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Research Article

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Measurement and deformation monitoring system for underground engineering robots based on Internet of Things architecture

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Abstract: In response to the deformation and displacement problems that exist during the construction and use of underground projects, this study develops an underground engineering robot measurement deformation monitoring system based on the Internet of Things (IoT) architecture, aiming to improve the accuracy and efficiency of underground engineering deformation monitoring. The system was designed with a multi-layer architecture, including a perception layer (real-time collection of deformation data) and a network layer (using a robot to carry a data acquisition terminal and transmit data to a cloud server through wireless communication technology), platform layer (using cloud computing and big data technology to store, process, and analyze collected data), and application layer (visualization platform, convenient operation, and analysis of data). Fifteen underground engineering projects were tested, with ten key monitoring points selected for each project. Multiple regression analysis was used to evaluate the monitoring accuracy and stability and to explore the relationship between monitoring data and geological conditions and environmental variables. The experimental results show that compared with traditional methods, this system has significant advantages in stress monitoring: the stress monitoring error of conventional methods is about 0.5 MPa, while the error of this system is only 0.01 MPa, a difference of 50 times. The system of the IoT significantly improved the detection efficiency compared with the traditional manual surveying and mapping method, and the underground engineering robot measurement deformation monitoring system based on the IoT architecture took only 4 h to monitor the small deformation. However, the traditional method took 15 h, i.e., the system based on the IoT was 11 h faster than the conventional method. The underground engineering robot measurement deformation monitoring system based on the IoT architecture has high reliability and operability, and provides strong support for the safety management of underground engineering.

Keywords: Internet of Things, data visualization, underground engineering robots, deformation monitoring, wireless communication

1 Introduction

Global urbanization is advancing [1,2], and developing and utilizing underground space [3,4] has become a top priority. In the construction and implementation process of underground engineering projects such as tunnels, subways, and mines [5,6], due to the complexity and variability of the underground environment, it is easy to be disturbed by various factors, causing deformation of the underground engineering structure, leading to safety accidents, significant economic losses, and casualties. Therefore, during the underground engineering construction process, it is essential to precisely and promptly detect deformation. According to statistics,

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mishaps brought on by subterranean engineering deformation generate billion-dollar losses in damages and numerous fatalities annually throughout the world. Conventional techniques for monitoring deformation [7,8] mostly depend on laser scanning technology, fixed-point monitoring, and human continuous measuring. Laser scanners are utilized to acquire three-dimensional point cloud data for subterranean projects. These scanners are capable of measuring and tracking structural deformation. The real-time monitoring requirements of contemporary complicated subterranean engineering cannot be addressed by these techniques since they are ineffective, expensive, and have a restricted monitoring frequency and density. It is challenging to deliver steady and precise data under extreme conditions because of the complexity and abrasiveness of underground engineering environments, which also poses a significant risk to the reliability of typical measuring equipment. With the development of the Internet of Things (IoT) [9,10] and robotics technology [11], new solutions have been brought to underground engineering deformation monitoring. By deploying high-precision sensor networks, real-time collection and wireless transmission of deformation data have been achieved, greatly improving the efficiency and accuracy of monitoring [12]. The development of robotics technology has made it possible to flexibly move, and perform inspection and data collection tasks in underground environments.

This study presents an IoT-based underground engineering robot measurement and deformation monitoring system to achieve effective and real-time monitoring of subsurface engineering. By combining a number of cutting-edge technologies, including sensor networks, wireless communication, cloud computing, and robots, the system increases the precision and effectiveness of deformation monitoring and offers reliable data support in challenging and complicated contexts. Extensive testing in real-world subterranean engineering settings has demonstrated the system's superior performance in terms of real-time performance, data transmission efficiency, and accuracy of monitoring. This means that the system developed in this study can detect smaller deformations, thereby providing timely warnings in the early stages of problem occurrence and avoiding potential catastrophic consequences. The architecture design based on the IoT also enables the system to quickly respond to deformation situations, greatly reducing monitoring and response time. The system not only improves the timeliness of monitoring but also provides a more accurate decision-making basis for engineering management personnel.

2 Related work

For deformation monitoring of underground engineering, Wang et al. [13] believed that it was crucial to regularly observe and measure the deformation of excavation surfaces and support structures during tunnel construction to ensure the safety of construction personnel and the long-term stability of tunnel structures. Monitoring the condition of tunnel structures usually involves measuring the deformation or convergence of specific points in the tunnel. However, the traditional use of total stations has some problems, such as the need to install reflective prisms, susceptibility to human errors, and insufficient monitoring frequency. The rapid development of machine vision and sensor technology has brought new solutions for tunnel monitoring and measurement. By integrating emerging technologies such as laser scanning, fiber optic sensing [14], GNSS, and wireless sensor networks [15], the field of structural health monitoring has seen revolutionary advancements in continuous data collection and multi-modal analysis. Laser scanning technology can provide high-precision 3D modeling and real-time monitoring, while fiber optic sensors achieve long-distance and high-sensitivity strain and temperature monitoring through distributed sensors. GNSS technology is mainly used for surface deformation monitoring, while wireless sensor networks can achieve real-time and dynamic monitoring of construction sites. The application of these technologies not only improves the accuracy and real-time monitoring but also makes early warning and risk management possible, ensuring safety during the construction process. Wu et al. [16] proposed a remote deformation monitoring system based on a three-layer IoT architecture, exploring the combination of IoT technology and traditional monitoring methods, which provides a reference for improving the efficiency and reliability of underground engineering surveying. These methods have played a positive role in regular observation and measurement during tunnel construction to a certain extent, but the relevant methods are more combined with sensors and not combined with new artificial intelligence technologies.

The application of IoT technology in monitoring and early warning systems not only improves the security and monitoring efficiency of infrastructure but also provides important support for scientific and technological innovation and development in related fields. Dong et al. [17] believed that using the IoT technology for real-time monitoring of landslide deformation and artificial intelligence [18,19] algorithms to predict landslide deformation trends can effectively predict and warn landslides. In this context, he introduced a real-time wireless monitoring system with multiple sensors, providing technical support for the design and implementation of steep slope safety solutions. Even after construction, most equipment is retained to monitor slopes. He introduced a machine learning [20] autoregressive recurrent network probability prediction model based on time series and probability prediction for predicting slope displacement. The prediction accuracy of the machine learning autoregressive recurrent network probability prediction model based on time series and probability prediction were verified through mean absolute error, root mean square error, and goodness of fit. The experimental results indicate that the proposed monitoring system and the introduced prediction model have good safety control capabilities during the construction process, and have good prediction accuracy during operation, which can help evaluate the safety of excavation slopes before constructing new infrastructure. Shi [21] designed a deformation monitoring system based on laser displacement sensors to address the issues of limited conditions for using level gauges or weak timeliness of total station and 3D laser scanning in bridge monitoring on highway sections. This system is based on the IoT and utilizes modules such as laser displacement sensors and tilt sensors to achieve real-time monitoring and danger warning of the deformation of bridges on high-speed road sections. Without the need for road closures, it improves the operational efficiency of surveying and mapping personnel and reduces safety hazards in the field. Previous studies have failed to develop a comprehensive system or effectively address the technical challenges and accuracy limitations associated with underground monitoring. On this basis, this study designs a multi-level data processing architecture combining distributed and edge computing, which improves the real-time monitoring and its efficiency. Visual simultaneous localization and mapping (SLAM) technology and laser radar technology enhance the positioning accuracy of robots in the underground environment, improve the accuracy and reliability of data through multi-sensor fusion technology, optimize the stability of data transmission by combining 5G and Long Range Radio (LoRa) dual-mode communication technology, and realize real-time assessment and prediction of structural health by using big data processing and machine learning algorithms. In summary, IoT technology can not only monitor data but also analyze and predict the trend of landslide deformation. This combination helps to identify safety hazards in advance and issue early warnings in time, providing important support for safety management.

3 IoT and robot technology design

3.1 IoT technology design

The deformation monitoring system for underground engineering robots based on the IoT architecture requires the use of various IoT technologies. To achieve real-time high-precision monitoring of underground structures and engineering deformation, and ensure the safety of the project, high-precision real-time detection of underground engineering deformation can be achieved by combining sensor technology, wireless communication technology, cloud platform technology, big data artificial intelligence technology, and visualization systems.

One type of high-precision measurement tool that is frequently employed in the mapping of subterranean structures is the laser scanner, which produces high-resolution 3D point cloud data that can represent structural deformation. Strain gauges are used to track changes in stress and to identify variations in metal foil resistance. Accelerometers and diameters are used to gather high-precision data in real-time while monitoring the displacement, vibration, and changes in diameter of subterranean structures. The use of multi-sensor fusion technology enhances data accuracy and supports subterranean structure maintenance and safety.

In order to achieve communication between the robot and the local gateway, short-range and high-bandwidth data transfer is made possible via WIFI technology. Data interchange between sensors with an optical domain distribution is made possible by LoRa technology, which can be utilized for long-distance, low-power data transfer [22]. Finally, the benefits of 5G technology's high bandwidth, low latency, and large-scale connectivity allow for real-time data transmission and large-scale IoT communication.

At the platform layer, the use of cloud platforms provides powerful data storage, processing, and analysis capabilities, allowing sensor data to be uploaded to the cloud platform for centralized management and analysis through wireless communication technology. The use of cloud platforms can reduce server usage costs, and the scalability of cloud platforms can provide sufficient space for future real-time data. The use of cloud platforms reduces server usage costs by paying on demand, reducing hardware investment, and optimizing resource usage. At the same time, its strong scalability ensures that future real-time data processing needs can be fully met. This makes cloud platforms an ideal choice for enterprises in the process of digital transformation and data-driven decision-making.

Data can be collected and processed in real-time through the big data processing platforms Hadoop and Spark, enabling efficient data processing and analysis [23]. Machine learning and big data processing can be combined to perform pattern recognition and predictive analysis on deformation data, thereby providing assessment and early warning of structural health status.

To enable users to monitor and analyze data intuitively, we leverage Python visualization tools that enable users to view and analyze data in real-time on charts and dashboards. Through mobile applications, it

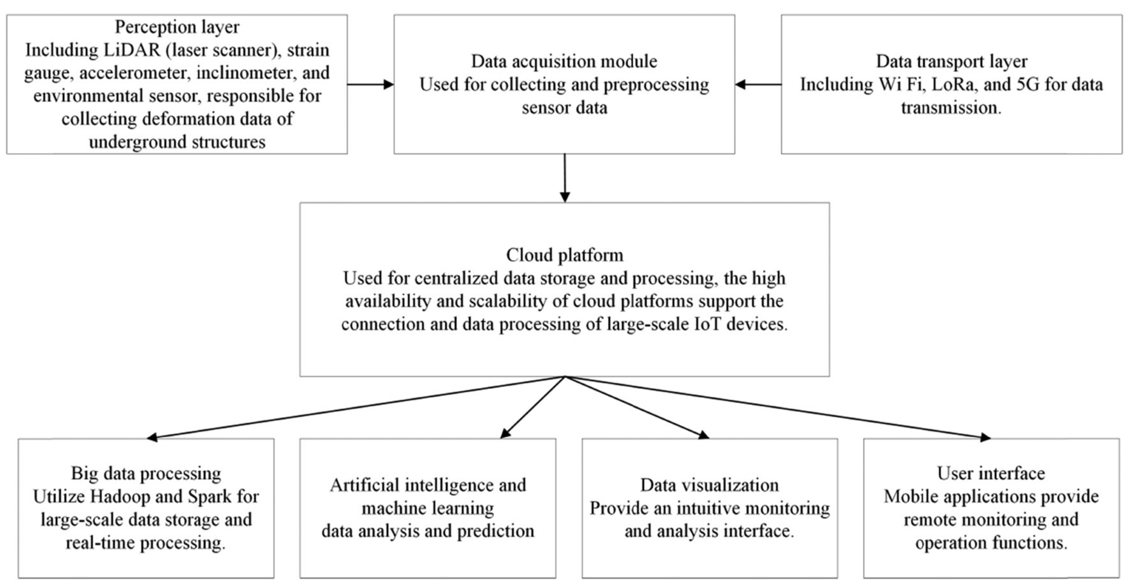

Figure 1: Schematic diagram of IoT technology framework. Source: Created by the author.

provides users with convenient remote monitoring and operation functions.

The schematic diagram of the IoT technology architecture is shown in Figure 1.

The deformation monitoring system for underground engineering robots based on the IoT architecture achieves real-time, efficient, and intelligent monitoring of underground engineering structures through the comprehensive application of sensor technology, wireless transmission, cloud platform, big data processing, artificial intelligence analysis, data visualization, and system management technology, providing strong guarantees for engineering safety.

3.2 Robot technology design

The deformation monitoring system for underground engineering robots based on the IoT architecture adopts various advanced robot technologies. The core technologies include autonomous navigation and positioning, multi-sensor data fusion, wireless communication, and data transmission, cloud platform data processing and analysis, as well as remote control and automation tasks.

Robots navigate autonomously using the Visual SLAM method, which creates real-time 3D maps of the environment by using cameras to capture environmental images. It is possible to achieve high-precision course planning and obstacle avoidance when combined with data from inertial measurement units. This method makes the robot far more accurate in its placement and more adaptive in intricate subterranean conditions. With the employment of laser radar, GPS modules, and ultrasonic sensors, multi-sensor fusion technology fuses data using the Kalman filtering technique to reduce the inaccuracies caused by individual sensors and enhance positioning stability overall [24]. Continuous and accurate location can be achieved using the combination of LiDAR and optical sensors in underground environments that lack GPS signals. In addition, the robot has accelerometers, inclinometers, and high-precision strain gauges for collecting and detecting subsurface structure deformation in real time. To guarantee the accuracy of data transferred to the cloud platform, embedded data acquisition modules perform preprocessing operations on sensor data, such as filtering, noise reduction, and preliminary data integration. Environmental sensors provide comprehensive environmental parameter assistance for structure health evaluation by monitoring the temperature, humidity, and gas concentration of subterranean settings. To enable effective data transfer under various communication needs, the wireless communication module uses dual-mode 5G and LoRa technology [12]. The 5G module is suitable for data transmission with high bandwidth and low delay, such as real-time video stream and large-scale data upload. The LoRa module is used for sensor data transmission with low power consumption and long distance, suitable for distributed sensor network applications. The data are safely transmitted to the cloud platform after being relayed by the gateway device, and edge computing technology is used to achieve preliminary data processing and analysis, thus reducing the computing burden on the cloud.

In the cloud platform section, the system adopts a big data processing architecture based on Hadoop and Spark, supporting the storage and real-time processing of massive data. Through a distributed computing framework, concurrent data streams from multiple robots can be efficiently processed to achieve real-time monitoring and analysis of underground structural deformation. Artificial intelligence and machine learning algorithms are further applied to data analysis and prediction. By training models to identify potential deformation trends and abnormal situations, warning information is provided to assist engineering management personnel in taking timely preventive measures [25].

The system also integrates remote control and automation task modules, allowing operators to remotely monitor and command robots through mobile applications.

4 System design

4.1 Framework design

The IoT technology is applied to real-time deformation monitoring and analysis of underground engineering structures. At the perception layer, the system is equipped with a variety of sensors and robots to obtain real-time changes in the underground environment and structure. Including displacement sensors, temperature, and humidity sensors. At the network layer, data are transmitted to the cloud platform through wireless communication modules and gateway devices. The platform layer uses big data and artificial intelligence technology to analyze data and identify structural deformation trends and potential risks. Through the organic combination of these modules, the system can achieve comprehensive and real-time deformation monitoring and analysis of underground engineering structures. The application layer provides mobile system monitoring, and the user module has the functions of analyzing monitoring data, setting alarm thresholds, and receiving notifications. The system has security measures such as data encryption and access control to make the system more reliable and secure.

The system framework diagram is shown in Figure 2.

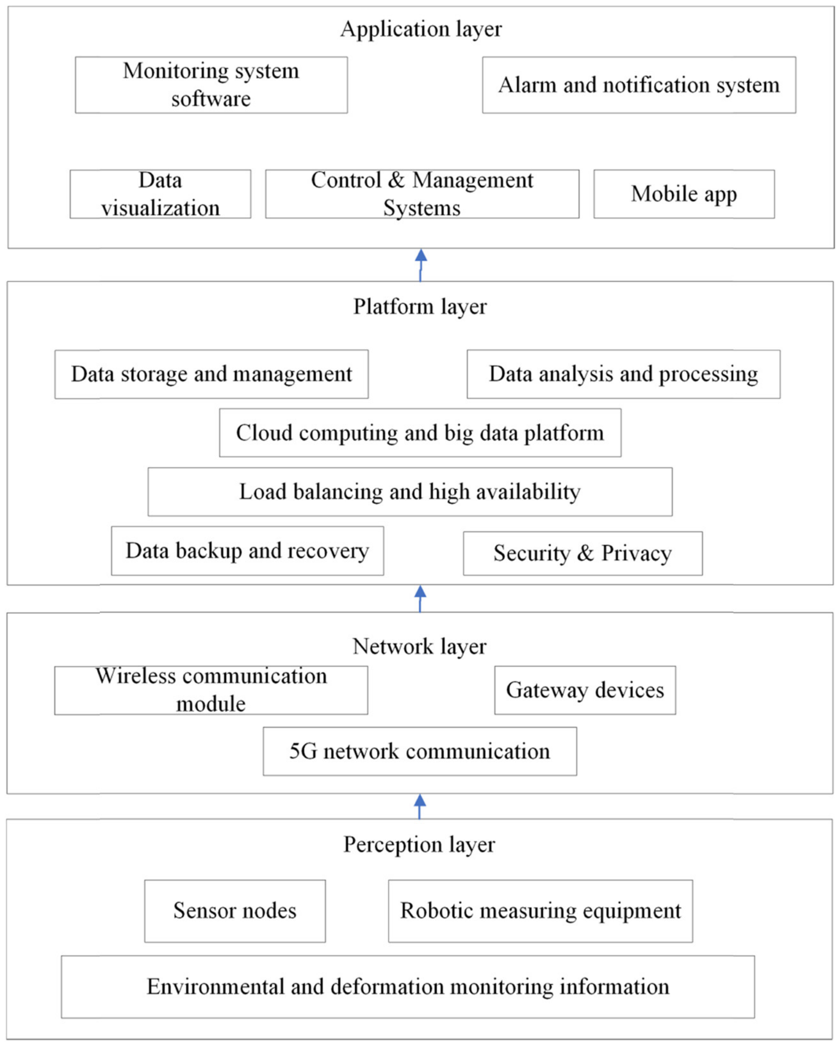

Figure 2: System framework diagram. Source: Created by the author.

Real-time deployment of the system is carried out through Figure 2, where sensor nodes are installed and network connections and preliminary debugging are carried out in key areas. Then, all components are integrated into a complete system. The deformation monitoring system for underground engineering robots based on the IoT architecture can achieve efficient and accurate monitoring and management, ensuring the safety and stability of underground engineering.

4.2 Software design

4.2.1 Perception layer software design

First, the software of the sensor node can be designed, which includes three modules: the sensor data acquisition module, responsible for real-time collection of structural deformation data; the data preprocessing module is responsible for preliminary processing and filtering of raw data to reduce noise and erroneous data; the data transmission module also sends data to the gateway through wireless communication calculation.

Afterward, the software for the robot's measurement equipment can be designed. The robot's measurement equipment software consists of three parts. First, the autonomous navigation module utilizes the SLAM algorithm to achieve autonomous localization and navigation [26]. This ensures that robots can perform high-precision work in complex underground environments. Second, there is a multi-sensor fusion module, which cannot effectively determine the underground environment through a single sensor. Through multi-sensor fusion, measurement accuracy can be improved. Finally, there is the data acquisition and transmission module, which collects and sends measurement data to the gateway.

4.2.2 Network layer software design

The network layer software is mainly designed for the software of gateway devices. The software of gateway devices mainly consists of two modules, namely, the data transmission module, which is responsible for transmitting processed data to the cloud platform through a 5G network. There is also a protocol conversion module used to handle data conversion of different communication protocols, ensuring compatibility of data transmission.

4.2.3 Platform layer software design

The platform layer software mainly implements three types of services: data visualization service, data analysis service, and control service. First, the data visualization service includes a front-end display module and a report generation module. The front-end display module provides real-time display and historical inquiry of data through mobile applications, and the report generation module can regularly generate monitoring reports and exception reports. The data analysis service consists of two modules, namely, the anomaly detection module and the trend analysis module. The anomaly detection module monitors data anomalies in real-time and potential risks of structural deformation. The trend analysis module predicts the development trend of structural deformation by analyzing historical data. Finally, there is the control service, and the main implementation modules of the control service are the device management module and the automation control module. These two modules are responsible for real-time monitoring of data anomalies, remote control and management of sensor nodes and robot devices, and automatic adjustment of device parameters and operations based on analysis results.

4.2.4 Application layer software design

Application layer software design includes mobile applications and alarm systems. Mobile applications have real-time monitoring modules that allow users to view monitoring data and alarm information in real-time on mobile devices while achieving remote control and management of devices through remote control modules. The alarm system includes a real-time alarm module. When the monitoring data exceed the set threshold, an alarm notification is sent, and alarm information is sent through multi-channel notification modules, such as SMS, email, and App notifications.

The user interface diagram is shown in Figure 3.

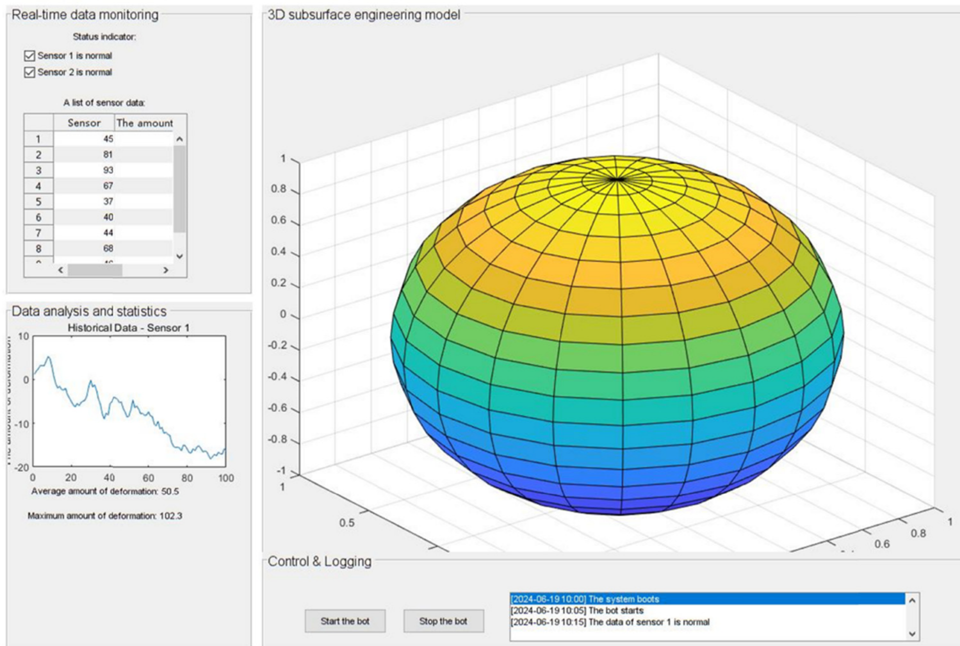

Figure 3: System interface diagram. Source: Created by the author.

5 Comparative experiments and analysis

5.1 Effectiveness of the monitoring system

By using an IoT-based underground engineering robot measurement and deformation monitoring system, real-time monitoring of a deformed underground structure can be achieved, as shown in Figure 4.

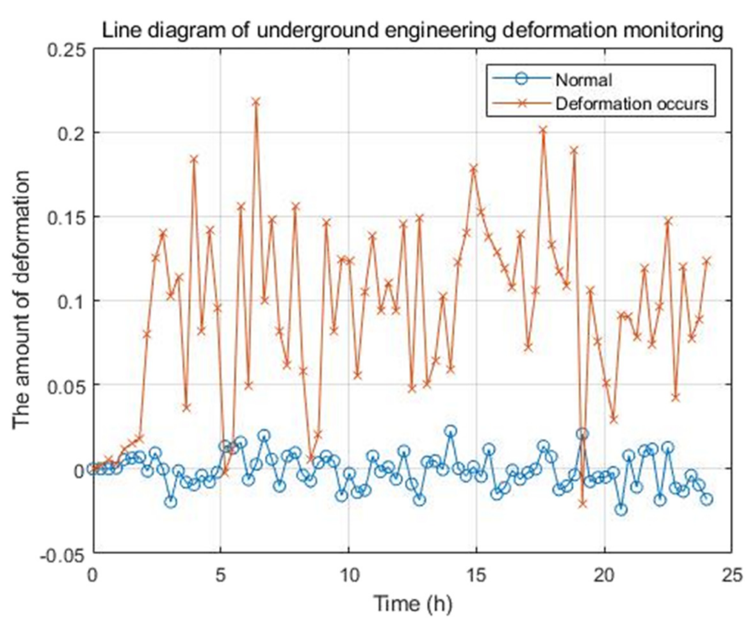

Figure 4: Deformation monitoring effect diagram. Source: Created by the author.

Figure 4 shows the data change in underground engineering during deformation monitoring, including fluctuations under normal conditions and abnormal changes when deformation occurs. The horizontal axis is 24 h, the monitoring interval is 1 h, and the vertical axis is the data monitored every hour. From Figure 4, it can be seen that the deformation monitoring system for underground engineering robots based on the IoT architecture has significant advantages in monitoring effectiveness. First, the real-time data collection and transmission ensure the timeliness and accuracy of monitoring data. The robot and sensor nodes are arranged in the underground engineering environment, which can accurately monitor the deformation of the structure, and quickly transmit the data to the edge computing node and cloud platform through wireless communication technology. The system can accurately monitor the deformation in real time.

5.2 Comparative experimental design and data collection

In this experiment, various high-precision sensors such as LiDAR, strain gauges, accelerometers, and inclinometers were used. The data acquisition module completed real-time collection and preliminary processing of sensor data to reduce noise and errors. The autonomous navigation module of robot measurement equipment combined with the SLAM algorithm has achieved high-precision operation in complex underground environments. The multi-sensor fusion module further improves the accuracy of data and ensures monitoring effectiveness in complex environments. All data are quickly transmitted to the cloud platform through wireless communication modules for centralized processing and analysis. Finally, the monitoring results are displayed through visualization tools for real-time monitoring and remote operation.

The test conditions of the experimental part of this study are designed to simulate the real underground engineering environment to ensure the representativeness of the data and the scientific nature of the results. The tests were conducted in a variety of subterranean engineering scenarios, encompassing intricate geological settings like mines, tunnels, and underground pipe galleries. Soft rock, hard rock, and mixed geology were among the geological conditions that were covered in the tests. In order to assess the system's performance in various real-world scenarios, environmental factors including temperature, humidity, and vibration intensity were also established at the same time. Ten important monitoring stations were chosen for each of the 15 subterranean engineering projects that provided the data for this investigation. Stress, strain, temperature, humidity, and horizontal and vertical movement were among the monitoring indicators. For 30 days, the frequency of data collection was once per minute in order to guarantee a large enough sample size and accurate results. In order to confirm the system's accuracy and adaptability, the statistical analysis employed the multivariate regression analysis approach to assess the stability and accuracy of the monitoring as well as investigate the relationship between monitoring data and environmental variables and geological conditions.

Analyze the improvement of underground engineering robot deformation monitoring systems based on IoT architecture and traditional monitoring systems through two sets of comparative experiments. The first group of experiments compared the accuracy and precision of two systems in collecting deformation data from underground engineering. The second group of experiments measured the performance of deformation monitoring systems using multiple IoT-based underground engineering robots and compared the differences in deformation detection time between the two methods.

5.3 Precision comparison experiment

The collected deformation data of underground engineering is shown in Table 1.

From Table 1, it can be seen that the deformation monitoring system for underground engineering robots based on the IoT architecture has significant advantages in data accuracy compared to traditional methods. The system can provide more accurate and stable data in multiple aspects, thereby improving the safety and reliability of underground engineering. The data accuracy of the underground engineering mechanical

Table 1: Collection of deformation data

Data type	Monitoring system data based on IoT architecture	Data collected by traditional methods
Horizontal displacement (mm)	0.01 ± 0.01	0.05 ± 0.1
Vertical displacement (mm)	0.01 ± 0.01	0.05 ± 0.1
Stress (MPa)	10.00 ± 0.01	10.00 ± 0.5
Strain (%)	0.02 ± 0.01	0.08 ± 0.05
Inclination (degrees)	0.01 ± 0.01	0.05 ± 0.01
Crack width (mm)	0.1 ± 0.01	0.4 ± 0.1
Crack depth (mm)	1.0 ± 0.1	4.0 ± 0.5
Vibration frequency (Hz)	1.0 ± 0.01	2.0 ± 0.5
Amplitude of vibration (g)	0.01 ± 0.01	0.1 ± 0.05
Temperature (°C)	20.0 ± 0.5	21.0 ± 1.0
Humidity (%)	45.0 ± 0.5	50.0 ± 1.0
Water level (m)	3.0 ± 0.1	3.5 ± 0.2
Pore water pressure (MPa)	0.1 ± 0.01	0.3 ± 0.05
Geotechnical pressure (MPa)	5.0 ± 0.1	6.0 ± 0.5
Sedimentation (mm)	0.1 ± 0.01	0.3 ± 0.05
Oxygen concentration (%)	20.8 ± 0.1	21.5 ± 0.2
Carbon dioxide concentration (%)	0.05 ± 0.01	0.1 ± 0.1

deformation monitoring system based on the IoT architecture is generally superior to traditional methods in terms of measured horizontal and vertical displacement data, stress and strain data, inclination data, crack width, and depth data, vibration, temperature and humidity data, water level and pressure data, and surface settlement and gas concentration data. Smaller errors mean that detecting even smaller deformations can help identify and solve potential problems promptly, ensuring the stability and safety of underground engineering.

Statistical analysis was conducted on the collected data, and the results are shown in Table 2.

Table 2: Statistical analysis table

Analysis type	Variable	*p*-value	*R*-squared	*F*-value
Multiple regression	Horizontal displacement	0.002	0.85	5.76
	Vertical displacement	0.003	0.82	4.89
	Stress	0.001	0.87	6.32

Table 2 summarizes the key results of statistical analysis, indicating that the monitoring system has strong predictive accuracy and significant differences exist between different geological types. The *p*-value indicates that the observed relationship is statistically significant, enhancing the reliability of the system under different conditions.

One of the most crucial data is the comparison of monitoring results between horizontal and vertical displacement data, as shown in Figure 5.

From Figure 5 and combined with Table 1, it can be seen that the deformation monitoring system for underground engineering robots based on the IoT architecture can control the measurement error within 0.01 mm in terms of horizontal and vertical displacement, while the traditional method has a larger error, which is 10 times that of the monitoring system in this article. This means that the monitoring system can detect even smaller deformations.

One of the most critical data is the comparison of stress [27] data monitoring, as shown in Figure 6.

From Figure 6 and combined with Table 1, it can be seen that in the monitoring of stress data, the error of the manual method is 0.5, which is 50 times that of the monitoring system (0.01) in this article. This indicates

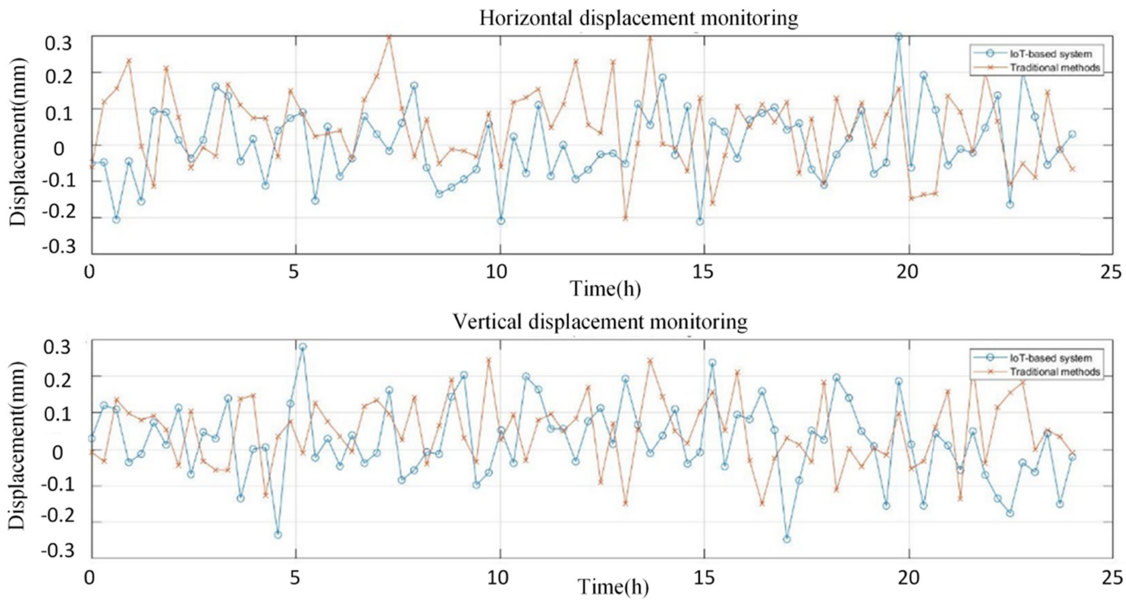

Figure 5: Comparison of monitoring situation between horizontal and vertical displacement data. Source: Created by the author.

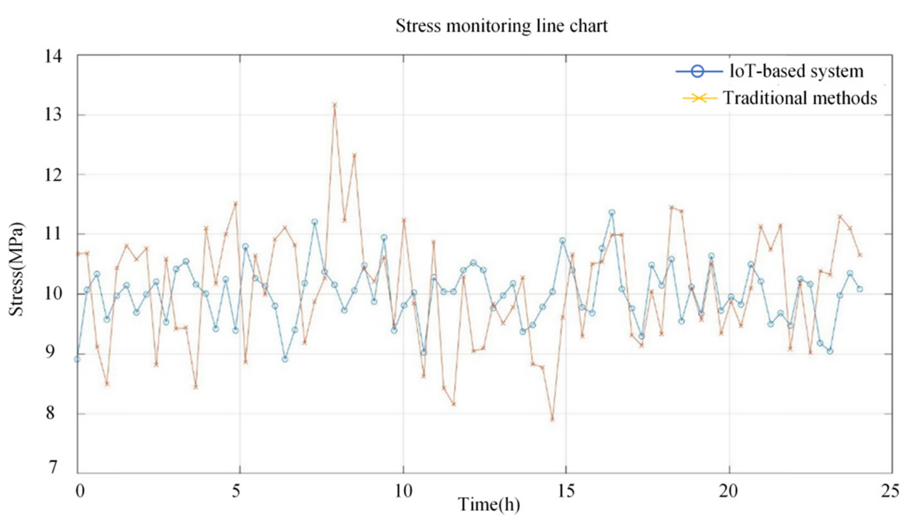

Figure 6: Comparison of stress data monitoring situation. Source: Created by the author.

that using an IoT-based underground engineering robot measurement deformation monitoring system can avoid misjudgment caused by measurement errors, effectively preventing structural instability [28] or damage.

5.4 Time comparison experiment

It is also very important to detect the deformation of underground engineering promptly. This article monitors five underground structures with different deformation conditions and compares the time spent on deformation detection between the IoT-based underground engineering robot measurement deformation monitoring system and traditional methods. The comparison is shown in Figure 7.

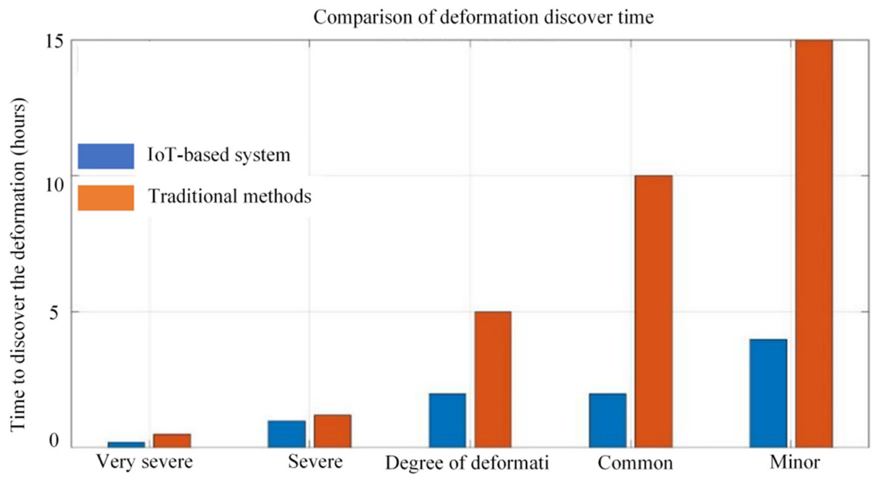

Figure 7: Comparison of time consumption for detecting deformation using two methods. Source: Created by the author.

It can be seen that the consumption time of both methods for detecting deformation situations is relatively short and not significantly different in both very severe and severe deformation situations. However, as the deformation situation becomes milder, the consumption time of traditional methods becomes longer. In the discovery of small deformations, the deformation monitoring system for underground engineering robots based on the IoT architecture only took 4 h to detect the deformation, while the traditional method took 15 h. The system based on the IoT is 11 h faster than the conventional method, indicating that the deformation monitoring system of underground engineering robots based on the IoT is more efficient. In all experimental situations, the system based on the IoT architecture achieved faster deformation detection times than traditional methods. IoT systems respond faster, achieving rapid detection and reporting of deformation. In general, the IoT system detects deformation quickly, takes timely prevention and repair measures, and improves the safety and efficiency of underground engineering.

6 Discussion

Based on the experimental results, the underground engineering robot deformation monitoring system designed in this study has demonstrated high accuracy and efficiency in practical applications. By comparing with traditional monitoring methods, the system controls the error within 0.01 mm in the measurement of horizontal and vertical displacement, which is significantly better than the traditional method's 0.1 mm. This result is consistent with the research proposed by Xu Wang et al. on improving the accuracy of tunnel deformation monitoring through fiber optic sensing technology, but this study further reduces the error range to one-fifth of it, indicating the practical application potential of multi-sensor fusion and high-precision data processing technology in complex underground environments.

The system has improved the accuracy of stress monitoring by 50 times compared to traditional methods, which supports Jian et al.'s conclusion that 3D laser scanning can improve accuracy in structural health monitoring. This system combines machine learning algorithms with big data analysis to achieve real-time prediction and anomaly detection of stress data, further enhancing the proactivity and foresight of monitoring.

The experimental results show that the system can maintain high accuracy and stability under both soft and hard geological conditions. Compared with the three-layer architecture IoT monitoring system proposed by Wu Zhanguang et al., it exhibits better reliability in complex geological environments, verifying the effectiveness of multi-level data processing and dual-mode communication technology. The system has high practicality in complex environments such as underground tunnels and mines and can achieve real-time data transmission and analysis in areas that are difficult to reach with traditional methods, demonstrating its potential for application in long-term underground engineering, geological hazard warning, and underground structural health management. Minority data fluctuations are related to sensor sensitivity and environmental interference. Future research can further optimize sensors and data transmission protocols to enhance the reliability of the system under extreme conditions.

7 Conclusion

Aiming at the problems of inaccurate data, long survey time, and high cost in traditional deformation monitoring, an underground engineering robot deformation monitoring system based on IoT architecture is studied in this work. The system adopts a multi-layer architecture design, including a perception layer, network layer, platform layer, and application layer. Through testing and comparison experiments, it is proved that the system has superior performance in the high-precision real-time measurement of deformation data in underground engineering. Compared with traditional manual measurement methods, the deformation monitoring system of underground engineering robots based on the IoT architecture improves detection efficiency and achieves the effect of reliable data transmission in complex environments. On the whole, this method provides a new way for the safety monitoring of underground engineering and also reduces the input of human resources and the overall operating cost. Although the system proposed in this article has demonstrated superior performance in experiments, there are still certain limitations. Some of the measurement errors in the experiment were caused by insufficient sensitivity of the sensors or interference from environmental factors, which had a certain impact on the overall performance of the system. In extreme environments, the stability and real-time performance of data transmission also face challenges. To further enhance the reliability of the system, efforts will be made in the future to improve the accuracy and durability of sensors and optimize data transmission protocols to adapt to complex and changing underground environments.

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Author contribution: Di Yao designed the experiment, collected and analyzed data, drew curves, and wrote the first draft of the study.

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Data availability statement: Data sharing is not applicable to this article as no datasets were generated or analyzed during the current study.

References

[1] Kamalipour H, Peimani N. On the ethics of researching informal urbanism. Int Dev Plan Rev. 2024;46(3):243–55. doi: 10.3828/idpr.2023.13.
[2] Yu J, Tang J, Li M. Impact of urban construction on pedestrian level wind environment in complex building group. Indoor Built Environ. 2024;33(5):876–94. doi: 10.1177/1420326X231225617.
[3] Gao YH, Shen JH, Chen L, Li X, Jin S, Ma Z, et al. Influence of underground space development mode on the groundwater flow field in Xiong'an new area. J Groundw Sci Eng. 2023;11(1):68–80. doi: 10.26599/JGSE.2023.9280007.
[4] Peng Z, Zhang Y, Tan F, Lv J, Li L. Variable-weight suitability evaluation of underground space development considering socioeconomic factors. Sustainability. 2023;15(4):3574. doi: 10.3390/su15043574.

[5] Wang X, Li Y, Zhang S, Chen J, Liu H, Zhao M. A review of underground engineering investigation and surrounding rock stability analysis and evaluation. Yellow River. 2023;45(3):131–6. doi: 10.3969/j.issn.1000-1379.2023.03.024.

[6] Wu J, Zhuo L, Pei J, Li Y, Xie H, Wu J, et al. Modularized and parametric modeling technology for finite element simulations of underground engineering under complicated geological conditions. State Key Lab Hydraulics Mt River Eng. 2024;140(1):621–45. doi: 10.32604/cmes.2024.046398.

[7] Xiong J. Research on deformation monitoring of tunnel engineering based on 3D laser scanning. Appl Math Nonlinear Sci. 2022;8(2):513–28. doi: 10.2478/amns.2021.2.00204.

[8] Liu D, Zhang D, Fang Q, Sun Z, Luo J, Li A. Field monitoring of the deformation and internal forces of the surrounding rock and support structures in the construction of a super-span high-speed railway tunnel – A case study. Appl Sci. 2020;10(15):5182. doi: 10.3390/app10155182.

[9] Cevdet B, Fei PW. More than two decades of research on IoT in agriculture: a systematic literature review. Internet Res. 2024;34(3):994–1016. doi: 10.1108/INTR-07-2022-0559.

[10] Kumawat B, Korah R. Performance analysis of Internet of things-enabled WSN for agriculture. Int J Syst Syst Eng. 2024;14(1):62–82. doi: 10.1504/IJSSE.2024.135912.

[11] Kim H, Choi Y. Self-driving algorithm and location estimation method for small environmental monitoring robot in underground mines. Comput Model Eng Sci. 2021;127(3):943–64. doi: 10.32604/cmes.2021.015300.

[12] Chengxuan TA, Peng ZH, Jiming WA, Chengjun FE, Bangshen QI, Huiqing WA, et al. Application of in-situ geostress measurement and real-time monitoring in deep underground engineering in areas with strong tectonic activity. Chin J Geomech. 2023;29(6):757–69. doi: 10.12090/j.issn.1006-6616.2023122.

[13] Wang X, Wang M, Jiang R, Xu J, Li B, Wang X, et al. Structural deformation monitoring during tunnel construction: A review. J Civ Struct Health Monit. 2024;14(3):591–613. doi: 10.1007/s13349-023-00741-1.

[14] Dai J, Yin K, Chen Z, Hu W, Yang M, Fu J, et al. Improved performance of a fiber-optic hydrogen sensor based on a controllable optical heating technology. Opt Lett. 2024;49(11):2962–5. doi: 10.1364/OL.522375.

[15] Liao S, Wang L, Hu C, Chen C, Zeng X, Wen J, et al. Architecture design and engineering implementation of underground infrastructure monitoring equipment. Piezoelectricity Acousto-Opt. 2022;44(1):161–5. doi: 10.11977/j.issn.1004-2474.2022.01.030.

[16] Wu Z, Zhang X, Zhang R, Yang L. A remote deformation monitoring system for underground engineering surveying robots based on the three-layer architecture of the Internet of Things. Surv Mapp Eng. 2017;26(2):42. doi: 10.19349/j.cnki.issn1006-7949.2017.02.010.

[17] Dong M, Wu H, Hu H, Azzam R, Zhang L, Zheng Z, et al. Deformation prediction of unstable slopes based on real-time monitoring and deeper model. Sensors. 2020;21(1):14. doi: 10.3390/s21010014.

[18] Dou J, Xiang Z, Xu Q, Zheng P, Wang X, Su A, et al. Application and development trend of machine learning in intelligent landslide disaster prevention and mitigation. Earth Sci. 2023;48(5):1657–74. doi: 10.3799/dqkx.2022.419.

[19] Xiaoen L, Liang Z, Fenzhen S, Wenzhou W. Research progress on the application of InSAR technology in landslide disasters. J Remote Sens. 2021;25(2):614–29. doi: 10.11834/jrs.20209297.

[20] Deng Z, Xie K, Li T, Su Q, Xiao X, Wang Y, et al. Study on spatiotemporal probability assessment method and application of slope instability based on ML prediction uncertainty. China Civ Eng J. 2024;57(9):109–22. doi: 10.15951/j.tmgcxb.23060451.

[21] Shi S. Research on deformation monitoring system of large-scale bridges based on Internet of Things sensors. Geol Surv Mapp. 2024;40(1):41–4. doi: 10.16864/j.cnki.dkch.2024.0011.

[22] Lin K, Hao T. Experimental link quality analysis for LoRa-based wireless underground sensor networks. IEEE Internet Things J. 2020;8(8):6565–77. doi: 10.1109/JIOT.2020.3044647.

[23] Lazaroiu G, Andronie M, Iatagan M, Geamanu M, Stefanescu R, Dijmarescu I, et al. Deep learning-assisted smart process planning, robotic wireless sensor networks, and geospatial big data management algorithms in the internet of manufacturing things. ISPRS Int J Geo-Inf. 2022;11(5):277. doi: 10.3390/ijgi11050277.

[24] Zhang Y, Zhang B, Shen C, Liu H, Huang J, Tian K, et al. Review of the field environmental sensing methods based on multi-sensor information fusion technology. Int J Agric Biol Eng. 2024;17(2):1–13. doi: 10.25165/j.ijabe.20241702.8596.

[25] Xu A, Quan X, Wang B, Shen Y, Tan L, Xie Z. Inverse analysis of initial stress field of soft and hard rock tunnels with high geostress. Railw Stand Des. 2022;66(8):137–42. doi: 10.13238/j.issn.1004-2954.202104200002.

[26] Yao J, Li Y. SiLK-SLAM: accurate, robust and versatile visual SLAM with simple learned keypoints. Ind Robot: Int J Robot Res Appl. 2024;51(3):400–12. doi: 10.1108/IR-11-2023-0309.

[27] Lei H, Cheng Z, Feng S, Lou J, Zhong H. Investigation on the macro- and microdeformation characteristics of silty clay under different shield construction stress paths. Bull Eng Geol Environ. 2021;80(12):9105–25. doi: 10.1007/s10064-021-02475-0.

[28] Jiang S. The causes of instability and stability design points of steel structure buildings. Doors Windows. 2019;13(3):78–9.