Integration of BIM, Sensors, and Remote Monitoring Techniques for Structural Health Monitoring: A Platform for Verona Arena

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ABSTRACT

This research emphasizes the importance of developing interoperable solutions that enable structural monitoring data to be directly comparable with other types of information and effectively utilized through Digital Shadow. The focus is on monuments of significant cultural and historical importance, which face threats from natural hazards such as earthquakes and environmental degradation, as well as human-induced stresses. These challenges highlight the urgent need for advanced tools and methodologies that enable the continuous and reliable assessment of their structural integrity, ensuring their preservation for future generations.

This study presents a comprehensive and integrated approach to information modeling methods for data management, specifically tailored for monitoring and preserving culturally significant structures. The Roman Arena in Verona serves as the case study, demonstrating how Building Information Modeling (BIM) systems and sensor networks can be integrated to assess structural health and manage large datasets efficiently.

The study explores the use of open data standards, such as IFC, to ensure interoperability and facilitate seamless integration of different data sources. It also highlights the application of SQL databases for handling real-time sensor data, enabling a dynamic and detailed digital shadow of the monitored structure. By combining cutting-edge digital tools, including BIM, remote sensing technologies, and environmental sensors, the proposed methodology provides a comprehensive system

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that not only facilitates real-time data analysis but also offers insights for conservation and restoration efforts. A framework that organizes monitoring data into an SQL database, which is subsequently linked to a specific database for Industry Foundation Classes (IFC) files is proposed. This linkage enables the real-time visualization and dynamic updating of the structure's digital representation.

An online platform is introduced to allow users to view and interact with the updated IFC model and query the database to monitor sensor data trends over time. This platform moves beyond traditional visualization tools by integrating monitoring data with actionable insights, offering advanced capabilities such as the identification of specific areas requiring intervention based on sensor readings. By providing decision-makers with a comprehensive view that combines real-time monitoring with historical and predictive data, the system supports more effective conservation and restoration strategies.

This research demonstrates how modern data management techniques and digital tools can be leveraged to enhance the long-term preservation of cultural heritage assets. The proposed framework is scalable and adaptable, offering a model that can be applied to other heritage sites facing similar challenges. By offering a robust and flexible framework for the interoperable use of data generated through structural health monitoring, enabling seamless integration with other information types, this work aims to contribute to the global effort towards preserving cultural heritage in the face of growing environmental and societal pressures.

INTRODUCTION AND BACKGROUND

The protection and monitoring of Cultural Heritage represent an urgent necessity to ensure its long-term preservation and safety. Cultural heritage constitutes the identity of a nation, yet over the years it has been exposed to numerous threats, both natural—such as earthquakes and environmental degradation—and human-induced. In this context, the monitoring of cultural heritage emerges as a crucial activity for the early diagnosis of potential structural and environmental vulnerabilities, enabling the adoption of preventive maintenance strategies and protection against disastrous events. Continuous monitoring of environmental and structural parameters supports the understanding of the current condition of the asset, reduces the risk of deterioration, and allows for the early detection of signs of decay.

Ensuring long-term durability and safety requires the implementation of advanced Structural Health Monitoring (SHM) systems. Data collection is a key aspect for obtaining real information from existing objects and structures. To this end, a variety of observation methods are employed, including Internet of Things (IoT) devices, imaging systems, sensors, and actuators, with the aim of monitoring the surrounding physical environment [1].

A valuable tool for managing this information is represented by monitoring platforms, which enable the collection, processing, comparison, visualization, analysis, and retrieval of heterogeneous data from various sources. This allows for a comprehensive and integrated view of the information related to the monitored asset [2]. These platforms also offer intuitive user interfaces, often based on 3D models (such as HBIM), which allow users to navigate within the detailed model, query, visualize, and manipulate both static and dynamic information - including sensor data - linked to their corresponding digital twins within the model [3]. Despite their numerous advantages, monitoring platforms applied to cultural heritage and structural monitoring also present several critical issues. The real-time management and visualization of 3D structural data remain a challenge for traditional SHM methods [4].

To support preventive conservation practices, the integration of real-time data from IoT monitoring networks with BIM models in open formats represents a promising—yet still complex—solution. According to [3], four key elements define the connection between BIM and IoT: the BIM model as a static repository of building data; IoT sensors and their dynamic time-series data; the data transmission via a specific protocol; and the integration method used to link dynamic data to the BIM model. The main challenges of this connection arise from the heterogeneity of the data sources to be integrated, the limited interoperability between software ecosystems, and the wide variety of data exchange protocols and standards adopted in both the construction and IoT sectors.

Industry Foundation Classes (IFC) data model, developed by BuildingSMART International, is the most widely adopted standard for digital information representation in the construction industry. Its popularity stems from its capacity to ensure interoperability, maintain data consistency, and support the full lifecycle of buildings, independent of the software being used [5]. The model is defined by ISO 16739-1 [6] and various file encoding formats are available, but the most widely used is IFC-SPF (STEP Physical Format).

To enable interoperability and ensure seamless integration between different formats and types of data, it is crucial that information is stored following well-defined and standardized protocols. This not only facilitates data exchange between different systems but also supports consistency, traceability, and long-term usability within digital environments. The aim of this article is to propose a structured framework to guide the effective use, management, and interconnection of data within web-based platforms, with particular focus on scalability, flexibility, and compliance with existing information standards.

This paper is organized as follows. First, it is presented a background on digital platform for monitoring cultural heritage. Then the case study is presented. After, it is described the method proposed to store data from different origins to create websites and its appliance on the case study. Finally, are discussed implications, potentialities and limits for researchers and practitioners.

METHODOLOGY AND CASE STUDY

This paper proposes a framework for the structured storage of data collected by the monitoring system, enabling its integration with the IFC model and allowing queries to be performed via web interfaces. It consists of three steps:

1. *Data Collection and Models*: In this phase, it is necessary to organize the transmission of data from the on-site sensors to the server through a dedicated router. Additionally, a BIM model for the architectural asset must be created and shared in the open IFC format.
2. *Database*: Sensor data is typically transmitted in tabular formats such as TXT or CSV, while the BIM model is in the open IFC-SPF file format. The sensors' data is inserted into an SQL database, which is updated as new data arrives. The IFC model is also converted into an SQL database. Subsequently, the sensor data is used to

update the SQL database, which is then re-exported in IFC STEP format. Conversion of the BIM model into SQL is necessary to write and modify specific information, while the use of the IFC STEP format is required for the use of libraries that allow the visualization of the BIM model.

3. *Web Page Development*: It is possible to implement web pages that allow for the visualization of the BIM model, real-time sensor data (IoT), and time series of sensor data by retrieving the information from the SQL database and the BIM model.

The implemented procedure with the appropriate scripts related to the case study is illustrated in Figure 1. A system collects from the structure real-time information, that is sent in a .txt file to a server (step 1). Then the information is processed and stored in an SQL database via the *database_update.php* script. The data stored in the database are then used to update the IFC-SQL database of the structure, which is subsequently exported in IFC-SPF format using the methodology described in a previous paper (step 2). Two web pages, namely “Graph Viewer” and “Model Viewer”, are then generated. These pages retrieve data from the SQL database through *get_chart_data.php* and *get_sensor_data.php*, respectively, and display the IFC-SPF model (step 3).

In the following paragraphs the file, script and libraries used to build the two web pages are described.

Case study: Roman Arena, Verona

The amphitheater—also known as the Arena—undoubtedly stands as the most imposing and complex architectural feat of Roman Verona. Over the centuries, the monument has endured numerous natural disasters and anthropogenic damage. In recent decades, the municipality of Verona has shown a strong interest in understanding the structural response of the Arena to various external forces, given its significant role and usage. Several investigative campaigns have been carried out to assess the stress state of the composite materials and to measure the vibration levels within the masonry structures. Maintenance is another critical concern for the monument, as it attracts hundreds of thousands of visitors annually, making safety a priority. Additionally, since Verona is located in a seismically active area - though the hazard level is moderate - it is essential to evaluate and, if possible, mitigate the seismic risk.

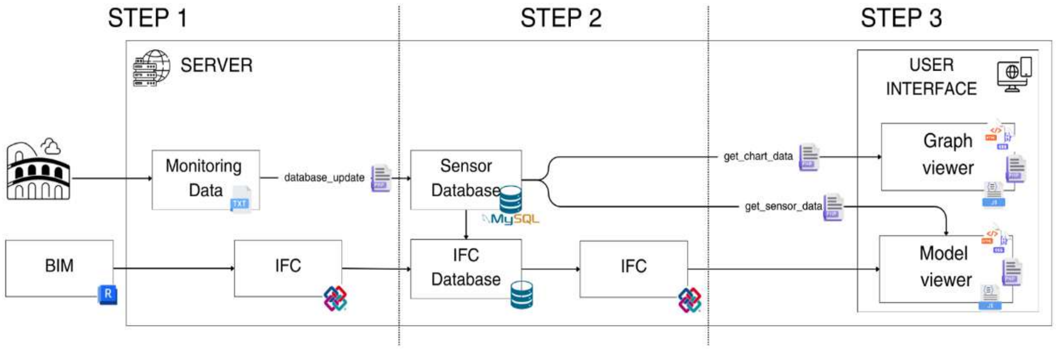


Figure 1. Methodological framework

Step1: Data collection and model production

SENSOR DATA

The monitoring system consists of sixteen single-axis accelerometers (acceleration transducers), twenty linear potentiometers (displacement transducers), and four integrated sensors that measure temperature and relative humidity. Displacement transducers are installed at key locations corresponding to the main cracks and lesions observed. Eight sensors are positioned on the ground floor in the first inner gallery, aligned with a significant crack that spans the entire length of the Arena's ellipse. Twelve transducers are placed within the vaulted niches (designated as "arcovoli") on the second level of arches. Some transducers are installed on isolated cracks, while others are positioned on the observed detachment between the perimeter stone wall and the radial walls. Six accelerometers are mounted on the wing of the Arena, while seven accelerometers follow the radial configuration of the monument. Additionally, three sensors are located at the base of the structure along two orthogonal horizontal axes and the vertical axis, with the goal of recording ground acceleration during seismic events and assessing the dynamic amplification of the structure. The system is equipped with a router for remote data transmission to the central server of the University of Padova.

Sensor data is transmitted and written in tabular formats such as TXT or CSV at regular time intervals and stored on the server. The structure of these files can vary and is dependent on the entity implementing the sensors.

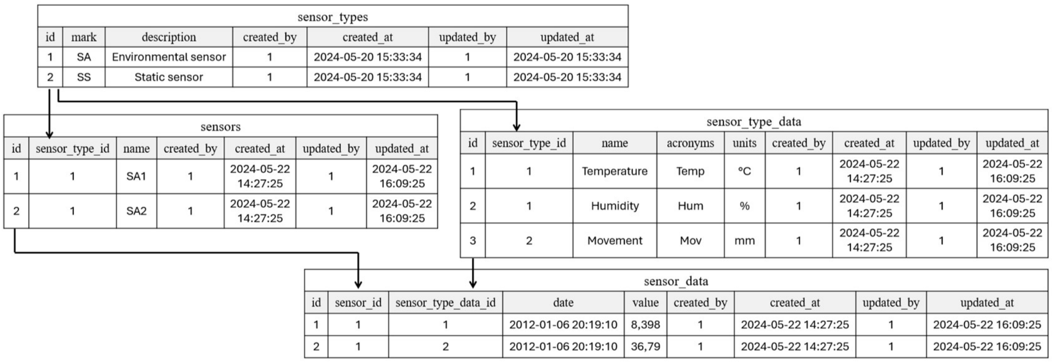
BIM MODEL

The IFC 4x3 [7] model of the Arena was generated by exporting a version developed in a BIM software. It is a simplified version of the amphitheatre, encompassing its primary structural components, including walls (IfcWall), columns (IfcColumn), floors (IfcSlab), arches (IfcBeam), arcovoli (IfcCovering), as well as the external steps and internal stairs (IfcStair). Additionally, the model incorporates monitoring elements (IfcSensor). Within this class, various types of monitoring data can be included. For example, properties such as AssessmentDate (from Pset_Condition) and AssetIdentifier (from Pset_ConstructionOccurrence) are part of the model. Each sensor family also has specific properties tailored to the type of data it collects. Static sensors, for instance, include the SetPointMovement property (from Pset_SensorTypeMovementSensor), while environmental sensors have properties like SetPointHumidity (from Pset_SensorTypeHumiditySensor) and SetPointTemperature (from Pset_SensorTypeTemperatureSensor).

Databases

SENSOR DATABASE

A MySQL database has been created and it is automatically updated hourly through the use of *database_update.php* script, that parses the monitoring .txt files and distributes the collected information into the appropriate columns of the database, based on the sensor that recorded them, preserving both the value and the timestamp of acquisition. As shown in Figure 2, several tables are created for data entry, ensuring efficient organization and retrieval of information:



sensor_types						
id	mark	description	created_by	created_at	updated_by	updated_at
1	SA	Environmental sensor	1	2024-05-20 15:33:34	1	2024-05-20 15:33:34
2	SS	Static sensor	1	2024-05-20 15:33:34	1	2024-05-20 15:33:34

sensors						
id	sensor_type_id	name	created_by	created_at	updated_by	updated_at
1	1	SA1	1	2024-05-22 14:27:25	1	2024-05-22 16:09:25
2	1	SA2	1	2024-05-22 14:27:25	1	2024-05-22 16:09:25

sensor_type_data								
id	sensor_type_id	name	acronyms	units	created_by	created_at	updated_by	updated_at
1	1	Temperature	Temp	°C	1	2024-05-22 14:27:25	1	2024-05-22 16:09:25
2	1	Humidity	Hum	%	1	2024-05-22 14:27:25	1	2024-05-22 16:09:25
3	2	Movement	Mov	mm	1	2024-05-22 14:27:25	1	2024-05-22 16:09:25

sensor_data								
id	sensor_id	sensor_type_data_id	date	value	created_by	created_at	updated_by	updated_at
1	1	1	2012-01-06 20:19:10	8,398	1	2024-05-22 14:27:25	1	2024-05-22 16:09:25
2	1	2	2012-01-06 20:19:10	36,79	1	2024-05-22 14:27:25	1	2024-05-22 16:09:25

Figure 2. Connection between all the different database/table.

- *sensor_types* shows the types of sensors (“description”), environmental or static, with label (“mark”) for each type, to which an id (1 or 2) is associated.
- *sensor_type_data* provides a classification of the data collected by each sensor type. Each sensor type (identified by the "sensor_type_id" attribute from the sensor_types table) is associated with a set of properties, including the name, acronym, and unit of measurement. The sensor type id1, which corresponds to the environmental sensor, is associated with the properties temperature and humidity. The static sensor type id2 is associated with property displacement. Consequently, the identifiers are linked to these properties.
- *sensors*, in which the type of each sensor (identified by the "name" designation) was recorded. This was expressed using the sensor_type_id value from the sensor_types table. The sensors are automatically linked with unique identifiers.
- *sensor_data* where all values measured in the Arena are collected using the previous indices. These include the sensor_id from sensors table, which corresponds to a particular sensor; the properties of the sensor_type_data table, each with its own id and the respective value collected; and the date and time at which the data was collected. Therefore, in the initial row, sensor id1 (which corresponds to an environmental sensor) is displayed, and for each hour, sensor_type_data (i.e., properties) 1 and 2, temperature, and humidity are presented, along with their respective values.

IFC-SQL DATABASE

In order to enable smoother information exchange between the two formats, the IFC file has also been exported into an SQL format. The ifcSQL database, which contains the IFC file, was created following the GitHub guide [8], [9]. This step is described in a previous paper [10].

Web pages

All the files and scripts necessary for the functioning of the web pages have been uploaded within the server. These files include images in .jpg and .png formats, .txt files, .html (HyperText Markup Language) files, containing the content and structure of the web pages, .css (Cascading Style Sheets) files, defining the style and appearance of the .html documents, .php (Hypertext Preprocessor) files, which are used to generate dynamic content and to interact in backend with databases or process form data, .js

(JavaScript) files, which are used to add interactivity and dynamic functionalities to websites; they can be included directly in the HTML or loaded separately.

External libraries are accessed in order to enhance the functionality of the page, obviating the necessity for the creation of a bespoke script. In the present study, two libraries were utilized: The libraries utilized were IFC.js and chart.js. IFC.js [11] is an open-source JavaScript library that enables the creation of web applications for the loading, visualization, and analysis of BIM models in the IFC format. The scripts allow for interaction with the model and the selection of elements. The library employs the Three.js [12] library for the visualization and rendering of geometric elements. Chart.js [13] is a free JavaScript library for the creation of online charts. The libraries enable the construction of various types of charts, including scatter plots, lines, and areas, through the modification of configuration settings.

In the backend there are some PHP scripts that integrate web pages with databases. The JavaScript frontend scripts send inputs provided by users on the website to PHP backend scripts that, based on inputs, send to the frontend the requested sensor data.

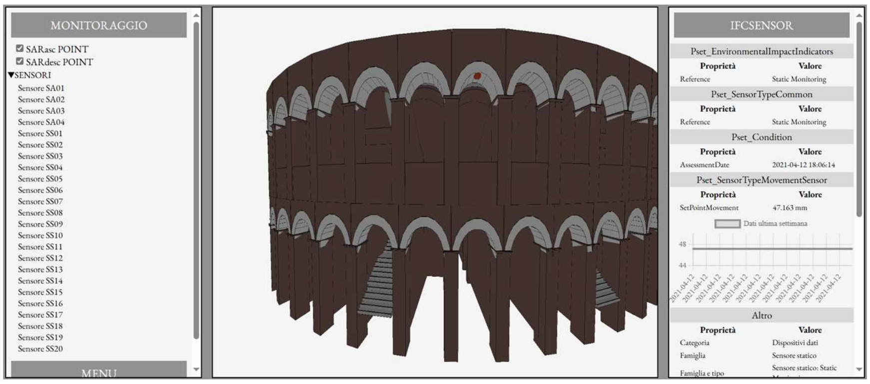
get_chart_data.php processes user input from a web form to generate data for graphical chart representation. The script returns sensor data based on the user-selected chart type, sensors, and date range. The script employs a format that is specific to the chosen chart type. For instance, in the case of a chart designated as "Spostamento + Temperatura" (Movement + Temperature) the script prepares datasets for both displacement and temperature, including appropriate labels and value ranges. In the case of the "Spostamento / Temperatura" (Movement / Temperature) chart, the script generates a combined dataset that represents displacements as function of temperature values.

get_sensor_data.php retrieves and formats sensor data from the SQL database with sensor's data. Upon selection of a sensor within the 3D BIM model, the script utilizes the sensor's "name" to retrieve and update its associated data. Specifically, the most recent data for that sensor are retrieved and its properties are updated accordingly. Furthermore, the script retrieves sensor data from the previous seven days (calculated as 7 x 24 hours) and prepares this information for charting. Subsequently, the script returns the data in a structured format that is suitable for visualization.

RESULTS

A website comprising two web pages was developed for the purpose of monitoring the Arena.

The initial page "Model viewer" (Verona Arena) presents the BIM Model and its associated attributes, displaying both real-time sensor data and the SAR points. The page is divided into three sections, as can be seen in Figure 3. The left section contains two checkboxes, which allow the user to display or hide SAR points (ascending and descending). Additionally, there are two three menus: one for all the elements of the model and one for the sensors only. The menus provide a convenient means of selecting elements and sensors, offering an alternative to relying solely on the 3D model. The central section constitutes the largest portion of the page and contains the 3D model viewer. In order to optimize the user experience, the viewer has been equipped with a variety of tools, including the ability to apply different colorings to various elements: upon hovering the cursor over an element, it is highlighted in orange, similarly, elements



Proprietà	Valore
Pset_EnvironmentalImpactIndicators	
Reference	Static Monitoring
Pset_SensorTypeCommon	
Reference	Static Monitoring
Pset_Condition	
AssessmentDate	2021-04-12 18:06:14
Pset_SensorTypeMovementSensor	
SetPointMovement	47.163 mm
Altro	
Categoria	Dispositivi dati
Famiglia	Sensore statico
Famiglia e tipo	Sensore statico: Static

Figure 3. View of the static sensor from the web page and its value.

selected by double-clicking are highlighted in red. The right section presents the IFC model properties pertinent to an element when it is selected, either within the 3D model or in the three menu. In addition to the sensor properties, data from the previous two weeks are displayed upon selection.

The second page “Graph viewer” (Arena Monitoring) serves as a graphic display of data from the sensors for static and environmental monitoring. This page is divided into two parts, as can be seen in Figure 4. The left section allows users to set various parameters, such as: the type of data to be displayed (displacement, displacement combined with temperature or displacement/temperature); the sensors, both static and environmental, whose data they want to view, users can select one or more sensors, either static or environmental, within the settings; the start and end dates of the measurement. Depending on the selected data type, for displacement or displacement and temperature, a graph is generated with the dates of the measurement on the x-axis and the measurement values on the y-axis. For displacement/temperature, a dot plot is generated with temperature values on the x-axis and displacement values on the y-axis. In the right section, when the ‘Display chart’ button is selected, the graph is created in this section. Users can also enter the y_{min} and y_{max} values for the chart if required. Finally, there is a ‘Print chart’ button, which, when selected, downloads an image of the chart. This setup ensures a comprehensive and customizable view of the monitoring data, allowing for detailed analysis and visualization.

DATI DA VISUALIZZARE: Spostamento + Temperatura

SENSORI

Sensori Statici

☐ SS01 ☑ SS02 ☐ SS03 ☐ SS04
☐ SS05 ☐ SS06 ☐ SS07 ☐ SS08
☐ SS09 ☐ SS10 ☐ SS11 ☐ SS12
☐ SS13 ☐ SS14 ☐ SS15 ☐ SS16
☐ SS17 ☐ SS18 ☐ SS19 ☐ SS20

Sensori Ambientali

☑ SA01 ☐ SA02 ☐ SA03 ☐ SA04

DATA

Inizio: gg/mm/aaaa

Fine: gg/mm/aaaa

VALORE MEDIO PER GIORNO

☑ Mostra solo valori medi

Ymin: 45

Ymax: 48

Figure 4. Example of graph generated by the web pages, selecting a static and an environmental sensor, no date and average value per day, from a minimum of 45 mm and a maximum of 48 mm.

DISCUSSION

In the context of monitoring and managing architectural heritage, the development of digital platforms tailored to the specific requirements of this domain is essential. These heritage assets, being integral components of public patrimony, demand the coordinated involvement of a wide range of stakeholders, including technical experts, researchers, and administrative personnel. In this regard, the adoption of solutions based on open data formats is a fundamental prerequisite to ensure effective data sharing and interoperability within multidisciplinary environments.

From a web implementation perspective, three core requirements are identified for the development of digital platforms that support the study, monitoring, and conservation of architectural heritage: (i) the use of open formats to facilitate interoperability across diverse systems and disciplines; (ii) the ability to query, store, and visualize time series data; and (iii) the availability of tools for three-dimensional visualization of the heritage asset, based on software compatible with the IFC standard and integrable into web-based environments.

The proposed methodology is grounded in the integration of heterogeneous data sources—such as sensor measurements, geometric information, and degradation indicators—enabled by the use of open standards. Among these, the IFC (Industry Foundation Classes) data model has emerged as a reference standard for the modeling and management of building-related information, due to its capacity to encompass both geometric and semantic data, including sensor outputs. This work establishes the foundations for linking various types of data (e.g., degradation phenomena) with a building information database, thereby ensuring interoperability among diverse disciplinary domains.

While the IFC standard provides support for the storage of historical data, a relational database based on SQL has been implemented to address specific requirements concerning efficient data management and query operations. Finally, three-dimensional visualization of the architectural asset—integrated with real-time sensor data—constitutes a key feature for the effective representation of the asset’s condition. This functionality is achieved through the use of specialized web-based libraries, which enable seamless integration of IFC models and dynamic datasets into accessible online platforms.

CONCLUSION

This article explored advanced modeling techniques for integrating structural monitoring data in historical structures like the Roman Arena in Verona. A BIM system combined with a sensor network enabled continuous monitoring and real-time data visualization, supporting informed decision-making for conservation. Using open standards like IFC ensured interoperability and broad data accessibility. While this approach enhances safety and preservation, challenges remain in data integration and scalability for larger or more complex structures.

Future developments should focus on enhancing the system's ability to incorporate more diverse data sources and improving the user interface for stakeholders involved in conservation efforts. One possibility involve adding dynamic monitoring sensors and their collected data to the BIM model. These data can then be used to automate seismic analyses or model updating, with the goal of generating automated alerts in case of issues in the results. Another development will focus on creating and linking a BIM model of the underground structures of the Arena, incorporating information obtained from geotechnical analyses. Finally, the model will be enriched with data on material degradation. All these elements will ultimately contribute to creating the most comprehensive monitoring platform possible.

This work highlights the potential for digital technologies to revolutionize the management of cultural heritage, providing a sustainable and dynamic framework for long-term preservation and analysis.

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