Analysis and Design of Preventive Protection System for Ancient Buildings from the Metaverse Perspective

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Abstract. The article analyses the damage characteristics and causes of traditional Chinese ancient architecture, and identifies corresponding risk monitoring indicators. Introduce a Process Performance Model to establish quantitative relationships between or among multiple monitoring indicators, and propose improvements to existing risk Evaluation methods based on the characteristics of ancient building beam structures. Using Building Information Modelling technology to establish a three-dimensional visual virtual model of ancient buildings, and combining IoT sensing technology to achieve Digital Twins of building entities. On this basis, the article designs a system logic architecture for preventive protection of ancient buildings from the perspective of the metaverse. Through the four Layers of the sensor layer, platform layer, data layer, and interaction layer, it realizes the automatic preventive protection process of ancient building components from monitoring, computing power, storage, modelling, to early warning, and achieves flat and efficient management of early warning on the Digital Twin model.

Keywords: Digital Twin; IoT; Ancient Architecture; Preventive Protection; Risk Evaluation Methods

1 Introduction

Traditional ancient buildings in our country are mainly made of brick and wood structures, and they are prone to damage. However, most of the current protection practices are still limited to salvage repairs after destruction. In this case, the authenticity of buildings has suffered irreversible damage[1]. The 14th Five Year Plan for Cultural Relics Protection and Technological Innovation proposes that China should basically achieve the transformation of national key cultural relics protection units from rescue protection to preventive protection by 2025. Therefore, it is necessary to establish a warning method and information system for ancient buildings. At present, except for a few ancient buildings at the world cultural heritage level, the protection of most ancient buildings in China is in a state of inefficient management. Whether it is the preventive protection file system or the digital ancient building management

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information system, they have not yet achieved efficient and preventive protection functions [2].

2021 is known as the Metaverse Year, and since 2022, many regions across the country have incorporated the Metaverse into government work plans to guide its implementation. The metaverse is based on Digital Twin technology to generate a mirror of the real world, achieving real-time monitoring, prediction, and simulation of physical entities in a virtual environment [3]. Building Information Modelling (BIM) has been able to establish three-dimensional visual building models based on the structural characteristics of traditional Chinese architecture. Combined with IoT technology, it can achieve three-dimensional Digital Twins of ancient buildings and map on-site monitoring data to virtual models [4].

At present, preventive protection has also had some effective application technologies in certain fields, such as using stress wave non-destructive monitoring technology to monitor the damage and residual elastic modulus of wooden components, which can accurately understand the internal information of wooden components without damaging the original structure of ancient buildings [5]. But compared to the actual types of damages in ancient buildings, this is far from enough. This article analyses the damage characteristics and causes of traditional brick and wood structure ancient buildings in China. It can identify and determine the risk and cause indicators that need to be monitored. By using statistical methods and artificial intelligence neural network models, the quantitative relationship between and among monitoring indicators can be analysed, and a Process Performance Model (PPM) can be established between multiple indicators. Combined with national and local health evaluation standards for ancient buildings [6], A new risk evaluation method for ancient buildings can be established, ultimately achieving component level warning of ancient building risks on the Digital Twin model.

2 Evaluation Methods

Monitoring is of great significance for preventive protection. Considering the characteristics of ancient brick and wood buildings in China, this study analyses the risks and their causes of ancient buildings, identifies monitoring indicators, analyses the quantitative relationship between and among multiple monitoring indicator data, and ultimately establishes a new risk evaluation method from the cause item to the risk item, providing support for the preventive protection system of ancient buildings in the metaverse perspective.

2.1 Monitoring Indicators

The common risks of ancient architecture are mainly divided into three categories: environmental factors, human factors, and structural factors. Among them, environmental factors such as typhoon, rainstorm, acid rain and earthquake can be obtained through the national public forecasting institutions online, while human factors can be found or avoided by means of strengthening daily inspection. The structural risk factors of buildings, such as deformation, cracking, tilting, decay and aging, correspond to the risk indicators of ancient building components, such as disturbance, cracks, inclination, and elastic modulus.

The risk of ancient buildings can be also divided into inevitable factors and abnormal factors in terms of volatility. The former refers to the risk factors that ancient buildings are exposed to in their usual environment, such as the normal vibration of the ground due to residential activities. In this case, the damage to ancient buildings may not have a clear correlation with vibration; The latter is a risk factor caused by special reasons, such as significant disturbance to the ground caused by subway construction, including strong vibrations and ground subsidence. In this case, the damage to ancient buildings is clearly related to the amplitude and duration of special vibrations, as well as the distance of ground subsidence.

Obviously, considering the direct risk indicators of ancient buildings alone is not enough for preventive protection, and we also need to analyze the underlying factors. By using techniques such as Fishbone diagrams and Plato to analyze the causes of direct risk indicators in ancient architecture, the main causes can be identified and confirmed. Taking the columns tilting (Q) of traditional brick and wood residential structure as an example, without special reasons, this is a slow and long-term process. The main causes may include horizontal force (S) generated by the beam deflection (R) connected to the top of the column, load-bearing capacity (C1), vibration (Z1), and ground settlement (J1). In special circumstances, the tilt of the column is also related to special load-bearing caused by non-long-term rainfall and snow (Y), special ground settlement (J2) and special vibration (Z2) caused by subway construction and their duration (t). The cause factors affect the direct risk indicators, and these cause factors, like the risk indicators, must be included in the monitoring indicators [7].

The identification and confirmation of the above monitoring indicators will directly determine the selection and deployment of suitable types of sensors. A monitoring indicator is usually a long-term process from its generation to triggering the threshold, which may span several years or even decades. Therefore, monitoring is a long-term process. We can use the process data accumulated before the monitoring indicator reaches the threshold to establish a PPM between multiple monitoring indicators, and use incentive indicators to more accurately predict direct risk indicators, thereby achieving more accurate preventive protection of ancient buildings..

2.2 PPM

A single monitoring item can be vague, uncertain, and sometimes contradictory for the overall health status of ancient buildings, and cannot fully and accurately express the risk status of ancient buildings. So, after identifying individual risk indicators and their main triggering indicators in the previous text, we can use statistical methods and artificial intelligence neural network models to analyze and train the relationship between monitoring indicator data, automatically establish a PPM, and detect data anomalies as early as possible [8].

Also taking the column inclination (Q) of traditional brick and wood residential structure as an example, we can try to establish a quantitative model between column inclination and its causes, such as Q=F (S, J), which represents the comprehensive impact of horizontal force and ground settlement on column inclination without special reasons; And Q=F (t) represents the relationship between the inclination of the column and the duration without special reasons; And Q=F (C2), Q=F (J2), Q=F (J2), represent the pairwise relationship between the inclination of the column under special reasons and the special load-bearing caused by rain or snow, ground settlement caused by special circumstances, and vibration caused by special circumstances; And C2=F (Y), J2=F (Z2) represents the relationship between the special bearing capacity of the column and the amount of rain and snow, as well as the relationship between special settlement and special vibration; And S=F (R), indicating the relationship between the horizontal thrust on the column and the beam deflection, and so on. These univariate models and multivariate models can be used as a means of mutual calling and calibration. After the above models are established, they need to be validated and adjusted through subsequent monitoring data and prediction tests before it can be put into predictive application.

With these PPM models, combined with relevant national and local standards for the identification of ancient buildings, on the one hand, it is possible to predict the threshold of another monitoring indicator based on one detection indicator, such as predicting changes in the inclination of columns through predicted rainfall and snow, in order to take early measures; On the other hand, it is possible to predict the trend process that triggers another monitoring indicator (such as column inclination) threshold in advance without triggering a set threshold for a single monitoring indicator (such as beam disturbance), thereby generating a more accurate warning.

Based on these PPM models, we can achieve risk control indicators by actively intervening in the triggering factors, thereby better achieving preventive protection of ancient buildings. After the targeted control of the relevant incentive items based on the PPM model, it does not mean the disappearance of the corresponding incentive items. These monitoring indicators and PPM also need to be recollected and reestablished.

2.3 Risk Evaluation Methods

At present, most research is based on the fusion of fuzzy membership degree based D-S evidence theory and multiple single items to comprehensively evaluate the risk of ancient buildings, ultimately achieving the evaluation of the overall risk status of ancient buildings. However, there is significant controversy over the rationality and validity of the D-S evidence theory itself, and in some cases, the results obtained may even go against common sense [9]. Based on Digital Twin models and PPM, we can achieve visual component level warning and processing on virtual models.

At present, the Three Layers and Four Level Health Evaluation Standards for ancient buildings introduced in China are mainly based on single indicator data, and the safety level of local and even overall buildings is formulated based on the most dangerous component state, without reasonable consideration of the overall structure. The results are quite one-sided and accidental [10] [11]. Although the monitoring indicators of certain components have reached the highest level of Critical Illness, they usually do not immediately affect the overall health of the building. For example, in ancient buildings with wooden beam frames, walls that are not intended for load-bearing purposes tend to tilt beyond the threshold. And the risk level of some components can immediately affect the overall safety of the building, such as the occurrence of tenoning or disturbance reaching the threshold of the main beam.

In the perspective of the metaverse, the virtual building model of Digital Twins is displayed at the component level. After PPM analysis of data from sensing systems, warnings can be directly displayed on the corresponding components of the virtual model. Users can click on the alarm to understand its specific alarm level and processing suggestions, thereby achieving more efficient and flat warning management.

It is worth noting that PPM based models can predict the conditions and trends for threshold triggering in advance, without the need to reach the threshold set under traditional standards before triggering alarms. In this sense, based on Digital Twins and PPM technology, the traditional "Three Floors and Four Levels" Evaluation Standards can be replanned. The Three Levels from components, parts to the overall building can be simplified to one level of component only, and the Four Levels of Health, Subhealth, Disease, and Critical Illness can be simplified to three levels after removing Subhealth Level. The component level display of Digital Twins allows for only one level of alarm for each component. At the same time, the Digital Twin model automatically provides a visual impact relationship between the warning component and its related components and triggers based on the structural characteristics between the components and the building. This provides more practical structural basis than simply integrating multiple single monitoring indicators through D-S theory to determine the overall health status of ancient buildings. In this way, we can achieve more efficient and concise component level visual warning flat management from the perspective of Digital Twins.

3 Functional Architecture Design of the System

The platform architecture of this preventive protection system for ancient buildings is designed based on the Four Layer architecture model of Sensing, Transmission, Knowledge, and Application in the national standard Smart City Technology Reference Model [12]. It supports the integration of multiple building monitoring systems, real-time monitoring of various risk data for ancient buildings, early warning of risks that reach the set threshold, and providing processing suggestions. The Digital Twin model can interact with physical building sensing devices to achieve preventive protection functions for ancient buildings from the perspective of the metaverse.

3.1 System Functional Architecture Diagram

The system architecture consists of four layers, as shown in Figure 1, namely the Sensing and Monitoring Layer (SML), System and Support Layer (PSL), Data and Model Layer (DML), and Display and Interaction Layer (DIL). Each Layer has different responsibilities. The Monitoring Layer is responsible for collecting monitoring data of ancient buildings; The System and Support Layer establishes a Cloud Computing System for the system, interfaces with other external systems, and communicates data with the SML Layer; The Data and Model Layer is responsible for data analysis and Digital Twin Modelling, etc.; The Display and Interaction Layer is responsible for the visual interaction of business applications.

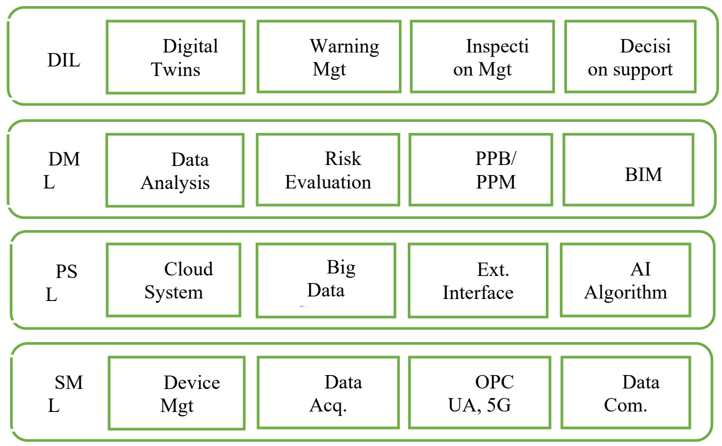

Fig. 1. Platform Architecture of Preventive Protection System for Ancient Buildings

3.2 Sensing and Monitoring Layer

This layer is the fundamental component of the system, including modules for sensor device management, data collection, and data communication. It is responsible for collecting data on monitoring indicators and receive them to the platform and support layers for data storage.

Based on the monitoring indicators determined by the specific building, considering factors such as the current risk, environment, structure, and component importance of the ancient building, configure the corresponding sensor attributes, such as type, quantity, parameters, and their deployment positions, to ensure effective monitoring. For example, for the monitoring of structural stability, equipment such as inclination sensors and stress-strain sensors should be installed in key parts and connecting points of beams, columns, walls, and foundations to capture potential risks or changes.

The OPC UA communication protocol module is used to solve the problem of multi-source heterogeneous data, providing a unified communication interface for the interaction between sensing devices of different monitoring ancient building units and this system. 5G is the foundation of massive data exchange communication, achieving ultra-high transmission speed of interactive data [13]. In addition, it is necessary to consider the importance of the building, the processing capacity of the system, and the transmission capacity of the network to set the frequency of data collection [14].

3.3 System and Support Layer

This layer provides Cloud Computing, Big Data storage, artificial intelligence, and a unified interface with external systems. Cloud Computing and Big Data platforms provide computing power and data storage and processing support from the monitoring layer for the access and management of multiple ancient architectural units, effectively enhancing the smooth interaction function of Digital Twins. The artificial intelligence module realizes automated analysis and modelling of monitoring indicator data. External system interfaces can instantly obtain monitoring indicators on the environment, security, and human factors of ancient buildings by linking public systems such as meteorology, earthquakes, and fires.

3.4 Data and Modelling Layer

This layer is responsible for analysing and modelling monitoring data which has been previously introduced, as well as establishing Digital Twin models of ancient buildings.

The Digital Twin model is the digital representation of physical entities in the virtual world, which can reflect the geometric, physical, and application characteristics of physical entities. There are different technologies and methods for establishing twin models. BIM combined with 3D scanning technology and AutoCAD can establish a 3D virtual model of accurate size data for ancient buildings. Then, through IoT sensing technology, Digital Twins of ancient buildings can be achieved, thereby achieving efficient visualization and automation maintenance for early alarming [15].

Chinese traditional ancient buildings are mostly beam lifting frame structures, which are composed of columns, beams, braces, purlins, arch of wooden architecture, rafters, and other components in the vertical direction. The beams bear the load, and the walls are mostly used as partitions. According to the CAD wireframe of components and the construction theory of ancient buildings, BIM can quickly establish the 3D models of columns, beams, arch of wooden architecture and other components by setting the main driving parameters of the shape and size of components, and visually and completely display the ancient buildings in the form of 3D disassembly models in the unit of components. Users can patrol and inspect buildings through roaming functions, viewing the structure and sensor layout of buildings from different perspectives. They can also click on components and sensors with the fingers or mouse to view their corresponding properties and monitoring data status curves [16].

3.5 Display and Interaction Layer

The main function of this layer is to achieve visual display and interactive functions of ancient architecture through Digital Twin models. Display the virtual building structure and layout at the component level in a roaming form, and display different levels of risk warnings through different colours, enabling users to quickly locate and obtain warning information. The Digital Twin model can also implement control over building entities, such as indoor water spraying and dehumidification, to restore the indoor dry and humidity indicators of ancient buildings to a healthy range.

The Decision Support Module provides maintenance recommendations based on the warning level of risk evaluation methods. The early warning management module can configure alarm thresholds and simulate emergency scenarios to assist relevant departments in simulating and practicing various emergency response measures.

Inspection Management Module includes online automatic inspections and on-site inspections. Online inspection supports users to query and display specific sensor data, and can analyse and process abnormal values in monitoring data, such as removing or fitting. On site inspection is an important means of daily maintenance and management, including security checks, cleaning, pest and mold treatment, temporary repairs, equipment maintenance, etc. It is a necessary supplement to online inspection.

4 Conclusion

This article proposes an improved method for traditional ancient building risk Evaluation by establishing a PPM quantitative model between and among multiple risk monitoring indicators and combining them with the Digital Twin model of ancient buildings. Finally, a system logic architecture based on Cloud Computing and Big Data platforms is designed to support the access and early warning management of multiple monitoring buildings.

The biggest challenge of PPM quantification model is the collection and analysis of monitoring indicator data. Because the risk of damage to buildings is usually a long-term process, monitoring is also a long-term process that requires regular evaluation and adjustment of the collected data and methods. Meanwhile, each individual ancient building has its own uniqueness, and the PPM Model established by one building may not necessarily be applicable to other buildings. After intervening in a certain risk item of ancient architecture, it does not mean that the cause has disappeared, it may only be of varying degrees. The monitoring indicator data needs to be restarted to collect again, and accordingly, the quantitative model needs to be reestablished to ensure the effectiveness of its risk evaluation. Therefore, the modelling method for identifying and quantifying the entire monitoring indicators proposed in this article is more important, and mastering this method can adapt to different scenarios.

In addition, as the simplest and most efficient part of preventive protection, manual inspection is indispensable. It can timely detect risks such as fire hazards, insect infestation and mold, as well as human factors, to make preventive measures for risks in the first time. It must serve as a necessary risk input interface for preventive protection systems.

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