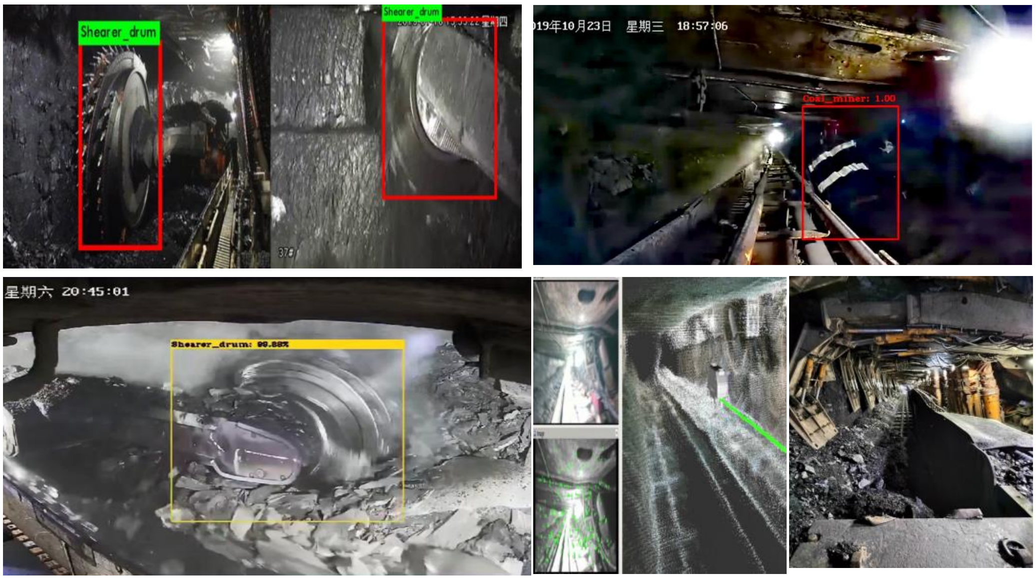

Figure 10. The practical application with intelligent video is applied to fully mechanized mining face in China.

It is necessary to study the intelligent process mode that is most suitable for robotized mining according to the new design concept of advanced intelligence and unmanned mining; to build a framework for robotized mining technology from the bottom; to break through the key technologies of heavy-duty robot design, manufacturing, operation, and maintenance; and to develop complete sets of robotized equipment, such as those used in coal mining and transportation to realize intelligent, safe, and efficient mining operations [24].

The actions targeting the individual motion structure of the robot crowd reserve the data-driven interface for single-robot and multi-robot action processes. This includes reserving virtual variables such as the forward and backward displacement, the roller rotation, and the rocker arm angle for the coal mining robot, as well as the top beam contraction, the plate opening and closing, and the propulsion for the hydraulic support. The virtual bus data from the intelligent mine industry's basic internet information platform is accessed through HTTP using the Unity engine to obtain the robot environment and motion pose data. The script mounted above the model structure based on the data reflection identifies and assigns real data to these reserved virtual variables, as shown in Table 2. Structural components are then used to generate movement. Taking a fully mechanized mining face as an example, Table 1 shows the digital twin of a coal mining face [25].

Table 2. Reserved variables of mining robot virtual entity.

Variable Name	Function Name	Scope of Variables
Shearer forward displacement	Shearer move forward-1_S1232	1~2000 m
Shearer back displacement	Shearer move backward_S1232	1~2000 m
Turning state of the left roller	Left drums state_S1232	0, 1
Turning state of the right drum	Right drums state_S1232	0, 1
Left rocking arm rotation angle	Left arm rotation angle_S1232	−15~+35°
Right rocking arm rotation angle	Right arm rotation Angle_S1232	−15~+35°
Left oil cylinder length	Left cylinder length_S1232	0~800 mm
Right oil cylinder length	Right cylinder length_S1232	0~800 mm

3.3. Roof Support Robot

For the support robot, the position of the combined force of the attitude support is calculated automatically.

The core control unit of the support robot is an electro-hydraulic control system that provides remote control and intelligent control of the support. The electro-hydraulic control system is equipped with a mining height sensor for collision detection, attitude detection, mining height measurement, and remote control. In addition to the conventional functions, the electro-hydraulic control system adopts the Ethernet transmission protocol and can be used as a data transmission platform for the working surface equipment. Fault self-diagnosis includes diagnosing the fault and determining the possible cause of the fault; this approach can provide an early warning of the failure of the hydraulic support and reduce the occurrence of failure [26]. The approach also has the ability to analyze the mine pressure of the working face.

The end support of the working face is complex and changeable, and it is also an accident-prone area that has a significant impact on fully mechanized mining production and needs timely detection and treatment [27]. For working faces with large inclination angles, there is the problem of up-sliding, the lack of coordinated promotion of the two lanes, and the monitoring of the conveyor up-sliding. It is still necessary for operators to make manual adjustments according to the actual situation of the working face.

3.4. Transportation Robot

For transportation robots, the core is the scraper conveyor, which controls the status monitoring and coal flow detection as well as the upward and downward movement of the scraper conveyor. Simultaneously, the adaptive control of the start/stop and intelligent speed control are needed. For example, ultrasonic sensors can be used to upload data and analyze the starting position of the coal flow, as shown in Figure 11.

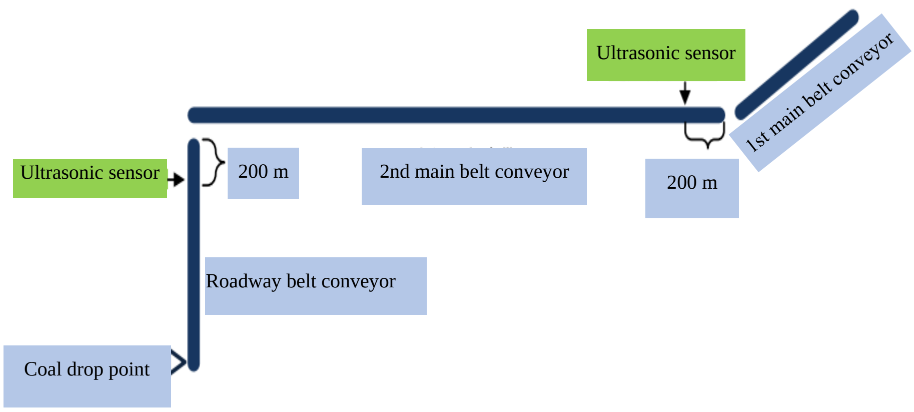

Figure 11. Ultrasonic sensor used to analyze the initial position of the coal flow.

3.5. Collaborative Management and Control of Robot Crowd Operations

The coal mine robot population is a series of coal mine robots that undertake certain production operation tasks. These tasks can be divided into heterogeneous robot operations in key operation scenarios and homogeneous robot operations in auxiliary operation scenarios, which complete production cooperation and inspection cooperation, respectively. The unified task planning and operation scheduling for the same robots in specific scenarios is carried out, and the crowd scheduling operation takes place according to the integrated scheduling strategy; then, the virtual simulation and visual remote collaborative monitoring of the heterogeneous robot crowd entities and environments in the coal mining, tunneling, support, transportation, and other scenarios is carried out.

a. Heterogeneous robot operation collaboration in key operation scenarios

Taking the heterogeneous tunneling robot and coal mining robot as an example, the environmental parameters and operation posture letter of each robot are obtained in real time in order to realize the virtual synchronization and operation collaboration between digital twins and physical entities. Coal mining robots, support robots (hydraulic support and advanced support), scraper conveyors, and other components of the heterogeneous machine crowd require multi-machine linkage and cooperation to complete the coal mining operations. Based on the Unity engine and on the real-time virtual simulation of a single robot, the linkage control script is written according to the cooperative relationship between the robots and the process, as shown in Table 3. The production coordination system and logical model are built to realize the collaborative operations between the coal mining robot crowd and the tunneling robot crowd [28].

Table 3. Control scripts and synergistic relationships.

Device	Control Script	Synergistic Relationship
Shearer	Height adjusted for shaking arm of shearer, shearer walk, speed, etc.	When the shearer is running, the front roller and the front roof support start to act and the guard plate shrinks.
Support	Drop roof support, roof support push slip, etc. Scrapper running, moving	Push the slip; after the roof support is completed, the roof support falls.
Conveyor	Scrapper running, moving	When the roof support is lowered, the scraper is lost.

b. Similar robot cooperation in auxiliary operation scenarios

For the belt inspection work; substation inspection; water pump room inspection; grouting; sweeping; cable auxiliary operation scenarios such as robot crowds; and application task scheduling according to the auxiliary work of the robot task, time, power, and operation status, the constraints are taken under the condition of the optimal solution to form a crowd scheduling strategy. If an abnormal alarm is raised along the belt, a robot will be assigned to conduct an emergency dispatch according to the belt inspection crowd scheduling strategy to complete the confirmation of the abnormal situation on site. By calculating the comprehensive generation value of each robot under the task (time) constraints, power constraints, and distance constraints, the task is assigned to the specified robot according to the principle of "minimum comprehensive cost" [29]. The multiple constraints of the robots are as shown in formula (1)~(4).

$$dist(R_i, T_t) = \sqrt{(r_{x}\_pos_i - t_{x}\_pos_t)^2 + (r_{y}\_pos_i - t_{y}\_pos_t)^2} \quad (1)$$

where $dist\ (R_i,\ T_t)$: distance constraint; $r_x\_pos_i$, $r_y\_pos_i$: robot coordinate; and $t_x\_pos_i$, $t_y\_pos_i$: task point coordinate;

$$bet(R_i, T_t) = dist(R_i, T_t) \times \gamma_{(R_i, T_t)} \quad (2)$$

where *bet* (R_i, T_t): power constraint; *dist* (R_i, T_t): distance constraint; and $\gamma_{(Ri,\, Tt)}$: power consumption per unit distance;

$$t_{cons}^{R_i,T_t} = \frac{dist(R_i, T_t)}{V_{Ri}} \tag{3}$$

where $t_{cons}^{R_i,T_t}$: time constraints; V_{Ri}: robot speed; and *dist* (R_i, T_t): distance constraint; and

$$cost(R_i, T_t) = \frac{dist(R_i, T_t)}{V_{R_i}} \times bet((R_i, T_t) \tag{4}$$

where *cost* (R_i, T_t): cost constraint; *dist* (R_i, T_t): distance constraint; V_{Ri}: robot speed; and *bet* (R_i, T_t): power constraint.

The robot crowd jointly performs the specified regional operation tasks according to the established strategy, thus improving the overall operation efficiency of the robot. This strategy is suitable for similar robots to complete daily auxiliary tasks and heterogeneous robots to complete special tasks. Combined with the crowd scheduling strategy, according to the charging threshold, the charging sequence, and the charging area preset by the similar charging robot single system, the remaining power is analyzed according to the preset strategy, so as to complete the unified scheduling and management of the charging of similar robots. The completion of the task scheduling is combined with the performance assessment and management of the online operation time and operation effect of the machine crowd and the single robot.

4. Coal Mining Robot Crowd 5G Technology Application

China's 5G technology is leading the world, and the application of 5G technology in domestic coal mines has also begun to increase. 5G+ robot technology combines 5G communication with the robots to achieve the remote operation and intelligent control of robots. It has been applied in intelligent coal mining in China, including for mining robots, intelligent coal mine inspection, intelligent monitoring and maintenance, intelligent power distribution, intelligent underground transportation, and other applications. These applications have improved the efficiency, safety, and collaborative capabilities of coal mining operations. The following subsection provides an overview of the application of 5G+ robot technology in intelligent coal mining.

4.1. Establishing a Dedicated Network Platform for Coal Mines with 5G

The 5G network is introduced into the fully mechanized mining face and integrated with the optical fiber ring network of the coal mine to realize the independent control and remote operation of the fully mechanized mining equipment. These characteristics give 5G technology wide application prospects in coal mining. The approach provides the high-density distributed adaptive redundancy control network of a fully mechanized mining face and two alleyways and provides the integrated control of the independent learning, self-control, and manual assistance of the mining equipment, as well as the video cloud identification of the mining and production, data cloud computing, and cloud-based fault diagnosis and equipment control.

(1) Huawei Technologies Corporation developed a batch of 5G chips, 5G base stations, 5G terminals, and other equipment made suitable for special functions, such as being explosion-proof in coal mines.
(2) Relying on the working face gigabit transmission links, we constructed multiple types of data VLAN isolation and control privatization, an integrated 5G wireless communication network, and customized self-organized topology optimization technology under non-line-of-sight and multi path conditions, as shown in Figure 12. The technology supports wide-area and large-capacity mobile terminal access, forming an underground Internet of Things network for coal mines.

Figure 12. Explosion-proof 5G chip and equipment is applied to coal mines in China.

4.2. Integrated Mining Intelligent Control System Connected to a Private 5G Network

The comprehensive mining electric control system is connected to the dedicated 5G coal mine network, as shown in Figure 13.

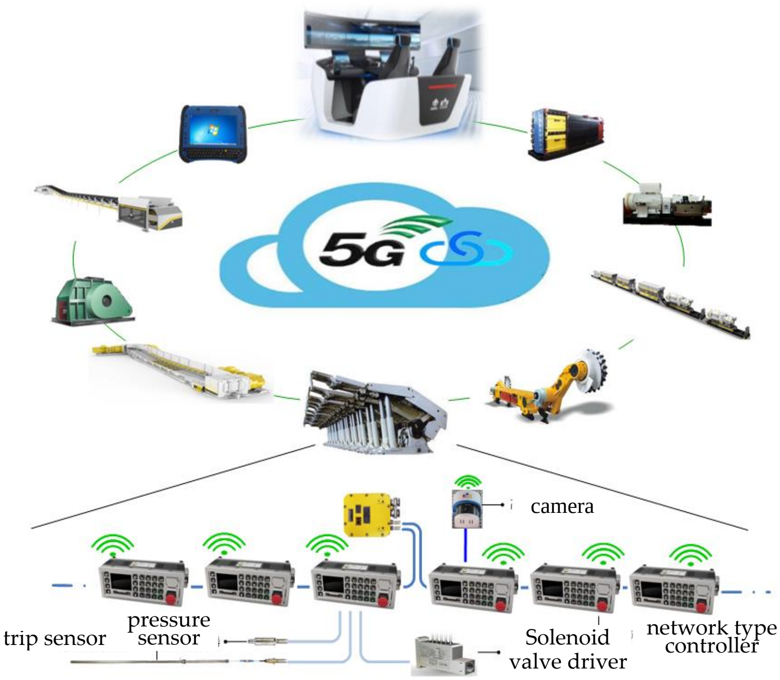

Figure 13. The internet of Things with 5G is applied to intelligent coal mines in China.

The electronic control system is integrated and applied through a CPE and 5G network to achieve ground remote control, with a remote control delay of ≤20 ms. Real-time and accurate control can be achieved at any time and anywhere underground. Flexible and efficient configuration monitoring should be implemented. The remote control delay of the device is less than 100 ms, and the concurrent upload delay of 22 channels of video is less than 300 ms.

The electro-hydraulic control communication system of the working face roof support is connected to 5G, and the system is integrated and applied through the CPE and 5G networks to achieve the ground remote control, as shown in Figure 14.

Figure 14. The electric control connection diagram with private 5G network access is applied to coal mines in China.

The remote control delay is less than 20 ms, and the method works in real time and is accurate. To determine the spatial position and posture of the hydraulic roof supports under high inclination conditions, combined with automatic lifting technology, the autonomous lifting strategy of a high inclination working face was explored. The efficiency of the working face in terms of the liquid supply and lifting was studied, and an efficient lifting strategy for the working face was explored. The real-time pressure data collected by the roof support robot on the working face were uploaded, and technologies such as edge services and cloud computing were utilized to analyze the pressure manifestation of the working face under roof fragmentation conditions. An independent lifting strategy was developed. The real-time perception of the roof support posture was achieved through inclination and height sensors, and video recognition and other technologies were integrated to develop collision prevention strategies between the roof support robot and the coal mining machine. The 5G network at workface 31004 in the Yangmei Mining Group Xinyuan Coal Mine (in Shanxi Province, China) is shown in Figure 15.

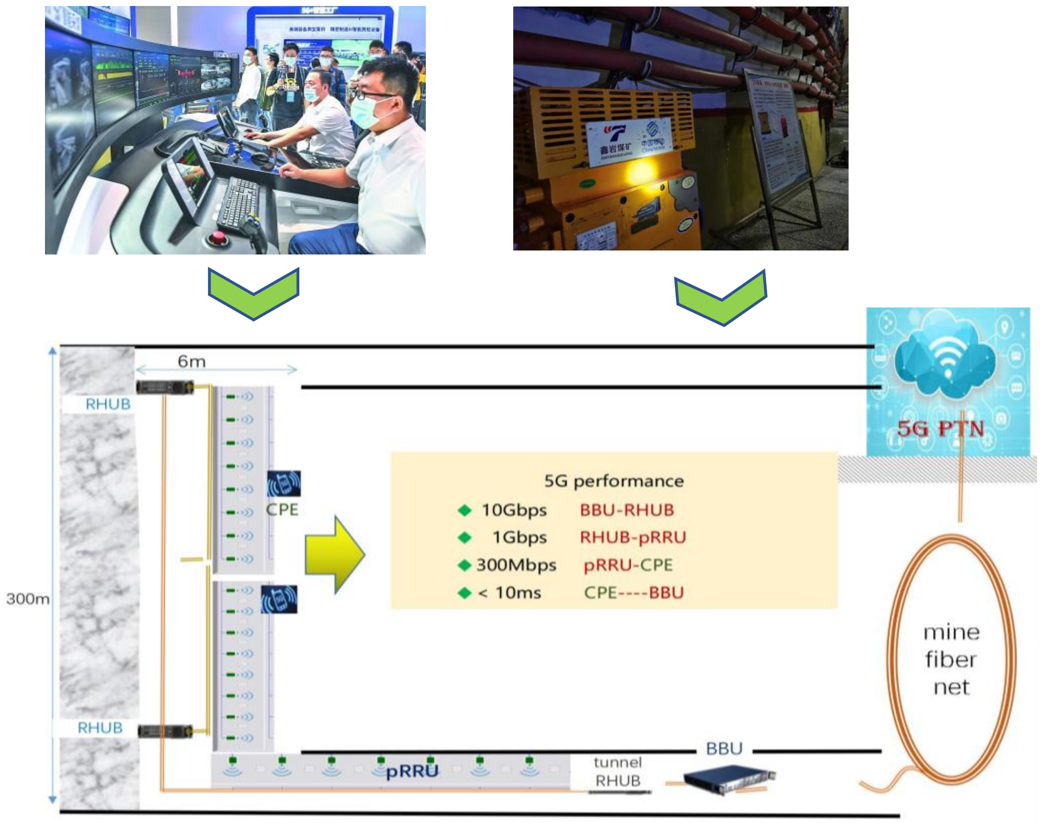

Figure 15. The 5G communication technology is applied to the #31004 workface in the Xinyuan Coal Mine (Yangquan, China).

A 5G control cloud with a network controller as the core was constructed, an electronic control system was incorporated into the industrial internet system for the first time to achieve "one network to the end", and an electronic control system was integrated with the 5G network for the first time.

5. Control Strategy of the Mining Robot

On the basis of technological breakthroughs in individual robots and the successful research and development of the individual robot equipment and systems, a reliability testing platform for the coal mining robots and a remote intelligent operation and maintenance platform for the robots have been proposed. Through reliability testing during the research and development process and the online evaluation of the health status of the application links, the optimized design and iterative upgrading of various types of coal mining robots have been achieved. At the same time, several intelligent coal mine system integration service enterprises have also developed a universal operating system and comprehensive control platform for all coal mine robots, thereby promoting the standardization, modularization, and industrial research and application of coal mine robots.

After nearly a decade of research and exploration, the current visual remote intervention mining mode has been the main mode of intelligent unmanned coal mining guided by various industry technologies, such as "unmanned operation, manned inspection", "visual immersion technology", a "transparent working face", and a "mining inspection robot", as shown in Figure 16. Video monitoring technology is adopted for fully mechanized mining faces to extend human sight to the working face, moving operators from harsh working faces to the monitoring center or ground sub-controlling center. Based on real-time monitoring videos, the equipment of the fully mechanized mining face is centrally controlled, allowing the coal mining equipment of the fully mechanized mining face to possess robot characteristics. The intelligent adaptive mining mode is based on visual remote intervention technology and further enhances the development of transparent mining by improving the capabilities of mining environment perception, intelligent decision making, and equipment adaptive control.

Figure 16. The inspection robot is applied to the scene of fully mechanized mining in China.

The application scenarios mainly include the following aspects:

(1) The mining robots can achieve greater flexibility and efficiency in remote operation and control, real-time monitoring, and autonomous control; and achieve autonomous control in coal mining operations, including autonomous navigation, autonomous obstacle avoidance, and autonomous operation. Real-time monitoring and control have been achieved, where robots monitor and control environmental parameters, such as temperature, humidity, and gas concentration, in real time during the coal mining operations, as shown in Figure 17.

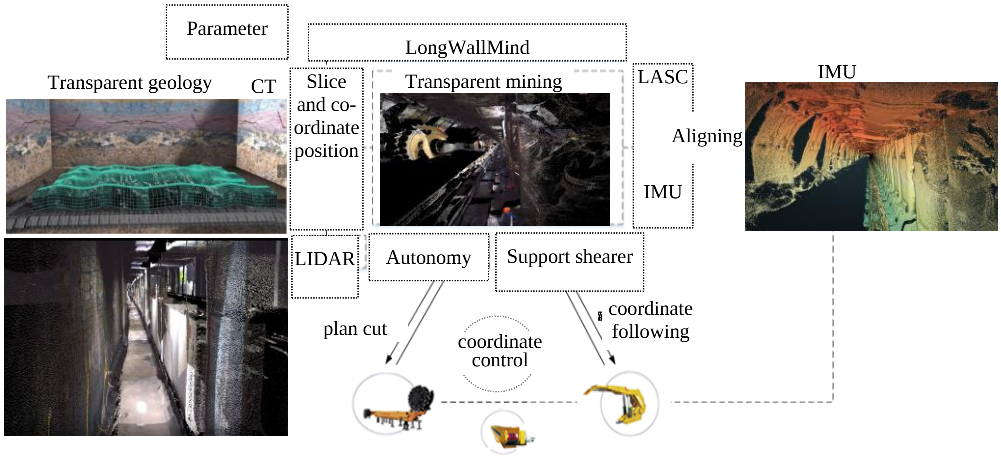

Figure 17. The transparent geological model for a workface was established by mining robot.

(2) Intelligent inspection: The automation of robot inspection, including automatic inspection, intelligent obstacle avoidance, and fault warning, provides high-speed and stable communication roof support and allows the robot to provide real-time feedback data from various items of equipment and sensors inside the coal mine to the control center for analysis and processing, as shown in Figure 18.

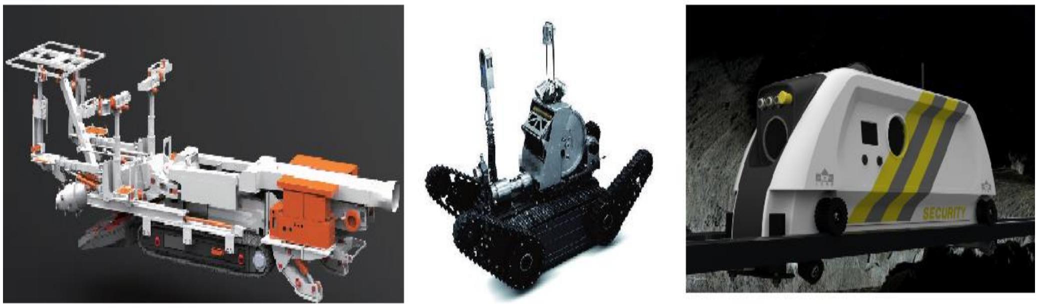

Figure 18. Future operation robots for coal mines.

(3) Remote control and command: A network using 5G technology has a fast transmission speed and low latency, enabling the remote control of robots, making coal mining more intelligent and automated, realizing more precise and faster remote commands, and communicating directly with on-site personnel through 5G technology to improve emergency response capabilities in emergency situations.
(4) Real-time monitoring and feedback and autonomous path planning: Robots can cooperate with 5G networks to establish digital maps, achieve autonomous path planning and navigation, and improve transportation efficiency and accuracy.
(5) Data sharing: 5G technology can achieve data sharing among multiple robots, allowing different robots to collaborate and jointly complete coal mining tasks. The low-latency communication capability and the high reliability of 5G networks enable robots to perceive and control their movements and postures more accurately, improving job accuracy and safety.
(6) Internet of Things application: In fully mechanized mining faces, various devices can be connected through 5G technology to form the Internet of Things. In this way, the centralized management and monitoring of the entire fully mechanized mining face can be achieved.
(7) Virtual reality technology: VR technology can provide miners with more realistic training and operating experience. The use of 5G technology can ensure the smoothness and stability of virtual reality images and improve training and operational effectiveness.

(8) Operation robots: Robots for special scenarios such as roof fall handling, advanced roof support, and safety detection are important auxiliary means for achieving intelligent mining.

6. Practice Case

The advanced automation system (ASA) and IMSC system developed by JOY in the U.S. have achieved the planning and cutting of coal cutters, significantly improving their work efficiency and programmable operational capabilities. The core of the roof support machine is still the electro-hydraulic control system, while the transportation robot is controlled through real-time monitoring and coal flow balance.

Through research on mining working faces in the CHN ENERGY Investment Group ShenDong Mining YuJiaLiang Coal Mine, ShaanXi Coal Chemical Group HuangLing Mining No.1, TianDi Corporation WangPo Coal Mine, and other coal mines, we have gained a deep understanding of the coal mining equipment and application situations of the working faces. Research has shown that encoders and rocker arm height sensors (the swing angle sensors) are bottlenecks that restrict the intelligent application of the shearers. Most domestic shearer manufacturers use angle sensors for the rocker arm height measurements, with large errors of up to 5 cm; these sensors cannot support advanced functions such as remote control and coal cutting planning. Due to the installation of the shaft encoder outside the traveling box of the coal mining machine, the shaft encoder is easily damaged, which limits the application of coal mining machine positioning and inertial navigation. The collaboration and straightness control of roof support robots are key factors that constrain the intelligence.

6.1. Successful Cases of Intelligent Mining Engineering Practice in China

(1) The HongFa Mine in YunNan: Intelligent mining at a height of 2.8 m has achieved an automation rate of 76% under complex geological conditions, with an average reduction of 30% (five people) in the number of workers on the working face. By adopting automatic machines following operation, the production efficiency was increased by more than 2%, achieving automatic, safe, and efficient production with fewer manned or even unmanned machines following operations and fewer people on duty, effectively promoting the construction of intelligent mines.

(2) Face 11203 of the RuiFeng Mine: After being debugged and put into use in March 2020, the overall system was stable, with a low failure rate and normalized operations. Manual operation is not allowed in areas where conditions permit.

(3) Face 2209 (medium–thick coal seam) of the ZiKuang YangJiaCun Coal Mine in ZiKuang: The average mining height is 2.3 m, and the working face length is 300 m. The automated cutting of triangular coal was realized, with an automation utilization rate of 70%. Usage effect: By using one centralized controller on the ground, the entire production system of the working face can be remotely controlled, reducing the number of people by more than 60% compared to the traditional fully mechanized working face of 12 in the past.

(4) DongTan Mine 63-06 working face (large mining height): As shown in Figure 19, the mining height is 5.7 m, and the inclined length of the working face is 265 m, achieving the normalized application of intelligent roof support following the operation. Usage effect: Each shift requires only eight operators, including one scaffolding worker, one three-machine driver, two end workers, and one shift leader, reducing the number of people by 50%. Bench marking project: The implementation of large-scale mining and normalized operations in the central and eastern regions has played a good demonstrative role.

(5) Working face 4104 of the YiTai BaoShan Mine (thin coal seam): The mining height is 1.2–1.4 m, the minimum mining height is 1.25 m, and the inclined length of the working face is 240 m. Implementation situation: The intelligent operation of the working face equipment is normal, with a roof support and machine usage rate of

up to 96.9%; an average daily coal cutting of 12 knives; and a daily production of 4500 tons. Application effect: The number of operators on the working face was reduced from 10–12 to 5–6, a reduction of more than 60%.

Figure 19. In the Dongtan Coal Mine of Shandong Energy Group (Jining, China), the intelligent fully-mechanized mining face tunnel is equipped with mining robots.

(6) WangJiaLing Mine 12309 face (top coal caving): As shown in Figure 20, four automatic coal caving technologies were officially produced on August 23, 2019, and successfully implemented. The concept of "pre-release detection, identification during release, and post-release monitoring" was developed. Application effect: Since the operation of the working face was normalized, the number of personnel in the first team of the WangJiaLing Mine has reduced from 100 to 75, a decrease of 24.8%. The project successfully passed the acceptance of the intelligent mining technology research project for top coal caving on 9 July 2020.

Figure 20. Real view of the intelligent working face.

(7) Working face 8202 of the TongXin Mine (top coal caving): The strike length is 2184.5 m, the inclined length is 200 m, the mining height is 3.9 m, the mining and drainage ratio is 1:2.91, and the coal seam dip angle is 1–2°. The normalization of the full face machine was achieved following automation and one-click start/stop, the number of personnel was reduced, the efficiency increased, and the production efficiency increased by 10%.

(8) The 220704 working face of the NingMei ZaoQuan Coal Mine (with complex geological conditions): The basic situation is that the length of the working face is 284.6 m and the average mining height is 3.85 m. The problem of controlling the upward and

downward movements of the inclined working face equipment was solved, and an upward bottom-sweeping knife and a downward top-cutting knife were used with high-definition video. Application effect: A maximum of 13 coal cuts were achieved per day, and only one monitoring operator was placed on the working face.

(9) DaBaoDing Coal Mine (large-angle complex coal seam): The average inclination angle is 26°. This is the first intelligent project in the southwest region with a large inclination angle. The authors achieved linkage between the anti-overturning oil cylinder of the roof support and the anti-slip oil cylinder of the scraper machine, thus achieving the normalization of the machine. Usage effect: The comprehensive mining team has a single shift of production workers, with only three people following the machine for inspection. On 8 April 2021, the “Intelligent System Project for Large-Dip Complex Working Faces” of the Sichuan Coal Group successfully passed the acceptance meeting at the DaBaoDing Mine project of the PanZhiHua Coal Company.

6.2. Details of a Practical Project at the YuJiaLiang Mine 43207 Unmanned Mining Face

In the China National Energy Group’s Yujialiang Coal Mine 43207 Unmanned Mining Face, the industrial test of the mining robot swarm’s control of the mining process reached the mining production during the “ground planning mining and unmanned working face” in the unmanned mining new mode. The realization of the “back-end analysis and decision, front-end interactive control” included the following: an integrated management and control platform to obtain a production data summary and analysis, background decision control, a shearer, shearer robot swarm master–slave scheduling, a working-face shearer, and hydraulic support according to the scheduled execution of the automatic operation. Control software was used with the robot swarm for the equipment operation monitoring, parameter online setting, fault prompt warning, active video promotion, and other human–machine operation interactions, as well as to reduce the subjective factors of personnel repeatedly opening and shutting down the system, which was not in accordance with the operating procedures and delay time, so that the whole mining process would be continuous and could achieve high production efficiency.

(1) The “ground planning mining, stope unmanned operation” unmanned mining new mode will be completely liberated from the low working face, heavy manual labor of the coal workers. Through the implementation of the project, the number of production shift downhole personnel gradually reduced from seven to three, and no one entered the working face during the production operation. This fits the “3 + 2 + X” production mode proposed by Yujialiang Coal Mine; that is, during the production shift, three people enter the well in the fully mechanized mining working face, two people enter the well for safety supervision and tile inspection, and X people enter the well for other supervision tasks.

(2) The shearer cutting template optimization editing algorithm is based on the fusion of historical data-filtering and mean processing. The cutting template trajectory collision algorithm is developed. The coal cutting planning template is proposed such that the accuracy will be higher than the shearer cutting template data planning, reaching 95%. The remote manual intervention is less than 10%. By enriching the visual remote intervention control technology, the image recognition system is used to carry out intelligent monitoring of the position of the shearer drum, the working face personnel, the upstream drum of the coal flow, the block coal, and the tail scraper conveyor; and abnormal working conditions are actively monitored with alarms.

(3) A highly integrated fully mechanized mining production video monitoring robot was developed to monitor two main production areas: the shearer drum and the hydraulic roof support. From using virtual reality-enhanced display technology to view real-time scenes, the intelligent recognition accuracy of the hydraulic roof support working condition was found to be greater than 95%. The shearer cutting state monitoring technology based on the sensory knowledge of sound characteristics in the process of shearer cutting and coal–rock wall impact was realized, and the recognition

accuracy of the shearer drum cutting voice print was greater than 75%. The voice print recognition system is used to sense the sound characteristics in the process of the shearer cutting and coal–rock wall impact and is able to recognize shearer coal breaking and rock breaking states. The application of enhanced visual remote-monitoring technology supports the remote monitoring and production decision making of the ground main control center personnel, providing technical support for the normalization of the intelligent unmanned mining on the working face.

(4) The production efficiency continues to improve. Since the adoption of unmanned supervision and remote patrol unmanned production on the working face on 1 October 2022, the single-shift production record was refreshed four consecutive times, and the goal of 12-loop coal production was achieved. On October 4, the single-shift unmanned production of 50 units in six loops exceeded the manual coal cutting efficiency for the first time. On October 7, the round-shift unmanned approach achieved 13 loops, refreshing the record again. From October 16 to October 22, the demonstration project completed 7 days of continuous unmanned coal mining. The number of working faces decreased, but the output increased, significantly improving the production efficiency. The mining statistics for a period of time are shown in Table 4.

Table 4. Statistical table of coal cutting using a coal mining robot crowd.

Duration	Work Shifts	Cut Loop Number	Detailed Information
29 September 2022	Middle shift	One loop	The first verification: one person on the face patrol.
30 September 2022	Middle shift	Two loops of 80 sets	Only one person on the face patrol.
4 October 2022	Midnight shift	Six loops	Ground cutting coal, the first two loops: one person with the machine patrol; and the last four loops: in the middle of the unmanned machine operation.
5 October 2022	Midnight shift	Six loops of 10 sets	Ground cutting coal, the middle of the machine operation, and the head and tail: one person monitoring.
7 October 2022	Regular shift	Thirteen loops	Ground cutting coal, the middle of the machine operation, and the head and tail: one person monitoring.
8 October 2022	Midnight shift	Seven loops	The ground is cut into coal, and for the whole face, no-one works with the machine.
15 October 2022	Middle shift	Six loops	Cutting coal is on the ground, and for the whole face, no-one works with the machine.
16 October 2022 ~22 October 2022	Regular shift	Eighty-seven loops	Ground cutting coal, the middle of the machine operation, and the head and tail: one person monitoring.
15 November 2022	Regular shift	Thirteen loops	Ground cutting coal, the middle of the machine operation, and the head and tail: one person monitoring.

6.3. Successful Practical Case of Mining Robot Crowds in Chinese Coal Mines

In the past decade, China has witnessed remarkable achievements in the application of shearer robot technology. Several coal mines that have implemented robotic systems have successfully achieved their objectives of the reducing workforce and enhancing operational efficiency. The precise operations performed by these robots have significantly improved the quality of the coal mining. Table 5 presents a compilation of outcomes attained by coal mines that have adopted shearer robot swarm technology.

Table 5. Mining robot crowds application results in coal mine from China.

Application of Coal Mine	Robotic Technology Used	Results with Mining Robot Crowds	Province	City
BaoDe Coal Mine	Mining and discharging collaborative working face based on the F5G network, which establishes the intelligent coal release algorithm and process model for mining and discharge coordination	The number of workers in a single class of the working face was reduced from thirteen to seven workers in a single class.	Shanxi	XinZhou
HuaNing Coal Mine	A full-height intelligent working face with shearer robot and support robot	The fully mechanized mining team was reduced from 124 during the coal period to 87. During the production class, there was one central control room operator, one shearer inspector, two shield inspectors, one three-machine inspector, and one tape machine inspector.	Shanxi	HouMa
NaLinHe Coal Mine	Intelligent fully mechanized mining system based on geological integration and inertial navigation	In the manual operation of the ordinarily fully mechanized mining face, at least 11 miners were needed for the working face. After intelligent mining, only five miners were needed for a single-shift production: one coal machine and one support inspector; one monitor, one person for the head and tail inspection; and one person for the console.	Inner Mongolia	Ordos
WangJiaLing Coal Mine	Intelligent integrated discharge working face with shearer robot and support robot	The coal working face was reduced by 30%, the working efficiency reached 181 tons/miner, and the annual production capacity increased by 960,000 t/a.	Shanxi	HouMa
ZhuanLongWan Coal Mine	Medium–thick super-long ten million tons of intelligent fully mechanized mining face	The maximum number of automatic coal cutters in the working face was 25, and the maximum daily output was 40,000 t. The number of working face support workers was reduced from four to one, and the number for normal production was no more than one.	Inner Mongolia	Ordos
HuangLing No.1 Coal Mine	Intelligent mining system based on transparent geological planning and cutting	The working face realized unmanned mining, completely liberating the inspection personnel and remote monitors of the working face, and made remarkable achievements in reducing the personnel and increasing efficiency. In the production process, the intervention control and adjustment of the operation time were greatly reduced, and the production efficiency was increased by about 30%.	Shaanxi	YanAn
XinJuLong Coal Mine	Intelligent coal mining working face with shearer robot and support robot	The production personnel were reduced. Through the normal operation of the basic functions such as machine removal, memory cutting, and the automatic cutting of triangle coal, the production mode of “7 + 5” (seven miners producing; five miners engaged in echelon training for civilized renovation, end-coal discharge, and floating coal cleaning) was realized, reducing to eight miners per day, and the working efficiency of the tons of coal was improved to 81.25 t/workers.	Shandong	HeZe

Table 5. *Cont.*

Application of Coal Mine	Robotic Technology Used	Results with Mining Robot Crowds	Province	City
XiaoBaoDang Coal Mine	The 450 m ultra-long intelligent mining working face with shearer robot and support robot	The automatic adjustment of the shield state was realized, along with the working face fluctuation change and the mining height and coal cutting speed. The shearer speed reached more than 10~15 m per minute, the production efficiency improved by 15%, the highest coal cutting was 19 knives, and the highest daily output was 46,000 t.	Shaanxi	YuLin
LongWangGou Coal Mine	Intelligent and efficient fully mechanized discharge working face of extremely thick coal seam	The number of direct production at the working face was reduced from twelve to five; the coal mining efficiency was increased by three times to 96.3 tons/day; the labor cost of coal was CNY 11.66; the comprehensive power consumption of coal was reduced to less than 8 degrees; the energy consumption rate was reduced by more than 30%; and the annual saving was more than CNY 10 million.	Shaanxi	Jungar
SanYuan Coal Mine	Intelligent fully mechanized mining working face with shearer robot and support robot	The panoramic video splicing system of the fully mechanized mining face provided a more intuitive and clearer control interface for the upper and lower operators, improving the safety and reliability of the remote control of the fully mechanized mining and providing another mode for the remote control of the fully mechanized mining.	Shanxi	ChangZhi
QianJiaYing Coal Mine	Intelligent mining working face of thin coal seam	The working face automatic production mode of "working face automatic control, supplemented by the remote intervention control of the monitoring center" was realized. Each shift can save six miners, and the labor intensity of the workers was greatly reduced by the automatic shift and the top slip.	Hebei	TangShan
PingBao Coal Mine	5G + intelligent coal mining system	The production staff at the working face was reduced from twenty-two to six, truly realizing safe, efficient, and intelligent coal mining.	Henan	XuChang
LongTan Coal Mine	Intelligent mining working face of thin coal seam with complex geological conditions	The number of single-shift production workers was reduced from 18 to 10, saving labor costs by CNY 1.12 million per year.	Sichuan	GuangAn
JiaYang Coal Mine	Intelligent fully mechanized mining face of thin coal seam	The production team of the working face was reduced from five teams in the original fully mechanized mining face (the working face layout) to two teams, and the daily production staff was reduced from sixty-one to eight, a reduction of 87%. The working efficiency reached 406 t/miner.	Sichuan	Leshan
MaDiLiang Coal Mine	Intelligent mining system with 5G+, shearer robot and support robot	In two shifts of production, the working face configuration was three miners (when the roof and the surface geological conditions are poor, five miners are needed) to meet the normal production work, compared with the traditional comprehensive working face where each shift, there were fifteen miners.	Inner Mongolia	Ordos

Table 5. *Cont.*

Application of Coal Mine	Robotic Technology Used	Results with Mining Robot Crowds	Province	City
XiaoNan Coal Mine	Intelligent coal mining working face with shearer robot and support robot	During the production period of the working face, the production team was reduced from fifteen to seven miners, realizing the purpose of fewer miners. Compared with the traditional fully mechanized mining face mining, where efficiency was 87 t, the mining efficiency of the intelligent coal mining face was 153 t.	Liaoing	TieLing
DongHuai Coal Mine	Intelligent fully mechanized mining working face with 5G+, shearer robot, and support robot	The working face reduced to 12 production miners, which could save CNY 1.7352 million per year.	Guangxi	BaiSe

7. Conclusions

Based on a detailed study of the development of existing intelligent mining automation and information technology in coal mines, a technical system framework centered on coal mining machine groups is proposed, including single coal mining robots, robotic equipment, robot crowds, and unmanned systems. The common key technical support for the research and development of coal mining machine personnel is elucidated, and cross-integration with new technologies such as 5G, the industrial internet, big data, artificial intelligence, and digital twins is proposed. By utilizing robot technology to enhance the adaptability of complex and safe production environments in fully mechanized mining, we can further enhance the level of autonomous and intelligent applications in fully mechanized safe mining production. Research should be carried out on coal mining robots, roof support robots, and transportation robots to bring about intelligence in fully mechanized mining faces, thereby providing equipment support for fully mechanized mining faces.

(1) An intelligent coal mine robot crowd management and control platform has been developed to realize the cross-domain integration of multi-source heterogeneous data from the whole mine; to realize the integrated control of coal mine robot crowd operations and mining operations for the first time; and to break down the information–interaction barrier among individual robots. The digital twin problem between virtual mapping and real mapping for the intelligent control of human power systems has been resolved.
(2) The high-precision control technology of underground heavy-load mechanical arms in coal mines has been created; a jet grouting robot, a pipeline installation robot, and a tunneling repair robot have been developed, and the man–machine collaboration of heavy-load robot–cloud edge synergy crowd collaborative control has been achieved.
(3) A hierarchical scheduling and planning strategy for coal mine machinery populations has been constructed. A process knowledge graph, based on the early innovation and application practice, has been created including information on intelligent tunneling, intelligent coal mining, intelligent transportation, and intelligent safety control.

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