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Research on an Adaptive Intelligent Compensation System of Anchor Cable Based on AI and Multimodal Perception

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Abstract: In order to ensure the anchoring effect of anchor cable in foundation pit and slope projects, and ensure the stability and safety of the project, this paper studies the design and implementation of an adaptive intelligent compensation system of anchor cable based on multimodal perception, relying on artificial intelligence (AI). This paper first discusses the design of multi-modal perception fusion monitoring, AI intelligent decision-making, loss prediction, IOT remote monitoring platform, adaptive closed-loop control, and so on. This paper analyzes the hardware system, AI model algorithm, IOT cloud platform, and app, system integration, and closed-loop control. The authors hope that this paper can provide a scientific reference for the subsequent application and optimization of the system.

Keywords: AI; Multimodal perception; Anchor cable; Adaptive compensation system

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1. Introduction

An anchor cable is an important component in maintaining the stability of the geotechnical engineering foundation pit and slope. However, it is prone to prestress loss under long-term continuous stress. If the traditional manual mode is used for monitoring and compensation, there will be obvious drawbacks in accuracy and efficiency, and the cost is higher, and the risk is greater [1]. In order to solve these problems, this study is mainly based on AI technology to design an adaptive intelligent compensation system for the anchor cable with multimodal fusion perception. The system can collect multi-dimensional data in real time and conduct intelligent analysis in real time. Thus, it can predict the anchor cable prestress loss value, and automatic tensioning compensation can be controlled in an integrated way, providing a guarantee for the safety of geotechnical engineering construction.

2. Overall architecture of the anchor cable adaptive intelligent compensation system

The self-adaptive intelligent compensation system of anchor cable in this study is mainly based on the requirements of prestress control in the whole life cycle of anchor cable. It uses AI technology and multimodal sensing equipment to design a four-layer closed-loop intelligent architecture, so that the whole process from data sensing to prestress compensation can be automated. The overall composition and basic information are shown in **Table 1**.

Table 1. Overall architecture and basic information of the anchor cable adaptive intelligent compensation system

No.	Layer	Major component	Basic function
1	Perception layer	High-precision seepage, displacement, and stress sensors	Collect the data of groundwater seepage state, structural deformation trend, and anchor cable stress change at the same time to provide multi-source data support for subsequent intelligent analysis
2	Transport layer	Signal conditioning module, ADC conversion module, 4G wireless communication module	Transmits real-time monitoring data to the IoT remote monitoring platform under complex working conditions to achieve stability, low latency, and anti-interference performance
3	Decision-making layer	32-bit high-performance microcontroller, AI intelligent analysis, and loss prediction model	Implement fusion processing on the obtained multi-source data to evaluate the safety status, determine the compensation threshold, calculate the tensioning parameters, and issue the adaptive compensation command
4	Executive layer	Micro hydraulic pump station, intelligent jack, automatic locking device	Receive and execute the adaptive compensation command, accurately complete the prestressed compensation operation, and adaptively lock the anchor cable to ensure the compensation accuracy and controllability

3. Key points of the anchor cable adaptive intelligent compensation system

3.1. Design of multimodal perception fusion monitoring

The multimodal sensing of the system is mainly achieved by using high-precision seepage, displacement, and stress sensors. The seepage sensor is mainly used to monitor groundwater flow and pressure. It reflects the effect of water erosion on the anchoring performance of bolts. The displacement sensor mainly uses laser ranging. It monitors the relative displacement between the rock and soil mass and the anchor cable structure. The stress sensor uses the resistance strain method. It collects real-time changes in the axial stress of the anchor. Its measurement range covers all prestress levels [2]. The multimodal data fusion algorithm is mainly the weighted fusion method. This algorithm normalizes the data and makes a combined judgment. It removes the effects of single-point failure and environmental noise [3]. The authors set the weight of stress data as ω_1, the weight of displacement data as ω_2, and the weight of seepage data as ω_3. The authors make the sum of these three weights equal to 1. The authors use the formula below to combine the weights and calculate the combined safety index.

$$S = \omega_1 S_\sigma + \omega_2 S_\delta + \omega_3 S_q \tag{1}$$

S_σ represents prestress safety factor; S_δ represents the displacement safety factor; S_q represents the seepage safety factor. The authors use the threshold crossing method to check the data and judge its validity. If a single data is abnormal, the authors can correct it with the other two types of data. The following is the calculation formula for data efficiency.

$$\eta\frac{N_{volid}}{N_{total}}\times 100\% \tag{2}$$

N_{volid} is the number of valid data points; N_{total} represents the total number of sampling points. After design optimization, the monitoring data efficiency of the system can reach more than 98%.

3.2. Design of AI intelligent decision making and loss prediction

The authors use long short-term memory networks to build the following prestress loss prediction model for the anchor cable. The authors input the historical parameters of stress, displacement, and seepage into this model. Then the authors can scientifically predict the prestress loss value for future time periods.

$$\overset{\wedge}{\sigma}(t)=f[\sigma(t-1),\delta(t-1),q(t-1),...,\sigma(t-n),\delta(t-n),q(t-n)] \tag{3}$$

Wherein: $\overset{\wedge}{\sigma}(t)$represents the predicted prestress loss value.$\sigma(t$-1)represents the stress value at time t-1. $\delta(t$-1)represents the displacement value at time$t$-1. $q(t$-1)represents the seepage value at time t-1. $\sigma(t$-$n)$ represents the stress value at time t-n. $\delta(t$-$n)$represents the displacement value at time t-n. $q(t$-$n)$ represents the seepage value at time t-n. The authors use a large amount of field-measured data to iteratively train this model. The authors make the model learn how factors such as rock and soil creep, environmental erosion, and load changes affect the prestress loss value of bolts. Then it can achieve early warning [4].

After that, the authors use the gap between the real-time monitoring value and the designed prestress value of bolts as a basis. The authors also consider the actual conditions, such as the elastic modulus of the rock and soil mass and the anchorage length of the anchor cable. Then, the authors design the following model to calculate the optimal compensation amount.

$$\Delta\sigma=\sigma_{set}-\sigma_{real}+\Delta\sigma_{loss} \tag{4}$$

$\Delta\sigma$ is the optimal compensation value of anchor cable prestress; σ_{set} represents the design value of anchor cable prestress; σ_{real} is the measured value of anchor cable prestress; $\Delta\sigma_{loss}$ represents the prestress loss predicted by the model. In the specific application, the system can also scientifically set the threshold of prestress compensation error according to the specific elastic modulus of rock and soil mass and the anchorage length of the anchor cable. This can avoid undercompensation or overcompensation.

3.3. Design of the IoT remote monitoring platform

The IoT remote monitoring platform is a key carrier for the digital management of the whole life cycle of the anchor cable. It relies on advanced technologies such as IoT, cloud computing, and mobile internet. It builds an integrated cloud-based management and control system based on the dimensions of equipment, data, management, and application. This system breaks through the traditional manual on-site inspection mode. The platform mainly uses a microservice architecture. It has high concurrent access capacity, high storage reliability, and high transmission security. It can also flexibly expand. It can provide technical support for real-time online management of multiple anchor cables in multiple projects at the same time. In this way, it meets the requirements of clustered anchor cables management and control in large geotechnical engineering projects [5]. The platform has four main functional layers: access layer, data storage layer, application service layer, and terminal display layer. **Table 2** shows the basic design.

Table 2. Basic design of the functional level of the IoT remote monitoring platform

No.	Layer	Major component	Basic function
1	Access layer	TCP/IP, MQTT, 4G, and other communication protocols	Adapt the data transmission format of various hardware devices, standardize the analysis and storage of multimodal perception data
2	Data storage layer	Time series databases, relational databases	Efficiently store and quickly retrieve on-site monitoring data, and save structured information such as equipment parameters, alarm logs and operation and maintenance records to ensure long-term traceability of data
3	Application service layer	Real-time calculation, intelligent analysis, alarm rule engine, and report generation module, etc.	Realize custom settings of alarm, security classification rules, and compensation strategies, automatically identify data exceptions, level alarm, and fast push
4	Terminal display layer	PC terminal and mobile app	Display the on-site monitoring data to users in real time, push the alarm information in time, and provide support for users' remote operation, online query, and historical record traceability

3.4. Design of adaptive closed-loop control

In this system design, the adaptive closed-loop control is a key operating mechanism to realize automated, intelligent, and precise compensation measures. It uses real-time perception, intelligent decision-making, precise execution, and effect verification as its basic logic. It builds an autonomous operation system for itself. This completely solves the problems of traditional anchor cable compensation, such as lag and low accuracy [6]. The system uses multi-modal fusion perception data as input indicators, an AI decision model as the core instruction generation model, each control unit as an actuator, and the compensated monitoring data as feedback. Thus, it forms a self-correcting and continuously controllable closed-loop operation link. The authors use the AI decision model to continuously collect all key data input into the system. The authors calculate the comprehensive safety index in real time. The authors then compare the calculation result with the preset threshold in real time. When the authors find that the compensation condition is met, the decision-making layer of the system automatically calculates the key parameters, such as compensation amount, tensioning speed, and load holding time. Then it sends the calculation result to the execution layer as a control instruction. After the execution layer receives the instruction, it immediately performs the supplementary tensioning process according to the instruction. After tensioning reaches the required position, it automatically locks firmly. After completing the compensation, the system enters a delay verification step. It collects and compares data again. Only after confirming that the error meets the requirement does it confirm completion [7]. If the error does not meet the requirement, the system starts a small-range secondary fine-tuning mode. This ensures the compensation accuracy of the bolt's applied stress.

4. Implementation analysis of a self-adaptive intelligent compensation system for the anchor cable

4.1. Implementation of the hardware system

The hardware design of this system focuses on high precision, good stability, strong anti-interference ability, and low power consumption. The system uses waterproof and dustproof high-precision sensor devices as sensing elements. Their protection level reaches IP67. They can maintain normal operation in humid, high-temperature, and vibrating environments. The system uses a high-precision 24-bit ADC acquisition module to convert data with high precision. The system also uses a 32-bit ARM architecture microcontroller to process multi-sensor data in parallel. The system integrates 4G wireless communication and multiple transmission protocols to enable stable data transmission without on-site wiring. The system uses a smart jack and a micro-integrated hydraulic power pack, which are specially developed for this system. They make the output pressure precisely adjustable. The matching automatic locking device can respond quickly. It ensures the reliability of anchoring and locking. It enables the whole supplementary tensioning process to be realized automatically [8].

4.2. Implementation of the AI model and algorithm

The system uses its database and its supporting functions to collect data in real time under various working conditions, such as engineering sites and laboratories. These data include seepage, displacement, stress, and anchor cable loss values. At the same time, the system builds labeled datasets for different data types. Based on these datasets, it performs data cleaning, data planning, and data enhancement. These operations meet the preprocessing requirements of the system for monitoring data. Using the TensorFlow framework, the system trains a prediction model based on long short-term memory networks for the prestress loss value of the anchor cable. Through training, the system can reasonably optimize the network structure and hyperparameters. This further improves the system's prediction accuracy. The system deploys the trained intelligent prediction model to the edge controller in a lightweight manner. This deployment provides strong AI technical support for real-time analysis of local data. In this way, the system further reduces its dependence on the cloud platform. It also significantly reduces the amount of data processing on the cloud platform. This ensures the operating efficiency of the overall system [9].

4.3. Implementation of the IoT cloud platform and app

The system uses Alibaba Cloud servers to build an IoT platform. This platform supports real-time data reception, storage, computation, and distribution. It also enables concurrent access from multiple devices and multiple projects, and the scalability is also very good. The system fully meets the human-computer interaction requirements of the system. It uses PC-side modules such as data visualization, dashboard permission management, form output, and trend analysis. It also uses mobile app functions such as historical query, remote control, real-time monitoring, and alarm push. The system uses the MQTT communication protocol. This protocol enables stable data interaction between the platform and terminals, as well as between the platform and devices. Meanwhile, the system implements a complete data encryption scheme. It uses encrypted transmission for key data. This provides good protection for information security. The platform can also automatically generate corresponding operation and maintenance reports. This meets the need for digital archiving of operation and maintenance data in actual engineering management.

4.4. Implementation of system integration and closed-loop control

The system mainly uses modular hardware, layered software, and standardized communication for integration. During hardware integration, the system connects sensors, acquisition modules, controllers, communication modules, and actuators according to electrical interfaces. This achieves a good connection among the power supply, signal, and control links. For software, during integration, the system adapts protocols such as the AI inference algorithm, edge control program, mobile app, and cloud platform interface. This standardizes data formats, alarm mechanisms, and instruction rules. For communication, the system sets up dual protocol stacks of TCP/IP and MQTT during integration. This provides good support for stable uploading of sensor data and reliable delivery of system control instructions. It enables full data exchange across the end-edge-cloud chain. For closed-loop control, its specific implementation process includes data collection, data fusion, intelligent decision-making, automatic execution, and result feedback. The system uses the perception layer to upload multi-modal data in real time and uses the edge controller to perform fusion calculation and security evaluation. If the prestress loss value reaches the design threshold, the AI model will automatically calculate the compensation parameters and trigger the corresponding execution process. This drives the execution layer to perform supplementary tensioning. The system locks the anchor in time after completing the compensation. After the compensation is completed, the system enters an automatic verification step. It compares the measured stress with the target stress and determines whether the deviation exceeds the allowable range. If the deviation exceeds the allowable range, the system immediately starts a small-range correction scheme. This ensures precise control of the prestress compensation value [10].

5. Conclusion

This paper mainly studies an adaptive intelligent compensation system for anchor cables based on AI and multimodal sensing technology. It builds four basic functional levels for the system: perception, transmission, decision-making, and regulation. Thus, it integrates key technologies such as multi-modal data fusion, AI intelligent prediction, adaptive closed-loop control, and IoT remote management. It completely eliminates various pain points in traditional manual monitoring and compensation modes. In the future, researchers can reasonably introduce advanced digital twin technology. They can use it to carry out a visual three-dimensional simulation. This will further optimize the adaptability of the AI model. In this way, they can provide more knowledge for the technological innovation and optimization of the results of the adaptive intelligent compensation system for the anchor cable. This will promote the intelligent development of geotechnical engineering.

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Disclosure statement

The authors declare no conflict of interest.

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