DOI: 10.61782/fa.2025.0106

ADVANCED MONITORING FOR HERITAGE CONSERVATION: TECHNOLOGICAL INNOVATION IN PREVENTIVE MAINTENANCE OF HISTORIC BUILDINGS

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ABSTRACT

Preventive maintenance of historical buildings through continuous structural monitoring is essential for the preservation of cultural heritage. It enables efficient management of the physical interaction between tourism and architecture and supports early detection of structural anomalies, facilitating data-driven decision-making.
The University of Valladolid has established a multidisciplinary research team composed of architects, mechanical engineers, and telecommunication engineers. This team has developed an innovative, reconfigurable, scalable, and low-cost technological platform based on MEMS (Micro Electro Mechanical Systems) sensors. These sensors allow real-time and synchronous monitoring of vibrations, mechanical stresses, inclinations, temperature, humidity, and crack evolution in structural elements.
The system integrates local and cloud-based data processing and storage using open-source technologies. Advanced signal processing, statistical analysis, and artificial intelligence techniques—including modal analysis and machine learning algorithms—enable the early identification of potential structural issues, reducing the need for costly corrective interventions and ensuring the longevity of historic structures.
A case study of the 45-meter-high tower of the Monastery of San Jerónimo in Granada is presented to demonstrate the effectiveness of the proposed monitoring solution in a real-world heritage setting.

Keywords: *Structural Health Monitoring, MEMS sensors, cultural heritage conservation, preventive maintenance, machine learning.*

1. INTRODUCTION

Preventive maintenance through continuous monitoring of historic buildings is a key factor in the conservation of cultural heritage, as it allows for efficient management of the physical interaction between tourism and architecture. Early detection of structural anomalies facilitates data-driven decision-making, minimizing the risk of severe damage and optimizing the resources allocated to conservation [1-3].
At the University of Valladolid, a multidisciplinary group has been established. It is composed of researchers from the Wood Structures and Technology Group, the Array Processing Group and the Structural Dynamics Group.
This interdisciplinary team combines the knowledge of architects in the field of heritage wooden structures and the expertise of mechanical engineers in vibration analysis and modal characterization of structures. It also leverages the skills of a team of telecommunications engineers who are capable of hardware design and development, as well as algorithm programming and the creation of open-access libraries for data acquisition, processing, and analysis.
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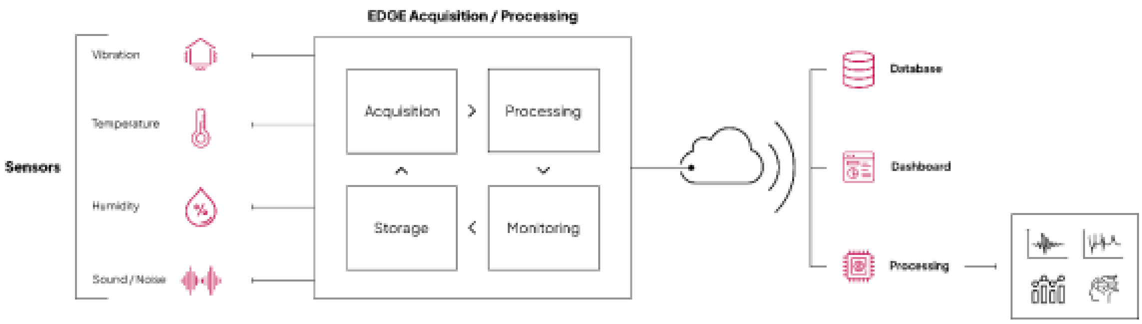

Figure 1. Smart Monitoring System for Architectural Heritage

This team has recently developed an innovative, reconfigurable, scalable, and low-cost technological architecture based on MEMS (Micro-Electro-Mechanical Systems) sensors. These sensors allow precise monitoring of vibrations, mechanical stresses, inclinations, temperature, humidity, and the progression of cracks in the structures. Integrating these data into a synchronous acquisition system provides a detailed and continuous view of the structural condition of the buildings [4-5].

In addition, a platform for processing and analyzing these data has been implemented using open-source technologies. This platform enables the logging, statistical analysis, and remote monitoring of key structural parameters. Thanks to its ability to identify anomalies before they become critical problems, it emerges as an efficient and cost-effective solution for managing preventive maintenance in historic buildings, reducing the need for costly and potentially disruptive corrective interventions.
This paper presents the technical characteristics of the monitoring system and its potential applications in the conservation of architectural heritage. A case study is also discussed: the monitoring of the 45 m tall tower of the Monastery of San Jerónimo in Granada, where the system's capabilities have been evaluated in a real heritage environment.

2. SYSTEM DESCRIPTION

As illustrated in the figure (Fig. 1), the structural monitoring platform is composed of three main components:

1. A set of sensors capable of detecting vibrations, temperature, humidity, and acoustic sources such as ambient noise and sound.
2. A hardware system with embedded software, responsible for four core tasks: data acquisition, local
3. A visualization and storage platform, where data are stored in a database and graphically displayed through a dashboard.

The resulting technological architecture is reconfigurable, scalable, and low-cost, making it suitable for the continuous structural monitoring of heritage buildings.

2.1 Sensors

The system uses MEMS (Micro Electro Mechanical Systems) technology, which integrates both the sensor and the associated electronics on a single chip. These devices capture signals, amplify them, and convert them to a digital format. The multisensor captures variations in mechanical stress, inclination, temperature, humidity, crack development, and even acoustic pressure.

2.2 Data Acquisition

During acquisition, data are collected synchronously (all sensors sample at the same time) and in real time. Preliminary local processing reduces the volume of data to be transmitted, optimizing computational and storage resources.
Several system implementations have been developed, some of which include over 40 triaxial acceleration sensors, operating at sampling rates close to 500 Hz. The large volumes of data generated are processed locally to extract key statistical parameters, which are then uploaded to the cloud for storage and visualization. When required, raw data can be transferred for advanced offline analysis.

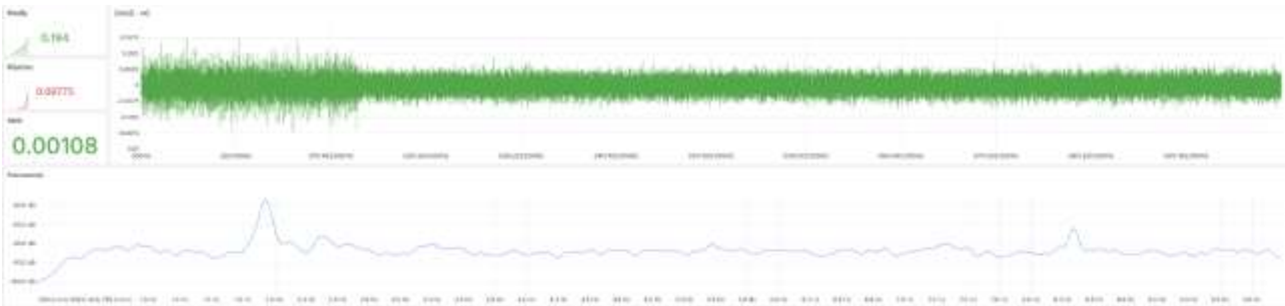

Figure 2. Vibration evolution recorded

2.3 Post-Processing

The system integrates technologies and algorithms across four main areas:

1. Signal processing algorithms that filter data within the desired bandwidth and remove bias.
2. A set of libraries that compute statistical metrics such as mean, variance, maximum, and minimum values.
3. Advanced algorithms including Experimental Modal Analysis (EMA) and Operational Modal Analysis (OMA).
4. AI-based techniques, including machine learning and deep learning classifiers, to support health status assessment and decision-making in heritage conservation.

All sensor data are uploaded to the cloud, where dedicated time-series databases and result visualization dashboards are deployed. Figure 2 shows an example of sensor-recorded vibrations evolution in a monitored building.

3. CASE STUDY

Since May 2024, in collaboration with the School of Civil Engineering at the University of Granada, a structural monitoring project has been carried out on the tower of the Monastery of San Jerónimo, located in the city of Granada (Fig. 3).

A set of five sensors has been installed, measuring triaxial acceleration, temperature, and humidity, along with two additional sensors monitoring the width of two major cracks located between the main nave and the tower. The tower comprises five levels, with the bell chamber located on the penultimate floor. Figure 4 highlights the placement of the five accelerometers within the interior slabs.

The primary objective of this project is to analyze the tower’s modal behavior and to correlate crack width evolution with environmental variables (temperature and humidity) as well as the vibrational response of the structure.

Sensor installation was completed in record time, ensuring proper placement on each level. Data acquisition is carried out using a system based on National Instruments' myRIO platform, equipped with 5G cellular communication capabilities. This technology enables real-time data transmission, facilitating the remote structural health monitoring of the tower.

4. CONCLUSIONS

This work presents an innovative technological architecture for the structural monitoring of architectural heritage, characterized by its reconfigurability, scalability, and low cost. The system has demonstrated its capacity to provide continuous and detailed insight into the structural health of historic buildings, enabling early detection of anomalies before they evolve into critical damage.

The developed system integrates advanced MEMS sensors capable of recording vibrations, mechanical stresses, inclinations, temperature, humidity, and crack evolution in heritage structures. Leveraging open-source technologies, collected data are processed in real time and stored in accessible platforms for remote analysis and visualization.

Furthermore, advanced artificial intelligence techniques, including machine learning and deep learning models, have been incorporated to enhance the system’s predictive capabilities, optimizing preventive maintenance strategies and supporting informed decision-making in heritage conservation.

Figure 3: Royal Monastery of San Jerónimo (Granada/Spain).

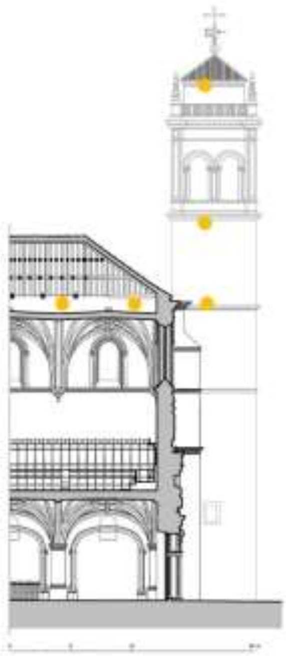

Figure 4. San Jerónimo Tower [6]

5. ACKNOWLEDGMENTS

This project would not have been possible without the multidisciplinary collaboration of architects, industrial engineers, and telecommunication engineers with extensive experience in regional and national research projects, as well as in real-world implementations in partnership with companies from the sector. We also acknowledge the collaboration between the University of Valladolid and the University of Granada

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