An Integrated Approach Using Machine Learning and Ecological Monitoring for the Preservation of Sichuan Watchtowers

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Abstract: The preservation of Sichuan's watchtowers, significant cultural heritage sites, is increasingly threatened by environmental factors, urbanization, and inadequate conservation efforts. This study proposes an integrated framework combining environmental monitoring and machine learning. Sensor networks tracked factors such as temperature, humidity, and air quality, while drone-based photogrammetry captured high-resolution spatial data for structural analysis. Machine learning models, including CNNs with 92% accuracy for crack detection and RNNs for forecasting deterioration trends, provided actionable insights for repair prioritization. A Decision Support System (DSS) integrated real-time data with predictive outputs, optimizing maintenance planning. This scalable framework enhances the sustainable preservation of Sichuan's watchtowers and offers a replicable solution for global heritage conservation.

1. Introduction

Sichuan watchtowers, originating from the Ming and Qing dynasties, are a unique form of traditional Chinese architecture with significant historical and cultural importance. Initially constructed for defense against bandits and invasions, these multi-story towers have evolved into symbols of local identity, showcasing a remarkable fusion of functionality and aesthetic design. Beyond their architectural significance, the watchtowers embody intangible heritage through oral traditions, folklore, and community narratives. However, their preservation faces considerable challenges, including environmental degradation caused by temperature fluctuations, humidity, and climate change, as well as threats from urbanization and insufficient funding or advanced restoration technologies.

Recognizing the global importance of cultural heritage, UNESCO emphasizes that preservation serves as a bridge connecting modern society with its historical memory [1]. Effective conservation of cultural assets like Sichuan watchtowers must consider not only structural integrity but also the ecological health of the environment and socio-economic impacts of urban development. Advances in technology, such as remote sensing, sensor networks, and machine learning, have created new opportunities for sustainable heritage management. Remote sensing enables real-time environmental monitoring, while machine learning enhances structural damage detection and repair prioritization through predictive analysis [2,3].

This study proposes an integrated framework for preserving Sichuan watchtowers, combining environmental monitoring and machine learning-based restoration. Continuous environmental monitoring is achieved using sensors to track factors such as temperature, humidity, vibration, and air quality, enabling early detection of risks to structural integrity. High-resolution imagery from drones and ground-based cameras is analyzed using image processing and deep learning techniques, such as Convolutional Neural Networks (CNNs), for automated crack and damage detection. Machine learning further supports repair prioritization by forecasting deterioration trends. Policy recommendations stress the need for increased government support, technological advancements, and public engagement to address both natural and anthropogenic threats effectively.

By integrating advanced monitoring systems with predictive technologies, this framework

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enhances the efficiency and precision of preservation efforts while providing a scalable solution applicable to other cultural heritage sites worldwide.

2. Research Methodology

This study proposes a comprehensive conservation strategy based on environmental monitoring and machine learning, aimed at improving the efficiency of preserving cultural heritage such as the watchtowers in Sichuan. The research methodology consists of two main parts: the first part focuses on the establishment of a comprehensive monitoring and assessment system for the watchtowers and its surrounding environment, while the second part presents a machine learning-based approach for the repair of building damage in the watchtowers.

2.1. Comprehensive monitoring and assessment of the watchtowers and its surroundings

To assess the preservation needs and environmental impacts on Sichuan's watchtowers, this study integrates sensor monitoring, remote sensing, and GIS for comprehensive environmental evaluation. Temperature and humidity sensors are installed both inside and outside the watchtowers to monitor real-time fluctuations that may cause expansion, contraction, or cracks in building materials. Vibration sensors are deployed at the foundation, walls, and surrounding areas to detect vibrations caused by wind, earthquakes, or human activities such as tourist foot traffic and vehicular movement. Air quality sensors are used to monitor particulate matter, including PM2.5, PM10, and CO_2 concentrations, providing insight into potential environmental stressors.

The study also incorporates satellite imagery and drone-based image analysis for remote sensing. Multi-spectral and high-resolution satellite imagery is used to analyze environmental variables such as vegetation coverage, land use changes, and water resource distribution. Drones capture high-resolution images of the watchtowers from multiple angles, which are processed into 3D point cloud models to identify structural issues such as wall cracks, tilting, or localized collapses.

GIS technology is employed to combine remote sensing data with ground sensor data for integrated analysis. A 3D spatial model of the watchtowers and their surrounding area is constructed, incorporating information about the buildings' form, topography, and vegetation distribution. This model allows for a visual assessment of potential environmental impacts on the watchtowers' stability. The study further analyzes land-use changes around the watchtowers, identifying risks such as increased stormwater runoff caused by urban expansion, which may lead to foundation erosion. This integrated approach ensures a thorough understanding of the environmental factors affecting Sichuan's watchtowers and provides a basis for informed conservation strategies.

2.2. Machine Learning-Based Repair Strategy for Watchtowers Structural Damage

This study employs drones and ground-based cameras to capture high-resolution images of Sichuan watchtowers, followed by preprocessing techniques such as noise reduction and contrast enhancement. Drones provide multi-angle façade imagery, while fixed and mobile cameras focus on cracks and foundation erosion points. Gaussian filtering and Non-Local Means (NLM) denoising reduce noise, histogram equalization enhances contrast, and Laplacian filters highlight crack edges for better input into machine learning models.

For crack detection, a CNN model based on ResNet is trained on labeled datasets to differentiate cracks from other features. Edge detection techniques, including Canny and Sobel filters, refine crack boundaries. Additionally, surface erosion detection utilizes Local Binary Pattern (LBP) and Gray-Level Co-occurrence Matrix (GLCM) texture analysis. LBP identifies rough erosion zones, while GLCM quantifies texture properties, aiding in erosion classification into "Mild," "Moderate," or "Severe" levels. A CNN further processes extracted texture features to generate an erosion heatmap.

To predict damage progression, an RNN analyzes time-series data of structural degradation and environmental factors. By processing historical damage features, it forecasts crack growth and erosion expansion. The model is optimized using Mean Squared Error (MSE) loss, the Adam optimizer, a learning rate of 0.001, and a batch size of 64, trained over 100 epochs. This framework enhances predictive maintenance, optimizing repair prioritization and long-term conservation planning.

2.3. Integrated Conservation and Decision Support System

An integrated decision support system is designed in this study, combining environmental monitoring data and repair strategies to provide comprehensive support for watchtowers conservation. This system integrates remote sensing, environmental sensor data, and machine learning models to provide real-time data and predictive analysis for conservation managers, assisting in the formulation of appropriate conservation measures and repair plans.

3. Results

This section presents the results obtained from the environmental monitoring system, machine learning-based damage detection, and predictive maintenance framework applied to the Sichuan watchtowers.

3.1. Environmental Data Collection and Analysis

The environmental monitoring system provided continuous data from the sensor network deployed at the watchtowers, capturing key parameters such as temperature, humidity, vibration, and air quality. The sensor data was collected over a seven-day period to assess fluctuations in environmental conditions and their impact on the structural health of the towers. Table 1 shows the environmental conditions.

Table 1 Environmental Data Summary

Date	***Temperature (℃)***	***Humidity (%)***	***Vibration (Hz)***	***Air Quality (PM2.5 µg/m³)***
2024-12-01	18.5	65	0.02	35
2024-12-02	19.0	63	0.03	37
2024-12-03	17.8	67	0.05	30
2024-12-04	16.5	70	0.06	40
2024-12-05	17.0	72	0.04	42
2024-12-06	18.2	68	0.05	39
2024-12-07	19.1	66	0.03	33

Temperature, humidity, and vibration monitoring revealed significant fluctuations, particularly during seasonal transitions. For instance, between December 1st and 4th, temperatures dropped from 19.0℃ to 16.5℃, while humidity increased from 63% to 70%, contributing to material expansion and crack formation. Vibration levels peaked at 0.06 Hz during high tourist activity. Air quality data showed PM2.5 concentrations ranging from 30 to 42 µg/m³, with the highest levels recorded on December 5th, indicating increased pollution that accelerates material degradation. As Fig, 1 shows, a correlation matrix confirmed strong links between temperature and humidity ($r = 0.85$) and a moderate correlation between vibration and air quality ($r = 0.55$), underscoring the need for integrated environmental monitoring to support watchtower preservation.

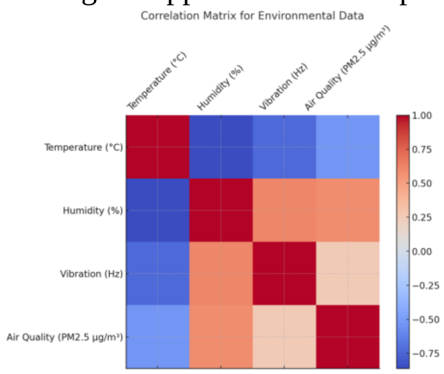

Fig. 1.Correlation Matrix for Environmental Data

3.2. Machine Learning-Based Damage Detection

Machine learning models were applied to analyze the images of the watchtowers, with a focus on crack detection and surface erosion assessment. The CNN model and texture analysis techniques were used to identify structural damage and surface degradation.

1)Crack Detection Accuracy: As Table 2 shows, the CNN-based crack detection model achieved an overall accuracy of 92%, with a precision of 91% and a recall of 93%. These results show that the model is highly effective in detecting cracks in the watchtower surfaces, including fine, difficult-to-detect fissures. The model was particularly successful in detecting cracks in the areas most exposed to environmental stress, such as the roof and foundation.The F1-score of 92% further confirms the reliability of the model in balancing both precision and recall. Notably, the detection time per image was only 0.5 seconds, making the model highly efficient for real-time monitoring and decision-making.

2)Surface Erosion Detection Using Texture Analysis: The texture analysis results showed that 5 areas exhibited mild erosion (12.3 m^2), 3 areas showed moderate erosion (7.8 m^2), and 2 areas had severe erosion (4.5 m^2). Furthermore, a new category of "critical" erosion was detected in one area (2.1 m^2), indicating advanced material degradation that required immediate attention.

Table 2 Crack Detection

Severity Level	***Number of Areas Detected***	***Area(m^2)***
Mild	5	12.3
Moderate	***3***	7.8
Severe	2	4.5
Critical	1	2.1

3)RNN-Based Predictive Maintenance: The Recurrent Neural Network (RNN) model predicted an increase in damage severity over the next five years. This predicted trend aligns with the ongoing environmental conditions observed, such as increasing humidity and vibration levels during tourist season, which accelerate material degradation. The RNN model also provided valuable insights into the prioritization of maintenance tasks. Areas with the highest predicted deterioration were identified as high priority for immediate restoration efforts, while other areas with slower deterioration rates were scheduled for later intervention.

3.3. Integrated Decision Support System (DSS)

The integrated DSS, which combined environmental data with machine learning-based damage detection and predictive maintenance, provided real-time actionable insights for heritage site managers. The DSS interface displayed key environmental parameters (temperature, humidity, vibration, and air quality) alongside real-time damage detection results, allowing for quick identification of critical areas needing attention.

The DSS was particularly effective in generating predictive maintenance schedules based on RNN predictions. For example, the system recommended immediate repairs for the roof and base of the watchtowers, where damage severity was predicted to exceed 0.8 by the end of 2025.

The integration of real-time environmental data with predictive analytics was a key strength of the DSS, providing heritage site managers with a holistic approach to preservation.

4. Discussion

This study integrates environmental monitoring and machine learning to develop a comprehensive conservation strategy for Sichuan watchtowers. Sensor data revealed that temperature, humidity, and air pollution contribute to material degradation, while vibrations from tourism and urban activity impact structural integrity. Remote sensing and drone-based 3D modeling enabled precise crack detection, with CNN models achieving 92% accuracy. RNN-based predictions facilitated proactive maintenance planning, while texture analysis identified erosion-prone areas. A Decision Support System (DSS) optimized resource allocation for repairs. Despite its effectiveness, challenges remain, including sensor durability and the need for larger labeled datasets. Future research should refine data collection and enhance AI integration.

5. Conclusion

This study successfully integrates environmental monitoring and machine learning for Sichuan watchtower preservation. Real-time sensor and remote sensing data revealed that humidity and pollution significantly impact material degradation. CNN-based crack detection and texture analysis effectively identified structural damage, while RNN models predicted future deterioration, enabling proactive maintenance. The decision support system optimized preservation efforts by combining environmental data, damage detection, and predictive analysis. This approach enhances conservation efficiency and provides a scalable model for protecting heritage sites facing similar environmental and structural challenges.

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