Design of Tunnel Automatic Monitoring System Based on BIM and IOT

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Abstract. At present, the application of BIM and IoT in construction is more and more common. However, few studies combine BIM with IoT for real-time monitoring of mountain tunnels. This paper have designed a tunnel automatic monitoring system based on BIM and IoT. Various sensing devices are arranged inside the tunnel to collect deformation, groundwater level and other monitoring data. Satellite monitoring data is collected through GNSS outside the tunnel. The above information is dynamically transmitted to the cloud computing platform by using the NTRIP and ZigBee wireless communication technology. At the same time, the data in the construction drawings are imported into the 3D model by BIM technology to informationize the tunnel model and visualize the monitoring data. This can effectively reduce the accident rate and improve the efficiency of tunnel construction management. At the same time, it provided a new idea for the joint application of BIM, IoT and GNSS in tunnel automatic monitoring system.

1. Introduction

With the development of social economy and production, the traditional highway construction mode dominated by mountain winding behavior has gradually been replaced by the way of crossing mountains. Affected by the complex topography and hydrological factors of the mountain, natural accidents such as landslides and water inrush often occur during the construction of mountain projects, which pose a great threat to the personal safety of relevant personnel and the normal operation of the project.

The Internet of Things (IoT) is an intelligent sensing network that exchanges and communicates information according to the agreed protocol through radio frequency identification (RFID), global navigation satellite system (GNSS) and other information sensing devices [1], which can achieve efficient and safe information interaction.

Building Information Modeling (BIM) is the multidimensional numerical information model of the building, which has inherent advantages in precision and information integration [2,3]. It can integrate all dynamic information of the project in the construction and operation process [4], integrate digital information into an intuitive three-dimensional model, so as to realize the visualization of monitoring information.

BIM can be integrated with IoT technology. BIM can be used to integrate information and form a central basic database, and IoT technology can be used to connect the received information with the model data to achieve efficient automatic monitoring and management mode. At present, the research
fields of BIM and IoT technology mainly focus on: (1) Construction site information supervision. (2) Periodic tracking and positioning. (3) Improving inventory management efficiency.

Jiang et al. proposed the integration method of BIM and IoT, which improved the ability of data sharing and multidimensional visualization [5]. Taking the 18R-36L runway of Balahaas in Madrid as an example, Pacios has established an integrated system of BIM, IoT and Distributed Ledger Technologies (DLT) to improve the efficiency in maintenance, repair and supervision [6]. The integration of BIM and IoT in engineering cases emerges in endlessly, which expand the rich comprehensive management mode and value. However, few studies combine BIM with IoT and apply it to real-time monitoring of mountain tunnels.

This paper intends to build a tunnel automation monitoring system based on BIM and IoT technology. Various sensing devices are arranged inside and outside the tunnel to collect deformation, settlement and other monitoring data. The above information is dynamically transmitted to the cloud computing platform by using the Networked Transport of RTCM via Internet Protocol (NTRIP) and ZigBee wireless communication technology. The cloud platform receives the monitoring data and automatically generates the real-time curve of various indicators. Users can remotely view and obtain the trend of various indicators through a variety of devices. At the same time, BIM model is used to establish an accurate multi-angle ground object model, and the collected state information of each region of the tunnel is displayed dynamically and intuitively, so as to realize the monitoring and early warning of risk factors, reduce the incidence of accidents and improve the management efficiency.

2. Technical principle of tunnel automatic monitoring system

2.1. Equipment composition
The monitoring instruments of this system include Leica TS60 fifth generation automatic total station, TH-SCC differential pressure settlement instrument, F9302 strain force sensor, PT124B-2512 tunnel pressure sensor, TH-VBR triaxial vibration instrument, HC-F800 concrete crack defect comprehensive tester, DATA-6218 integrated pressure water level meter, and TH-L40 laser convergence meter, as shown in Figure 1.

![Figure 1. Instrument physical information](image)

The monitoring objects and related parameters of each instrument are as follows:
Table 1. Main monitoring items and corresponding instruments

| Monitoring content                        | Monitoring program                  | Instrument name                                      | Remarks                                      |
|-------------------------------------------|--------------------------------------|------------------------------------------------------|----------------------------------------------|
| Displacement and deformation monitoring   | Surrounding rock lining deformation  | Automatic total station                              | Precision 0.6mm ± 1ppm; Angle measurement 0.5"
|                                           | Vault settlement                     | Differential pressure settler                         | Accuracy ± 1 mm; Resolution 0.01 mm           |
|                                           | Lining crack opening and depth       | Concrete crack defect comprehensive tester           | Measurement range:
|                                           | Deep displacement                    | Laser convergence meter                              | Width 0.01 ~ 10mm; Depth 5 ~ 500 mm          |
| Groundwater level monitoring              | Groundwater level                    | Integrated pressure water level meter                | Resolution 0.1 cm; Range 0-100 m              |
| Strain and stress monitoring              | Concrete strain                      | Strain force sensor                                  | Range 0 ~ 200 με to 0 ~ 2000με               |
|                                           | Soil pressure                        | Tunnel pressure sensor                                | Comprehensive accuracy 0.25FS %               |
| Vibration intensity monitoring            | Blasting vibration intensity         | Triaxial vibration meter                             | Resolution 0.1 %; Accuracy ± 0.5 % FS        |

2.2. Main technologies and principles

2.2.1. Global Navigation Satellite System (GNSS)
It is necessary to set up a reference station with known coordinates and calculate the distance correction from it to the satellite. Monitoring stations with receivers are set where monitoring is needed. Users receive satellite corrections from the reference station while receiving satellite data from the monitoring station, as shown in Figure 2.
This technique can be used to correct the positioning results, so as to eliminate the error caused by tropospheric delay and improve the positioning accuracy. Moreover, the inversion of atmospheric precipitable water vapor (PWV) can also be carried out by using the signal delay caused by the troposphere when the GNSS satellite signal crosses the atmosphere to the receiver. The total tropospheric delay can be divided into Zenith Hydrostatic delay (ZHD) caused by dry air and Zenith Wet delay (ZWD) caused by water vapor. Under the assumption of fluid mechanics equilibrium and ideal gas, ZHD expression can be obtained as follows [7].

\[ ZHD = \left[ 0.002279 \pm 0.0000024 \cdot \frac{p_0}{f(\varphi, H)} \right] \]  (1)

\[ f(\varphi, H) = 1 - 0.00266 \cos 2\varphi - 0.00028H \]  (2)

\[ p_0: \text{Atmospheric pressure at receiver height, } \varphi: \text{Station latitude, } H: \text{Station height.} \]

By solving the above formula, the value of ZHD is obtained and then ZWD can be calculated by subtracting ZHD from ZTD. Finally, PWV can be obtained as follows:

\[ PWV = \Pi \cdot ZWD \]  (3)

Generally, there is a strong correlation between water vapor and rainfall, which has a great influence on the seepage field inside the construction mountain. With the extension of rainfall duration, the stability of the slope will continue to decline, which is easy to cause landslide disasters. According to the principle above, atmospheric precipitable water vapor in a certain range around the tunnel can be inversed to achieve more accurate monitoring and forecasting of precipitation, so as to carry out forecasting precipitation and take timely measures to reduce the hazards caused by landslides.

2.2.2. Networked Transport of RTCM via Internet Protocol (NTRIP)

NTRIP is an application layer protocol for data stream network transmission of global navigation system. It can effectively overcome the shortcomings that traditional radio is vulnerable to terrain, meteorology, geomagnetic and other factors [8]. It consists of Ntrip Client, Ntrip Caster, and Ntrip Server, as shown in Figure 3.
Ntrip can be used to transmit differential data, which ensures the security of system as well as communication process, real-time, accuracy and efficiency of monitoring data. At the same time, Ntrip can realize the data sharing of each monitoring station. Users can use various types of receiving devices to obtain the real-time monitoring data.

2.2.3. ZigBee short-range wireless communication technology
ZigBee is a short-range wireless communication technology with low energy consumption and low cost. The communication delay and activation delay of ZigBee are very short, which meets the requirements of rapid transmission of monitoring data. Compared with other wireless transmission technologies, ZigBee is able to connect up to 254 devices, which is more suitable for automatic control, sensing and monitoring fields. ZigBee protocol is composed of high-level application specification, application convergence layer, network layer, data link layer and physical (PHY) layer, as shown in Figure 4.

The system of ZigBee is very simple and less complex so the demand for system resources is also very low. The low cost of communication makes it suitable for systems with wide monitoring area and more sensor equipment. It reduces the interference to the operation of the whole system and improves the efficiency of preventive maintenance. At the same time, ZigBee provides data integrity checking, authentication functions and three-level security mode to prevent illegal access to data and it also uses advanced encryption standard (AES-128) symmetric password to ensure safe and reliable data transmission.

3. Design of tunnel automatic monitoring system

3.1. System composition
Tunnel automatic monitoring system mainly includes three parts: perception layer, transmission layer and application layer. The perception layer mainly senses all the changes inside the tunnel structure through the deployed instruments, and collects the original data of each monitoring project in real time. The transmission layer mainly uses wireless communication technology to dynamically transmit the monitored data to the cloud computing platform, in which it completes the processing, analysis and calculation of these data. The application layer is mainly responsible for generating the trend curve of
each index and displaying the dynamic information change of BIM model. The principle of the entire monitoring system is shown in Figure 5.

Figure 5. Principle of automatic monitoring system

The basic idea of the design of the monitoring system is as follows: GNSS reference stations and several monitoring stations are arranged in the open area of the excavated mountain to collect satellite observation data at the same time. Using these data to retrieve atmospheric precipitable water can achieve more accurate monitoring and forecasting of precipitation, so as to take measures in advance to reduce the hazards of landslides. Inside the tunnel, the parameters of each monitoring part are observed and collected in real time, and transmitted to the cloud computing platform by ZigBee short-range wireless communication technology. Cloud platform receives data and stores them distributedly to generate real-time curves of each index.

In addition, machine learning technology will be used to train the cloud computing platform so that it can sense whether the parameters are beyond the permissible range. The cloud platform can predict the possible future trend of the indicators according to the real-time data information in a certain period of time. Users can log on to the cloud platform remotely through multiple devices to view the intuitive deformation curves and trends of various indicators. Create a family of components in a tunnel and determine their parameters in Revit. The Dynamo plug-in is used to establish an accurate three-dimensional model according to the determined project parameters, and the state information of each area of the tunnel is dynamically and intuitively displayed. This can realize the monitoring and early warning of risk factors, reduce the incidence of accidents and improve management efficiency.

3.2. System function architecture

This tunnel automatic monitoring system can be divided into (1) Data acquisition. (2) Data processing. (3) Analysis of early warning. (4) Visual modeling, as shown in Figure 6.

Figure 6. Function Architecture of Tunnel Automatic Monitoring System
Accordingly, the main functions of this tunnel automatic monitoring system are as follows: (1) Real-time data collection and timely forecasting. (2) Synchronous output of deformation curve. (3) Safe and reliable data transmission. (4) Multi-device information sharing. (5) Forecast of trends in indicators. (6) Visualizing the dynamic three-dimensional model. (7) The connection between the index information and the model data. (8) Controlling the growth of deformation variables in vulnerable and deformed parts. (9) Equipment remote maintenance.

3.3. Point layout and monitoring section design

3.3.1. Point layout

Point layout mainly includes reference point layout, target point layout and working point layout.

As the core control point in the whole tunnel automatic monitoring system, the reference point is the premise of the entire deformation monitoring work. It is required to have stable and reliable properties, and should be far away from the deformation zone in the layout. At the same time, it should also be considered that the reference point can control more monitoring sections in the tunnel. The reference point can be placed in a place that is long-term stable and not affected by deformation.

The target point is the basis for monitoring and should be deployed in a combination of key and high-risk locations. To reflect the exponential changes in the tunnel structure, it should also ensure that there are no or less obstacles in the monitoring perspective. The target point should also be able to quickly monitor the deformation or displacement of the structure to improve the timeliness of early warning.

The working point is the position where the instrument is erected. More target points should be observed as much as possible in the layout, and the side of the pipeline should be generally avoided. Some instruments are also ought to set up mandatory centering devices to reduce errors of centralization and improve monitoring accuracy. In the subsequent construction process, the monitoring equipment and components should be regularly overhauled.

The monitoring items of this system include tunnel vault settlement, horizontal displacement, lining strain, rock wall pressure, vibration amplitude, crack opening and depth, groundwater level and deep displacement of rock mass. The target points are placed on the vault, bottom and waist of both sides of the tunnel, as shown in Figure 7.

![Figure 7. Schematic diagram of tunnel monitoring section](image)

GPS reference stations and monitoring stations should be laid on the mountain where the tunnel construction is located, as shown in Figure 8.
3.3.2. Design of monitoring section

Monitoring section refers to a section with multiple target points and orthogonal to the tunnel, which should be evenly distributed throughout the tunnel mileage. The section spacing can be determined according to the route planning of the tunnel, the geological environment of the construction site and the stratum properties. The monitoring section can be arranged in important sections such as weathering groove section, fault fracture zone, and the junction of soft and hard rocks passed by the tunnel. The spacing of each monitoring section should be appropriately reduced for long tunnels and extra-long tunnels.

3.4. Information architecture model

BIM technology is a multidimensional digital information model of architecture. By building the three-dimensional model of various components within the building, and attaching to the parameters of information, such as size, material, relative position, it is possible that the created three-dimensional model has visual data information. At present, the main ways to establish three-dimensional models are: three-dimensional laser scanning technology, parametric modeling using BIM software and oblique photogrammetry technology.

Revit is a software widely used in spatial modeling, which completes the establishment of the whole model by combining various components inside the building. Based on the basic components as the combination unit, the components are classified according to different characteristics, forming a Revit family for archiving. This makes the three-dimensional model not only display the overall information of the building, but also obtain the position, material, size and other data of each component. Moreover, when the parameter information of these components changes, the whole three-dimensional model can change in real time with this change to realize the dynamic information update of the model.

The component values of the BIM 3D model should be one-to-one corresponding to the project, so high precision is needed. The Level of Detail (LOD) proposed by the American Institute of Architecture is usually used to specify the accuracy requirements of each stage of project construction. It includes five levels: LOD100, LOD200, LOD300, LOD400 and LOD500.

| Grade   | Use phase                          | Inclusion information                        | Requirement                                      |
|---------|-----------------------------------|---------------------------------------------|-------------------------------------------------|
| LOD100  | Project plan formulation stage    | Area, position, volume, etc.                | Basic shape and outline                         |
| LOD200  | Project preliminary design stage  | Some component parameter information         | General geometric properties                     |
| LOD300  | Construction drawing stage        | Accurate parameter information of components | Reflect the actual shape of each component       |
| LOD400  | Actual construction stage         | Detailed entity                              | It can be constructed according to the model    |
| LOD500  | Completion submission stage       | Information required for completion submission | It can be constructed according to the model    |

Table 2. Model depth level requirements
The tunnel model is established by Revit software to meet the standard of LOD300. First of all, the information of each component in the tunnel should be determined, including the name, size, material, and location of the component. A new family library can be created, broken down step by step according to the different characteristics and categories of components, and these components can be grouped, as shown in Figure 9.

![Hierarchical component system of tunnel](image)

**Figure 9.** Hierarchical component system of tunnel

Usually, the components in a tunnel section include anchor, secondary lining concrete, drainage pipe, cover plate, etc. According to these components, a two-dimensional plane model of a lining structure can be drawn. Then according to the specific construction drawings, it is easy to write node commands and make components achieve automatic connection through the formula in the software's own auxiliary plug-in Dynamo visual coding program. Then the data in the drawings are imported to make each structure layout along the actual line mileage of the tunnel, so as to complete the construction of three-dimensional information model. At the same time, the monitoring points are also added into the entire tunnel family as components, and the early warning field is set in the component information. After a certain parameter exceeds the limit value, the system will make mandatory reminders through operators and send information to relevant construction personnel in time to realize automatic early warning.

4. Conclusion

In view of the limitations of traditional construction management in monitoring scope and early warning speed, this paper expounds the construction method of tunnel automatic monitoring system based on BIM technology, Internet of Things technology and differential global positioning system technology. This system can collect and calculate multiple monitoring indexes such as tunnel vault settlement, horizontal displacement and lining strain in real time. It can informationize the tunnel model, visualize the monitoring data, systematize the equipment management as well as timelyize the emergency treatment measures. At the same time, the system has the functions of predicting the change trend of parameters, multi-platform information sharing, and remote maintenance of equipment. It can also realize the monitoring and early warning of risk factors in the process of tunnel construction, ensure data security and accuracy, reduce the incidence of tunnel accidents, and improve the management efficiency of project construction. It provides a new idea for the mutual application of BIM technology, Internet of Things technology and differential GPS technology in tunnel monitoring system.

With the development of automatic monitoring technology, there are many improvements in this system. (1) Adding the best emergency route. The construction-related personnel may quickly plan the
emergency route after a certain index exceeds the limit value, so as to eliminate the construction risk factors in a timely manner. (2) Reduce mutual interference of signals between monitoring instruments. In the process of noise reduction, it should also optimize the monitoring equipment acquisition terminal and set up some shielding measures. (3) Optimize the data platform. Users can quickly query the parameter information of each component by searching keywords to accelerate the subsequent processing. (4) Explore the intelligent early warning method of tunnel based on deep learning and multi-source data fusion to further improve the safety of tunnel construction.

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