



Research and practice of intelligent coal mine technology systems in China

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Abstract

This study considered the role of coal as China's basic energy source and examines the development of the coal industry. We focused on the intelligent development of coal mines, and introduced the “Chinese mode” of intelligent mining in underground coal mines, which uses complete sets of technical equipment to propose classification and grading standards. In view of the basic characteristics and technical requirements of intelligent coal mine systems, we established a digital logic model and propose an information entity and knowledge map construction method. This involves an active information push strategy based on a knowledge demand model and an intelligent portfolio modeling and distribution method for collaborative control of coal mines. The top-level architecture of 5G+ intelligent coal mine systems combines intelligent applications such as autonomous intelligent mining, human-machine collaborative rapid tunneling, unmanned auxiliary transportation, closed-loop safety control, lean collaborative operation, and intelligent ecology. Progress in intelligent mining technology was described in terms of a dynamic modified geological model, underground 5G network and positioning technology, intelligent control of the mining height and straightness of the longwall working face, and intelligent mining equipment. The development of intelligent coal mines was analyzed in terms of its imbalances, bottlenecks, and the compatibility of large-scale systems. Implementation ideas for promoting the development of intelligent coal mines were proposed, such as establishing construction standards and technical specifications, implementing classification and grading standards according to mining policy, accelerating key technology research, and building a new management and control model.

Keywords Intelligent coal mine · Digital logic model · 5G+ intelligent coal mine · Top-level architecture · Application system

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1 Introduction

Over the past 40 years, China's coal industry has achieved significant progress through comprehensive mechanization. From 2016 to 2019, the long-term safety production mechanisms were improved, coal mine mechanization, automation, and intelligence were accelerated, and the efficiency and safety levels were comprehensively enhanced. The withdrawal of outdated coal production capacity is currently running at over 900 million t/a, which significantly reduces the environmental footprint of the coal industry. At present, there are more than 3000 coal mines in China, including more than 1000 large-scale coal mines with an annual output of more than 1.2 million tons.

In 2020, the national raw coal output was 3.84 billion tons and the total coal consumption was nearly 4.14 billion tons (Wang et al. 2020a). Coal accounts for 55.3% of primary energy production and 56.8% of primary energy consumption. China is not yet fully industrialized, and so the level of urbanization will continue to increase and the level of electrification still has great room for improvement (Wang and Du 2020). China has a huge demand for energy consumption. In 2019, China's per capita primary energy consumption was 3.47 tons of standard coal per year, which is far lower than that of the United States, Canada, and other developed countries (the OECD per capita average is about 6 tons of standard coal per year, while Canada, the United States, Australia, and other developed countries have a per capita energy consumption of about 10 tons of standard coal per year) (Grossner et al. 2008). The development of China's economy requires strong support from energy, and so China's energy demand is likely to grow, with coal remaining the main energy source for some time to come.

Given the coal resources in China, underground mining is the main method of extraction, with open-pit mining accounting for less than 15% of coal production. Scientific research has enabled underground mining to shift from mechanized mining to automated and intelligent mining. Coal mine intelligence is the core technical support for the high-quality development of the coal industry in this new development stage, and has become the industry consensus. In recent years, the research and development of intelligent coal mine technology systems have achieved significant progress. Currently, 71 intelligent coal mines are in construction, and the development of intelligent coal mines is accelerating.

2 Overview of intelligent coal mine development in China

2.1 Transformation and development from mechanization to intelligence

The coal seams in China are complex and diverse. In the last century, artificial mining and blasting mining were used for a long time, resulting in low efficiency and high casualty rates. In the mid-1980s, fully mechanized mining equipment for the medium-thick coal seams was introduced to carry out longwall comprehensive mechanized mining. However, the incompatibility of the hydraulic supports required for fully mechanized mining with the complex and changeable coal seam conditions in China led to the hydraulic supports often being crushed at the working face. In view of the problems encountered in longwall fully mechanized mining, systematic research and development has focused on the theory, technology, and equipment of fully mechanized mining, leading to a complete set of technologies and equipment for fully mechanized mining in thin and medium-thick coal seams, at large mining heights, and for caving mining.

In the past 10 years, innovative research and development on intelligent mining technology and equipment have seen breakthroughs in a number of key core technologies and important achievements in intelligent fully mechanized mining of thin and very-thin coal seams, at large and super-large mining heights, and in the equipment required for extra-thick coal seams. Some mines in Huangling, Shaanbei, Shandong, and other mining areas have achieved varying levels of automation, resulting in intelligent unmanned mining of thin coal seams (less than 1.3 m) and intelligent fully mechanized mining at super-large mining heights of 6–9 m. This provides a solid foundation for comprehensively promoting the intelligent development of coal mines.

The rapid development of modern information and control technology has modified many traditional industries and promoted changes in human lifestyles, forcing the mining industry to move away from traditional high-intensity work methods. Intelligent mining pioneers and pilot companies enjoy cost and development advantages. At the same time, the recruitment difficulties faced by coal mining companies have forced coal mines to transform from comprehensive mechanization to intelligent development, and accelerate the construction of intelligent coal mines (Wang et al. 2018). Intelligent coal mines are

characterized by deep integration of the Internet of Things (IoT), cloud computing, big data, artificial intelligence, automatic control, mobile internet technology, and intelligent equipment with coal development technology to enable comprehensive autonomous perception, real-time and efficient interconnection, intelligent analysis and decision-making, independent learning, dynamic prediction and early warning, and accurate collaborative control. The result is efficient and intelligent operation across the whole process of mine geological protection, coal mining, production, and operation management. The fundamental goal of developing intelligent coal mines is to increase safety, improve efficiency, increase the recovery rate of resources, and achieve high-quality development of coal mines (Wang et al. 2020f).

2.2 Intelligent development of underground coal mines

2.2.1 Intelligent classification and grading standards for underground coal mines

China's coal occurrence conditions are complex and diverse. There are vast differences in mining technology and equipment levels, engineering foundations, technical pathways, and construction goals at different coal mines, all of which is subject to the development level of intelligent mining technology and equipment. The difficulty and final effect of the intelligent construction of coal mines with different coal seam occurrence conditions are also different. It is difficult to use a single indicator to evaluate the intelligent construction and mining level of all coal mines. After thorough research and discussion, various classification schemes and evaluation standards have been formulated (Wang et al 2020b, c). These define terms such as intelligent coal mine, intelligent coal mining face, intelligent centralized control center, and intelligent mining mode, and propose general technical requirements and supporting conditions for intelligent coal mines and coal mining faces. First, the mining modes of intelligent coal mines and coal mining faces are classified according to the thickness of the coal seam, the occurrence conditions, the mining methods, and the mining technical parameters. Second, taking the coal seam occurrence conditions as the basic index and the mining technical parameters as the reference index, a classification and evaluation index system is established for intelligent coal mines and intelligent coal mining faces. According to the technical conditions of mine classification and evaluation, intelligent coal mines can be divided into three categories: Category I mines have good intelligent construction conditions, Category II mines have medium intelligent construction conditions, and

Category III mines have complex intelligent construction conditions. Finally, the construction level of intelligent coal mines is evaluated through the development of an information infrastructure, geological support system, intelligent tunneling system, intelligent mining system, main coal flow transportation system, auxiliary transportation system, comprehensive support system, safety monitoring system, intelligent sorting system, operation management system, and other indicators. The level of the intelligent coal mining face is evaluated based on the formulation of intelligent coal cutting, intelligent support, intelligent transportation, intelligent control, network communication, intelligent video, intelligent spray, intelligent liquid supply, intelligent inspection, intelligent power supply, working face lighting, working face voice, ventilation, fire prevention, safety monitoring, and other indicators.

2.2.2 Cases of intelligent construction of production coal mines

The upgrade and transformation of Shenmu Zhangjiamao Mining Co., Ltd., of Shaanxi Coal Group into an intelligent coal mine operation was launched in early 2018. Development was based on a standard system, a comprehensive perception network, a high-speed data transmission channel, a big data application center, and a business cloud service platform. The overall system realizes information technology services for different business needs and creates a world-class intelligent coal mine construction plan. After 2 years of construction, Zhangjiamao coal mine has consolidated the top-level design and produced a development blueprint for constructing intelligent key technology and equipment research and development. The key intelligent technologies cover mining, tunneling, transportation, ventilation, and the protection and utilization of resources. This will create a new pattern of comprehensive intelligent safety management and enable auxiliary projects such as underground high-speed industrial ring networks, 5G private networks, intelligent management and control platforms, and intelligent safety production management systems. Essentially, this development will ensure the transition from traditional extensive production to refined, customized, and intelligent production and operation management.

2.2.3 Intelligent construction case of new coal mine

The Balasu coal mine, operated by Shaanxi Yanchang Petroleum and Mining Company, is currently under construction and is expected to have a capacity of 10 million t/a. The mine adopts the full vertical shaft development mode. The mine field is divided into three levels

according to the positions of the coal group. The construction goal was determined at the beginning of construction of Balasu coal mine. It is being constructed in accordance with the principles of “high starting point, high standards, high efficiency, and high benefit”, and “first-class design, first-class equipment, first-class management and first-class efficiency”. The mine integrates artificial intelligence, big data, and other new technologies to change traditional production methods to a new industrial model and operating system. According to the top-level design, the coal mine will have an efficient 5G-based information network and a precise location service system, and will be connected to the 4D-GIS transparent geological model and dynamic information system to realize the integration of control, management, and operation of the coal mine. An integrated cloud data center and regional control core are being built based on the “cloud edge” data architecture and three-tier hierarchical control strategy to achieve cloud edge collaboration and distributed control. During the construction process, an intelligent management system and the specific requirements and management processes of intelligent coal mine production and operation are being determined, and a management model that is compatible with intelligent coal production methods is being established. This will improve management efficiency and maximize the intelligence of the coal mine. Eighteen intelligent systems and integrated management platforms, including an intelligent working face system, rapid tunneling system, and unattended fixed-site system, have been built to realize full-time space monitoring, operation automation, decision-making intelligence, real-time control, knowledge modeling, information management, and digitalization of the business flow. Data integration, capability integration, and application integration are expected to be realized.

2.3 Intelligent development of open-pit coal mines

The development of open-pit coal mines in China started late, and coal resources suitable for open-pit mining only account for 10%–15% of the total coal resources of China. Since the beginning of this century, open-pit coal mines (characterized by low investment and quick results) have increased in number, and the development of the associated mining technology and equipment has accelerated (Li et al 2019; Zhang et al 2019). Relatively independent system modules, such as remote intelligent slope monitoring, truck anti-collision, overspeed alarms, and automatic navigation of drilling rigs, have been successfully applied in open-pit coal mines. The informatization of mine management and safety production focuses on information collection and sorting, networked transmission, automatic control, visual display,

and standardized integration of the mining enterprise. However, there is currently little interconnection and data sharing between production systems. The intelligent construction of open-pit coal mines is still in its initial stage. The automation of equipment, design, and management information does not meet the requirements of intelligent mining. Therefore, the intelligent transformation, upgrading, and development of open-pit coal mines is an urgent and difficult task.

3 Digital foundation of intelligent coal mines

Effective correlation and efficient transmission of data and information are the basic characteristics and requirements of intelligent coal mine systems. By establishing data association relationships among the major systems of intelligent coal mines, an efficient data push strategy can be constructed, which enables the cooperative control of mining equipment with “active analysis and intelligent decision making” (Ren et al 2019).

3.1 Digital logic model of intelligent coal mines

With the continuous integration of more extensive and in-depth information covering geological exploration, environmental monitoring, mining equipment status, and production systems, the production and operation management data associated with coal mines have increased exponentially. However, as there is no unified and effective data model, it is difficult to complete in-depth information processing, knowledge discovery, and application. Therefore, it is necessary to establish a digital logic model suitable for expressing data association relationships in intelligent coal mines, map the actual coal mine production-related objects and their related relationships into information “entities” in a unified manner, and establish an interaction mechanism between information “entities”. This would provide an effective method for studying the correlation among the massive volumes of data produced by coal mines.

3.1.1 Construction of intelligent coal mine information entity

Many types of coal mine information have complex inter-relationships involving multi-dimensional attributes. An information entity is a data description of a physical entity extracted and abstracted from the original description of the physical entity, that is, the metadata of the information. The information entity is at the node position in the intelligent coal mine information network system. Building a clearly

classified information entity is the basis for building a coal mine information network and realizing the mapping from the physical space to the data space.

According to the theory of complex networks, information entities should have basic entity attributes and associated attributes. Entity attributes reflect the manifestation of information, whereas associated attributes express the level of the information entities and the relationship between them in the information network. Multiple information entities are associated to form an information whole, which can be regarded as a higher-level information entity. The coal mine data attributes and forms of expression can be decomposed into coal mine information attributes including entity attributes, correlation attributes, and space-time attributes. Entity attributes provide a basic description of information entities, including attribute information, structure information, and function information. Correlation attributes describe the relationship attributes between information entities, including association attributes such as grouping/classification, hierarchical relationship attributes, importance relationships, influencing relationship attributes, and behavior descriptions. Space-time attributes include spatial orientation attributes based on geographic information and state attributes that change over time.

Mathematically, intelligent coal mine information entities can be expressed as follows:

$$O_i = \{E_i|(N, P(n), S(n), F(n)), R_i|(C(n), L(n), \dots), ST_i|(T(n), U(n))\} \tag{1}$$

where, O_i represents the i -th information entity unit; E_i represents the entity attribute of the unit, which is composed of attribute information $P(n)$, structural information $S(n)$, and functional information $F(n)$; R_i represents the associated attribute of the entity, and ST_i represents the space-time attribute of the entity, which is composed of time attributes $T(n)$ and $U(n)$.

The construction of an intelligent coal mine digital logic model is an iterative process of building a knowledge map from the bottom up. The construction process of information entities involves describing the decomposition of the key nodes in complex tasks after semantic modeling of the data; knowledge fusion is completed by determining the relationships connecting information entities, that is, the virtual and real mappings. On this basis, the entities are clustered to construct the ontology library, and the new associations between the entities are established by reasoning. Through a continuous iterative update process, an intelligent coal mine knowledge graph is formed, providing data services and decision support for various scenarios.

Due to the dynamic changes in the data content of intelligent coal mines, it is difficult to guarantee the quality of information entities when using a manual predefined entity

system. To realize the classification and clustering of information entities, a bidirectional long short-term memory (BiLSTM) module is combined with a conditional random field (CRF) method for entity recognition and relationship extraction. The basic idea is to calculate the corresponding scores of the objects to be labeled and each label sequence through the Bi-LSTM, and then obtain the dependency relationship between the entity tags and complete the labeling task. The CRF is then applied to introduce the constraints between the tags, enabling the tag sequence to be selected. Finally, a more reasonable information entity classification is obtained.

The calculation of the CRF layer adopts the linear chain formulation designed by Lample. Given the input sequence $w = \{w_1, w_2, \dots, w_{t-1}, w_t, \dots\}$, the probability of labeling sequence y is:

$$P(y|x) = \frac{1}{Z(w)} \exp \left(\sum_{t,n} \beta_n \Psi_n(y_t, w, t) + \sum_{t,m} \alpha_m \Gamma_m(y_{t-1}, y_t, w, t) \right) \tag{2}$$

where $\Psi_n(y_t, w, t)$ is the state function, representing the probability that sequence w is marked as y_t at position t ; β_n is the weight of the state function; $\Gamma_m(y_{t-1}, y_t, w, t)$ is the probability transfer function; α_m is the weight of the probability transfer function; and $Z(w)$ is a normalization factor.

On the basis of obtaining the information entity, the BiLSTM-CRF method is used to extract its attributes, as shown in Fig. 1, providing a complete outline of the entity attributes according to the association relationship.

3.1.2 Construction of intelligent coal mine knowledge map

Through the establishment of information entities, the mapping from the physical space to the digital space is realized. This mapping includes not only physical entities (e.g., coal mining machines, hydraulic supports, and tunneling machines), but also time entities (e.g., roof pressure, gas overruns, equipment failures) and functional entities (e.g., spatial position relationships and surrounding rock coupling relationships). The basic association between the various information entities is described by a semantic network, but the degree of the association relationship needs to be described in detail. The *Apriori* algorithm is used to mine the association rules among information entities, calculate the support and confidence, and describe the degree of association.

Let task T be decomposed into four tuples:

$$Schema(T) = \langle TaskSet, State, Action, QSet \rangle \tag{3}$$

where, $TaskSet = \{T_1, T_2, \dots, T_n\}$ is the set of sub-tasks decomposed according to the ontology knowledge base, $State = \{S_1, S_2, \dots, S_n\}$ is the basic environment information in the process of completing the task,

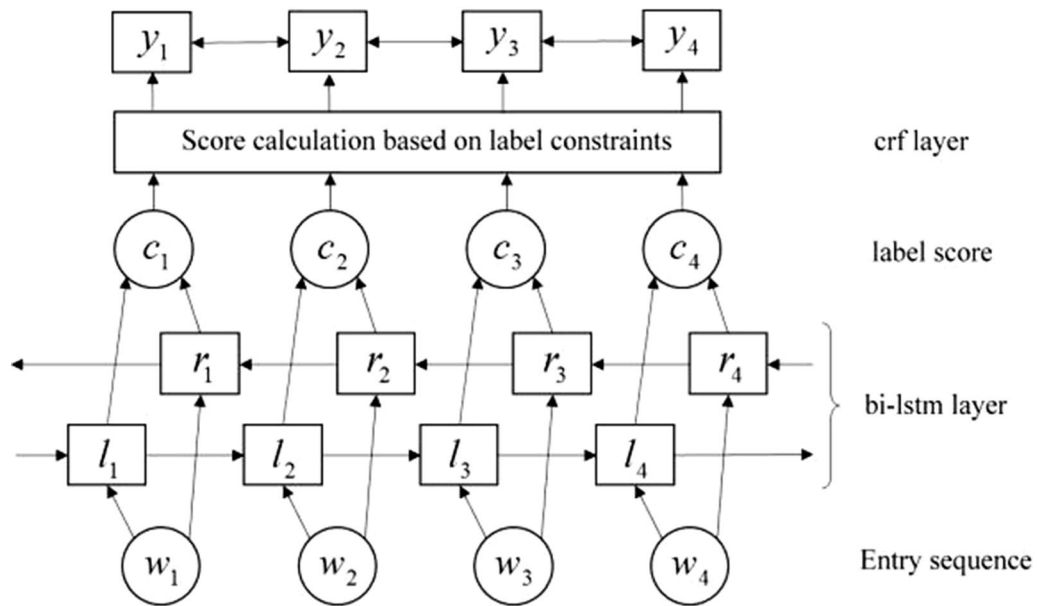


Fig. 1 Schematic diagram of information entity extraction based on BiLSTM-CRF (Wang et al. 2020b)

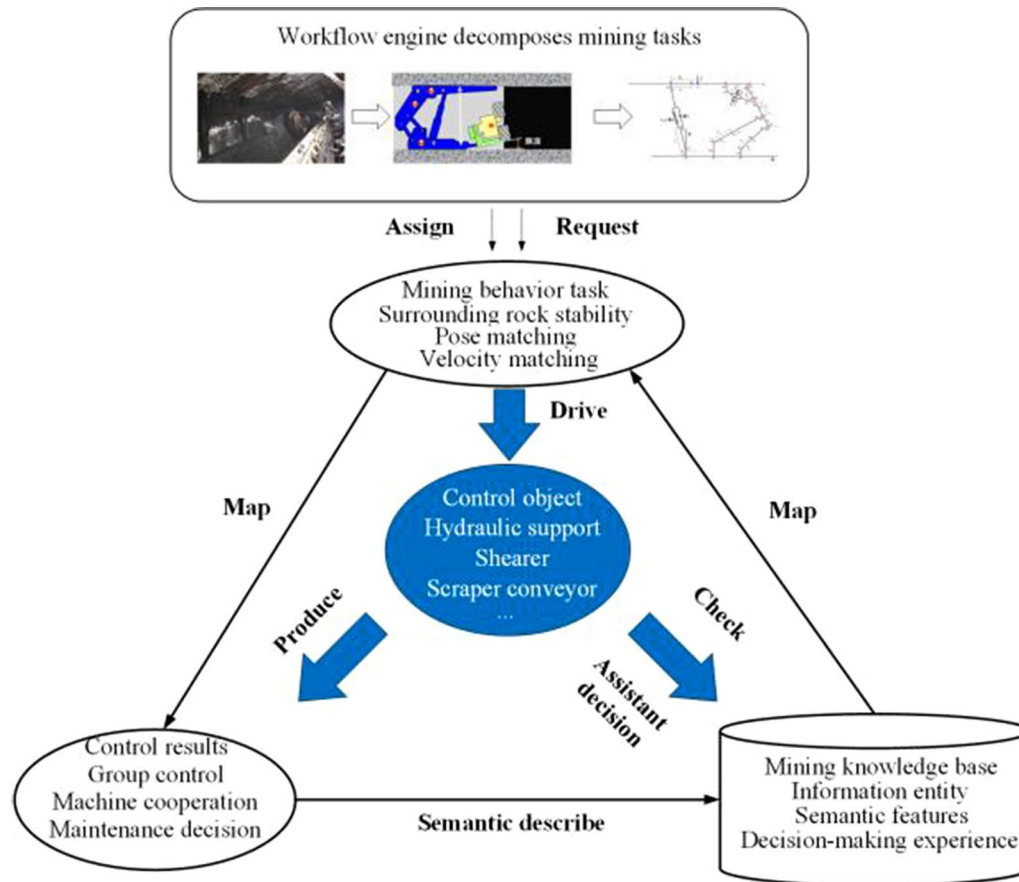


Fig. 2 Schematic diagram of mining decision and control based on knowledge map (Wang et al. 2020b)

Action = {A₁, A₂, ..., A_n} is the behavior decision made by each agent to complete the task, and QSet = {Q₁, Q₂, ..., Q_n} is the environmental information required to complete the subtask.

On the basis of task decomposition, the existing entity relationship data are calculated, and then new associations between information entities are established. This enables new knowledge to be discovered and an ontology database for coal mine multiagent control and decision-making to be constructed. Through continuous iteration and updating, an intelligent knowledge map of the coal mine can be developed, as shown in Fig. 2.

3.2 Data push strategy of intelligent coal mines

The traditional data application is a query–feedback mechanism. The low efficiency of data utilization is unsuitable for active analysis, intelligent decision-making, or the autonomous operation of a comprehensive management and control system. Therefore, the relevant technologies for the analysis and processing of big data and the mining of associate relationships are introduced, and an information entity database for intelligent coal mine applications is established. This section describes an active information push strategy based on demand preference analysis.

From the perspective of real-time demand, coal mine data can be divided into two categories. One is real-time feedback control data, which usually require direct feedback to the controller; the other is trend query data, which usually have low real-time requirements and are mostly used for data mining and situation analysis. The application of the first type of data and system is contained within existing

subsystems with independent functions, which ensures the efficiency and agility of execution. The second type of data, and their fusion with the first type, are the basis for comprehensive management and multi-system collaboration. To ensure the agility of the intelligent mining system and realize the synergy of multiple systems, an information active push system is proposed to build a knowledge update mechanism and an active push model within a query–feedback loop, as shown in Fig. 3.

First, the application scenario is described in detail and the preferred outcomes are analyzed. The attribute information E_i of the information entity is then updated using machine learning. Second, the association relationships of the scenario data are mined, and the association attributes R_i of the information entity are updated through matching degree analysis. Big data analysis is then used to analyze historical data, and pushing events are triggered based on predicted and early warning information. At the same time, the space-time information ST_i containing the time baseline is passed to the information entity, so that the information entity O_i can be unified with the time baseline. The information entity is then passed to the corresponding scenario by the functional operation library to provide timely, comprehensive, and reliable information for scenario-based applications and decision-making control.

3.3 Intelligent coal mine combination modeling and distributed cooperative control

The intelligent operation of coal mines is determined by various basic conditions, such as dynamic geological conditions, development deployment, and production equipment.

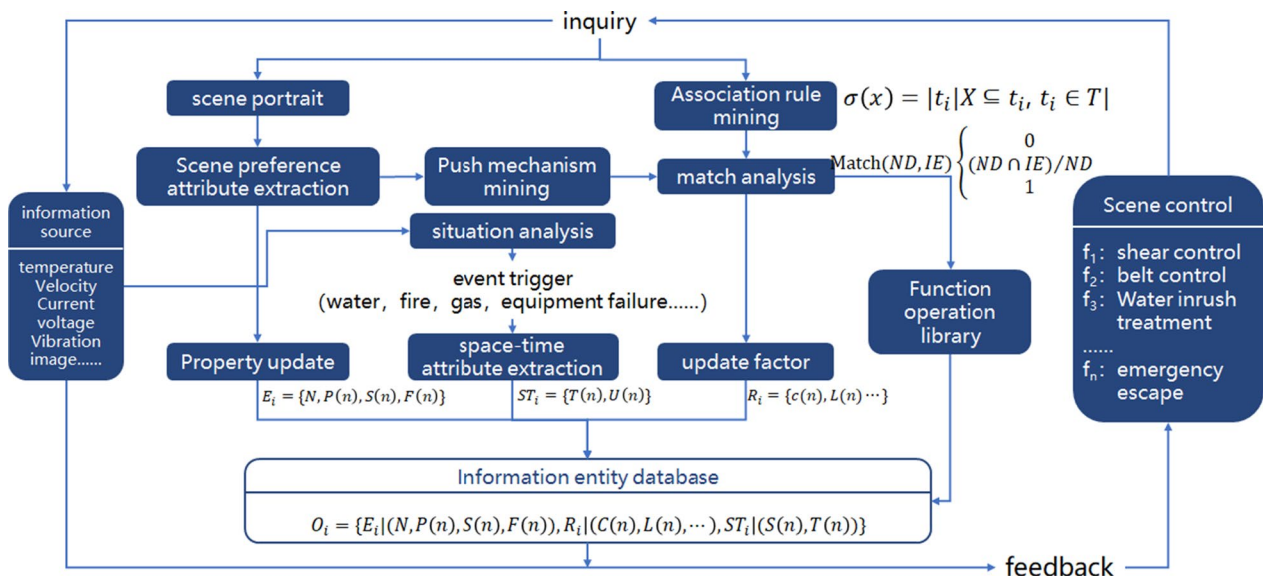


Fig. 3 Data update and active push architecture

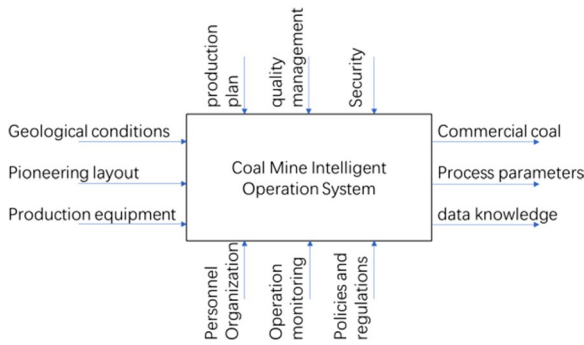


Fig. 4 Overall function model of intelligent coal mine

Operations are oriented to the goals of production planning, quality management, and safety assurance. In accordance with the constraints of policies and regulations, personnel organization, and operation monitoring, the operation is systematically optimized to export coal according to demand by setting process parameters suitable for the basic conditions. The overall function model of the intelligent coal mine is shown in Fig. 4.

Intelligent coal mines are complex systems that cannot be expressed, analyzed, and researched by a single model. On the basis of a multi-source heterogeneous data information model and data interaction strategy for intelligent coal mines, a method based on a multi-agent system (MAS) is

proposed. The method of combinatorial modeling comes from the “hierarchical” view of system theory and the modular structure of complex systems (Liu et al 2007). The main idea is to divide the system into a number of subsystems (independent agents) according to their functions, establish models of each subsystem separately without considering the associations between the systems, and then establish an association model between them. Finally, the models of each subsystem are integrated to form the overall system model. The subsystem model and correlation model are generally established by mechanism analysis, system identification, or a combination of the two. From a simulation perspective, combination modeling can be described as (Zeigler et al 2000):

$$N = [T, X_N, Y_N, D\{M_d | d \in D\} \{I_d | d \in D \cup (N)\} \{Z_d | d \in D \cup (N)\}] \tag{4}$$

$$M_d = [T_d, X_N, Y_N, \Omega, Q, \Delta, \Lambda] \tag{5}$$

where, N is the global model; T is the system internal relational model collection; X_N is the system external input quantity; Y_N is the system output quantity; D is the collection of all internal subsystem models, $d \in D$; M_d is the input and output system of the subsystems, $d \in D \cup N$; T_d is the internal relation model of subsystem d ; I_d is the set of influential subsystems of d ; Z_d is the interface mapping of subsystem d ; Ω is the allowable input partition; Q is the state set; Δ is

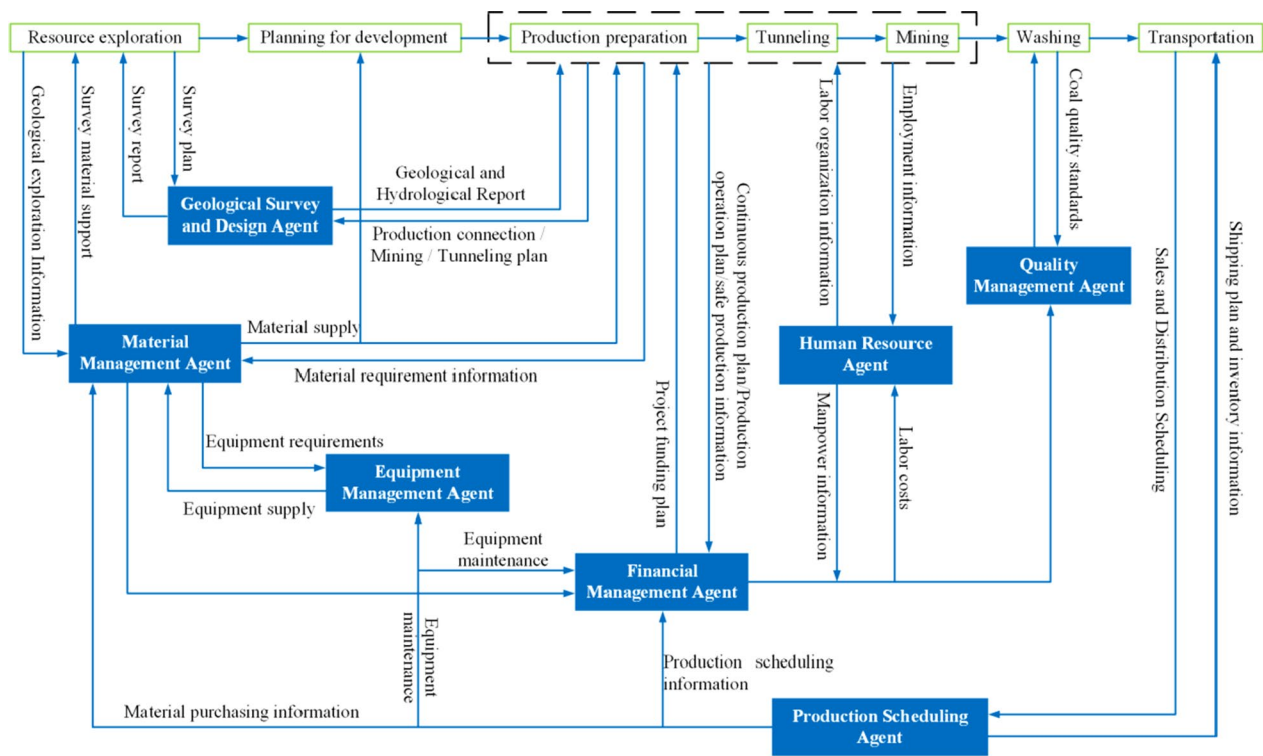


Fig. 5 MAS agent combination model of intelligent coal mine

the system output function; and Λ is the subsystem global state transfer function.

According to the combination modeling method, the overall model of the intelligent coal mine can be decomposed into the combined model of the MAS, as shown in Fig. 5.

The intelligent coal mine combination model includes seven intelligent combination models: geological survey and design, material management, equipment management, financial management, human resources, quality management, and production scheduling, which comprehensively support the process links of resource exploration, planning and development, production preparation, tunneling, mining, washing, and transportation. These agents correspond to relatively independent subsystems, which interact with the outside world autonomously, possess certain knowledge and reasoning capabilities, and complete corresponding tasks independently. The unified agent-based model is shown in Fig. 6.

Each agent needs to perceive environmental information and process it into a data structure applicable to the system. With the support of a professional knowledge base and adaptive technology, the agents can realize decision-making and intelligent control, allowing the execution module to perform and operate accordingly. Related status information and knowledge are exchanged among the agents through the communication module. Each of the above links requires different modeling and control methods to realize functions such as data signal processing, state prediction, intelligent decision-making, and collaborative linkage. For example, the geological survey and design agent uses various information about drilling and geophysical exploration to form a three-dimensional information model of the stope with the support of professional interpretation. This model supports the subsequent deployment and mining process. The production scheduling agent is affected by gas emissions, thus a gas emission prediction model based on the Petri model should be established (Kong 2011). This is associated with the production system of the working face, whereby the

mining control strategy for working faces in high-gas mines is established.

The MAS combination model is an adaptive and flexible dynamic system composed of multiple agents. It is suitable for the modeling, optimization, and control of coal mines that are greatly affected by external dynamic geological conditions, the coexistence of black box/gray box models, high dependence on knowledge and experience, and relative lack of data accumulation and analysis. Based on this model, centralized, distributed, and hybrid control methods can be implemented, with distributed collaborative control overcoming the nonlinear problems between agents that cannot be described or solved by mathematical equations. The primary method of control between coal mine production equipment must be able to consider the various characteristics and random interference of the system.

Taking the production system of a fully mechanized mining face as an example, equipment groups with strong motion correlation (e.g., coal mining machine, hydraulic support, and scraper conveyor) work in coordination with auxiliary, weakly related equipment groups (e.g., transportation and ventilation equipment). The main feature of this system is the chain-locked relationship between the controlled objects, with relatively little loop control. To form a global optimal control strategy for equipment groups in accordance with the fully mechanized mining conditions, a three-level control architecture for single-group clusters and a distributed control architecture are established. The optimal operation trajectory planning and the cooperative control method, under the influence of multiple time-varying factors, are adopted to solve the optimal cooperative control problem of a complex mining system.

In the specific control process, a variety of state perception methods and models for the surrounding rock and equipment are established to form the state description model, prediction model, and correlation model of the mining environment–production system. This process uses data fusion (Gu et al 2015), proportional-integral-derivative control (Xue et al 2019), a mathematical machine following

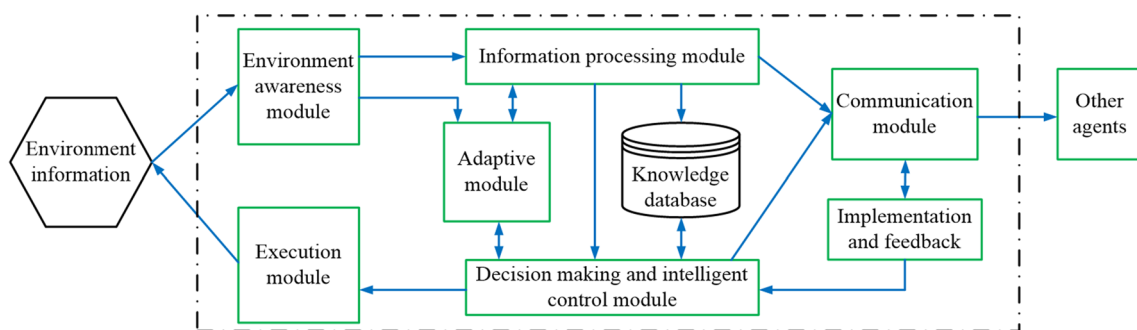


Fig. 6 Unified agent model

model (Shi et al 2016), and fuzzy control. Data pertaining to the hydraulic support posture and load are fused, and a collaborative group hydraulic support method is established. The shearer's self-adapting coal cutting control logic is developed based on the cutting parameters and stope environment. At the same time, by considering the asynchronous and variable time-delay characteristics of the sensor data, multi-scale information interaction analysis can be used to predict the operation status of the mining equipment with respect to environmental changes in the fully mechanized working face. In this way, distributed cooperative control can be employed to formulate an appropriate response.

4 System architecture of 5G+ intelligent coal mines

Coal mine systems include a wide variety of subsystems with numerous, complex connections. There is a lack of interconnection among the processes of coal mine production and operation management, such as coal mine development, mining, transportation, washing, operation, and management. An important task of building an intelligent coal mine is to study the logical connections among each link system, construct the control logic, and finally realize an intelligent system. Communication technology is vital for intercommunication within the coal mine system and between related subsystems, and the widespread application of advanced technologies such as big data, artificial intelligence, and virtual reality is necessary in an intelligent mining system. By building a high-speed digital communication network, the channels for the efficient exchange of information between different application scenarios in coal mining and management are opened up, allowing traditional industries to be empowered and reshaped towards a digital transformation.

4.1 Technical characteristics of 5G+ intelligent coal mines

The development of intelligent coal mines is inseparable from the efficient interconnection of data and information. The characteristics of large bandwidth, low latency, and comprehensive connection, as well as micro-base stations, slicing technology, and end-to-end 5G connections, provide the core technological support for overcoming the bottleneck of data transmission and processing for intelligent mining.

The fifth-generation mobile communication system is characterized by an ultra-high data rate, ultra-low delay, and ultra-large-scale access. Compared with 4G technology, 5G offers great improvements in traffic density, connection density, delay, and peak rate, enabling the core technical support for enhancing data transmission and processing in intelligent

coal mining (Wang et al 2020d). Based on the communication environment and characteristics of underground mines, effective "digital highways" can be constructed by integrating 5G+F5G+WiFi6.

The use of 5G technology alongside the integration of new-generation information technologies such as big data, artificial intelligence, blockchain, edge computing, cloud computing, and the IoT characterizes a 5G+ intelligent coal mine. This combination of technologies empowers and reshapes coal mine development design, geological surveys, mining, transportation, washing, security, ecological protection, operation, and management. As a result, the coal mine has the basic capabilities of self-perception, self-learning, self-decision-making, and self-execution, thus realizing the intelligent operation of the intelligent system (Fan et al 2020). In summary, 5G+ intelligent coal mine technology has the following characteristics:

(1) Deep interconnection. The 5G network has the ability to integrate multiple types of existing or future wireless access transmission technologies and functional networks, and can be controlled through a unified core network to provide ultra-high data rates and ultra-low delays with consistent and seamless service in multiple scenarios.

(2) Comprehensive and thorough perception. The environment and equipment status can be perceived accurately, enabling improved command and control of mining and production.

(3) Data-driven business. On the basis of deep interconnection and thorough perception, data mining and knowledge discovery are carried out through the use of data.

4.2 Top-level architecture of intelligent coal mines

The intelligent construction of coal mines needs to be planned in a unified manner from the strategic perspectives of safety, intensity, efficiency, and sustainable development. Therefore, the overall reform and innovation of top-level design aspects should be conducted, focusing on the intelligent coal mine safety management and control mode, information system architecture, intelligent decision-making, and situation analysis mode. The aim is to create a smart, convenient, efficient, and secure coal mine ecosystem covering all aspects of production and associated services.

The main purpose of the intelligent coal mine is to utilize an intelligent application system with an ubiquitous network and big data cloud platform for the core intelligent management and control functions. Through the coordination of basic resources, including intelligent management and control platforms, 5G converged networks, cloud data centers, and GIS spatial information services, it is possible to realize the perception, analysis, decision-making, and control of the entire process of coal mine development, production, and operation (Wang et al 2020e). Specifically,

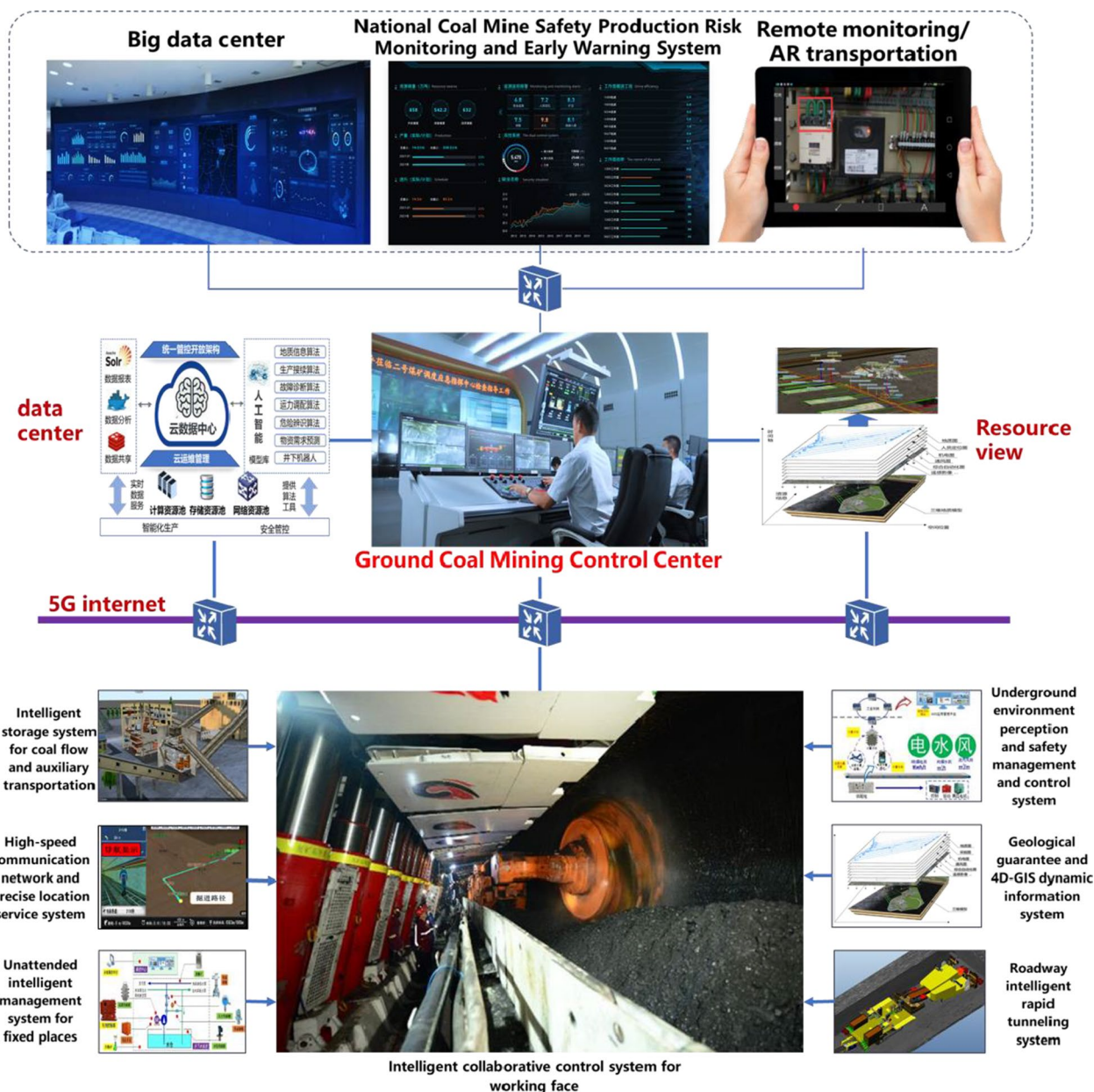


Fig. 7 Top-level architecture of 5G+ intelligent coal mine

the construction of intelligent coal mines enhances the perception, execution, and management systems, and creates a solid and reliable industrial operation system based on advanced, intelligent, and highly reliable production equipment. Additionally, intelligent coal mines rely on cutting-edge technology to achieve industrial empowerment and upgrading. Based on the control mode of “global optimization, regional classification, multi-point coordination,” the construction process includes eleven major intelligent systems (as shown in Fig. 7): (1) integrated

coal mine management system, (2) safe and efficient coal mine information network, (3) precise underground location service, (4) geological support and 4D-GIS dynamic information system, (5) rapid roadway tunneling system, (6) mining face collaborative control system, (7) coal flow and auxiliary transportation and storage system, (8) coal mine environment perception and safety management/control system, (9) coal washing system, (10) fixed-place unattended management system, and (11) coal field area and ecological system.

4.3 Application system

Based on the main activities of coal mines, intelligent application systems are constructed using basic networks, data centers, and GIS spatial information services, including autonomous intelligent mining, human–machine collaboration and rapid tunneling, unmanned auxiliary transportation, safety closed-loop control, unmanned fixed places, lean collaborative operation, and smart ecology (Fan et al 2016; Wang et al 2019; Pang et al 2019; Wu et al 2020).

The autonomous intelligent mining system is based on the coordinated mechanism of the shearer, hydraulic support, and scraper conveyor to realize the two-way communication of fully mechanized mining equipment, solve the problem of differentiated and refined control requirements of the complete set of working face equipment, and achieve the goal of intelligent mining.

The human–machine collaborative rapid tunneling system improves the tunneling efficiency through equipment integration, digital monitoring, and control automation, and achieves remote centralized monitoring of tunneling working faces and high-efficiency intelligent tunneling with fewer workers. Thus, efficient production is realized through man–machine cooperation.

The driverless auxiliary transportation system is based on a 5G positioning and navigation system and Ultra-Wideband (UWB) digitalization of underground roadways, using precise positioning and navigation modules combined with GIS technology to achieve unmanned, precise positioning and intelligent dispatch of underground vehicles.

The safety closed-loop management and control system uses IoT data collection, video pattern recognition, and intelligent analysis to create a systematic and collaborative system of mine safety situation awareness and information sharing, effectively forming a 360° intelligent monitoring platform.

The fixed places unattended system monitors the health of equipment and facilities in the mine and forms a collaborative intelligence and management platform for underground robot groups. Robots are used to replace manual operations and inspections, thus achieving unmanned fixed positions in underground mines.

The lean collaborative management system has an intelligent resource supply configuration, which can realize intelligent management and control of material procurement, equipment deployment, warehousing distribution, collaborative coal blending, and intelligent marketing. The result is an improvement in the efficiency of enterprise production resources.

The smart ecosystem is based on cloud computing, big data, IoT, and other technologies. A comprehensive digital ecosystem is constructed with full system connectivity and data integration.

5 Research progress on key technologies of coal mine intelligence

The ultimate goal of coal mine intelligence is to realize self-perception, self-learning, self-decision-making, and automatic operation of major systems such as coal mine development design, geological surveys, mining, transportation, washing, safety assurance, and production management. Through continuous scientific research and innovative practices, breakthroughs have been made in related technical equipment.

5.1 Intelligent mining technology based on dynamically revised geological model

For intelligent mining, knowledge of the geological conditions is a prerequisite, for which the information system is the foundation and intelligent control and reliability of equipment are key factors. Only by accurately detecting and predicting the static and dynamic geological conditions in the mining process, and building a dynamic 3D geological model of the working face, can reliable technical support be provided for intelligent mining (Mao et al. 2020, 2018).

To realize precise identification of the geological conditions of the working face, advanced technical methods such as high-density 3D seismic ground exploration and 3D seismic data interpretation are used to identify the geological conditions of the coal mining area. This helps to prevent unfavorable factors such as faults, collapse columns, and thinning coal seams being encountered in the design stage of the working face. Second, geological data are obtained through channel wave seismic surveys, bedding-oriented directional drilling, borehole geophysical exploration, or gas drainage holes in the working face. These data describe hidden geological structures (such as small folds, small faults), changes in coal thickness, and other geological anomalies (such as collapsed columns and magmatic rocks) in the working face. In the process of mining the working face, directional drilling and mining detection dynamically modify the working face geological model. On the basis of an accurate 3D geological model, an absolute digital model of the working face is constructed to implement autonomous intelligent coal cutting. This technology has been successfully applied in Yujialiang coal mine and Huangling No. 1 coal mine.

5.2 Underground 5G network and positioning technology

Accurate location services in the underground space are essential for intelligent coal mines. The mine geology and mining conditions are complex, the production systems are

huge, and the mining environment is changeable. Thus, it is necessary to apply IoT technology for real-time monitoring to obtain more information. In this way, the interconnection of all underground personnel, equipment, and environment data can be realized, and a comprehensive perception network can be constructed. Initially, location information must be obtained.

Zhangjiamao Coal Mine has established a 5G network transmission system for underground roadways and key safety monitoring sites. The underground 5G transmission performance, attenuation characteristics, and actual power consumption of 5G micro- and pico-base stations were tested in a pioneering exploration for the underground application of 5G networks. Xinyuan coal mine further studied the use of a 5G network for underground high-definition video transmission and remote control issues, and proposed that the uplink and downlink time slot ratio used in underground coal mines should be 3:1. The actual delay of 5G in underground remote control was found to be less than 50 ms, providing a valuable reference for scenario-based applications based on 5G technology.

At present, underground coal mine positioning systems are mostly based on traditional wireless transmission technologies such as Bluetooth, ZigBee, and ultra-wideband. The dynamic positioning accuracy is not high, and the related infrastructure must be deployed separately. Real-time performance cannot be guaranteed. The development of millimeter-wave technology and low-delay characteristics based on 5G, as well as underground integrated positioning and application services based on 5G networks, will enable underground vehicle management, improved mining precision, and solve the real-time control and management problems associated with mobile equipment.

5.3 Intelligent control technology for mining height and straightness of working face

The basic requirements for safe production in longwall coal mining are a straight and flat working face. The straightness generally refers to that of the hydraulic support, the cut coal wall, and the scraper conveyor of the fully mechanized mining face. The flatness refers to the flat top (bottom) plate of the fully mechanized mining face. Control of the mining height is related to changes in the thickness of the coal seam in the direction and the inclining direction of the working face. On the basis of “memory cutting” by the shearer to adjust the height of the drum, several core technologies are adopted to realize adaptive coal cutting following changes in the coal seam. These technologies include a precise positioning and measurement robot system, the construction and dynamic correction of the 3D geological model, construction of a transparent working face, and an intelligent visualization management and control platform.

The straightness of the scraper conveyor is controlled by the inertial navigation of the shearer, which involves measuring the curvature of the scraper conveyor and then cooperating with the difference algorithm and self-displacement feedback to complete the quantitative “push-shift” hydraulic support arrangement, thus correcting the deviation of the scraper conveyor. To reduce the positioning error of the inertial navigation system, a fully automatic measuring robot is introduced to dynamically correct the absolute coordinates of the inertial navigation, enabling the automatic relay transmission of the geodetic coordinates and accurate pose measurement of the fully mechanized mining face equipment. Heze Coal and Electricity Co. Ltd. integrated the above technologies in their Guoton coal mine, and realized a high level of integration of intelligent mining technology in the working face under the support of the latest communication, control, information, big data, and industrial IoT.

5.4 New development of intelligent mining equipment

Intelligent mining equipment and coal mine robots are the core support of intelligent coal mines. At the beginning of 2019, the National Coal Mine Safety Supervision Bureau released the “R&D Catalog for Key Products of Coal Mine Robots”, which included intelligent mining equipment.

5.4.1 Intelligent heavy-duty coal mining robot group for 1.1-m hard coal seams

Limitations in the installed power, machine height, and automation technology make it difficult to mine hard and thin coal seams. The installed power of existing thin seam shearers is less than 730 kW, the supporting machine face height is greater than 845 mm, and the mining height is greater than 1.3 m. The small working face production capacity and the low degree of automation do not meet the safety and intelligent mining requirements of hard, thin coal seam of less than 1.1 m. Therefore, it is necessary to improve the support for thin coal seam mining equipment, improve the cutting and propulsion capabilities, enhance the perception and control capabilities, and build a group of coal mining robots that



Fig. 8 Coal and rock boundary of 1.1-m thin coal seam working face

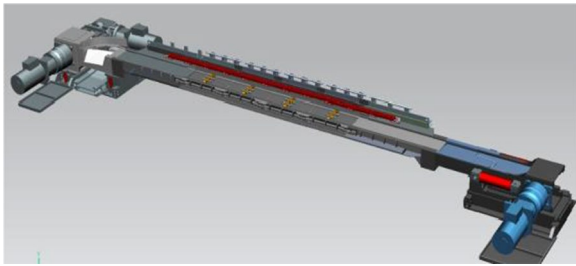


Fig. 9 Complete sets of equipment for thin coal seams

can cut independently and advance cooperatively, as shown in Figs. 8 and 9.

Technology with a high performance–volume ratio (PVR = 402) that allows for space-time cooperation and flexibility, with a large drop between the laneway and the face end of the coal mining face, has been proposed. This technology can support safe and efficient mining of 1.1-m hard thin coal seams.

A robot cluster for 1.1-m hard thin coal seams has been developed, including a semi-suspended body, full-suspended cutting low body shearer, coal shearer with an installed power of 1050 kW, and a high-rigidity anti-dynamic load hydraulic support with a working resistance of 9000 kN. Additionally, 34/86 × 126 ultra-flat chain transportation equipment with a large capacity, low body, and overlapping side unloading has been adopted for the first time.

An intelligent control device for thin coal seams has been developed. An intelligent monitoring system with wired and wireless dual-network communication and multi-data fusion has been adopted, including automatic straightening by high accuracy inertial navigation, coal flow balancing, an automatic towing trolley, and a high-definition intrinsically safe camera. Together, these items form the “perception, control, and execution” system of the coal mining robot cluster, enabling remote fault diagnosis, whole lifecycle management, the application of a new underground intelligent control system and centralized control center for thin coal seams, and unmanned operation along the thin coal seam face.

The intelligent heavy-duty coal mining robot group developed for hard thin coal seams has been applied in the Huisen Liangshuijing coal mine in Yulin. The equipment and system are stable and reliable, reaching an annual output of 1 million t/a. Collectively, this promotes the collaboration of the mining equipment cluster and plays an important role in demonstrating the advancement of China’s thin coal seam mining technology.

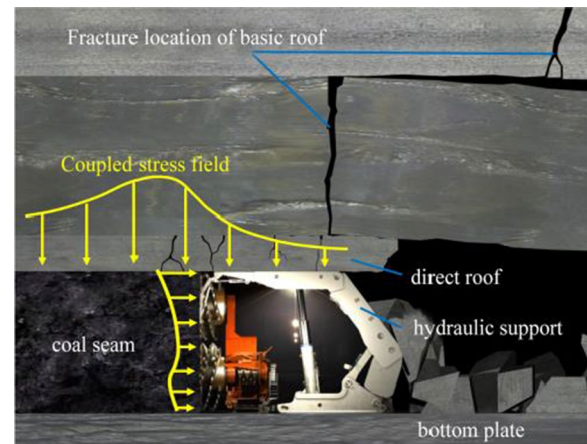


Fig. 10 Coupling of super-large mining height hydraulic support and surrounding rock

5.4.2 Complete set of intelligent fully mechanized mining equipment for 6–10 m super-large mining heights

Shanxi, Shaanxi, and Inner Mongolia are large coal bases with mainly high-quality hard coal, and account for 70% of the total coal output of China. Fully mechanized mining with super-large mining heights faces problems such as rib spalling, roof collapse, roof impact, super-high-power equipment structures, control reliability, and stable operation. To solve these problems, intelligent fully mechanized mining equipment for super-large mining heights has been developed in Hongliulin, Jinjitan, Shangwan, and other coal mines.

The theory and technology of fully mechanized mining with super-large mining heights have been proposed, as shown in Fig. 10. This is the first time that a full-thickness, fully mechanized coal mining method has been developed for multiple-stress-field coupling and intelligent control of the surrounding rock in coal seams of more than 6-m thick. The coupling principle of the support and the surrounding rock strength, stiffness, and stability, and the collaborative technology of support, mining, and transportation are proposed. This solves the problems of super-high mining technology and surrounding rock control. The mining efficiency can be increased by up to 70%, and the resource recovery rate has increased by more than 25%.

The super-high mining height hydraulic support, self-adaptive support of the surrounding rock, and cooperative control technology have been proposed. The 3D dynamic optimization design of the hydraulic support, capacity-increasing buffer anti-impact column, three-stage cooperative support device, automatic compensation of the initial



Fig. 11 Complete set of fully mechanized mining equipment for super-large mining heights

support force and rapid moving frame system, and adaptive cooperative control technology for the hydraulic support group were developed, which solved the problems of the original rigid support structure not adapting to the dynamic load impact conditions and the difficulty of realizing real-time cooperative control. As a result, fully mechanized mining support has been established with a new super-large mining height concept and technical realization path.

The key technologies and mechanized equipment for super-high mining height high-power autonomous cutting and continuous transportation of over-heavy loads have been proposed. A low-carbon micro-alloyed cast steel material was developed for the cutting part of the shearer, and its manufacturing process and automatic cutting control system were established. Additionally, a scraper conveyor with a pre-crushing function for large pieces of coal, a variable-frequency drive speed control method, and a super-large chain drive system were developed. This equipment constitutes a complete system for super-large mining heights, as shown in Fig. 11.

The complete set of equipment has been used in 39 super-large coal mines, including Hongliulin and Jinjitan. The output of the working face has been increased from less than 30,000 tons per day to more than 60,000 tons per day. At present, ultra-large mining height technology and equipment for working heights above 10 m are being developed and implemented in the Caojiatan coal mine of Yubei, Shaanxi Coal. This continues the development of core technologies



Fig. 12 Shield-type intelligent tunneling robot system

using high-strength materials, distributed liquid supplies, and super-high-power shearer and scraper conveyors, and will lead to the development of fully mechanized mining technology and equipment.

5.4.3 Coal mine tunneling robot system

In recent years, intelligent rapid tunneling has received increasing attention. A variety of supporting models have been explored for different geological conditions in China, and rapid tunneling equipment has been developed. The level of footage and the degree of automation have been significantly improved. A gantry shield-type intelligent tunneling robot system, developed by Xi'an University of Science and Technology and Xi'an Coal Mining Machinery Co., Ltd. (Fig. 12), includes tunneling robots, anchor drilling robots, temporary support robots, drill supplement robots, anchor net transportation robots, a ventilation system, a second transport system, and a self-moving tail. The anchor drill robot, temporary support robot, and drill supplement robot are all frame structures, arranged one after the other to provide a safe working space for the tunneling robot. They complete the tasks of anchor mesh support and drilling and anchoring. The tunneling robot and the second transport system are arranged in sequence, located inside the frame structure formed by the anchor drilling robot, temporary support robot, and drill supplement robot, and realize coal mining and transportation alongside the parallel operation of tunneling and support.

The tunneling robot system integrates the functions of digging, supporting, anchoring, transportation, ventilation, and dust removal. It has functions for positioning and navigation, automatic cutting, remote control, intelligent network deployment, multi-robot cooperative control and parallel operation, and remote intelligent monitoring. The result is virtual intelligent measurement and control, with one-key start and stop of the whole system on and under the ground (Fig. 13). The application was implemented in the working



Fig. 13 Underground monitoring center

face of a smooth channel in the No. 1 Coal Mine of Xiaobaodang Company. At present, the single-row operation time is controlled at 20 min, the footage per day exceeds 45 m, the per capita work efficiency has been improved to 3 m per worker, and the monthly footage has reached 816 m.

6 Future prospects

The development of intelligent coal mines is a continuous process, and enhancing the degree of intelligence is an iterative task. At present, China's coal mine intelligence is still in the cultivation and development stage, and there are still some problems such as inconsistent understanding, unbalanced development, a lack of relevant technical standards and specifications related to coal mine intelligence, and weak basic theories. Several key technical bottlenecks need to be overcome, and the research and development of technology and equipment lags behind the development needs of enterprises. Additionally, there is an imperfect research and development platform and the lack of resources in high-end coal mines restricts the development of intelligent systems. The next 5 years is an important development period for the intelligence of coal mines. It is necessary to recognize the objective laws of the development of intelligent coal mines and the existing problems at this stage. According to the occurrence conditions and development status of different coal seams, it is necessary to formulate and improve the intelligent coal mine development plan according to the various regions of China and the existing technical basis of the coal mines. It is important to plan the development modes of intelligent coal mines at different levels and to clarify the technical systems, implementation paths, construction tasks, and construction goals of different development modes. In addition, the resource allocation of coal mine enterprises should be optimized and an innovative ecological environment should be created for the intelligent construction of coal mines. Finally, there is an urgent need to actively promote the transformation and upgrading of the traditional coal industry to the status of a truly intelligent system.

6.1 Vision for intelligent development of coal mines

The vision for the intelligent development of the coal industry involves realizing the real-time perception of all-time and multi-source information in coal mines alongside closed-loop risk control and intrinsic safety. The efficient and collaborative operation of human-machine-environment-management digital interconnection in the whole process is vital, as is the full automation of the production site. This will result in greater job satisfaction for coal mine employees and more value creation for coal enterprises.

6.2 Development goals for the next 5 years

The intelligent construction of coal mines adheres to the principles of classified construction and the implementation of policies according to the differences among mines; the promotion of comprehensive and graded compliance, safety and efficiency, and the quality-first principle are also important.

The key development goals for the next 5 years are the comprehensive upgrade and transformation of Category I (good mining technical conditions) and II (medium mining technical conditions) coal mines, focusing on improving the intelligence level of the coal mining face, reducing the number of people and improving the efficiency of the tunneling face, ensuring full coverage of intelligent security control, realizing unattended operations in all fixed positions, and forming an intelligent integrated management and control system based on a comprehensive management and control platform. For Category III (poor mining technical conditions) coal mines, the focus should be on the basic information systems, mechanized and intelligent mining systems, monitoring and early warning of major safety hazards, and improving safety monitoring systems to reduce risks to personnel, increase safety, and improve efficiency. For new coal mines, the design of an intelligent top-level architecture should be completed to enable advanced development and production technology, intelligent equipment, and intelligent basic systems, production systems, integrated management and control platforms, comprehensive management. The overall objective should be an intelligent coal mine with a coordinated and efficient operation and maintenance system.

The construction goals of intelligent open-pit coal mines are as follows. Production should focus on improving the construction of mine networks, data centers, and perception systems, including the construction of remote control systems, unmanned driving systems, and remote operation and maintenance systems. The goal is to realize the digitization of the mining environment, with intelligent mining equipment, remote control of the production process, an information transmission network, and informatization of operation and management. New mines should build an information infrastructure from a high starting point, enabling open-pit mine information transmission, processing, and storage platforms as well as centralized management and control systems. Remote intelligent control of the mining process and unattended operations at fixed positions should be ensured, alongside an open-pit mine intelligent integrated management and control platform and intelligent mining based on big data analysis and cloud computing.

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