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Review Article

Automatic Monitoring System in Underground Engineering Construction: Review and Prospect

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Automatic monitoring system is one of the main means to ensure the safety of underground engineering construction. This paper summarizes the current international research and application status of the underground engineering monitoring system from three aspects of data acquisition, data transmission, and data processing and emphatically introduces the mainstream new technology of the monitoring system. Furthermore, this paper puts forward specific and implementable technical routes based on the current intelligent technology and the challenges faced by future monitoring, which can provide direction and reference for future research, including high-precision real-time acquisition and safe and reliable transmission of monitoring data, multisource data fusion, and the visual intelligent early warning platform.

1. Introduction

With the increasing complexity of underground engineering, the impact on the surrounding environment is more prominent [1–4], and the various technical problems follow. In the construction process, the increasing attention to ensure the safety of the surrounding environment and the requirement for automated industrial production has greatly increased the demand for the automatic monitoring system.

At present, the study of construction safety of underground engineering mainly adopts the traditional manual monitoring methods whose data collection process are cumbersome and time-consuming. With the development of industrial technology, more and more sensors are used in monitoring, including vibrating wire sensor [5], optical fiber sensor [6], and MEMS sensor [7]. Optical fiber sensors are the most widely used because of their high sustainability, high durability, long-term stability, spatial resolution, and high immunity to electromagnetic interference [8, 9]. Photogrammetric technology, which is often used in bridge monitoring, is gradually applied to the underground engineering monitoring system [10]. In data transmission, traditional manual monitoring methods cannot provide high spatial and temporal resolution. Most of the research focuses on the wireless sensor network technology (WSN), and it is widely used in coal mining monitoring. Bo et al. [11] proposed a safety monitoring system for an underground coal mine based on the wireless sensor network. Li and Liu [12] put forward a wireless sensor network system for early detection of underground coal mine collapse and roof fall accident. Based on Bayesian decision-making, Chen et al. [13] discussed the correcting method of WSN nodes in monitoring and identifying hidden dangers of mine tunnel. In recent years, the research on monitoring data analysis and processing has aroused great concern. Adoko et al. [14] established a model based on Regression Spline (MARS) and Artificial Neural Network (ANN) to predict the convergence of tunnel diameter in high-speed railway and achieved good results. Xiao et al. [15] put forward an effective method to estimate the optimal construction time of secondary connection of a circular tunnel based on the grey prediction model GM (1.1). At the same time, linear, nonlinear models, wavelet analysis, and chaotic time series are also well applied in underground engineering monitoring data processing, but there is still no better model to meet the needs of underground engineering monitoring, and the prediction accuracy needs to be further improved.

With the rapid development of big data and cloud computing technology, the application of the Internet of Things (IoT) is becoming more and more popular. Ding and Zhao [16] carried out a critical review on the application of Internet of Things in underground mining of coal mines, pointing out the lack of low-power intelligent sensors, environment energy capture technology, data protection safety network, public service platform, and underground IoT technical standard for further application in underground coal mines. Based on the IoT, Zhang et al. [17] designed a three-dimensional visualization monitoring system and safety control platform for an underground coal mine.

This paper summarizes the current research status of the underground engineering monitoring system from three aspects of data acquisition, data transmission, and data processing and emphatically introduces several typical monitoring systems at present. Based on the current intelligent technology and the challenges faced by future monitoring, this paper proposes specific and implementable technical routes which can provide direction and reference for future research.

2. Layout of Monitoring Points and Safety Control Standards

In order to ensure the safety of construction period, some monitoring standards have been formed, including tunnel engineering [18], foundation pit engineering [19, 20], and urban rail transit underground engineering monitoring [21]. The layout of monitoring points during the construction period can usually be arranged according to relevant standards. The three-dimensional numerical simulation can be used to simulate and calculate the distribution of displacement, stress, and plastic zone of the structure and surrounding environment in underground engineering construction; the monitoring points are located at the position where the control parameters (displacement, stress, or plastic zone) are larger. At present, the commonly used monitoring safety control index are horizontal displacement, vertical displacement, surface vertical displacement, and so on, as shown in Table 1. The technical standards for monitoring construction foundation pit engineering [20], Shanghai foundation pit engineering technical standards [21], and Shenzhen urban rail transit underground engineering monitoring standards [22] are presented.

Qian and Rong [23] pointed out that the standards related the technical control index for underground engineering are not comprehensive enough. For example, according to the existing standards, the control standards for ground subsidence in underground engineering construction are not more than 30 mm which is considered loose in some projects with higher risk levels; but for some projects, the control values are unnecessary. In addition, the safety control index database system adapted to different geotechnical, hydrogeological, and environmental conditions in different cities and different construction methods has become a top priority. Therefore, the research on the safety control index of underground engineering monitoring will be the key research direction [24].

3. Framework of the Monitoring System

As shown in Figure 1, the typical underground engineering monitoring system is composed of four parts: data acquisition, data transmission, data analysis and processing, and security state early warning. The data acquisition terminal mainly uses sensors and cameras. Data transmission adopts wired and wireless modes; data analysis and processing adopt a variety of intelligent algorithms and early warning system forecasts security status based on the processing results.

3.1. Data Acquisition

3.1.1. Traditional Data Acquisition. Underground engineering monitoring content generally includes the stress, strain, displacement, and other parameters affecting the stability of rock mass. According to "Technical Standards for Highway Tunnel Construction" [25], the necessary items include observation inside and outside the tunnel, settlement of vault, surrounding displacement, and ground settlement. The observation inside and outside the tunnel is mainly recorded by manual field, and the surrounding displacement of rock mass after excavation is monitored by using a convergence meter [26]; the surface subsidence and vault subsidence are monitored mainly by using a leveling instrument and steel ruler or total station instrument. There are also some selected items, for example, the relative displacement between anchoring points of different depths in rock mass is monitored by using an extensometer [27, 28]; tunnel anchor axial force is monitored by using a steel bar gauge [29]. The main monitoring methods and instruments are shown in Figure 2. Traditional monitoring methods acquire data manually, which makes the person exposed to dangerous environment for a long time. Also, the method is time-consuming and will affect the excavation schedule. Therefore, the automation of data acquisition has attracted more and more attention.

3.1.2. Sensor Acquisition. Due to the limitations of traditional monitoring methods, it has become a hotspot to collect data automatically with various sensors in recent years, among which vibrating wire sensors, optical fiber sensors, and MEMS sensors are used more frequently.

(1) Vibrating String Sensor. The vibrating string sensor is a kind of sensor, which expresses the magnitude of tension by the change of natural vibration frequency of a metal string sensor and converts it into an electrical signal [30, 31]. The

Table 1: Early warning value (mm) [20–22].

Monitoring projects	Horizontal displacement	Vertical displacement	Deep horizontal displacement	Soil pressure	Wall internal force	Supporting force
[20]	25–30	10–20	30–35	(60%–70%) f_1	(60%–70%) f	80% f_3-70% f_2
[21]	15–25	15–25	30–50		(60%–70%) f_2	
[22]	30	40	—		—	

f: design limit value; f_1: load design value; f_2: bearing capacity design value; f_3: prestress design value.

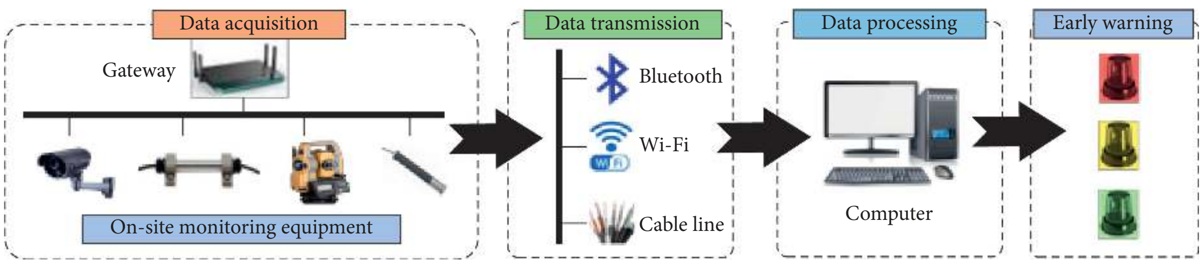

Figure 1: Overall architecture of the monitoring system.

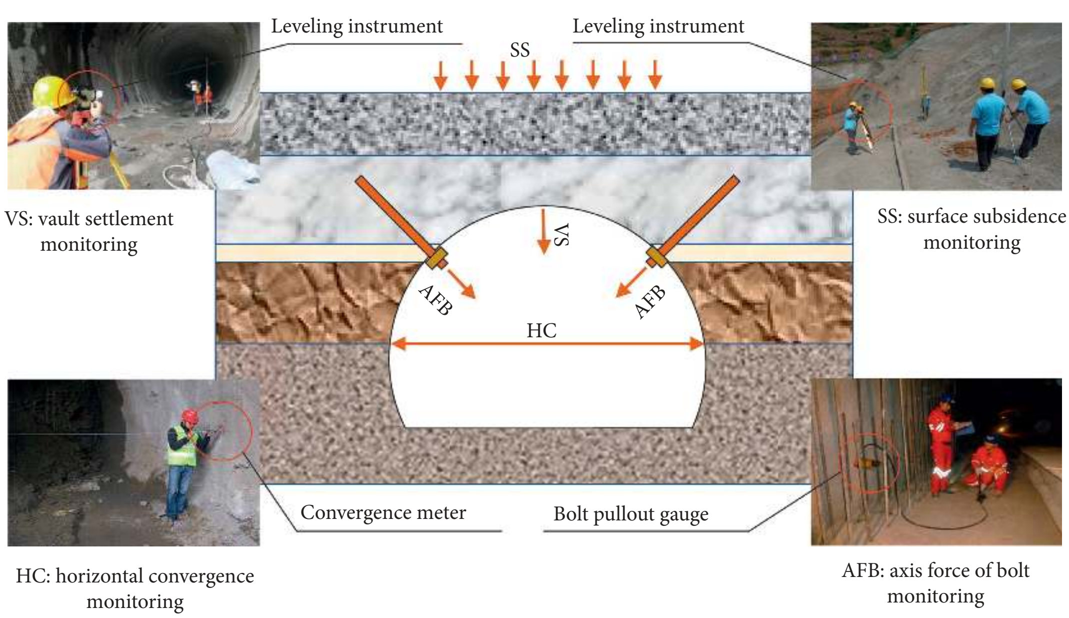

Figure 2: Traditional monitoring data acquisition.

principle is shown in Figure 3. Vibrating string sensors are widely used in long-term monitoring of civil buildings, reservoirs, dams, tunnels, and bridges in harsh environments due to their strong anti-interference ability and resistance to temperature. Based on the principle of the vibrating string sensor [5], a steel frame was designed to estimate the prestress of concrete effectively and reduce the monitoring cost greatly. In order to evaluate the operation performance of the Wuhan Yangtze River underwater tunnel, Yang et al. [32] used the vibrating-string surface strain gauge and joint measurement to monitor tunnel deformation; the instrument has been installed for more than three years, and 83.3% of the sensors work well. Moyo [33] found that the vibrating string strain gauges installed on bridges could still operate after eight years in Singapore and Malaysia. All these

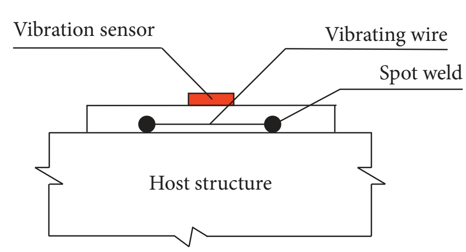

Figure 3: Vibrating-string sensor structure.

studies clearly show the long life performance of the vibrating-string strain gauge.

(2) Optical Fiber Sensors. Hill et al. [34] first proposed Fiber Bragg Grating (FBG) in 1978. It was developed for telecommunication technology originally. But, since the 1990s, optical fiber technology has developed rapidly in the sensor field with the advantages of multiplexing, anti-electromagnetic interference, high precision, and good reliability. Its principle is shown in Figure 4. When the stress, strain, or other physical quantities of the grating environment change, the grating period Λ or the refractive index n will change, so that the reflected light wavelength λ will change. By measuring the change in the wavelength, the change in the physical quantities to be measured can be obtained. Sato et al. [6] used FBG sensing technology to measure ground strain, compared with the traditional measurement results, and verified that FBG has better accuracy. Wu et al. [35] developed a new type of optical fiber displacement sensor based on the bending single-mode-multi-mode-single-mode (SMS), which has a larger displacement monitoring range.

In recent years, Brillouin Optical Time Domain Analysis (BOTDA) based on FBG sensors has attracted the attention of many researchers. As a new type of fully distributed strain monitoring sensor technology, the main advantage of BOTDA sensor technology is that it does not reduce the spatial resolution in long-distance monitoring. In order to verify the practicability of BOTDR, Mohamad et al. [36] used this sensing technology to monitor the strain distribution along the tunnel based on Singapore's New Ring Line Metro Project and has good consistency with the traditional monitoring results. Using the Brillouin Optical Time Domain Reflectometry (BOTDR) technology, Cheung et al. [37] established a strain monitoring system for monitoring the displacement of concrete tunnel lining joints in London underground tunnels.

(3) MEMS Sensors. The microsensor is the most successful and practical microelectromechanical device at present. It has the characteristics of small size, light weight, and good performance. In addition, there are micro-temperature sensors, magnetic field sensors, gas sensors, and so on. The area of these microsensors is mostly less than $1\,mm^2$.

Microelectromechanical system (MEMS) sensors have been widely used in airbag deployment in the automotive industry. They are also gradually used in geotechnical engineering monitoring. Danisch et al. [38] fused the MEMS sensor with the automatic geodetic monitoring system to provide the necessary information for determining the three-dimensional displacement, strain field, and rigid body motion of deformable objects. Dasenbrock [7] used the shape acceleration array SAA based on the MEMS sensor (SAA is a new geotechnical instrument developed by Rensselaer Institute and Measureand Inc.) to monitor landslides. SAA is an array consisting of hundreds of MEMS accelerometers, which has achieved better results than traditional methods. Rollins et al. [39] used the shape accelerometer array (SAA) to determine the horizontal displacement and depth profile during the lateral pile load test.

In view of the abovementioned three sensors commonly used in underground engineering monitoring, their advantages and disadvantages are compared as shown in Table 2.

As can be seen from the table, the three types of sensors have their own advantages and disadvantages, among which the advantages of optical fiber sensors are prominent, and they have developed rapidly in the recent years. From 2012 to 2017, the average annual increase of consumption value of global optical fiber sensors has reached 20.3%. The United States occupies the vast majority of the global market share of optical fiber sensors. At the same time, it is expected that the Asia-Pacific region will become the fastest growing market with an annual compound growth rate of 12.7% between 2015 and 2020.

Although the optical fiber sensor technology has been applied in practical monitoring, there are still some problems, namely, the output signal of the optical fiber sensor will be affected by the fluctuation of the light source, the change of the transmission loss of the optical fiber, the aging of the detector, and other factors, which will reduce the accuracy of the measurement. In view of the special environment of underground engineering, the performances of sensors need to be further improved.

3.1.3. Photogrammetry. In order to better realize the automation of monitoring, photogrammetry technology [43–46] has gradually attracted more and more attention. The timely triggering and management of monitoring results can be strengthened through immediate visual inspection of photogrammetry, which has been widely used in bridge monitoring [47, 48]. However, it is seldom used in other infrastructure projects. Take et al. [10]proposed a real-time monitoring technology of construction settlement based on photogrammetry, which combines remote digital photography technology, automatic file transmission technology, and image processing technology of particle image velocimetry (PIV). The technology is applied in monitoring the settlement of retaining wall caused by tunnel excavation. White et al. [49, 50] explained how to apply some effective algorithms to photogrammetric systems to track and monitor objects. For long-term environmental change monitoring, Alhaddad [51] developed software named CSATTAR (Satellite Image Tracking) based on the existing photographic monitoring technology. Although considerable progress has been made in the field of tunnel monitoring, due to various challenges in this field, the application of photogrammetry has not been fully developed.

3.2. Data Transmission. Traditional manual monitoring methods cannot provide high spatial and temporal resolution. In order to alleviate this problem, advanced countries have adopted online monitoring systems. However, these systems adopt wired communication, which has some shortcomings such as damageable communication cable, high failure rate, and inconvenient system maintenance. In the recent years, more and more scholars have used wireless communication technology to transmit data collected by

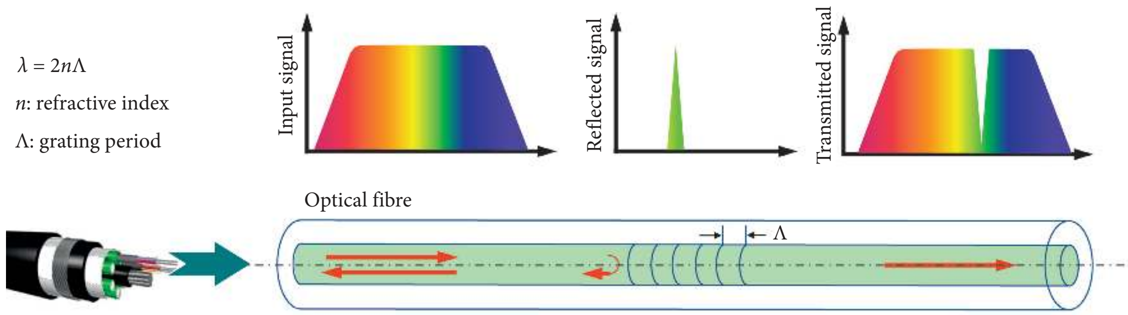

Figure 4: Principle of the optical fiber sensor.

Table 2: Comparative analysis of the three types of sensors.

Sensor type	Advantage	Disadvantage	Common	Application engineering
Vibrating-string sensor	(1) Strong structure (2) Suitable for long-term monitoring (3) Easy to install (4) Long life	(1) Static strain can only be monitored (2) Vulnerable to external noise (3) Cable transmission is required	Only some characteristic parts can be monitored	(1) Monitoring of Earth Pressure in Excavation of Rail Transit Station (Singapore) [40] (2) Strain monitoring of round steel pillars [41] (3) Strain monitoring of the Botlek Railway Tunnel in the Netherlands [42]
Optical fiber sensor	(1) Small size and light weight (2) Corrosion resistance and durability (3) Freedom from electromagnetic interference (4) No need for long cables	(1) Vulnerability (2) High price		(1) Strain distribution along the third stage of Singapore New Ring Line [36] (2) Joint displacement of London Metro [37]
MEMS sensor	(1) Small size (2) Light weight (3) Good performance	(1) Not customizable (2) Low resolution measurement (3) Expensive	—	(1) Pile cap lateral load test [39] (2) Crexton city landslide [7]

sensors, which is called wireless sensor network technology (WSN) [52–54]. This technology has outstanding advantages such as easy configuration, flexible topology change, strong fault tolerance, and mobility.

3.2.1. Transmission Principle. As shown in Figure 5, a typical WSN is usually composed of various monitoring sensor nodes, cluster head nodes, and base stations. WSN nodes with an information acquisition function are scattered in the designated monitoring area. The collected data are sent to cluster head nodes in the form of wireless communication. The cluster head is only used to route information to receivers to reduce power consumption. Then, it is transmitted to the base station by the multihop relay transmission mode. Base station is a nonmobile node, which can receive and transmit data throughout the system and finally reach the control center through the Internet or LAN [55, 56].

3.2.2. Comparative Analysis of Transmission Modes. At present, Bluetooth, Wi-Fi, Ultra Wideband Technology (UWB), and ZigBee are widely used in underground engineering monitoring. It has different parameters in frequency band, transmission power, transmission power, channel number, and so on, as shown in Table 3 [57–60].

It can be seen from the table that Wi-Fi is suitable for long-distance transmission and the other three communication technologies are suitable for short-distance. In terms of data transmission efficiency, UWB technology has the highest transmission efficiency, while ZigBee is suitable for low data transmission efficiency requirements; in terms of power consumption, Bluetooth and ZigBee have the lowest power consumption for the output of short-distance transmission signals; in the signal frequency band, Bluetooth, ZigBee, and Wi-Fi all use spread spectrum technology in the free 2.4 GHz band; and the maximum number of nodes that ZigBee can reach is 65000.

Underground engineering monitoring needs a large number of sensor nodes to collect and transmit data in the detection area, and the underground environment is more complex, which also puts forward high requirements for wireless communication technology. By comparing the abovementioned four communication technologies, we can see that the communication technology based on ZigBee is a good choice for underground engineering because of its advantages of low cost, low power consumption, more

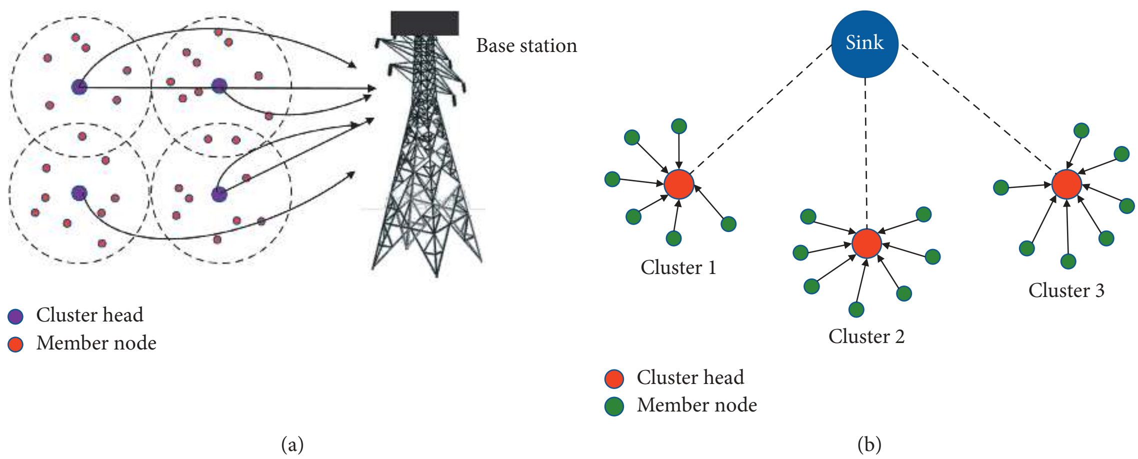

Figure 5: WSN transmission principle.

Table 3: Comparative analysis of communication technologies.

Parameter	Bluetooth	UWB	Wi-Fi	ZigBee
Frequency band	2.4 GHz	3.1–10.6 GHz	2.4 GHz	2.4 GHz
Maximum data transmission rate	1 Mb/s	110 Mb/s	54 Mb/s	250 kb/s
Transmission distance	10 m	10 m	100 m	10–100 m
Power	0–10 dBm	−41.3 dBm/MHz	15~20 dBm	(−25)~0 dBm
Network extension	Scattering network	Point-to-point	ESS	Tree/reticulate
Maximum number of nodes	8	8	2007	>65000

nodes, and long transmission distance. Also, the ZigBee technology adopts spread spectrum technology, which effectively improves the antijamming ability and maintains stability [61, 62].

3.2.3. Transmission Problems. The high-frequency data acquisition of automatic monitoring causes a large amount of monitoring data, and the wireless transmission is susceptible to interference. Therefore, data compression [63–66] and data reliability become the main problems in data transmission.

Compression ratio, data recovery error, energy consumption, transmission delay, and complexity are considered to evaluate the performance of data compression. Based on the traditional single-node compression technology, distributed data compression, such as distributed K-L transform, distributed wavelet transform, and distributed compressed sensing, is carried out by utilizing the temporal correlation within sensor nodes and the spatial correlation between sensor nodes [67]. The research of technology is of great significance to improve the performance of data compression in deformation monitoring of wireless sensor networks [68].

Current research mainly focuses on two aspects to solve the problem of data reliability: the design of reliable transmission protocol and the recovery of lost data. Nagayama and Spencer [69] designed a reliable communication protocol in wireless sensor network monitoring. Data interpolation is the common recovery technology. Bao et al. [70] studied the technology of data recovery using compressed sensing. Data recovery reduces data retransmit rate and saves network resources.

3.3. Data Processing and Analysis. For the safety of underground engineering, forecasting is the ultimate goal and monitoring is only the means of analysis. There are many factors causing deformation in underground engineering. It is of great significance to correctly analyze and explain the various factors affecting deformation. Nowadays, artificial intelligence is a hot research field and the direction of future social development. Machine learning, as an important research field in artificial intelligence, has been paid more and more attention to. How to use the construction status and monitoring data to predict underground engineering construction is still a big problem. Monitoring data is a small sample; exploring learning rules in limited samples is a difficult problem.

3.3.1. Common Data Processing Model. The regression analysis method, time series method, Kalman filter method, grey model method, wavelet analysis method, and neural network algorithm are commonly used in the processing and prediction of underground engineering deformation monitoring data. Kim et al. [71] used the neural network model to predict ground subsidence caused by tunnel excavation. Lai et al. [72] applied the neural network to prediction of soil deformation in tunnels. Relying on this project of Karaji Metro Line 2, Moghaddasi and Noorian-Bidgoli [73] proposed a prediction model, which combines independent component analysis (ICA) with artificial neural network (ANN).

In order to overcome the shortcomings of the traditional neural network algorithm, a single hidden layer feed forward neural network algorithm (ELM) was proposed. The algorithm has fast learning speed and good generalization performance, so it has better application. Liu et al. [74] first proposed an improved extreme learning machine (ELM) algorithm based on convergent data to predict transverse shear stress. The accuracy of the improved ELM algorithm was verified by practical engineering cases. Lian et al. [75] predicted landslide displacement by using the ELM model of modified empirical mode decomposition. The principles and characteristics of deformation data processing and prediction methods are shown in Table 4.

3.3.2. Problems in Data Processing

(1) Less samples

The prediction model has too few training samples, which makes it difficult to guarantee the reliability of the prediction model.

(2) Adaptability

Lack of data mining of internal characteristics and lack of discussion on the applicability of the prediction model.

(3) There are many factors

There are many factors that affect the construction safety of underground engineering. However, most of the prediction models only analyze the data for a single measurement point and do not consider the spatial characteristics of the data.

4. New Technique of an Underground Engineering Monitoring System

4.1. Wireless Multimedia Sensor Network Monitoring System. In the recent years, with the rapid development of MEMS, wireless communication, embedded system, distributed processing, and wireless sensor technology, the technology of wireless sensor network (WSN) has been greatly improved. Considering the constraints of underground engineering environment, WSN has been widely used and developed in underground engineering monitoring due to its advantages of no wired connection and the efficient data transmission mode by sensor nodes.

Muduli et al. [98] proposed an underground fire monitoring system of coal mine, which is based on the wireless sensor network technology. The system used the fuzzy logic method to improve the reliability of the decision-making process and reduce the hidden danger of coal mine fire. Othman and Shazali [99] summarized the application of wireless sensor networks in environmental monitoring and verified the effectiveness of wireless sensor networks. Mishra et al. [100] designed a wireless real-time monitoring platform for geotechnical sensors based on vibration string, which realizes continuous, real-time, and remote monitoring of stratum dynamics. The results are in good agreement with laboratory tests and field demonstrations. Taking the tunnel under construction in Shaanxi Province as the engineering background, the vibration response of the tunnel under blasting was monitored by using the wireless sensor network system [101], as shown in Figure 6. For the safety of workers, Yun et al. [102] developed a set of working face safety monitoring systems to judge the risk of working face collapse during tunnel construction.

Han et al. [103] proposed a wireless multimedia sensor network technology for underground coal mine based on traditional wireless sensor network and applied it to underground coal mine monitoring. The framework fills the gap in the design of an underground engineering wireless sensor network which lacks efficient and comprehensive structure.

The abovementioned research shows that the existence of the wireless sensor network monitoring system can achieve better target parameters for underground engineering monitoring, which has many types and large number of sensors, wide monitoring area, scattered layout of measuring points, low frequency data acquisition, and high networking requirements, but it has not been widely used. In addition, in order to improve the effectiveness of the underground engineering monitoring system, the concept of intelligent monitoring combined with advanced technologies such as Internet of Things attracted more attention.

4.2. Deformation Monitoring System of Underground Engineering Based on Internet of Things. The Internet of Things (IOT) is regarded as a new generation of ICT industry. It combines sensors, RFID tags, actuators, and mobile phones to achieve integrated sensing and intelligent processing [104, 105]. The development of Internet of Things technology provides great benefits to establish a fast, high precision, real-time, and high reliability automatic monitoring system for underground engineering.

Zhou and Ding [106] proposed a security barrier early warning system based on Internet of Things (IOT) to achieve a safe underground construction. The implementation of the construction site of the Yangtze River crossing subway tunnel shows that the safety performance of the project has been improved and the occurrence of dangerous energy accidents on-site can be prevented. Jo and Khan [107] introduced a reliable, efficient, and cost-effective Internet of Things air quality monitoring system for monitoring a complex, dynamic, and harsh underground coal mine environment and added evaluation and pollutant prediction functions, which achieved good results. Wu et al. [108] have established a dynamic information platform for underground coal mine based on the Internet of Things technology. The platform consists of six functional layers, including a support layer, perception layer, transmission layer, service layer, data extraction layer, and application layer. It provides a three-dimensional virtual mine system, safety diagnosis system, safety detection system, and emergency rescue system for coal mines.

Table 4: Deformation data processing and prediction method analysis.

Model	Principle	Advantage	Disadvantage
Regression analysis [76–80]	According to the correlation between the observed external causes and the measured deformation, the mathematical model of load-deformation relationship is established	Static data processing; empirical model simulation; and simple calculation	A lot of data is needed
Kalman filter [81–84]	Find the law between input and output data of the system, and evaluate the state of the system based on the linear state equation	Data dynamic processing; only focuses on input and output, no need for historical data; and noise is white noise	Poor transient data processing
Grey model [15, 85–89]	Based on partial displacement information, the long-term deformation of underground structures is analyzed	Prediction can be based on incomplete data; a disordered sequence can be transformed into an ordered sequence	It is difficult to accurately predict the data with large fluctuation, which is suitable for the prediction that meets certain characteristics
Wavelet analysis [90–94]	According to the time-space frequency localization, the displacement variation law is analyzed, and the specific parameters of the input-output relationship function of the system are refined step by step	Localization analysis; adaptive analysis data; and good denoising ability	The selection of wavelet bases is difficult
Wavelet analysis [14, 95–97]	A new information processing system imitating and extending human functions	Parallel collaborative processing of data; efficient identification of nonlinear transforms; reduction of irrelevant factors, consideration of a large number of quantitative and qualitative factors, and assurance of accuracy	Overtuning, local minimum, stop criteria, and long calculating time

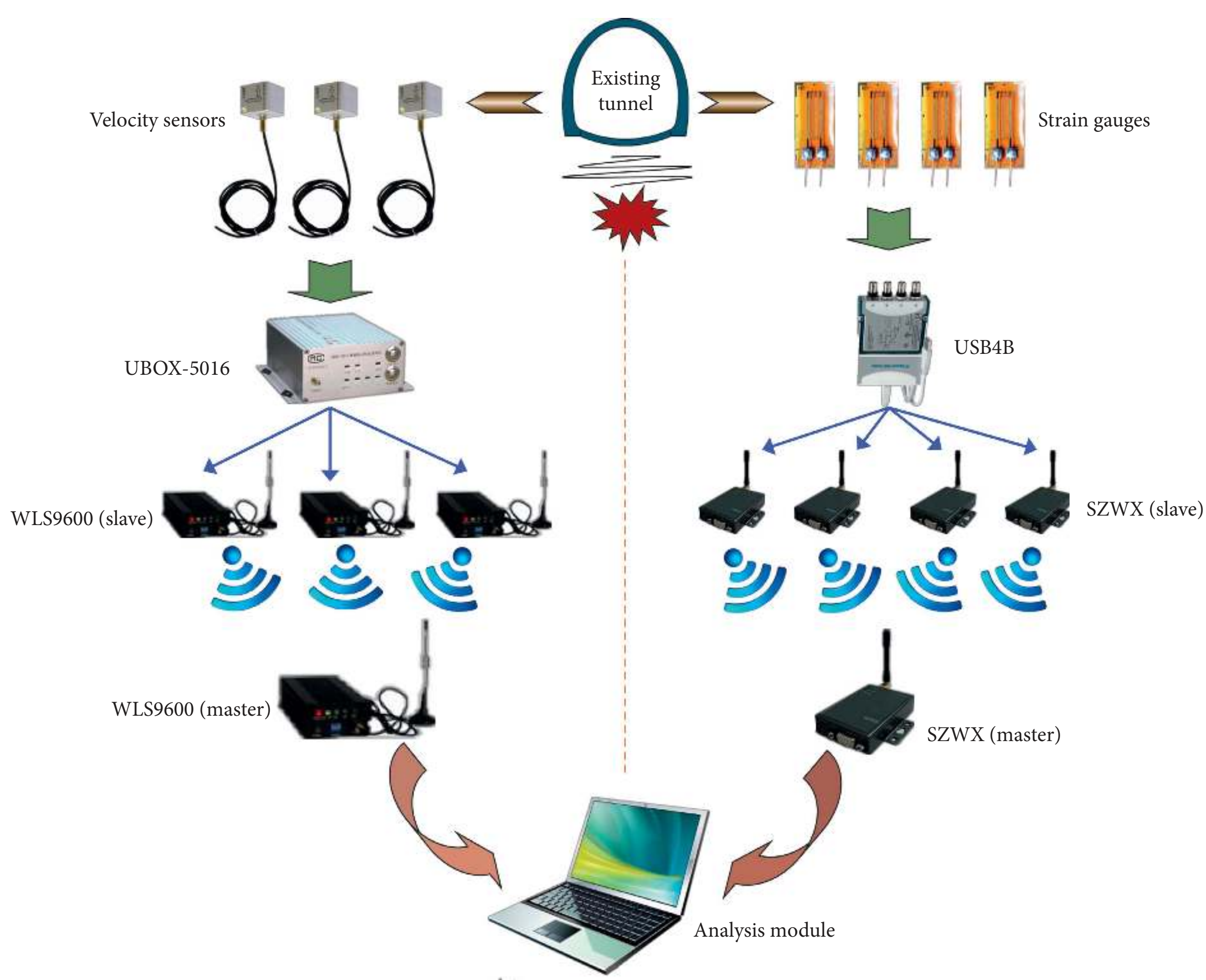

Figure 6: Wireless sensor network system [101].

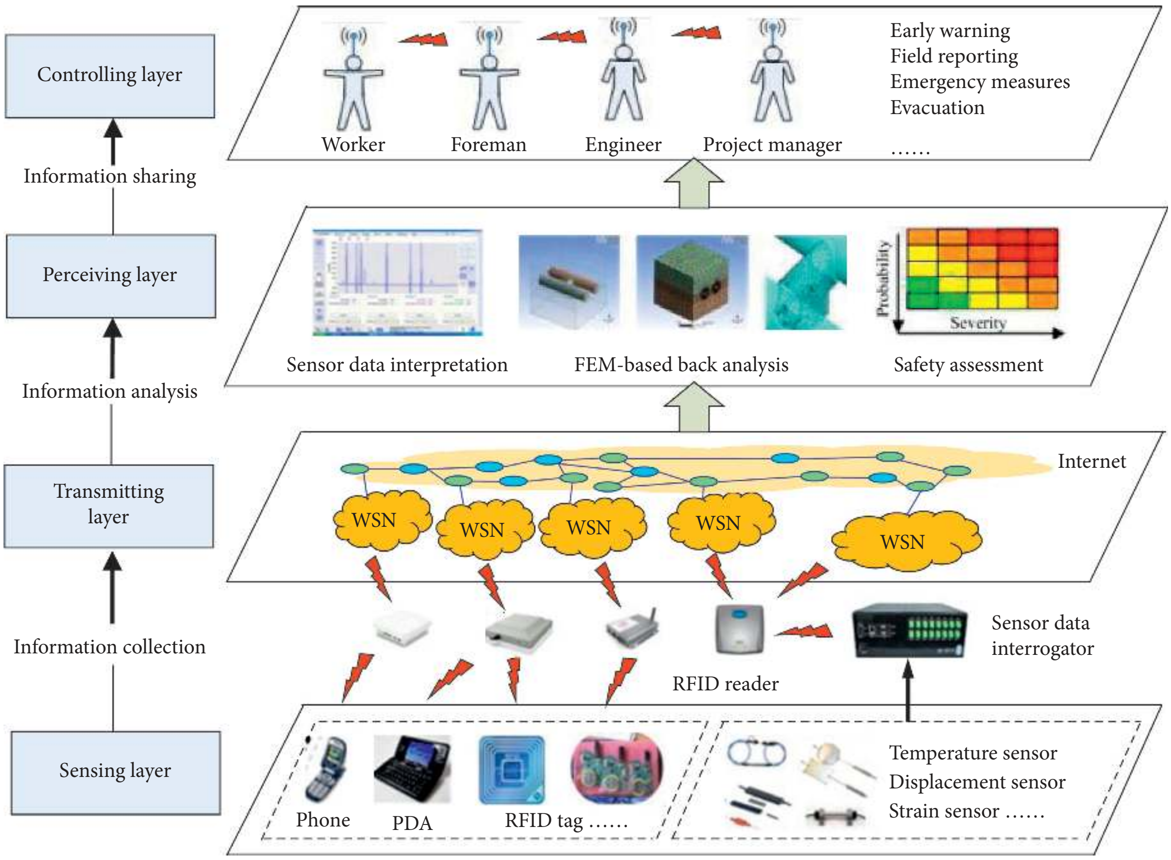

Figure 7: Real-time early warning system for underground construction safety based on Internet of Things [111].

Jo et al. [109, 110] have studied a highly accurate FBG monitoring system and developed a comprehensive mine structural safety system by only output data-driven methods on the Internet of Things (IOT) platform. The system has been successfully implemented in Hassan Kishor Coal Mine in Salt Field, Pakistan. Ding et al. [111] proposed a real-time early warning system for underground construction safety based on Internet of Things. The system can realize real-time perception, real-time transmission, and real-time early warning and can timely inform every underground construction site works. It has been successfully applied to the construction site of the Bed Metro Tunnel crossing Yangtze River. Most importantly, the system pays more attention to the integration of security monitoring and real-time early warning compared with the traditional methods. Therefore, more potential accidents can be identified and prevented before they occur, as shown in Figure 7.

The current prominent problems are "more conceptual solutions, less practical systems; more experimental systems, less scale applications," which is not enough to form a representative system solution.

5. Development Trend Prospect of Underground Engineering Monitoring

Underground engineering will develop towards a super-large-scale, superdeep, integrated, interconnected, and more complex construction environment [112–115], which put forward higher requirements for its monitoring and control [116, 117]. In order to meet the needs of safety construction of underground engineering, the development trend of the existing automatic monitoring system for safety status of underground engineering can be summarized as follows.

5.1. High-Precision Real-Time Acquisition and Safe and Reliable Transmission of Monitoring Data.

BOTDA monitoring technology is the hottest research field at present, but the accuracy of the sensing technology cannot meet the requirements for some special environments. It is necessary to develop high-precision data acquisition equipment and reserve relevant data and communication interfaces to form a unification.

In the construction environment of an urban underground large space, the multipath propagation of wireless signals is very serious (even causes communication blind area) because of its semiclosed or fully closed structure. Therefore, the transmission of data or information will face three challenges: power supply of communication equipment, transmission mode, and layout of communication nodes. For large space communication between inside and outside: large space internal monitoring data are linked to external public network (4G/5G) or management private network through a gateway. For large space internal communication: a leak communication mode is adopted, and a uniform and continuous electromagnetic field around the

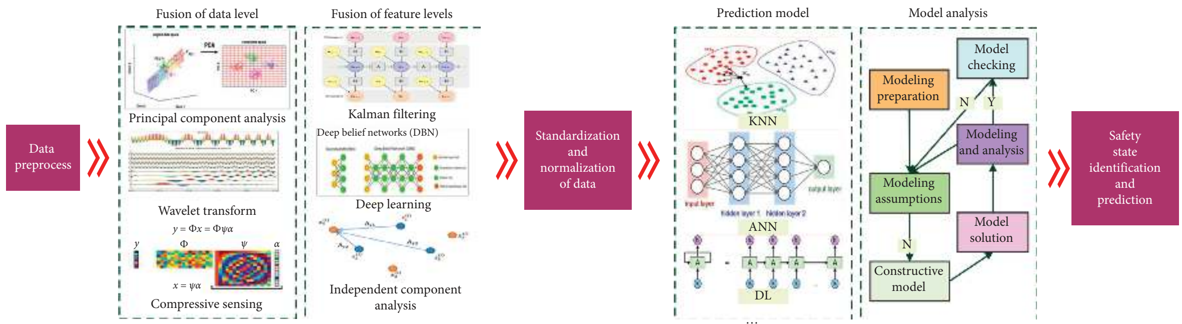

FIGURE 8: Data fusion technology for multisource collaborative monitoring.

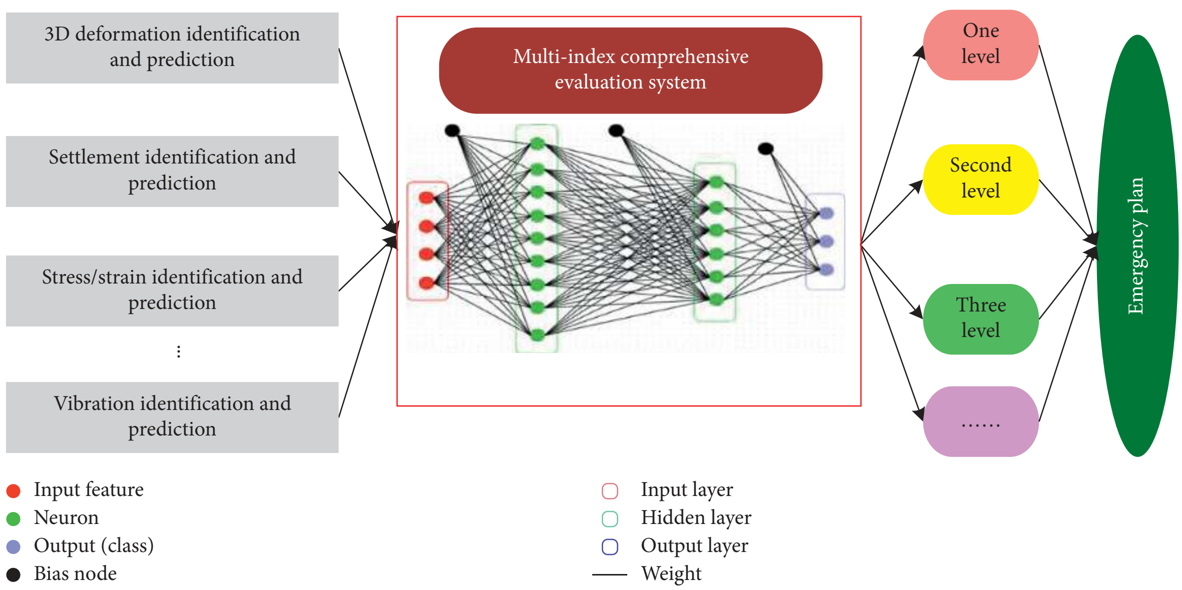

FIGURE 9: Classified early warning and emergency plan.

coaxial cable is used as a transmission medium to realize the communication between monitoring point and data gathering center; in a wireless local area network (WLAN), the wireless transmission node gathers and forwards data by laying many wireless signal hotspots in an underground large space. These nodes and access points constitute the construction monitoring network of an urban underground large space; the node antenna can adopt a directional mode or antenna array mode.

5.2. Multisource Data Fusion, Security State Prediction, and Hierarchical Early Warning

5.2.1. Preprocessing and Fusion of Multisource Massive Monitoring Data

Data preprocessing: Fourier transform, multiscale wavelet transform, and singular spectrum analysis are used to reduce the noise of various monitoring data with weak signal change and strong interference. In view of the possibility of abnormality and loss of complex environment data, historical smoothing, proximity algorithm, machine learning, and other methods are used to elimination of data and completion of missing data. The preprocessing technology can improve the validity and reliability of the data which is important for the evaluation and evaluation model of construction safety state.

Data fusion: according to the space-temporal correlation characteristics of monitoring data, singular value decomposition and compressed sensing are used to fuse information at the data level, feature level, and decision level to reduce data redundancy. Based on the traditional random fusion methods such as the weighted average method, Kalman filter method, and multi-Bayesian estimation method, multivariate data fusion is the next development trend combined with artificial intelligence algorithms such as fuzzy logic theory, neural network, rough set theory, and learning technology. It lays a foundation for improving the accuracy and robustness of the evaluation model of construction safety state.

5.2.2. Prediction of Safety State. On the basis of data fusion, through deep mining of historical construction monitoring

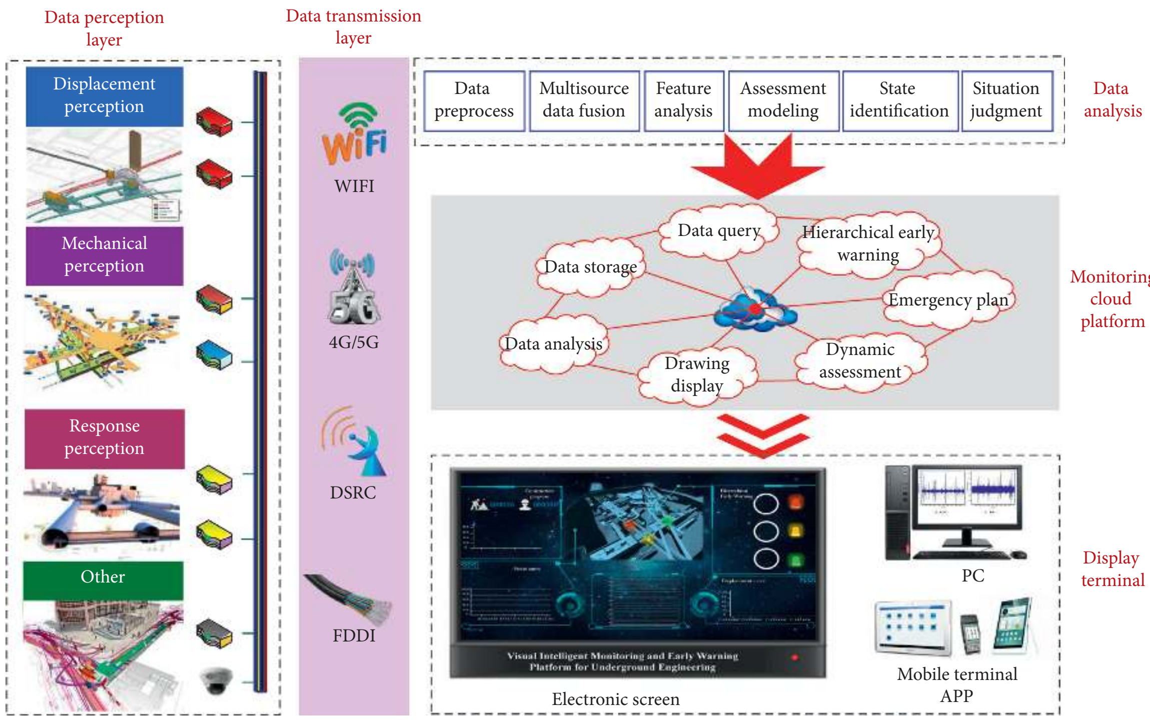

Figure 10: Intelligent automated monitoring framework.

data, the intrinsic logic and law of the data are found. In addition to the traditional linear prediction model, artificial intelligence algorithms based on the stochastic forest, deep belief network, cyclic neural network, and long-short sequence model should be studied for single monitoring index data [118–120]. The data processing and prediction process is shown in Figure 8.

5.2.3. Hierarchical Early Warning. Through statistical analysis of a large number of engineering cases, emergency plans of different levels are determined according to different environments and different work methods. The emergency plans include a specific emergency treatment process, information feedback and processing mechanism, personnel dispatching scheme, risk control scheme, and related management rules and regulations [121–124]. An information tracking system for postemergency disposal is established and an emergency plan system associated with an environment and construction method is formed, as shown in Figure 9.

5.3. Cloud Platform for Visual Intelligent Monitoring and Early Warning. The real-time transmission data and engineering information model are calibrated in the space and time dimension by using a computer, and the trend of data change and real-time monitoring video are presented in the information model. Monitoring data can be knowable and visualized by using graphics, image processing, computer vision, and a user interface. Figure 10 shows the framework of an automated monitoring system based on intelligent algorithms. It includes a data acquisition layer, data transmission layer, data analysis layer, monitoring cloud platform, and display terminal. It can realize large-scale underground engineering safety visualization monitoring during construction, rapid analysis and command control, and early warning and timely feedback control of structural and environmental imperfections.

6. Conclusions

(1) In view of the necessity and urgency of underground engineering monitoring, this paper introduces the underground engineering monitoring system from three aspects of data acquisition, data transmission, and data processing. In data acquisition, optical fiber sensors have obvious advantages and rapid development; in data transmission, ZigBee-based wireless transmission has become the mainstream trend; in data processing and analysis, various models emerge endlessly, and each has its own advantages and disadvantages. The neural network model has developed rapidly in the recent years; the combination model of the neural network model and other models shows better prediction accuracy.

(2) The new methods and new technologies of the underground engineering monitoring system are shown in this paper, including the wireless multimedia sensor network monitoring system and deformation monitoring system of underground engineering based on IoT. Although these new technologies have good monitoring effect, they have not been widely used.

(3) Based on our previous research results, this paper expounds the development trend of underground

engineering monitoring technology and puts forward specific and implementable technical route. It mainly includes high-precision real-time acquisition and safe and reliable transmission of monitoring data, multisource data fusion, security state prediction and hierarchical early warning, and cloud platform for visual intelligent monitoring and early warning. It can provide direction and reference for future research.

(4) The heterogeneity and diversity of materials and the complexity of construction environment will pose further challenges to the design and application of monitoring systems in the future because of the development of underground engineering structures towards super-large-scale, superdeep, comprehensive, and interconnection.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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