Construction of digital twin system for intelligent mining in coal mines

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ABSTRACT

In order to fulfill the functions of comprehensive perception, real time interconnection, analysis and decision making, autonomous learning, dynamic prediction and cooperative control, an overall framework of Digital Twin Smart Mining Workface was established. Firstly, the digital twin smart mining face system was divided into 3 levels, and the functions and characteristics of each level were given. Secondly, based on the physical domain entities contained in the intelligent mining face, the data perception models of coal shearer, scraper conveyor, stage loader, crusher, hydraulic support, belt conveyor support, emulsion pump station and environment in the digital twin working face system were expounded in detail, and the collaborative constraint relationship among shearer, hydraulic support, coal flow transportation system, workface environment and equipment was analyzed in depth. Finally, the application scheme of the digital twin intelligent mining face system was designed. Based on the digital twin intelligent mining face system, the virtual-real mapping and real-time interaction between physical mine entities and digital mine twins could be realized, and the intelligent perception and cooperative control of digital twins could be performed, which provides a basis for improving the intelligent level of coal mining face.

Keywords: digital twin; intelligent mining face; perceptual model; collaborative constraint relationship

1. Introduction

Coal is an important basic energy in China. According to the latest data released by the State Administration of mine safety, China’s coal mine intelligent construction has made positive progress. In 2019, there were 275 coal mine intelligent mining faces in China, increasing to 494 in 2020, an increase of 80% year-on-year. In March 2021, in order to guide and standardize the construction of intelligent coal mines, the coal department of the National Energy Administration organized the preparation of the guide for the construction of intelligent coal mines (2021 version) (Exposure Draft), which defined the three phased objectives of the development of intelligent coal mines, and finally formed a coal mine intelligent system with...
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comprehensive perception, real-time interconnection, analysis and decision-making, autonomous learning, dynamic prediction and collaborative control[1].

The intelligent fully mechanized mining face of coal mine is usually composed of “five machines and one set” such as shearer, scraper conveyor, transfer machine, crusher, belt conveyor, hydraulic support and emulsion pump station. Although the basic key technologies such as intelligent state perception and information communication interconnection of corresponding electromechanical equipment have made great progress, the intelligent technologies related to the coordinated control and safety management of the whole process flow of intelligent fully mechanized mining, such as intelligent coordination between equipment, autonomous dispatching and equipment group association management, are still relatively weak[2–4]. In addition, the data communication interface of electromechanical equipment is not unified, which increases the difficulty of field equipment integration and makes it difficult to realize the organic integration of fully mechanized mining face equipment[5], which limits the holographic perception of physical space of underground intelligent fully mechanized mining face. Therefore, it is imperative to build a twin intelligent mining system based on full information perception analysis, process simulation, collaborative control and real-time optimization decision-making of fully mechanized mining face based on visual three-dimensional model[6].

Digital twin (DT) technology is a key technology to create a virtual model of physical entities[7] by digital method and realize two-way mapping, dynamic interaction and real-time connection between the physical world and the digital world. Digital twin can map the attributes, structure, state, performance, function and behavior of physical entities to the digital world[8], forming a high fidelity dynamic multi-dimensional, multi-scale and multi physical quantity model[9], so as to provide more real-time, efficient and intelligent operation or operation services for physical entities. Digital twin technology has been widely used in product design, manufacturing and operation and maintenance services. In the innovative design of complex products, the digital twin 3D design platform is used to update the twin design model through human-computer interaction information feedback, and finally mapped to physical entity products. In the manufacturing stage, digital twin technology is used to realize the interactive mirror image of production process model and automatic production line, so as to support the intelligent integration of the whole production chain. In terms of equipment operation and maintenance services[10], by constructing digital twins equivalent to physical entities, the fault prediction of complex systems is realized, which provides a basis for the health management of the whole life cycle of equipment.

The application of digital twin technology in coal mine is still in its infancy. Ge et al.[11] pointed out that Digital Twin Smart Mining Face (DTSMW) is a highly realistic three-dimensional mirror scene of coal mining face with three-dimensional data visualization, strong human-computer interaction and self-optimization of the whole process. The system can realize two-way communication and information interaction between twins and physical entities, so as to realize holographic perception of the physical space of underground unmanned fully mechanized mining face, real-time monitoring of production process and performance, and three-dimensional visual reproduction of virtual scene, so as to effectively improve the intelligent level of coal fully mechanized mining face.

2. System architecture of digital twin intelligent mining face in coal mine

2.1. System reference framework

The digital twin system of intelligent mining face (hereinafter referred to as intelligent mining face) is composed of intelligent mining face digital
twin application service, intelligent mining face digital twin, intelligent mining face real physical domain and 10 key technologies\(^\text{(11)}\), as shown in Figure 1. The digital twin of intelligent mining face is a virtual coal mining process with two-way mapping and dynamic interaction with the real physical domain of intelligent mining face through the digital twin intelligent mining face system of coal mine, it can provide users with real-time state perception and analysis, full scene virtual 3D online, fault and anomaly online analysis, whole process iterative scheduling optimization, safety situation evaluation and whole life cycle management.

Figure 1. The frame of digital twin system for intelligent mining workface.
The physical entities of digital twin intelligent mining face of coal mine are divided according to electromechanical equipment and working condition environment, as shown in Figure 2. Geographic information is a high-fidelity working face 3DGIS map based on the geological survey CAD map of the working face, using computer graphics and three-dimensional visualization technology and rendering of terrain, image and model. Through the analysis of drilling records at different positions, angles and orientations, the drilling detection data of the roof and floor of the coal seam roadway are obtained to determine the occurrence of the coal seam in the roadway of the pre mining face. Environmental safety includes working face gas environment, spontaneous combustion in goaf, rock burst and water gushing, etc.

Figure 2. Physical entity of digital twin system for intelligent mining workface.

There is a one-to-one correspondence between the digital twin of intelligent mining face and its real physical domain. The second part includes intelligent mining face modeling, multi-dimensional simulation and multi-dimensional simulation, including intelligent mining face modeling and multi-dimensional simulation. Every entity in the real physical domain has a digital twin model corresponding to it. The completed model evolves synchronously with the physical entity in multi-dimensional, multi state and multi time and space. After the intelligent mining simulation modeling is completed, the simulation model can accurately describe the entities of the real physical domain to a certain extent. After the accurate mapping, information duality, information interaction and co-evolution of the intelligent mining twins, the simulation model is transformed into the intelligent mining twins in the real sense.

2.2. Hierarchical division of system evolution of digital twin intelligent mining face in coal mine

The technical layer model of digital twin intelligent mining face system in coal mine is shown in Figure 3, and its evolution process includes three stages.

Virtual model stage

Complete the digital twin modeling of physical entities. According to the geological conditions and coal mining technology of the coal mining face, the three-dimensional physical model of the intelligent mining face is established by using the three-dimensional modeling tool. Firstly, the structure, geometry, material, state and other parameters of the three-dimensional model are determined. Secondly, the three-dimensional model is established by using solid works modeling software, and then the model is rendered by 3D max software and further imported into unity 3D to build a visual physical entity simulation model[12]. Finally, the unity 3D interface program is written in C# language for data information transmission, and the applicability of the model is analyzed. The core of this stage is to establish the digital twin of shearer, scraper conveyor, transfer machine, crusher, belt conveyor, hydraulic support and emulsion pump station.
Basic digital twinning stage realize data information exchange between twins and physical domain. Information exchange includes information exchange and collaborative control between different digital twin models, as well as data exchange and interaction between digital models and physical models. According to the association relationship and mining process of multiple.

Equipment in intelligent mining face, the interaction model between digital twin models is established to realize information interaction and collaborative control. At the same time, the data interaction between the digital twin and the physical model is established. By obtaining various state monitoring information in the physical domain, the state of each main mechanism of the intelligent coal mining face is monitored in real time, and the synchronous state update of the digital twin model and the physical domain entity is realized through the information transmission interface with the digital twin. Data transmission depends on the unified access of various hardware interfaces and protocols, mainly including the support of wired and wireless communication networks such as Ethernet, RS485, can, 5g, Wi-Fi 6, ZigBee, Lora and UWB, as well as the unified knowledge description of perceived information at the software level.

Adaptive digital twin stage: through the unified processing of multi-source heterogeneous data, realize the real-time driving and correction of digital twins and physical entities in intelligent coal mining face. Its core lies in using big data analysis and machine learning technology to build a unified knowledge model, semantic description and data model of digital twins\textsuperscript{13}, so as to obtain accurate prediction of the physical world. Integrate artificial intelligence algorithm and edge computing theory to realize real-time analysis of data, as well as full state perception and analysis of intelligent mining face, collaborative scheduling and control of the whole process, intelligent prediction and maintenance of the whole life cycle.

![Hierarchical model of digital twin technology of intelligent mining workface.](image)

3. System construction of digital twin intelligent mining face in coal mine

3.1. Perception model of digital twin intelligent mining face in coal mine

The construction of digital twin intelligent
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mining face in coal mine depends on the accurate and efficient model of various equipment. The perception model of “five machines and one machine” provides strong data support for the digital twin system of the whole intelligent mining face.

**Shearer perception model**

Shearer is the core of “five machines and one frame” in the working face, which is mainly composed of drum, rocker arm, cutting motor, traction walking part, control box, high-voltage box, etc., which can be divided into electrical, hydraulic and mechanical parts the sensing information of shearer mainly includes state sensing, position and attitude sensing and cutting state sensing. The sensing model parameters are shown in Table 1.

| Sensor | Monitoring location and quantity |
|--------|----------------------------------|
| Three phase instantaneous current transformer | Left and right cut-off current  
| | Left and right traction current  
| | Left and right frequency converter current  
| | Left and right oil pump motor current  
| | Crushing motor current  
| Temperature sensor | Temperature of left and right cutting motors  
| | Temperature of left and right planetary heads  
| | Left and right oil pump motor temperature  
| | Traction transformer temperature  
| | Crushing motor temperature  
| | Left and right traction motor shaft temperature  
| | Temperature of left and right frequency converters  
| | Increase the oil temperature of pump tank  
| | Oil temperature of left and right traction boxes  
| | Temperature of left and right rocker shaft  
| Pressure sensor | High pressure of left and right cylinders  
| | Increase the oil pressure at the low-pressure side of the pump  
| | Cooling water pressure  
| | Brake pressure  
| Voltage transmitter | Shearer voltage  
| | Output voltage of left and right frequency converters  
| Leakage detection | Left and right cutting motors  
| | Left and right traction motors  
| | Oil pump motor  
| | Crushing motor  
| Encoder | Angle of left and right rocker arms  
| | Position of shearer traction part  
| Inclination sensor | Inclination of left and right rocker arms  
| Travel sensor | Mining height of left and right rollers  
| Liquid level sensor | Oil level of oil tank  
| Tension sensor | Tension of power supply cable  
| Vibration sensor | Left and right rocker arm transmission boxes  
| | Left and right traction transmission boxes  
| Infrared camera | Both sides of Shearer  
| IMU inertial navigation unit | Center position of Shearer  

Table 1. Parameters of sensing model for a coal shearer
By fusing the above multi-modal information, the dynamic identification of coal rock interface is realized to provide information basis for cutting state adjustment\(^{[14]}\).

**Scraper conveyor perception model**

The sensing information of scraper conveyor mainly includes the operation status of reducer and motor, and automatically adjusts the chain tightness by monitoring the chain tension of scraper chain to prevent chain fracture. At the same time, the possibility of chain breaking accident is predicted by obtaining the parallelism information of the scraper in the middle slot.

In addition, according to the inclination sensor information arranged on the middle slot of the scraper conveyor, determine the double axis inclination of the middle slot, restore the three-dimensional terrain of the working face by solving the attitude of the middle slot of the scraper conveyor, complete the state analysis of the bottom plate shape of the fully mechanized mining face\(^{[15]}\), and guide the attitude adjustment of related equipment.

The sensing model parameters of scraper conveyor are shown in Table 2.

| Position          | Monitoring quantity                      | Sensor          |
|-------------------|-----------------------------------------|-----------------|
| Retarder          | Cooling water flow value                 | Flow sensor     |
|                   | Cooling water temperature value          | Temperature sensor |
|                   | Cooling water pressure value             | Pressure sensor |
|                   | Oil level height value of reducer oil tank | Liquid level sensor |
|                   | Oil temperature of reducer oil tank      | Temperature sensor |
|                   | Reducer high speed shaft bearing temperature | Temperature sensor |
|                   | Reducer low speed shaft bearing temperature | Temperature sensor |
|                   | Vibration detection of reducer           | Vibration sensor |
|                   | Reducer noise detection                  | Sound sensor    |
| Motor             | Winding temperature of two speed motor   | Temperature sensor |
|                   | Bearing temperature of two speed motor   | Temperature sensor |
|                   | Cooling water flow value                 | Flow sensor     |
|                   | Cooling water temperature value          | Temperature sensor |
|                   | Cooling water pressure value             | Pressure sensor |
|                   | Double speed motor                       | Current sensor  |
|                   | Two speed motor voltage                  | Voltage sensor  |
|                   | Vibration detection of two speed motor   | Vibration sensor |
|                   | Noise detection of two speed motor       | Sound sensor    |
|                   | Two speed motor power                    | Power sensor    |
| Scraper chain     | Chain tension monitoring                 | Tension sensor  |
| Middle groove     | Scraper parallelism monitoring           | Parallelism sensor |
|                   | Slot attitude monitoring                 | Inclination sensor |
|                   | Bottom plate shape monitoring            | Inclination sensor |

**Crusher perception model**

The crusher is mainly used to crush coal and gangue, so as to adjust the coal discharge clearance and ensure the safe operation of the retractable belt conveyor in the transportation link. See Table 3 for its sensing model parameters.
Table 3. Parameters of sensing model for a crusher

| Position | Monitoring quantity                                      | Sensor         |
|----------|---------------------------------------------------------|----------------|
| Retarder | Cooling water flow value                                | Flow sensor    |
|          | Cooling water temperature value                         | Temperature sensor |
|          | Cooling water pressure value                            | Pressure sensor |
|          | Oil level height value of reducer oil tank              | Liquid level sensor |
|          | Oil temperature of reducer oil tank                     | Temperature sensor |
|          | Reducer high speed shaft bearing temperature            | Temperature sensor |
|          | Reducer low speed shaft bearing temperature             | Temperature sensor |
|          | Vibration detection of reducer                          | Vibration sensor |
|          | Reducer noise detection                                | Sound sensor   |
| Motor    | Winding temperature of two speed motor                 | Temperature sensor |
|          | Bearing temperature of two speed motor                 | Temperature sensor |
|          | Cooling water flow value                                | Flow sensor    |
|          | Cooling water temperature value                         | Temperature sensor |
|          | Cooling water pressure value                            | Pressure sensor |
|          | Motor current                                           | Current sensor |
|          | Motor voltage                                           | Voltage sensor |
|          | Motor vibration detection                               | Vibration sensor |
|          | Motor noise detection                                   | Sound sensor   |
|          | Motor power                                             | Power sensor   |
| Crushing part | Crushing shaft temperature                             | Temperature sensor |
| Feed inlet | Pile coal                                               | Coal stacking sensor |

Table 4. Parameters of sensing model for a stage loader

| Position | Monitoring quantity                                      | Sensor         |
|----------|---------------------------------------------------------|----------------|
| Retarder | Cooling water flow value                                | Flow sensor    |
|          | Cooling water temperature value                         | Temperature sensor |
|          | Cooling water pressure value                            | Pressure sensor |
|          | Oil level height value of reducer oil tank              | Liquid level sensor |
|          | Oil temperature of reducer oil tank                     | Temperature sensor |
|          | Reducer high speed shaft bearing temperature            | Temperature sensor |
|          | Reducer low speed shaft bearing temperature             | Temperature sensor |
|          | Vibration detection of reducer                          | Vibration sensor |
|          | Reducer noise detection                                | Sound sensor   |
| Motor    | Winding temperature of two speed motor                 | Temperature sensor |
|          | Bearing temperature of two speed motor                 | Temperature sensor |
|          | Cooling water flow value                                | Flow sensor    |
|          | Cooling water temperature value                         | Temperature sensor |
|          | Cooling water pressure value                            | Pressure sensor |
|          | Motor current                                           | Current sensor |
|          | Motor voltage                                           | Voltage sensor |
|          | Motor vibration detection                               | Vibration sensor |
|          | Motor noise detection                                   | Sound sensor   |
|          | Motor power                                             | Power sensor   |

**Repeater perception model**

The transfer machine is the intermediate transfer equipment of the coal transportation system of the fully mechanized mining face. The falling coal on the scraper conveyor of the working face is transferred to the roadway belt conveyor through the transfer machine and the automatic transfer device at the tail of the conveyor belt. The length of the transfer machine is small, which is easy to move with the advance of the coal mining face and the movement of the self-moving device at the tail of the conveyor belt. It is usually installed in the transportation roadway of the coal mining face and connected with the scraper conveyor of the coal mining face.

The perception information of the repeater mainly comes from the state analysis of the reducer and motor, and the perception model parameters are
shown in Table 4.

**Emulsion pump station sensing model**

Emulsion pump station is the hydraulic power source of the whole intelligent mining face, which mainly provides enough high-pressure power emulsion for the hydraulic support of the face. The pump station is mainly composed of emulsion distribution tank, electromagnetic unloading valve, emulsion pump set and high-pressure filtration backwash water treatment device. The control core of emulsion pump station is to dynamically adjust the output emulsion pressure and flow of distribution hydraulic support according to the current geological environment of intelligent mining face, to provide guarantee for the safe operation of intelligent mining face. See Table 5 for its perception model parameters.

| Table 5. Parameters of sensing model for an emulsion pump |
|---------------------------------------------------------|
| **Position** | **Monitoring quantity** | **Sensor** |
| Pump set | Motor current | Current transformer |
| Pump set | Motor voltage | Voltage sensor |
| Lubricating oil level of pump set | | Liquid level sensor |
| Pump set motor shaft temperature | | Temperature sensor |
| Pump set motor winding temperature | | Temperature sensor |
| Emulsion pump | Pressure of liquid supply system | Pressure sensor |
| | Emulsion tank level | Liquid level sensor |
| | Emulsion tank concentration | Concentration sensor |
| | Backwash pipeline pressure | Pressure sensor |
| | Pump unit vibration monitoring | Vibration sensor |
| | Pump unit noise monitoring | Sound sensor |
| Distribution tank | Motor current | Current transformer |
| Distribution tank | Motor voltage | Voltage sensor |
| Distribution tank | Motor current | Temperature sensor |
| Motor shaft of liquid distribution tank | | Liquid level sensor |
| Liquid level of distribution tank | | Liquid level sensor |
| Oil level of distribution tank | | |
| Concentration of liquid distribution tank | Concentration sensor | |
| Distribution tank | Emulsified oil delivery flow emulsified oil tank oil level | Flow sensor |
| Liquid level sensor | | |
| Water treatment | Motor current | Current transformer |
| Water treatment | Motor voltage | Voltage sensor |
| Liquid level of purified soft water tank | Liquid level sensor | |
| Pressure of purified soft water pipeline | Pressure sensor | |

**Hydraulic support sensing model**

In order to meet the needs of hydraulic support attitude adjustment, the support attitude is obtained through IMU inertial navigation units arranged at the top beam, rear connecting rod and base; Judge whether the upper guard plate and expansion beam are retracted in place through the proximity sensor; Judge the moving state of the support through the displacement sensor of the moving oil cylinder; The infrared camera is used to detect the temperature difference between coal and rock mass near the cutting pick and identify the coal rock interface[16]. See Table 6 for the parameters of hydraulic support perception model.
### Table 6. Parameters of sensing model for a hydraulic support

| Position          | Monitoring quantity       | Sensor                                      |
|-------------------|---------------------------|---------------------------------------------|
| Top beam          | Roof beam attitude        | IMU inertial navigation position and attitude| Pressure sensor |
|                   | Liquid supply pressure    |                                             |                  |
| Rear connecting   | Connecting rod attitude   | IMU inertial navigation position and attitude| Pressure sensor |
| rod               | Liquid supply pressure    |                                             |                  |
| Base              | Base attitude             | IMU inertial navigation position and attitude| Pressure sensor |
|                   | Displacement              | Displacement sensor                         |                  |
|                   | Liquid supply pressure    |                                             |                  |
| Protect the gang  | Distance quantity         | Proximity sensor                            |                  |
|                   | Liquid supply pressure    | Pressure sensor                             |                  |
| Telescopic beam   | Distance quantity         | Proximity sensor                            |                  |
|                   | Liquid supply pressure    | Pressure sensor                             |                  |
| Column            | Shearer position          | Infrared transceiver sensor                 | Infrared camera  |
|                   | Video information         |                                             |                  |

### Table 7. Parameters of sensing model for a belt conveyor

| Position          | Monitoring quantity       | Sensor                                      |
|-------------------|---------------------------|---------------------------------------------|
| Conveyor belt     | Belt deviation            | Deviation sensor                           |                  |
|                   | Belt speed                | Speed sensor                               |                  |
|                   | Coal level height         | Coal stacking sensor                        |                  |
|                   | Idler temperature         | Temperature sensor                         |                  |
|                   | Spontaneous combustion of conveyor belt | Smoke sensor |                  |
|                   | Coal quantity detection  | Laser sensor                               |                  |
| Nose              | Video surveillance        | Video camera                               |                  |
|                   | Wire rope tension         | Tension sensor                             |                  |
| Tensioning device | Hydraulic pump station pressure | Pressure sensor |                  |
|                   | Cooling water flow value  | Flow sensor                                |                  |
|                   | Cooling water temperature value | Temperature sensor |                  |
|                   | Cooling water pressure value | Pressure sensor |                  |
| Retarder          | Oil temperature of reducer oil tank | Temperature sensor |                  |
|                   | Reducer shaft bearing temperature | Temperature sensor |                  |
|                   | Vibration detection of reducer | Vibration sensor |                  |
|                   | Reducer noise detection   | Sound sensor                               |                  |
|                   | Motor winding temperature | Temperature sensor                         |                  |
|                   | Motor bearing temperature | Temperature sensor                         |                  |
|                   | Cooling water flow value  | Flow sensor                                |                  |
|                   | Cooling water temperature value | Temperature sensor |                  |
|                   | Cooling water pressure value | Pressure sensor |                  |
| Motor              | Motor current             | Current sensor                             |                  |
|                   | Motor voltage             | Voltage sensor                             |                  |
|                   | Motor vibration detection | Vibration sensor                           |                  |
|                   | Motor noise detection     | Sound sensor                               |                  |
|                   | Motor power               | Power sensor                               |                  |
**Belt conveyor perception model**

The belt conveyor in the transportation roadway is the key equipment in the production process of coal mine. The coal cut by the shearer passes through the scraper conveyor and transfer machine to the belt conveyor in the transportation roadway. The belt conveyor in the transportation lane is generally composed of unloading end, driving device, belt storage bin, tensioning trolley and tensioning device, self-moving tail, etc. At present, the belt conveyor in the transportation roadway is mostly composed of PLC monitoring operating system to realize the functions of soft start, power balance and comprehensive protection of the equipment. Its sensing model parameters are working face dangerous gas concentration methane sensor T2 return air roadway methane sensor T3 inlet air roadway methane sensor coal miner carbon monoxide sensor return air roadway, as shown in Table 7.

**Working face environment perception model**

The “Coal Mine Safety Monitoring System and Management Specification for the Use of Testing Instruments (AQ1029-2019)” stipulates the requirements for the arrangement of environmental monitoring sensors in working faces. Methane sensors T0–T4 are arranged in the air inlet, upper corner, and return airway of the working face respectively, and the corresponding regional power-off protection control is carried out according to the concentration value of the methane sensor. A methane sensor is installed on the fuselage of the shearer, and the over-limit power-off control is carried out through the on-board methane power-off instrument. By setting corresponding sensors, real-time monitoring of carbon monoxide concentration, temperature, air supply and dust concentration in the working face. The parameters of the working face environment perception model are shown in Table 8.

| Table 8. Parameters of sensing model for workface environment |
|---------------------------------------------------------------|
| **Monitoring quantity**                                       | **Sensor**          | **Installation position** |
| Dangerous gas concentration in working face                   | Methane sensor T₀   | Upper corner of working face |
|                                                               | Methane sensor T₁   | Face                       |
|                                                               | Methane sensor T₂   | Return air lane             |
|                                                               | Methane sensor T₃   | Air inlet roadway           |
|                                                               | Methane sensor      | Shearer                    |
|                                                               | Carbon monoxide sensor | Return air lane         |
| Working face wind speed                                       | Wind speed sensor   | Return air lane             |
| Working face temperature                                      | Temperature sensor  | Coal face                   |
| Working flour dust                                            | Dust sensor         | Coal face return air roadway|
| Natural ignition of belt conveyor                             | Smoke sensor        | Belt conveyor head          |
|                                                               | Dust sensor         | Belt conveyor head          |
|                                                               | Carbon monoxide sensor | Belt conveyor head |
| Goaf fire                                                     | Optical fiber temperature measuring device | Goaf |
| Working face water level                                      | Water level sensor  | Roadway catchment           |
|                                                               | Pressure sensor     | Hydraulic support           |
|                                                               | Roof separation sensor | Roadway roof               |
|                                                               | Bolt stress sensor  | Roadway roof                |
|                                                               | Borehole stress sensor | Roadway roof              |

Laser optical fiber technology is used for temperature and fire monitoring in goal of coal mine. According to the principle of laser Raman scattering and optical time domain reflection (OTDR), the temperature anomaly is located to realize the distributed temperature measurement along the optical fiber temperature field, which can not only accurately measure the temperature of the measured location, but also accurately locate the temperature anomaly location and accurately detect the fire.

The roof separation sensor is used to monitor the roof separation. Bolt stress sensor is used to monitor the axial stress change of bolt (cable), analyze the action law of stope dynamic pressure, and carry out initial prediction and trend analysis of
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3.2. Digital twin collaborative constraint relationship of intelligent coal mining face

Cooperative constraint relationship of shearer cooperative constraint relationship of Shearer

As shown in Figure 4. Before coal seam mining, the corresponding mining technology shall be determined according to the geological exploration data, and the memory cutting strategy shall be independently generated in combination with the historical cutting trajectory. In the process of coal seam cutting, the shearer analyzes the position, attitude and cutting state of the shearer in real time through the perception model of digital twin, identifies the dynamic of coal rock interface by using multi-modal information, and adjusts the attitude of shearer cutting drum.

There are collaborative constraints between the shearer and the hydraulic support, that is, on the premise of meeting the reliable support technology, the intelligent obstacle avoidance control strategy is adopted to avoid the collision between the shearer and the hydraulic support. The hydraulic support adjusts its posture according to the running direction and speed of the shearer to avoid the shearer.

There are collaborative constraints between the shearer and the scraper conveyor, that is, according to the sudden load information in the coal cutting process, the scraper conveyor can adapt the traction speed in real time, to realize constant power coal cutting and automatic straightening.

Cooperative constraint relationship of hydraulic support

The cooperative constraint relationship of hydraulic support is shown in Figure 5. The hydraulic support is moved in turn through the sequential process of retaining, lowering, moving, lifting, extending and moving of scraper conveyor. At the same time, the hydraulic support adjusts the support height according to the perceived top and bottom plate stress, and realizes the position and posture adjustment by adjusting the column, bottom lifting, side pushing and balance Jack.

There are collaborative constraints between the hydraulic support and the shearer, that is, the hydraulic support must follow the coal cutting process of the shearer, move the hydraulic support in time and quickly, and independently correct the inclination and deflection of the hydraulic support, so as to maintain the reliable and stable support of the hydraulic support to the roof.

There are collaborative constraints between the hydraulic support and the scraper conveyor, that is, in the coal cutting operation, the moving mechanism of the hydraulic support needs to cooperate with the scraper conveyor to realize independent moving, ensure the continuous advancement of the working face, and automatically maintain the
straightness of the hydraulic support and the scraper conveyor.

There are collaborative constraints between the hydraulic support and the emulsion pump station, that is, through the coordination between twins, predict the power demand of the hydraulic support according to the traction speed of the shearer, dynamically optimize and adjust the output flow and pressure of the emulsion pump station, so as to realize the power matching of the emulsion pump station.

**Collaborative constraint relationship of coal flow transportation**

The cooperative constraint relationship of coal flow transportation system is shown in Figure 6. The scraper, transfer machine, crusher and belt conveyor in the transportation system need to ensure their own adaptive soft start and adaptive speed regulation under the condition of load change, and ensure the intelligent cooperation, efficient and smooth flow of the transportation links of coal flow loading, transfer and crushing, so as to independently adapt to the changes of coal block size and flow. The coordinated control of coal flow transportation volume and coal cutting volume forms a closed-loop control of coal cutting and transportation to avoid the imbalance of mining and transportation and affecting the production efficiency of the working face.

**Collaborative constraint relationship between working face environment and equipment**

The cooperative constraint relationship between working face environment and equipment is shown in Figure 7. The equipment of intelligent mining face is composed of shearer, scraper conveyor, transfer machine, crusher, belt conveyor, hydraulic support and emulsion pump station. The equipment carries out the “mining, support and transportation” operation of the working face according to the pre-designed mining process. While improving the mining efficiency of the working face, the environmental safety of the working face shall always be guaranteed. According to the construction of phase 2 digital twin intelligent mining face system of coal mine in the environmental perception model of the working face, judge whether the ventilation and gas emission of the working face are abnormal, whether there is natural fire in the goal, whether there is abnormal pressure on the roof of the mining face, whether there is abnormal water permeability in the working face, whether there is fire in the belt conveyor of the transportation roadway, and adjust the equipment operation in real time according to the environmental conditions. The big data artificial intelligence technology is used to deeply mine the environment perception model data of the working face, which can realize the prediction of dangerous accidents, adjust the production plan, and take effective measures to avoid accidents.

4. Application scheme of digital twin intelligent mining face system in Coal mine

The application framework of digital twin intelligent mining face system in coal mine is shown in Figure 8. Many electromechanical equipment...
Construction of digital twin system for intelligent mining in coal mines and working condition information of intelligent mining face are obtained through multi-modal sensing equipment on physical domain entity. Then, the sensing layer data is connected to the coal mine intelligent big data platform through the IoT gateway module. The IoT gateway module in the access layer supports access to OPC-UA, MODBUS, MQTT, 5g, F5G, Wifi6 and other protocols.

4.1. Spatial big data platform

The geological environment information of intelligent mining face mainly comes from geospatial data, ground penetrating spatial data and coal mine related design data. The above multi-modal data, through computer graphics analysis and three-dimensional visualization technology, through coordinate transformation, error correction, data repair and format conversion, generate a multi-source fusion environment model integrating terrain, image and structured data, and realize the construction of high fidelity environment twins of intelligent mining face through the simulation platform supporting Direct3D, so as to provide location services and environment interaction services for the intelligent mining twins in the whole process. It is worth noting that the environmental twin is continuously updated in real time following the intelligent mining process, that is, the coal seam distribution map of the roadway in the working face is continuously updated by analyzing the drilling detection data of the roof and floor of the coal seam roadway obtained from the drilling in different positions, angles and orientations; reconstruct the three-dimensional scene by using the environmental image and video stream data of the working face; using multi-sensor fusion such as lidar and IMU strapdown inertial navigation, updated slam map[17].

4.2. Internet of Things big data platform

Access the shearer control subsystem, hydraulic support control subsystem, three machine control subsystem, pump station control subsystem and safety monitoring system through standard network transmission protocols (MQTT, OPC UA, NB-IOT, 5G, F5G and wifi6). The platform requires special IOT gateway access equipment and edge intelligent equipment. It can also collect equipment data in real time, stably and reliably in the environment with many underground interference and unreliability.

4.3. Digital twin data platform

Based on the above physical domain aware information platform, the digital twin data platform defines the data infrastructure and provides data management, twin object construction, relationship management and machine learning management.

![Figure 8](image-url) Application framework of digital twin system of intelligent mining workface.

| Real time state perception and analysis | Online fault and anomaly analysis | Full scene virtual 3D online | Whole process iterative measurement optimization | Life cycle management | Security situation assessment |
|----------------------------------------|---------------------------------|----------------------------|---------------------------------|----------------------|-----------------------------|
| API(WebSocket)                          |                                 |                            |                                 |                      |                             |

Data management includes spatial data, equipment data, data integrated storage, data operation and other modules, which are used to realize the integration of structured data, unstructured data, three-dimensional model storage and business data, and deploy the environment and optimize the performance of the database.

Twin object construction and relationship management mainly focus on object-oriented dictionary, object construction, metadata description
and unified identification to realize the functions of object sorting, data element definition, data structure analysis and so on.

Machine learning management provides the deployment scheduling, algorithm rule base, simulation rule base and control rules of the platform, which is used to deploy and build a large-scale distributed machine learning training platform, support real-time big data calculation and complete reasonable resource scheduling. Among them, the algorithm, simulation and control rule base are used to provide AI basic components and machine learning and deep learning algorithms suitable for smart mines, realize multi-dimensional simulation analysis of mine big data and application scenarios, and build collaborative control model based on massive structured/unstructured mine data. Taking the shearer as an example, the coal rock cutting pattern recognition of the shearer has always been the technical difficulty and focus in the field of intelligent control of the shearer. The representative detection methods include γ Ray detection method, infrared detection method, pick stress detection method, vibration detection method, image detection method, shearer load detection method, etc. Most detection methods need to effectively filter and denoise the corresponding sensing signal data, and then use time-frequency analysis to study the change of signal spectrum with time. This involves many algorithms and models, including wavelet analysis algorithm, EMD empirical mode decomposition algorithm, support vector machine algorithm, decision tree algorithm, neural network model, deep learning network model, deep residual network model, improved genetic mutation particle swarm optimization algorithm, etc. Therefore, it is necessary to establish a machine learning management platform for unified coordination and management. It can also expand the associated equipment in different scenarios and use the combined algorithm and model for machine learning to solve the limitations of single signal processing. The platform also adopts model compression and model segmentation technology to prune, quantify and decompose the trained model at the platform end[18], and then optimize, compress and segment algorithm models to facilitate migration to the edge intelligent end. The control rule management of this layer carries out unified collaborative control on the digital twin system equipment of intelligent coal mining face according to the collaborative constraint relationship of shearer, hydraulic support, coal flow transportation system and working face environment and equipment.

4.4. Visual development platform

The visual flat hair platform mainly includes digital twin visualization engine, three-dimensional chart group engine and three-dimensional modeling algorithm. According to different modeling purposes and measurement data, including mapping, product design, three-dimensional laser scanning and other data from different sources, the reconstruction and restoration of mine 3D model are constructed by using high-efficiency three-dimensional modeling algorithm, three-dimensional computer graphics and digital image technology.

4.5. Application of digital twin system

Based on the above data integration platform, the application layer of the twin system of intelligent mining face provides users with real-time perception and analysis of the state of mechanical and electrical equipment of the working face, full scene 3D virtual online service, fault diagnosis and anomaly online analysis of the whole process of mechanical and electrical equipment and coal mining, iterative scheduling optimization of the whole process, safety situation evaluation and life cycle management.

5. Conclusions

For the digital twin intelligent mining face of coal mine, this paper gives the system reference framework, deeply analyzes the functions and characteristics of the three levels of the digital twin system, constructs the digital twin perception model of shearer, scraper conveyor, transfer machine, crusher, belt conveyor, hydraulic support and emulsion pump station, and analyzes the cooperative constraint relationship between multiple equipment
Construction of digital twin system for intelligent mining in coal mines

in complex coal mining process. The purpose is to
to provide detailed reference for the implementation
and application of digital twin intelligent mining
face system in coal mine, and provide guidance for
the construction of digital twin system in coal mine
intelligent tunneling.

At present, the virtual model of digital twin
intelligent mining face in coal mine and the basic
work of basic digital twin stage have been basically
completed. How to make full use of artificial intel-
ligence and big data analysis technology, promote
the perceptual information intelligent analysis and
knowledge mining of digital twins in intelligent
mine, and realize the collaborative control and
scheduling optimization between digital twins are
the core work to speed up the intellectualization of
cell mine.

Conflict of interest

The authors declare no conflict of interest.

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