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# A Remote Monitoring and Diagnosis Method Based on Four-Layer IoT Frame Perception

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**ABSTRACT** In this study, a real-time remote monitoring and fault diagnosis method has been developed based on the Internet of Things (IoT) frame perception, and successfully applied to a mine hoist system. The proposed method combines the sensor technology, online monitoring technology, wireless transmission technology, and fault diagnosis technology. The basic structure of the traditional IoT comprises a perception layer, a network layer, and an application layer, the proposed structure contains an additional middleware layer between the network layer and the application layer. This four-layer system is used in a mine hoist remote monitoring and fault diagnosis framework to process heterogeneous multi-source information. The sensors and parameters are connected in the perception layer, the characteristic parameters are obtained using the configuration software, and the mine local area network is saved to the data server, thereby synchronizing real-time data in the local area network. The network layer utilizes mature Internet and long-distance wireless transmission communication technologies, whereas the middleware layer comprises of a Service-Oriented Architecture (SOA)-based IoT data processing framework that integrates the multi-source heterogeneous data. Further, the fault diagnosis method is analyzed and verified based on the gray association rules. In the application layer, a human-computer interface is used for the remote monitoring and diagnosis of the mine hoist and to provide the diagnosis results as feedback to the user. The results using the aforementioned analyses are applied to the remote monitoring and diagnosis of a mine hoist system. In this study, experimental tests are conducted in this study to significantly improve the fault monitoring, diagnostic capabilities, and reliability of the mine hoist system, indicating the good application good prospects of the proposed method.

**INDEX TERMS** Internet of Things, mine hoist, remote monitoring, fault diagnosis, service-oriented architecture.

## I. INTRODUCTION

Mine hoist is used to upgrade coal gangue and to provide mine workers with decentralized equipment and materials. Mine hoist is an indispensable transportation methodology in case of coal mine production [1]. FIGURE 1. depicts a multi-rope friction mine hoist that is practically used. A multi-rope friction mine hoist is operated by placing a wire rope on the leading wheel and suspending lifting vessels at both the ends. A friction force is generated when the motor drives the leading wheel, enabling the transmission wire rope between the liner and wire rope, installed on the leading wheel, to lift and place heavy objects. Based on scientific and technological advances along with the improvements at the industrial production level, mine lifting equipment is continuously being researched and developed to achieve considerable automation and complexity. The occurrence of a fault directly affects the safety and results in massive economic losses and casualties. Recently, faults in mine hoist have resulted in increasingly high requirements with respect to the reliability and safety of the hoisting operations, hence, a highly complex fault diagnosis technology is required. Therefore, it has become increasingly difficult for an operator acting alone to solve operating problems or to perform daily maintenance and

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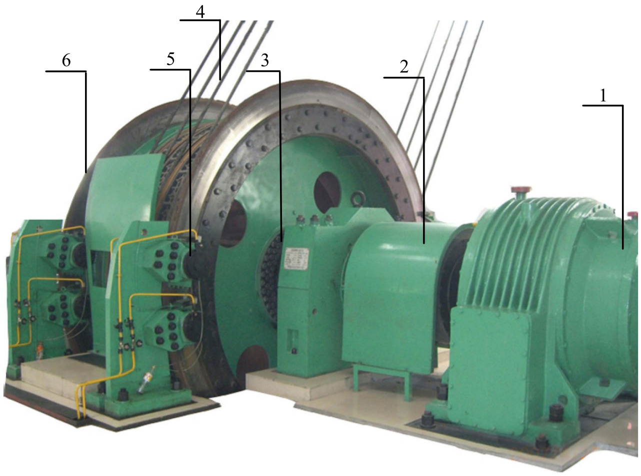


1-motor; 2-reduction gearbox; 3-principal axis;
4-wire rope; 5-brake; 6-guide wheel

**FIGURE 1. Multi-rope friction mine hoist.**

forecasting for the lifting device. An effective solution for the aforementioned problems is to establish a network-based lifting device containing a remote monitoring and fault diagnosis system.

The significance of remote equipment fault diagnosis has been recognized in academia and business circles, leading to many insightful discussions among researchers at home and abroad on the structure of the system structure, development modes, and key technologies of remote fault monitoring and diagnosis systems, and the construction of several practical systems. Asea Brown Boveri Ltd. (ABB) in Sweden developed a mine hoist safety protection system for operation control, condition monitoring, and safety protection of a complete mine hoist system [2]. This system was equipped with an over-speed protection system over the entire course of the mine hoist. The system also contained special monitoring, display, and protection circuits, was highly automated, and did not require human operators. Siemens AG in Germany developed an all-digital mine hoist monitoring system that featured a constant deceleration function during emergency braking, an improved dynamic monitoring function of the wire rope tension, and an improved dynamic display and fault self-diagnosis function of the system and equipment [3]. Siemag in Germany developed the mine hoist-safety protection system, and it monitors and controls majority of the operating system parameters, the speed control system, and the braking system of the mine hoist [4]. However, in majority of the research methods that are independently applied in the field, resource utilization is insufficient and remote monitoring and fault diagnosis are not allowed.

Recently, Internet has resulted in a new generation of information and communication technology that has continuously infiltrated daily life. Increasing demand in consumer markets, such as the Internet of vehicles, health, home,agriculture, intelligent hardware, and wearable devices, has led to a direction in traditional industry that is people-centered, incorporates information physics, digital twins, and virtual reality [5]. Equipment fault diagnosis is a key field in the application of Internet technology, which requires the incorporation of the Internet concept and advanced technology, such as cloud computing, big data, IoT, mobile Internet, and artificial intelligence (AI), to improve the management and control of fault monitoring and diagnosis [6]. The following monitoring and diagnosis system elements have be improved to satisfy the lean management requirements: the integration and application of information data, the integration of information systems and diagnostic systems, the maintenance and management of mechanical equipment, and reliable controllable equipment operation. Feng designed a smart WSN contact with a signal processing capability that was verified by bearing fault diagnosis, improving the transmission efficiency of the wireless sensor networks [7]. Tang developed a mechanical fault diagnosis method based on the multilayer and multilevel information integration of wireless sensor networks to transmit a large number of vibration signals in real-time in mechanical fault diagnosis applications [8]. Preliminary studies related to the applications of AI monitoring and diagnosis methods have been conducted based on wireless sensor networks [9]–[13]. In particular, the IoT concept has usurped the traditional thinking that information and physical infrastructures are separate entities [14]–[16]. A three-layer framework, including the perception, network, and application layers, is used in a comprehensive, intelligent, and efficient diagnostic detection mode that integrates fault prediction, remote monitoring, remote diagnosis, and AI. Sensor technology, radio frequency(RF) technology, and intelligent processing technology have been combined with the industrial Ethernet, wireless sensor networks, and the Internet into the mine hoist perception systems for monitoring and diagnosing mine hoist faults [17], [18]. In the systems, remote fault diagnoses are performed using IoT real-time effective monitoring, and faults are remotely diagnosed by the management system. The designs improve the reliability and fault diagnosis capability of the mine hoist system. Using a three-layer IoT architecture, the authors study the cooperative information acquisition of main components related to the mine hoist , the data were collected in real-time using the ZigBee short-range wireless communication technology, and an improved fault diagnosis reasoning method was developed based on Dezert-Smarandache theory (DSmT) [19]. They also developed a humanized and visualized fault diagnosis platform exhibiting a fault diagnostic reasoning function. This monitoring and diagnosis system has been extensively applied in practical applications. The aforementioned studies, which apply the IoT mainly to remote monitoring, serve as references for this study. However, the large-scale data involved in the fault diagnoses of mine hoist include both structured (the relevant data collected by the monitoring system and the historical diagnostic data) and unstructured data (such as the standardized diagnostic data obtained from the mechanical manuals, coal mine safety regulations, and diagnostic knowledge of domain experts). Such data are multi-sourced and heterogeneous; however, the diagnostic systems mentioned in the literature generally use structured data. Therefore, the intelligent, advanced, and interconnected features of the IoT cannot be completely utilized. Furthermore, these diagnostic systems cannot use the entire diagnostic data because they lack the ability to process multi-source heterogeneous information. Based on the traditional three-layer IoT architecture, this study considers multi-source heterogeneous information in the system and proposes a four-layer architecture based on the IoT perception. It also establishes an IoT-based monitoring and diagnosis system for mine hoist faults, which will reveal the real-time operation status of the mine hoist and determine the failure reasons of its important mechanical parts. By adopting our architecture, the enterprises will be guided toward fast equipment maintenance and effective production arrangement.

The remainder of this paper is organized as follows. Section II introduces the overall framework of the mine hoist remote monitoring system based on IoT perception and considers some related work. Section III, Section IV, Section V and Section VI propose the realization methods of the perception, network, middleware and application layers, respectively. Section VII discusses the application and prospects of the system. Section VIII summarizes this study.

## II. MINE HOIST REMOTE MONITORING SYSTEM STRUCTURE BASED ON IOT PERCEPTION

The IoT structure was constructed in accordance with the application using the Internet and wireless communication technologies for data collection, processing, analysis, and application. The hierarchical establishment of technology, function, and structure can improve the convenience associated with the usage of IoT. The classic IoT structure includes a perception layer, a network layer, and an application layer.

The IoT data processing middleware must provide a solution to the critical problem of multi-source heterogeneous information processing. The desired IoT system structure should be open, layered, and flexible to achieve interoperability between interconnections, internal communications, and heterogeneous information. In this study, such a structure is used to construct a mine hoist remote fault monitoring and diagnosis system based on IoT perception and is presented in FIGURE 2.

The proposed structure comprises four layers, i.e., the perception, network, middleware, and application layers.

The perception layer realizes a series of functions, including data collection and display.The sensors are connected to an industrial computer in the lifting machine room; thus, the characteristic parameters are collected by the configuration software and saved to the server through the mining local area network, these characteristic parameters refer to the observed physical quantities, which are reflected in Section III. Real-time data synchronization with respect to the monitoring center, the dispatch center, and other sites is facilitated by the local area network. An over-the-limit warning or alarm is transmitted to the relevant personnel in the form of a short mobile phone message to ensure that timely measures are performed. The real-time display screen can be observed in King View software, which is used to develop monitoring system. Moreover, it is a new type of industrial automatic control system. It replaces the traditional closed system with an integrated system comprising standard industrial computer software and hardware platforms.

The network layer mainly performs long-distance data transmission using mature Internet and long-distance wireless transmission communication technologies. After classifying the field data, the data corresponding to real-time information are processed and transmitted to the remote diagnosis center through general packet radio service (GPRS). A large quantity of the normal data is regularly transmitted to the remote monitoring and diagnosis center via Internet after backing up the data.

The middleware layer solves the data heterogeneity problem using a flexible interface design. The middleware layer functions include data storage, heterogeneous data retrieval, data mining, data security, and privacy protection.

The application layer mainly performs the data application and provision functions of a human–machine interface. The received information is targeted, the feature parameters are characterized, and the human–machine interface is presented to the user to achieve intelligent management, application, and service. In addition, the data are diagnosed and provided as feedback to the user.

## III. FIELD MONITORING OF PERCEPTION LAYER

### A. HARDWARE STRUCTURE FOR FIELD MONITORING

The monitoring hardware mainly comprises a host computer and a lower computer. The communication medium between the host computer and the lower computer is an industrial Ethernet switch and a twisted-pair cable. The hardware structure diagram of the system is presented in FIGURE 3. The lower computer is responsible for the real-time monitoring of the working conditions of the mine hoist system. The measured values of mine hoist system parameters are displayed, analyzed, and stored; subsequently, the analyzed and processed parameters are transmitted to the host. Further, the host computer saves the parameter signals transmitted from the lower computer to prepare for remote monitoring of the mine hoist; thus, the operation of the mine hoist system can be monitored.

A sensor is an important part of this monitoring system. The sensor detects the measured change and converts it into an exportable signal based on a prescribed rule; the portion that responds to the measured change is considered to be the sensing component, whereas the portion that is used for conversion into a transmittable and measurable voltage or current signal is considered to be the conversion component. The selection criteria for sensors in engineering practice include sensitivity, response characteristics, linear range, reliability, accuracy, measurement mode, and cost. Different types of sensors, such as hole-type radial pressure

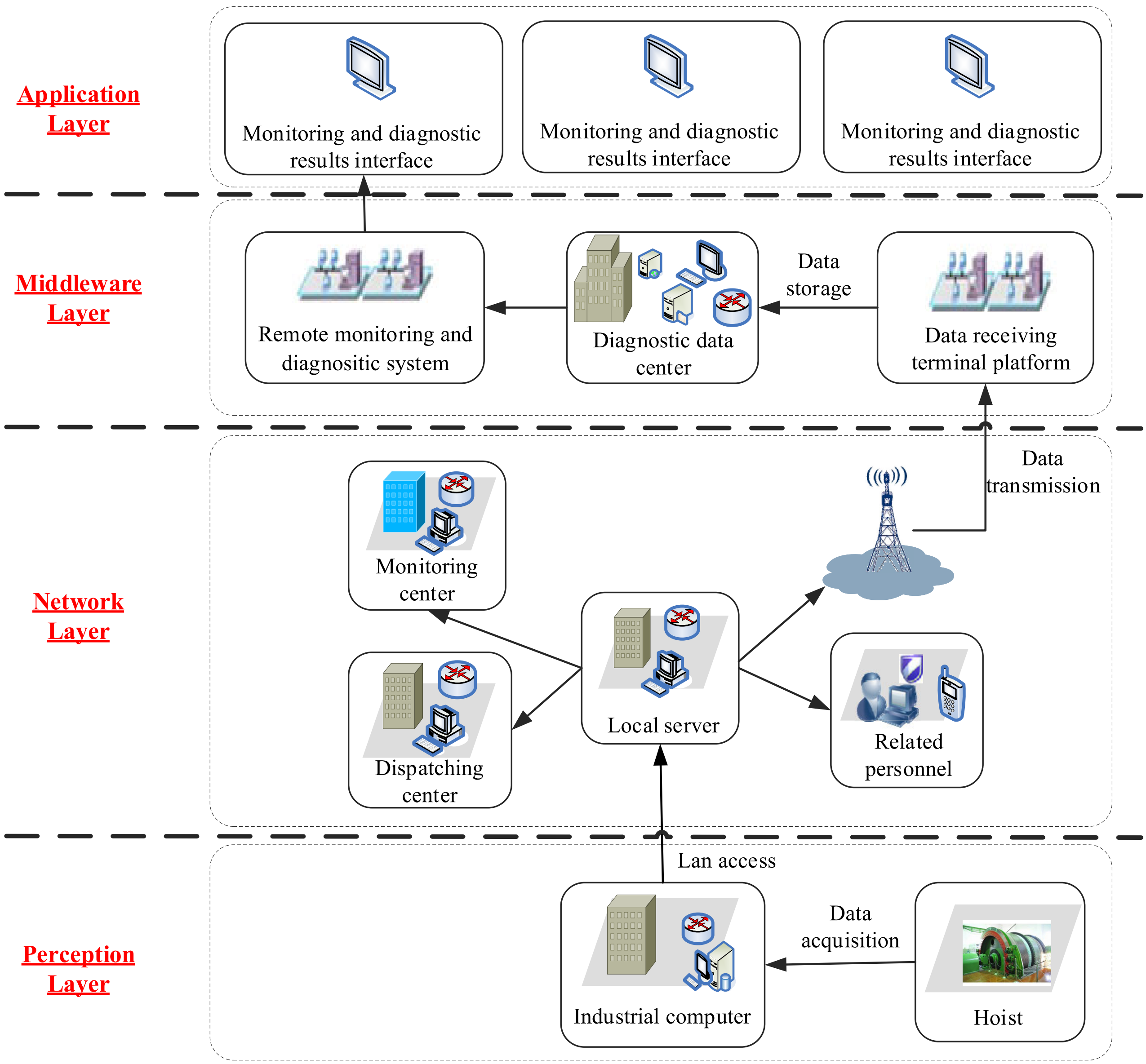


**FIGURE 2.** The structure of a mine hoist remote fault monitoring and diagnosis system based on IoT perception.

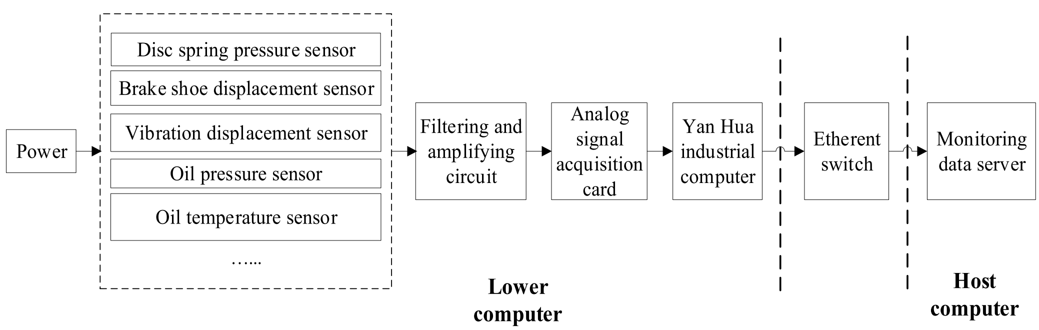


**FIGURE 3.** The hardware structure diagram of the system.

sensors, CYA-type 16-MPa pressure sensors, brake displacement sensors, and eddy current displacement sensors, are available.

### B. SOFTWARE STRUCTURE FOR FIELD MONITORING

The lower computer configuration software and database communication are implemented as follows: the

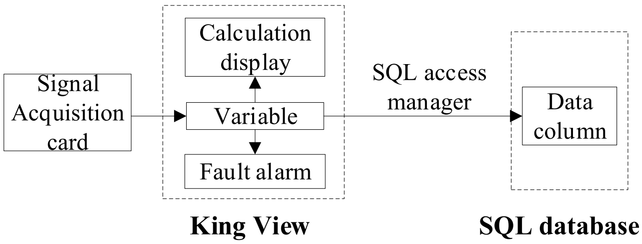


**FIGURE 4.** The software structure of the monitoring system.

correspondence between the King View software variables and the database column is established using SQL, which is an access manager tool of King View software, and a table in the database is created as a template of the configuration software in the database. The host computer can be used as a database server and is connected to the lower computer through a local area network based on the TCP/IP protocol. The software structure of the monitoring system is presented in FIGURE 4.

### C. FIELD TESTING SYSTEM

The operating state of the mine hoist system is characterized by several parameters to obtain comprehensive monitoring information; the parameters that significantly impact the mine hoist operation must be selected, and the fault characteristics should be extracted for monitoring purposes. These parameters are determined with respect to the mine hoist fault, and physical quantities that can be monitored for analyzing the fault must then be obtained. Considerable mine hoist fault data and maintenance data are collected and analyzed to determine the mine hoist parameters that require monitoring; these parameters are mainly related to the operating system, spindle system, braking system, mechanical transmission system, lubrication system, electronic control system, and rope lining system. For the operating and spindle system, the lifting speed, acceleration, main motor current, spindle speed, motor speed, guide wheel speed, left and right bearings of the motor, input and output bearings of the reducer, vibration acceleration of the left and right bearings of the drum shaft (in the X-, Y-, and Z-directions), vibration displacement peak, and root-mean-square value of the vibration velocity were monitored; for the brake system, the pressure and temperature of the oil in the hydraulic station, total braking torque, brake pump operation, brake shoe displacement, spring force, and amount of left and right yaw were monitored; for the electronic control system, the host command, host decentralization, safety circuit, shutdown signal, variable frequency natural rotation, frequency conversion, and other switching signals were monitored; for the rope lining system, the wire rope tension, amount of wear in the main rope and tail rope, dynamic friction coefficient of the wire rope and liner, and dynamic anti-skid and static anti-slip safety factor were monitored; and, for the lubrication system, the lubricating oil pressure and temperature were monitored. Further, the sensors that monitor the mine hoist system were connected, the power supply voltage was supplied according to the sensor requirements, and the functioning of the King View software and SQL server database were verified. This study has designed and realized real-time monitoring system of a mine hoist and has comprehensively monitored and collected the aforementioned physical quantities to achieve fault diagnosis of the mine hoist system.

The monitoring interface displays the value of each monitored variable during the mine hoist operation. An alarm lights up if a variable exceeds the preset threshold value, as shown in FIGURE 5.

## IV. NETWORK LAYER REMOTE TRANSMISSION

A large amount of monitoring data is accumulated during the mine hoist operation. In this study, regular backup and recovery methods are used to transmit these data to the diagnostic center, and a disk array is used to permanently save the data for later usage. The real-time mine hoist monitoring data obtained from the wireless transmission system is used to complete the real-time on-site transmission of key monitoring data. This wireless transmission system will be presented in this section, and the wireless transmission system framework is presented in FIGURE 6.

To satisfy the operational safety requirements for production equipment, some monitoring data must be transmitted to the remote data center through the Internet in real-time to ensure remote monitoring of the equipment; hence, a highly reliable network is required. However, various interference factors can be observed at the mine hoist work site, and the industrial and mining enterprises are often located in remote areas; therefore, wired networks cannot be installed in certain factories and mines. Furthermore, the existing network transmission is not highly stable, and network interruption is commonly observed. Therefore, data are often not transmitted to the remote data center in time, affecting the remote technicians' real-time understanding of the equipment operation and normal operation of the subsequent fault diagnosis system. The existing public network wireless data transmission technology includes public network GPRS, 2G, 3G, and 4G. With the rapid development of the Internet and communication technologies, the 3G and 4G technologies are playing an increasingly important role in wireless transmission. However, many mines are located in remote areas, where network signals, such as those of 3G and 4G, are extremely unstable and even non-existent. Therefore, the data are transmitted through GPRS to ensure the stability of the transmission system, and the important data required for device processing are wirelessly transmitted to the remote data center. Data can also be integrated into the remote data center database to provide a basis for the subsequent equipment fault diagnosis and to improve the reliability of the monitoring system.

### A. PRETREATMENT AND DATA SELECTION OF TRANSMISSION DATA

Data extraction is the first step in the transmission of monitoring data. The mine hoist operation and alarm status are

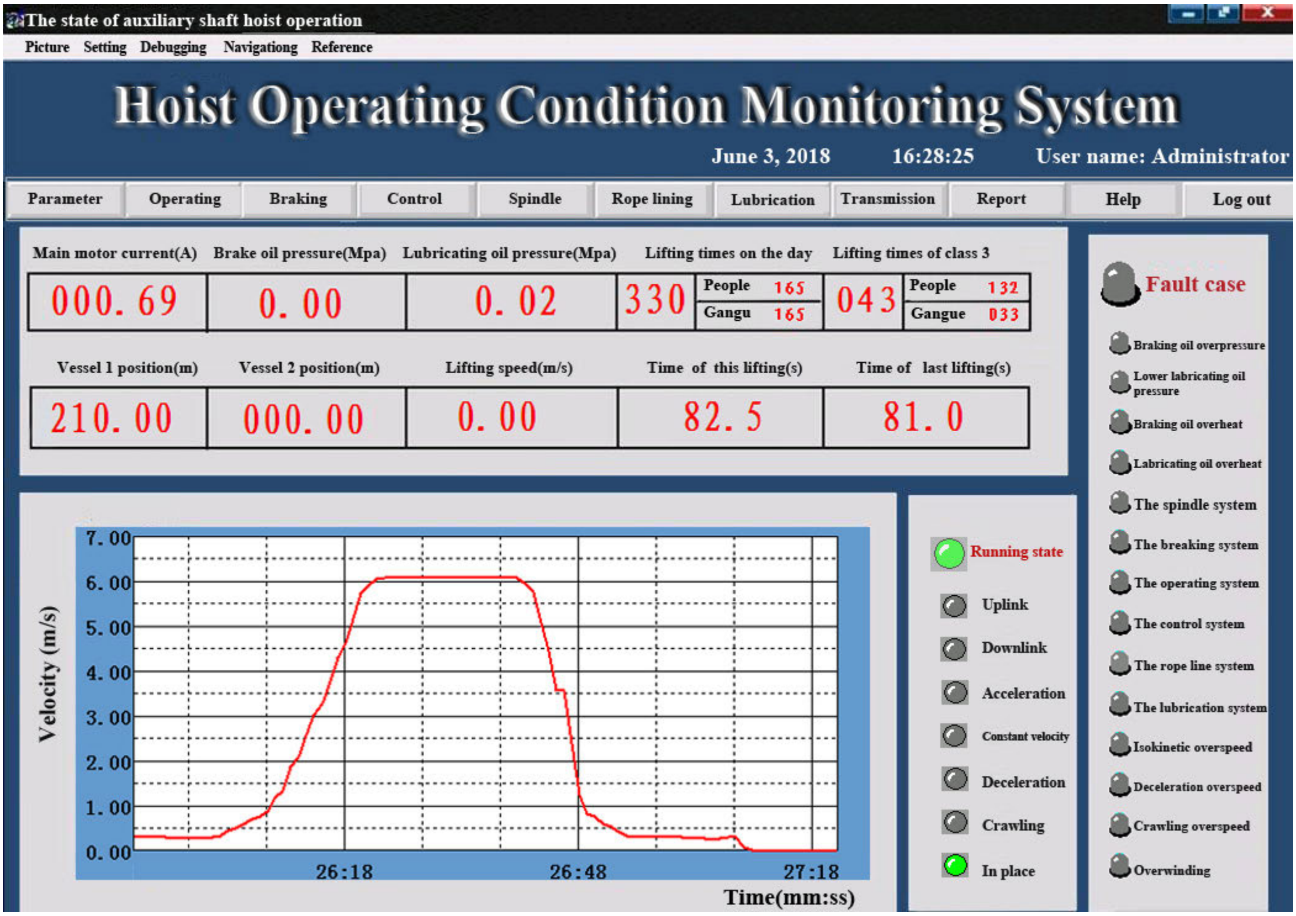


**FIGURE 5.** The monitoring system interface.

characterized by the development of the data extraction software that is installed in the data server of the real-time monitoring system of the on-site mine hoist. The database in the server saves real-time data during mine hoist operation. The operational program automatically extracts relevant data from the server database and transmits the data to the server serial port in the required format; subsequently, the data are sent to the remote data center through the a wireless data transmission module. The data center further processes the received data packets according to the prescribed rules. The software automatically tracks the most recent data in the database to ensure that the new monitoring data will arrive at the data center in a timely manner. The software pretreats the data, cleans the collected data, eliminates the null values and redundant data, and reduces the data based on rough set theory. The reduction method can be found in one of our previous reports [20] and will not be repeated in this study.

## B. GPRS WIRELESS TRANSMISSION

### 1) GPRS WIRELESS DATA TRANSMISSION MODULE

Many types of GPRS modules are currently available in the market; all these modules have their own hardware features. The GPRS modules produced by different manufacturers exhibit different functional structures, technical characteristics, and applications. Module selection must consider the functional requirements of the monitoring system in terms of efficiency, transmission quality, compatibility with other hardware, installation convenience, and several comprehensive factors, including the working environment, anti-interference, and economy. After weighing the advantages and disadvantages offered by the available modules, the GPRS232-730 DTU transmission module produced by USR IOT is selected because of its abundant interfaces, excellent technology, and complete software functions.

### 2) SELECTION OF SIM CARD FOR THE GPRS MODULE

The GPRS module produced by USR IoT Technology Limited in China that is selected for this study supports the following capabilities: GSM/GPRS network communication, 2G/3G/4G mobile phone operation business SIM 2G network model, up to four simultaneous remote network connections online, and TCP and UDP; therefore, the module must be used in conjunction with a SIM card of the GPRS network operation business to enable remote data transmission. Factors, such as the geographical location, data transmission speed, and transmission stability of the industrial site, should

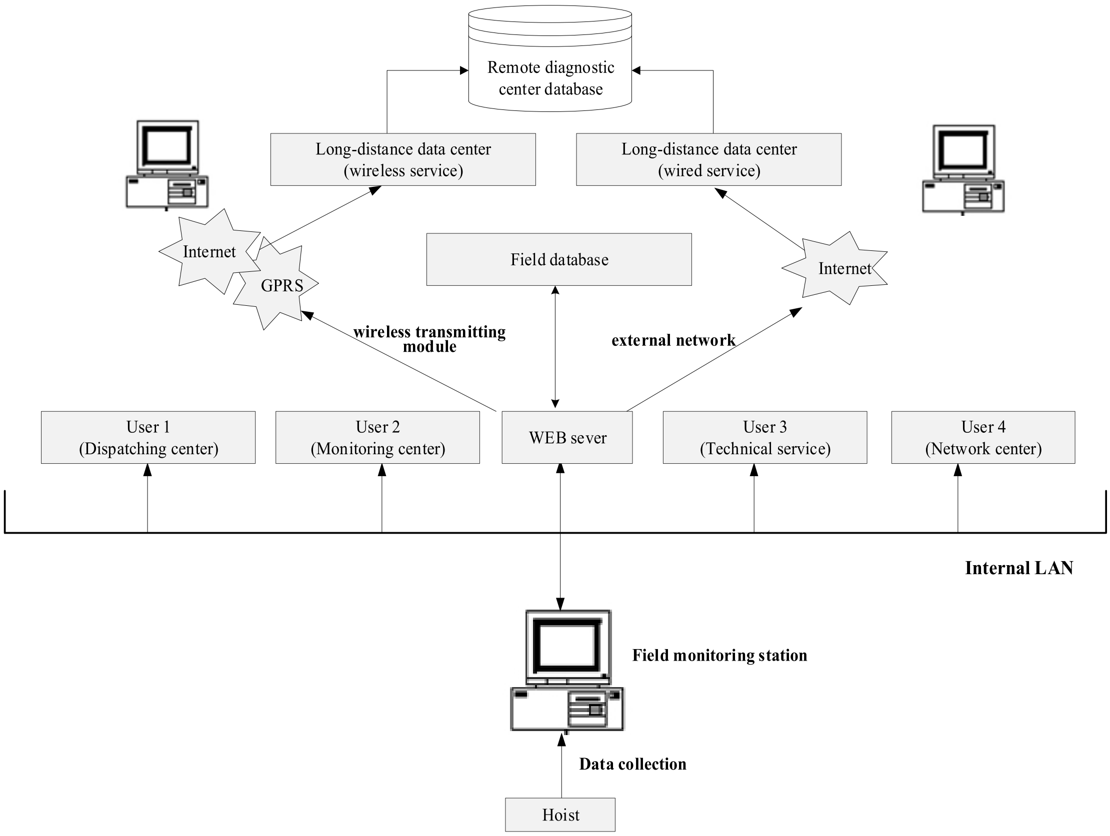


**FIGURE 6.** **The wireless transmission system framework.**

be considered to monitor the stability of the system. Because the mining areas are generally located in remote mountainous areas, a wide signal distribution range should be available for business operation. Comparative research shows that China Mobile's GPRS network offers the widest coverage and exhibits a considerable advantage in terms of signal penetration in remote areas. This company's network signal covers more than 250 cities across the country. China Mobile GPRS was launched by China Mobile toward the end of 2000. This GPRS offers the advantages of being a mature communication technology, wide signal coverage, and diverse service modes [21], [22]. China Mobile's SIM card is selected for the GPRS module of the monitoring system to provide data services because the various technical advantages offered by this card easily enable the wireless transmission of data at a considerably low cost.

#### 3) DATA TRANSMISSION PROCESS

Data must be formatted during transmission and packaged in a specific format. This is a standard format specified by both the sender software and receiver software. The data can only be sent out in a prescribed format. The receiver may process the transmitted data according to prescribed rules, including parsing of the data packet, identification, and processing of abnormal data.

Data sent once may contain various information; thus, different aspects of this information must be separated to enable post-processing of the data on the receiving end. Data isolators can be specified by themselves. Generally, characters that are not included in the sent data can be selected and can be obviously different from ordinary data.

The sender software arranges the data in a predetermined order and inserts isolators between different data. Then, the initial identifier and end identifiers are added at the beginning and end of the data stream, respectively, and the data are finally packaged and sent in this format as a whole. The data package is received at the data center, and the integrity of the data package is determined based on the prescribed standards, followed by data transmission. The data transmission process is presented in FIGURE 7.

### C. DATA ACCEPTANCE AND PRESERVATION

The data server of the remote diagnostic center is a data-receiving and storage terminal; therefore, a fixed IP is required for the server in the public network, and the IP address is configured as that connected by the wireless data transmission module.

After the diagnostic center receives the data packet, the type of data packet is determined from the format. If the data are a link maintenance package or some other type of data, the data are only displayed in the server run log and the received data information box. If the data are determined to be a normal data packet, the completeness of the data is verified.

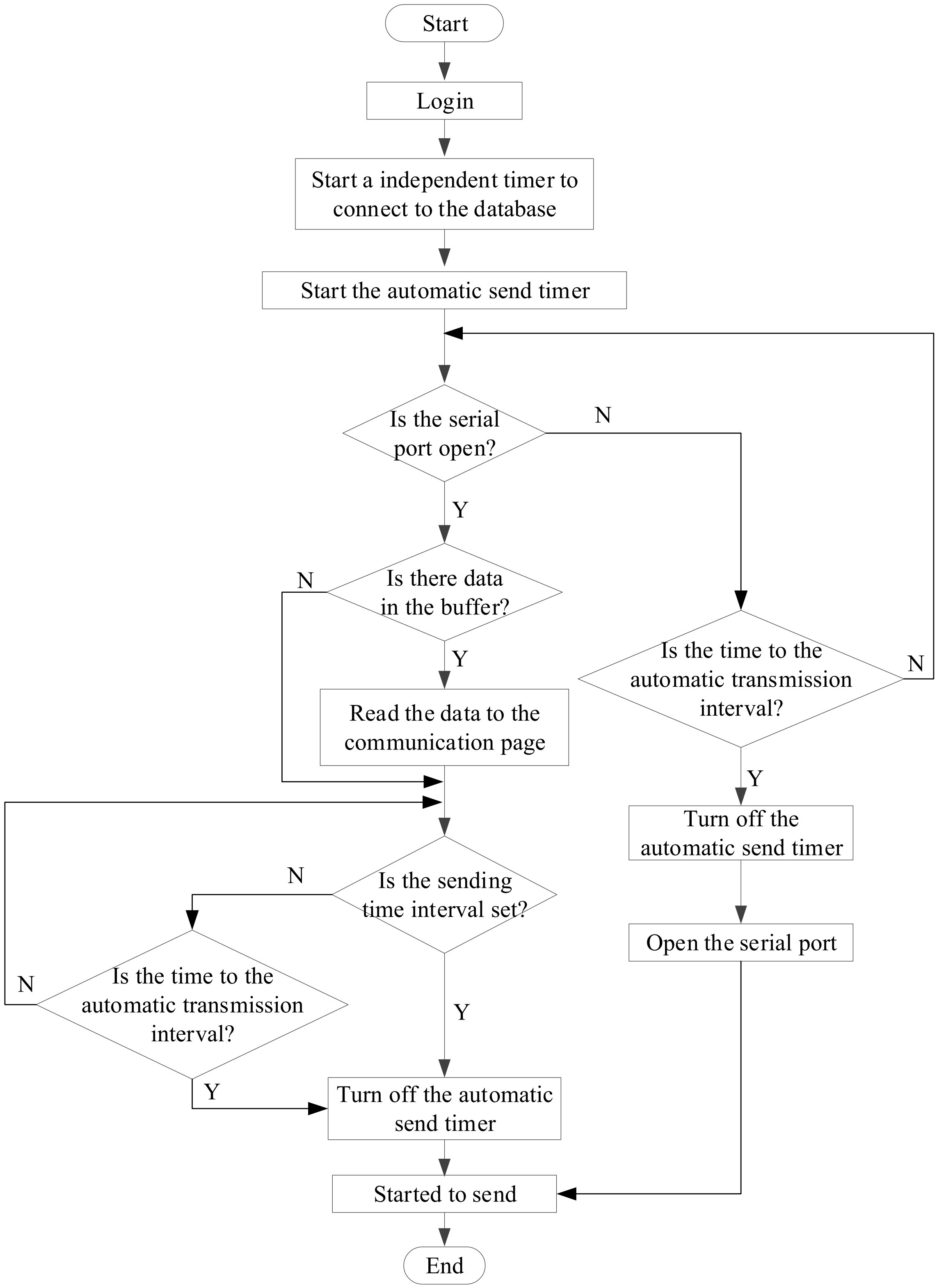


**FIGURE 7.** **The data transmission process.**

If the data packet is incomplete, the packet is discarded. Only a complete data package can proceed to the next step. The data processing flow is shown in FIGURE 8.

The data center parses the complete received data packet, obtains each piece of monitoring data, and displays these data in the corresponding list box of the main monitoring

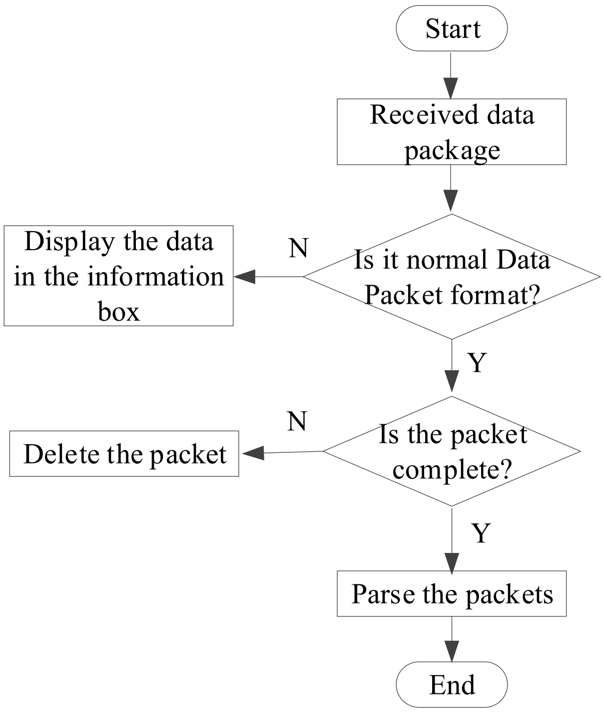


**FIGURE 8.** The data processing flow.

interface. When the next valid data packet arrives, the new data are stored and entered into the corresponding list of the database. Simultaneously, the main interface displays the new monitoring data. Each piece of newly stored data is assigned a unique identifier by the SQL server. The data center managers can access the database and use structured queries to find any piece of monitoring data. Other users can also connect to the database to find and retrieve data.

## V. DESIGN AND IMPLEMENTATION OF THE MIDDLEWARE LAYER

Current research on IoT has generally focused on the network layer. However, the main problem associated with the data processing infrastructure of the IoT is the large number of heterogeneous IoT terminals. In the fault diagnosis of mine hoists, the diagnostic data include both the structured knowledge collected by the monitoring system and the unstructured knowledge such as pictures and documents. A flexible architecture developed based on the service-oriented architecture (SOA) can fuse the heterogeneous information into IoT data processing [23]. Tang *et al.* [24] suggests some future research directions, such as integrating the SOA model, information modeling, and IoT based on web services, integrating the information and management standards, solving interoperability problems, and cloud computing, to overcome the limitations associated with the existing methods. Chen *et al.* [25] proposes adaptive and scalable trust management to support the service composition applications in SOA-based IoT systems. The effectiveness of such a management scheme can be evaluated via comparative performance analysis against EigenTrust and PeerTrust in various service composition scenarios . The SOA architecture can integrate a wide range of services from multiple sources into IoT applications, providing personalized services for enterprises and individuals.

SOA is a component model developed based on services. SOA develops applications using defined interfaces and contracts between services. The interfaces are defined in a neutral manner and should be independent of the hardware platform, operating system, and programming language that are used to implement the services. Therefore, the services can interact in a unified manner in various systems. Meanwhile, the components can directly and effectively interact with the application systems and software agents. The typical business operations in SOA comprise many different components and usually reflect the needs of the underlying business processes in an event-driven or asynchronous manner. In the IoT framework, traditional and emerging resources are available as services on the Internet. Therefore, researching the data fusion application technology based on SOA in the IoT is of high practical value.

### A. DESIGN OF MIDDLEWARE BASED ON SOA IoT

The design of the SOA-based IoT middleware developed in this study comprises the client application layer, the data integration layer, and the heterogeneous data source layer (see FIGURE 9, left to right). The client application layer

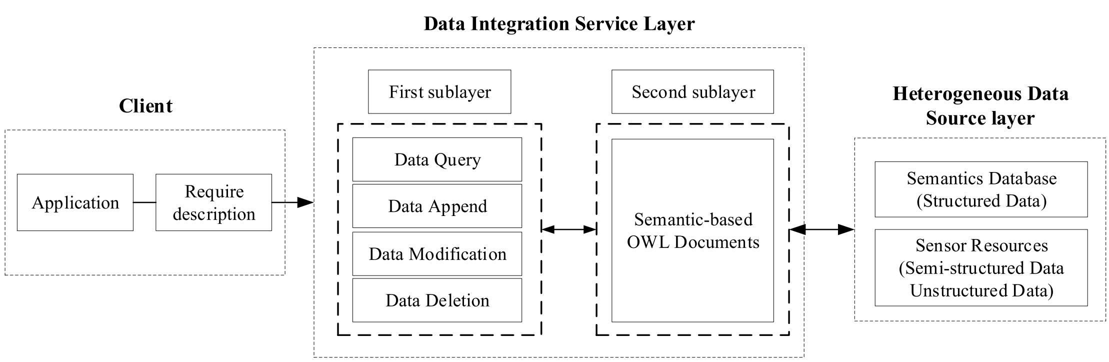


**FIGURE 9.** The design structure of the SOA-based IoT middleware.

includes a unified access interface for user data operations, which can be a specific application or a web browser. The data integration service layer is the core of the architecture and provides heterogeneous data integration. Further, the designed structure contains two layers of services to increase the scalability of the system. The first sub-layer is the metadata model layer. In this study, different data types are transformed into a Web Ontology Language(OWL) common format and handled using uniform operation rules to resolve the large differences in metadata models caused by heterogeneous sensor data resources. Thus, a data access and maintenance system is established for the querying, adding, modification, and deletion of heterogeneous data. The second sub-layer service is based on the development of heterogeneous data source OWL documents. The application layer invokes the corresponding upper services that satisfy the operational requirements. Further, the upper services invoke the corresponding specific data from the client that manipulate the underlying services based on the parameter data. In this design, the changes in the underlying heterogeneous data source alter only the mapping between the underlying service and the upper application; the upper layer remains unchanged. The data integration is completely transparent to the user and is compatible with and interoperable in different systems. The components and representation techniques of the mine hoist ontology have been reported in one of our previous reports [26] and will not be repeated in this study.

A typical service-oriented IoT application usually requires the integration of multiple services. The combination of many services can provide a rich and integrated functionality for the application. Semantic annotation service design and semantic data aggregation interfaces for heterogeneous data enable the integration of SOA-based heterogeneous data in various applications. A simple set of sensor data contains only values, which exhibit low application value. Such simple data-sets can be enriched with the location information or additional data and contextual information such as multimedia sensor data or integrated web ontology information, providing added value in mining. However, the combined information is heterogeneous and exhibits different properties of the entity during a transaction. Such information is often difficult to be directly integrated. In this study, OWL not only describes the related requirements but also allows the representation, management, and use of heterogeneous data.

### *B. KEY TECHNOLOGY FOR FAULT DIAGNOSIS*

#### 1) GRAY ASSOCIATION RULE

The system information for mine hoist fault diagnosis may or may not be clear; that is, the system is gray. In gray association analysis, the degree of association between things, systematic factors, or main behavioral factors are determined using incomplete and random characteristic factors for representing the system behavior. The degree of association between many factors in the system can be obtained by comparing the similarities of the geometrical sequence curves of the system [27]. The more similar the geometries of the curves of two objects, the greater will be their degree of association. This theory can be applied to fault diagnosis to associate a certain fault mode with the basic event importance coefficient sequence. The larger the value of the importance coefficient sequence, the more likely will be the occurrence of the fault mode.

In gray association analysis, various mathematical methods are used to comprehensively analyze systems with incomplete information, often in conjunction with the fault trees. This method can be used to analyze and calculate the degree of association of various causes of system failures. The main causes of failures can also be obtained, and effective local methods can be developed to improve the system reliability and safety [28].

In gray association analysis, the association coefficients for $x_j$ to $x_i$ are denoted as $\xi_{ij}$, and the sampling points for $x_j$ to $x_i$ are denoted by $k$ such that

$$\begin{aligned} \alpha_{\mathrm{ij}}(k) &= \left|x_j(\mathrm{k}) - x_i(\mathrm{k}), \mathrm{k} \in \{1, 2, \cdots \mathrm{N}\}\right| \\ \alpha_{\min} &= \min_j \min_k \alpha_{ij}(k) \\ \alpha_{max} &= \min_j \min_k \alpha_{ij}(k). \end{aligned} \tag{1}$$

The association coefficient $\xi_{ij}$ can be defined as

$$\xi_{\mathrm{ij}}(k) = \frac{\alpha_{min} + m\alpha_{max}}{\alpha_{ij}(m) + m\alpha_{max}}, \quad k \in \{1, 2, \cdots N\} \tag{2}$$

where $m$ is the resolution coefficient, $m \in [0, 1]$. The resolution can be generally improved by using a value of 0.5 for $m$.

Then, the degree of association $\gamma_{ij}$ between $x_j$ and $x_i$ is

$$\gamma_{ij} = \frac{1}{N-1} \times \frac{1}{2}\left[\sum\nolimits_{k=1}^{N} \xi_{ij}(k) + \sum\nolimits_{k=2}^{N-1} \xi_{ij}(k)\right] \tag{3}$$

Let us assume that the fault standard mode eigenvector $X_{ri}$ can be given as

$$[X_{ri}] = \begin{bmatrix} X_{r1} \\ X_{r2} \\ \vdots \\ X_{rn} \end{bmatrix} = \begin{bmatrix} X_{r1}(1) & X_{r1}(2) & \cdots & X_{r1}(k) \\ X_{r2}(1) & X_{r2}(2) & \cdots & X_{r2}(k) \\ \vdots & \vdots & \cdots & \vdots \\ X_{rn}(1) & X_{rn}(2) & \cdots & X_{rn}(k) \end{bmatrix} \tag{4}$$

where $r$ corresponds to the standard reference model, $n$ denotes the number of standard failure modes of the device, and $k$ denotes the number of eigenvectors for each fault mode.

The eigenvector of the $j$ character pattern can be given as

$$\left[X_{tj}\right] = \left[X_{tj}(1) \quad X_{tj}(2) \quad \cdots \quad X_{tj}(k)\right] \tag{5}$$

The value of the association formula can be calculated from the formula for $\gamma_{ij}$ as

$$\left[\gamma_{tjri}\right] = \left[\gamma_{tjr1} \quad \gamma_{tjr2} \quad \cdots \quad \gamma_{tjrn}\right] \tag{6}$$

Finally, the calculated association sequence values are arranged in an ascending order as follows

$$\gamma_{tjrm} > \gamma_{tjrh} > \gamma_{tjrk} > \cdots \tag{7}$$

**TABLE 1. Monitoring parameters.**

| Monitoring parameter code | Monitoring attribute | Units |
|---|---|---|
| Y1 | brake disc deflection | mm |
| Y2 | brake clearance | mm |
| Y3 | residual pressure of hydraulic station | MPa |
| Y4 | lifting velocity | m/s |
| Y5 | friction coefficient | - |
| Y6 | over-falling distance | m |

Thus, the degree of association between the fault mode can be detected and the standard fault mode is obtained in this way.

### 2) DIAGNOSTIC TEST

When the mine hoist container approaches the end point during vertical shaft hoisting, it must decelerate and stop within a specified time. If it does not decelerate, the upstream and downstream containers can easily exceed their normal parking positions, causing an over-winding accident and an over-falling accident, respectively. Both the accidents can damage the wheel and break the rope, considerably endangering the equipment and personal safety.

We consider the example of an accidental "over-falling" by the mine hoist to illustrate the application of the gray association rule in mine hoist fault diagnosis. First, a fault tree is generated for accidental over-falling, as shown in FIGURE 10.

The fault tree "Fussel-Vesely" [29] can be used to find eight minimal cut sets.

$$T_{K1} = \{X_1, X_5\}; \quad T_{K2} = \{X_1, X_6\}; \ T_{K3} = \{X_2, X_5\};$$
$$T_{K4} = \{X_2, X_6\}; \quad T_{K5} = \{X_3, X_5\}; \ T_{K6} = \{X_3, X_6\};$$
$$T_{K7} = \{X_4, X_5\}; \quad T_{K8} = \{X_4, X_6\},$$

The fault characteristic matrix is written as follows:

$$T_K = \begin{bmatrix} X_{K1} \\ X_{K2} \\ \vdots \\ X_{KM} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 & 0 & 1 \\ 0 & 1 & 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 & 1 \end{bmatrix}$$

Each fault (X1–X6) is mainly determined from the data collected by the monitoring system in Section III. The relevant monitoring parameters for judging over-falling accidents are presented in TABLE 1, and the partial monitoring data are presented in TABLE 2.

According to "Safety Regulations for Coal Mines" [30], X1, X2, X3 and X4 faults are judged when Y5 $<$ 0.25, Y3 $>$ 0.5 Mpa, Y2 $\geq$ 2mm, and Y1 $\geq$ 1 mm, respectively. X6 fault is judged to occur according to Y4 and Y6. If the over-falling safety distance Y6 corresponding to the lifting speed Y4

**TABLE 2. Partial monitoring data.**

| Y1 | Y2 | Y3 | Y4 | Y5 | Y6 |
|---|---|---|---|---|---|
| 0.44 | 1.75 | 0.83 | 4.01 | 0.78 | 2.83 |
| 0.23 | 1.58 | 0.64 | 4.28 | 0.69 | 3.72 |
| 0.32 | 2.21 | 0.44 | 5.64 | 0.21 | 4.65 |
| 1.24 | 3.09 | 0.15 | 4.75 | 0.38 | 2.85 |
| 0.17 | 1.65 | 0.32 | 6.52 | 0.45 | 4.33 |
| 0.22 | 1.79 | 0.76 | 6.78 | 0.76 | 5.48 |
| 0.69 | 2.76 | 0.58 | 7.80 | 0.98 | 6.85 |
| 0.13 | 3.28 | 0.22 | 8.25 | 1.25 | 7.23 |
| 0.29 | 1.99 | 0.33 | 6.78 | 0.73 | 6.84 |
| 0.19 | 1.77 | 0.48 | 9.10 | 0.59 | 8.65 |
| 0.43 | 3.98 | 0.55 | 9.82 | 1.15 | 8.79 |
| ... | ... | ... | ... | ... | ... |

(see TABLE 3) exceeds the specified range, the X6 fault occurs; conversely, an over-falling accident is judged as X5.

Based on the analysis of historical monitoring data, the probability of occurrence of the eight aforementioned minimum cut sets given above is

$$\{0.003, 0.002, 0.0006, 0.0004, 0.0012, 0.008, 0.0048, 0.0032\}.$$

The probability of occurrence of the accidental over-falling is $Q_s = 0.034$.

The mode vector to be verified is

$$X_0 = \left\{ e_1, \quad e_2, \quad \cdots \quad e_6 \right\} = \{0.1471, 0.0294, 0.5882, 0.2353, 0.6000, 0.4000\}.$$

The calculated relevance values after the mean processing can be given as follows:

$$\gamma_1 = 0.6060, \quad \gamma_2 = 0.5235, \ \gamma_3 = 0.6514, \ \gamma_4 = 0.4745,$$
$$\gamma_5 = 0.7555, \quad \gamma_6 = 0.6729, \ \gamma_7 = 0.6332, \ \gamma_8 = 0.5507$$

Among the eight fault modes that could have caused the accidental over-falling,oversized brake clearance and driver's misoperation are found to be the most harmful and should be flagged during corrective maintenance.

## VI. APPLICATION LAYER INFORMATION PUBLISHING

The application layer is the top layer of an IoT system. The main function of this layer is to analyze and organize the collected and shared data and to express these data to the users in an intuitive form. The requirements of the application layer are given below.

### A. EFFICIENT DATA PROCESSING FUNCTIONALITY

The monitoring data must be processed in real-time; further, the potential value of the data is mined according to the corresponding algorithm to perform remote monitoring and management of the mine hoist.

**TABLE 3. Over-falling safety distance corresponding to the lifting velocity of the hoist.**

| Monitoring parameter code | Over-falling safety distance corresponding to the lifting velocity | | | | |
|---|---|---|---|---|---|
| Y4 | ≤3 | 4 | 6 | 8 | ≥10 |
| Y6 | 4.0 | 4.75 | 6.5 | 8.25 | 10.0 |

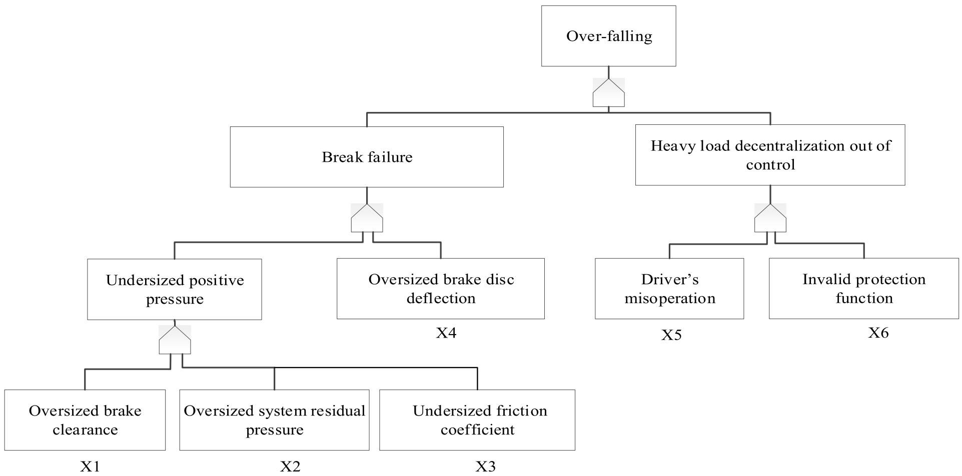


**FIGURE 10. Fault tree of the over-falling accident of hoist.**

### B. LARGE CAPACITY DATA STORAGE

The comprehensive perception information of the IoT produces a large quantity of several types of information data. Therefore, an application layer must be developed to achieve large data storage. Furthermore, a large quantity of historical data is used during the analysis process, which requires the application layer to include a historical data search function.

### C. EFFECTIVE HUMAN–MACHINE INTERFACE

The final development terminal of the application layer is user-oriented. The terminal should be able to visually display the current working condition of the mine hoist, plot a corresponding historical curve, respond to operator-related activities, and save the corresponding operational activity record.

In this study, a remote monitoring and diagnostic system has been developed to satisfy the aforementioned requirements and is presented in FIGURE 11.

## VII. SYSTEM APPLICATION

The proposed system monitors the main parameters of the mine hoist operation online in real-time and generates a fault alarm when the threshold is exceeded. After analyzing the fault symptoms, it infers the possible causes of the fault and provides treatment advice, avoiding maintenance blindness. It also controls economic losses owing to excessive maintenance, prevents accidents caused by under-maintenance, and scientifically creates maintenance plans to improve the economic performance of the equipment.

The proposed system has been successfully applied to a mine. In the traditional fault diagnosis of a mine hoist, the diagnosis is observed to be dependent on the experience of the staff. The diagnosis period is long, and the diagnosis results are not sufficiently reasonable. Therefore, the fault cannot be identified and solved in less amount of time, and information sharing is deficient. Recently, these problems have been compounded by the construction and application of overall informationization. In February 2016, the developed system was introduced to the mine. After more than one year of trial operation, the effect was judged to be positive. Because the monitoring system displays the running status of the mine hoist in real-time and synchronizes it using the network, the manager can observe the working status of the mine hoist without any geographical restrictions and can find the alarm signal and diagnostic results before the development of problems. The fault monitoring system prevents malignant accidents of the hoisters, reduces the amount of equipment maintenance, improves the reliability of the equipment and production efficiency, and provides economic benefits to enterprises.

As an example, we consider the economic loss caused by ‘‘excess repair’’. As stipulated in the ‘‘Safety Regulations for Coal Mines’’, if the the diameter of the mine hoist roller is less than 3 m,then the minimum repair period, the medium repair period and the overhaul period are 4 months, 12 months and 48 months respectively. The corresponding repair times are 1 day, 2 days and 4 days.The mine produces 4 million tons of raw coal per annum at a market price of 520 RMB/ton. The mine hoist is required to conduct two minor repairs

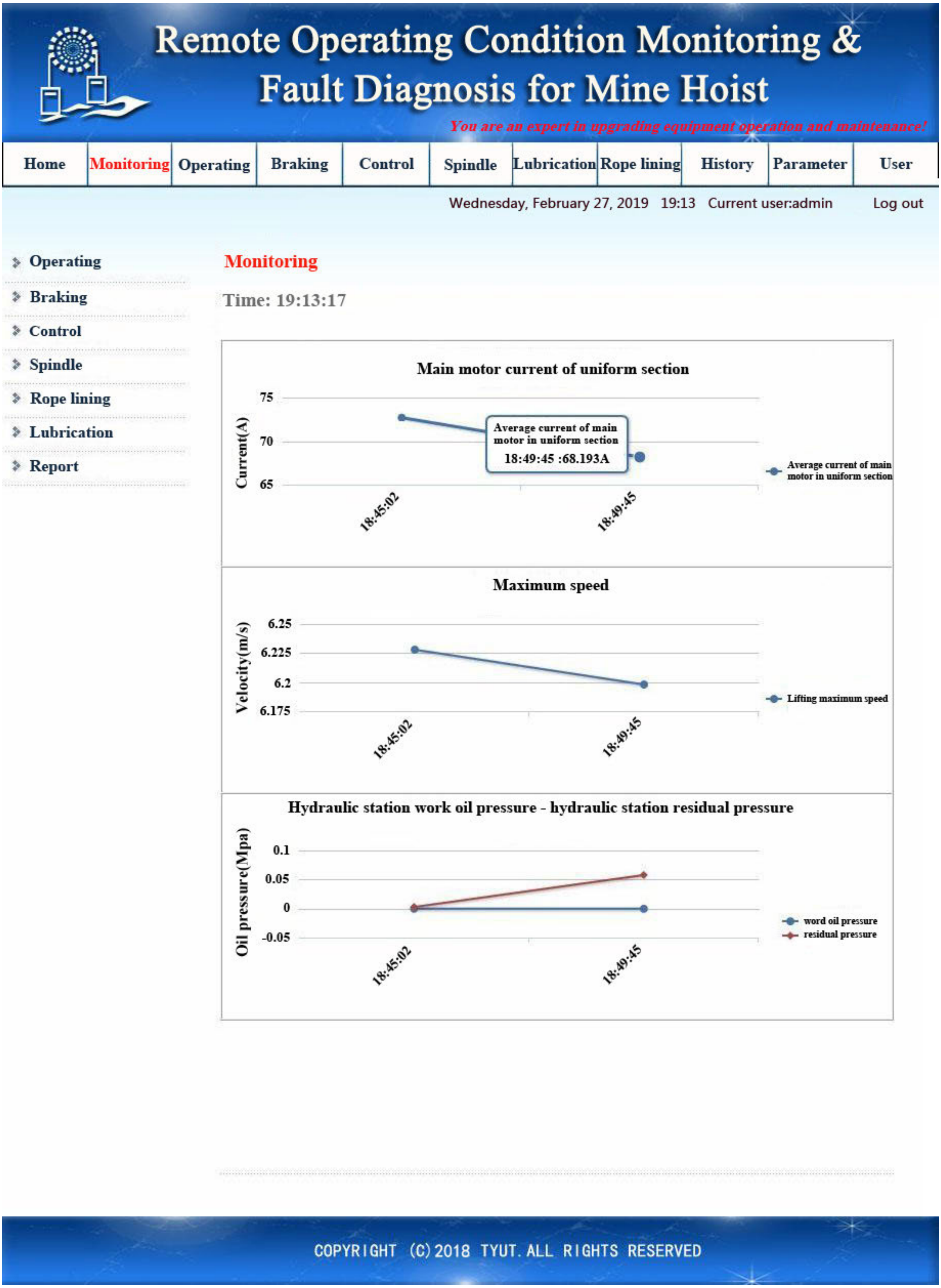


**FIGURE 11.** The remote monitoring and diagnostic system interface.

and a medium repair per year. Thus, the repairing time is 4 days. During the four days of maintenance, the inactive equipment incurs a loss of 22.794 million RMB. In addition to the maintenance cost, a considerable amount of excess maintenance loss is observed. Therefore, the mechanism of mine hoist faults, monitoring the operating state of the mine hoist system in the IoT environment, analysis and prediction research, remote signal acquisition of the mine hoist, analysis software design, remote diagnosis modeling, other related technologies, and applications of the mine hoist are important research targets. Remote diagnosis provides remote technical support and guarantee for enterprises. Furthermore, the implementation and application of the system is of both academic and technical interest. The system is expected to achieve the safe and reliable operation of coal mine hoists, resulting in considerable economic and social benefits.

## VIII. CONCLUSION

1) In this study,a four-layer architecture was constructed for a mine hoist fault monitoring and diagnosis system based on the IoT perception. Structurally, it comprised a perception layer, a network layer, an application layer, and a middleware layer. This four-layer system was used in a mine hoist remote monitoring and fault diagnosis framework to process heterogeneous multi-source information.
2) A collaborative information acquisition system for the key components of mine hoist equipment was established based on the sensor technology and configuration technology to collect data in real-time.
3) A transmission and receiving platform was developed based on GPRS for real-time long-distance wireless data transmission in real-time.
4) A unified representation of multi-source heterogeneous data was developed based on the SOA middleware technology. Gray association theory was used to prove that the fault diagnosis of the mine hoist equipment is efficient, accurate, and intelligent.
5) The aforementioned results were applied to the remote monitoring and diagnosis of a mine hoist system. The experimental tests confirmed that the system significantly improved the fault monitoring, provided diagnostic capabilities, and ensured the reliability of the mine hoist system. Therefore, when installed in an actual mine, the developed method is expected to provide economic and social benefits.

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