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Bridging past and present: cutting-edge technologies for predictive conservation of built cultural heritage

Manlio Montuori [1]

[1] University of Ferrara, Department of Architecture, 44121 Ferrara, Italy – manlio.montuori@unife.it

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Abstract

The technical provisions for protecting built cultural heritage originate from the interdisciplinary disciplines of architecture and engineering, which mutually operate despite encountering specific challenges. Therefore, the lack of adaptable applications capable of integrating the management of complex data originating from various sources has prompted the development of an Internet-of-Things-based application that enables "on-the-fly" data acquisition and information processing from distant locations, records the timeline on a remote desktop, and sends email and brief early warning text messages of alarm when a programmed threshold is exceeded. Furthermore, a dedicated platform is designed to administer and grant users access to a database containing data gathered through the analysis of diagnostic non-destructive methods (i.e., archival documentation, image processing for infrared thermography, acoustic and ultrasonic tomography, and so forth). The system architecture is distinguished by a distributed intelligence consisting of multiple nodes, which enables the remote processing of locally acquired information. The arrangement was strategically planned to optimize the utilization of the wireless digital bus connecting sensors and data storage units. This enables the examination of the case study to be conducted remotely, with all collected data accessible in a suitable semantic web environment. The data can then be analysed and interpreted following the investigation's context. Hence, the present paper aims to provide a detailed vision of the tests conducted on the case study, showcasing the prototype demonstrator's stress test, the analysis layout, and the project's architecture.

1. Introduction

1.1 Current challenges in built heritage monitoring

The widespread diffusion of pervasive and low-cost technological solutions for monitoring structural behaviour has radically changed the approach to risk prevention and conservation of the built cultural heritage (Acierno and Fiorani, 2019). The availability of less expensive devices, characterized by their small size, has enabled the realization of wireless sensing infrastructures applied in different scenarios, e.g., environmental monitoring, industrial monitoring, and agriculture (Granell et al., 2020). The broader context of the Internet-of-Things involves the integration of local infrastructures into a global architecture that exploits the 'anytime, anywhere' paradigm of the traditional Internet (Astorga González et al., 2020), and the built heritage conservation sector has also been able to benefit from the technical advances brought about by the emergence of critical enabling technologies such as wireless sensor networks (Jornet-Monteverde et al., 2021).

Solutions for monitoring the built heritage have been tested and developed in different areas and sites, presenting many different architectures. Still, these applications have mainly proposed a local approach, while in literature, solutions that adopt an IoT approach for managing the flow of data from monitoring stations are rare. Furthermore, most IoT applications developed for the broader cultural heritage sector focus on enhancing the visitor experience. In contrast, few solutions have developed an IoT architecture for cultural heritage monitoring, as implementing this type of system suffers from severe limitations (Samijayani et al., 2017).

Energy consumption must be given due consideration. In order to monitor structural behaviour, monitoring infrastructures should be designed and developed for placement on buildings and in areas without access to the electrical grid or wired data transmission. This necessitates the provision of wireless connectivity for the sensor nodes, encompassing both local and global options, e.g., Zig-Bee, WiFi, GPRS, LTE (Rodriguez-Sanchez et al., 2011). Moreover, while it is possible to optimize these communication technologies to decrease energy usage, most sensors can function independently for extended durations without relying on energy harvesting solutions.

Another constraint arises from the scale of the object being monitored. A wireless sensor network utilizing IEEE 802.15.4 data transmission can be effectively implemented to monitor a building alone (Cappella et al., 2011). However, this approach could be more practical for infrastructures that monitor monumental sites, such as city walls, castles, or archaeological sites (Bezas et al., 2019). Given the circumstances, the aforementioned communication technologies cannot deliver the necessary data transmission range. Furthermore, equipping every sensor node with 3G-GPRS/4G-LTE+ connectivity could be more practical due to the substantial power supply demands and service expenses associated with preparing a SIM data card for each sensor node.

1.2 The project approaches

By introducing a novel node-sensor-network architecture that is energy-efficient to enable long-lasting node operation on standard lithium-ion batteries and supports broad-spectrum communication, this solution aims to address the issues mentioned above. Furthermore, it facilitates the development of a potentially urban-scale monitoring infrastructure.

Implementing a pervasive communication infrastructure that enables real-time monitoring of large-scale buildings and different sites in urban areas, the solution is established on a

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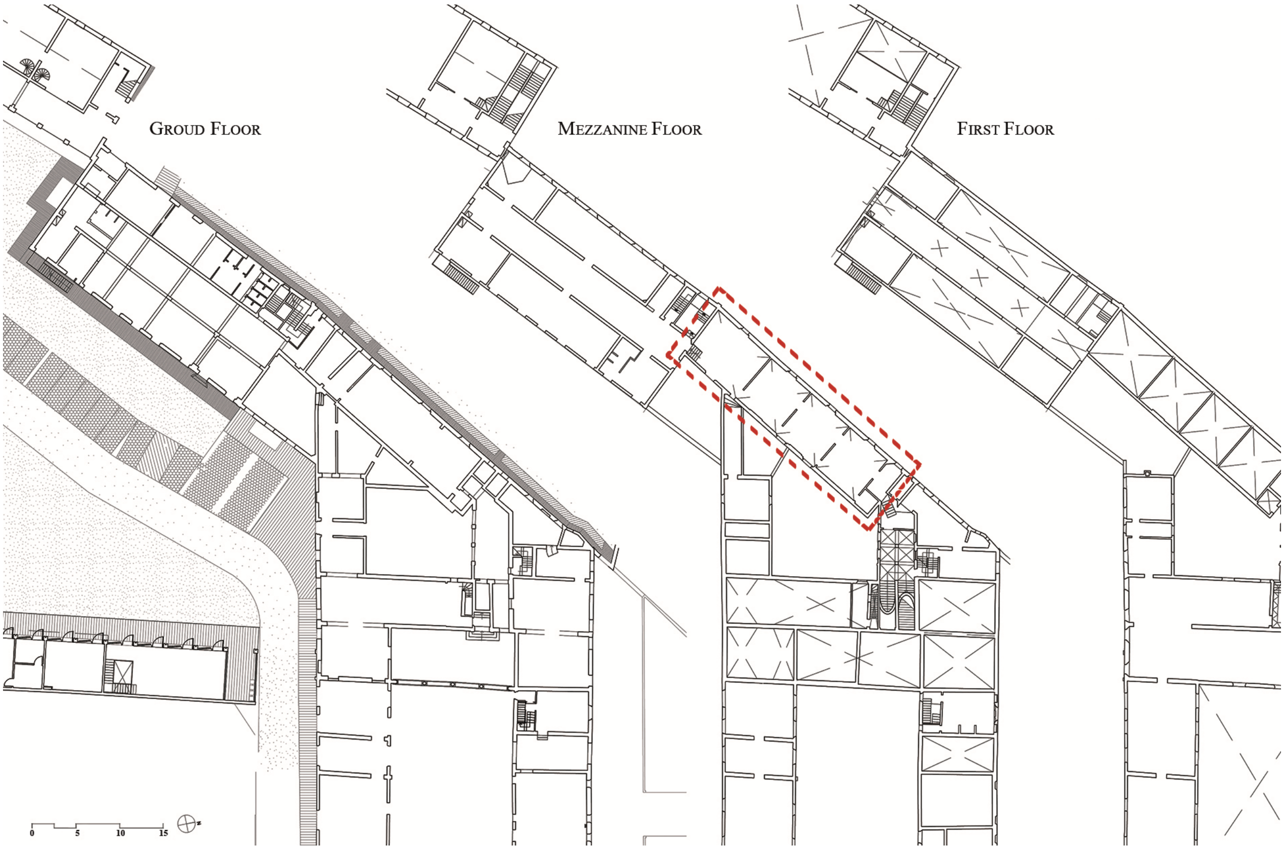

Figure 1. The pilot site of *Sale delle Sibille*, *Palazzo Tassoni Estense* in Ferrara (Italy), house of the Department of Architecture of the University of Ferrara.

wireless telecommunications network, i.e., Low Power Wide Area Network, specifically engineered to facilitate long-range communications (del Campo et al, 2020). Following the IoT paradigm, the network architecture of the case study is devised using a modular structure so that all gathered data could be accessed in real-time via the Internet.

The demonstrator prototype is put into operation by adapting the system to observe the structural condition of the wing, not yet recovered to an academic function, consisting of the *Sale delle Sibille* at the *Palazzo Tassoni Estense* in Ferrara, Italy, (Figure 1, 2) home to the Department of Architecture of the University of Ferrara (Anderson, 1991). Furthermore, the platform is equipped with a relational database that enables accurate analysis of potential accelerations, inclinations, and relative displacements among the fracture edges deemed critical in the progression of the damage mechanism. This enables the retrieval of archived documents that pertain to diagnostic investigations carried out during prior seismic consolidation and structural enhancement projects. The proposed architecture is designed to be readily replicable in various contexts by modelling the network infrastructure following the implementation site's requirements concerning the number of points to be monitored.

2. The monitoring platform features and the case study implementation

2.1 The planned preventive conservation strategy

The task of monitoring the current condition of built cultural heritage, particularly in relation to issues of exposure to risk and its potential to damage, is always regarded as crucial for the development of suitable policies and instruments. In reality, the types and extent of risk to which this asset is exposed can only be determined through a specific understanding of the heritage characteristics and through ongoing and organised monitoring of the asset's conservation status and the site in which it is located (Della Torre, 2020).

The most influential decision support for correct planning and the related allocation of economic resources, including those to respond to emergency and imperative aspects, derives from the results of an analysis process. Two primary objectives address the planning of conservative interventions: to monitor the structural safety of the most vulnerable buildings and artifacts of cultural interest (e.g., slender structures such as towers and bell towers) and specialize monitoring shields that consider the environment in which these items are situated. Additionally, it provides the cultural asset owners, managers, and institutions involved with a decision-support tool in the form of a monitoring platform that enables the personnel responsible for the asset to activate procedures and conservative interventions to protect it. This approach enables mitigating the interventions' impact by managing the residual risk in an active manner. In the context of the built cultural heritage, this approach combines the principle of minimal structural intervention, which is respectful of the asset and its original conception, with the principle of maintaining an acceptable level of risk without the need for invasive interventions to enhance the resistant capacity, particularly in the face of exceptional actions.

2.2 Towards cognitive built cultural heritage

When considering the Internet of Things as a medium where electronic sensors and physical devices, such as cameras, desktop workstations, mobile phones, tablets, and network infrastructures, exchange data and collect information via network-enabled connectivity, it becomes evident that this approach offers a compelling path for technological integration in the monitoring of built cultural heritage (Chianese et al., 2016). Acquiring levels of valuable knowledge for comprehending the current state of conservation and structural behaviour, promptly identifying the activation of damage mechanisms, and enabling effective intervention following the principle of minimum intervention are all goals of a monitoring system (Remondino and Stylianidis, 2016; Saisi, Borlenghi and Gentile, 2023). To achieve this, a variety of data should be collected from multiple sensors installed on the subject under investigation (Chianese et al., 2015). In addition to conventional data processing and management systems, the acquisition of sampled data necessitates an intelligent platform capable of stocking extended quantities of data arising from the sensor nodes of the monitoring system. Such a platform should enable remote access, interrogability, and data interoperability, even among concurrent users. The Mu.S.A. platform - the acronym stands for *Multi-Sensor Assessment. Smart platform for integrating multi-spectrum sensors in specialized monumental buildings* - is designed in response to this demand. The primary project objective is to improve the understanding of the case study's static and dynamic behaviour, appraise its structural health behaviour, and provide information on any damage that may occur in operational conditions and during exceptional events through the development of decision management support tools. The system platform's architecture is scalable and adaptable, making it straightforward to deploy on infrastructures and buildings. It consists of a monitoring control dashboard that collects and analyses data from the sensor networks installed on the pilot site. In particular, the Mu.S.A. platform comprises an integrated wireless sensor network to enable the acquisition of structural and environmental data. This system offers a low-cost, high-resolution, low energy consumption, and limited visual impact monitoring solution. It is characterized by the components of a publish/subscribe communication paradigm that is both dependable and adaptable in the context of IoT communication. The platform takes the form of a monitoring control dashboard designed according to a cloud architecture. The dashboard offers services for storing, processing, and interpreting data from the wireless sensor network. Subsequently, it facilitates the numerical simulation of the dynamic behaviour of monitored structures and the analysis of the collected data using algorithms and models. Additionally, the platform provides multi-channel and multi-platform interfaces to access and analyse data, images, and documents. This occurs to promptly notify the monitoring system of any trespassing of the alert thresholds or any other events of interest. Designed to assist users in managing substantial volumes of data by detecting, transmitting, and receiving digital information, such as images and data, via the network, this intelligent platform facilitates the integration of multispectral sensors into specialized monumental buildings.

2.3 The system architecture for remote data acquisition

A structural survey is carried out using both terrestrial laser scanning and structure-from-motion applications to define the sensors and installation points. This survey provided information about the bearing structures, mechanical behaviour, and constituent materials. The task aims to support the analysis of the cracking framework and potential vulnerabilities (Figure 3). The minimum units of intervention are defined as bottom-up contiguous sections subdivided into homogeneous structural units (Lagomarsino and Giovinazzi, 2006). These units are intended to contain the flow of stresses caused by vertical loads. They are delimited by open spaces, structural joints, or adjacent buildings built according to different construction and structural types. In addition, the identification process considers the consistency of the structural behaviour for both static and


South masonry walls survey, original drawing scale 1:80.

South masonry walls orthophoto, original drawing scale 1:80.

Figure 2. Palazzo Tassoni Estense, Ferrara (Italy). In red, the pilot site area monitored by the Mu.S.A. platform.

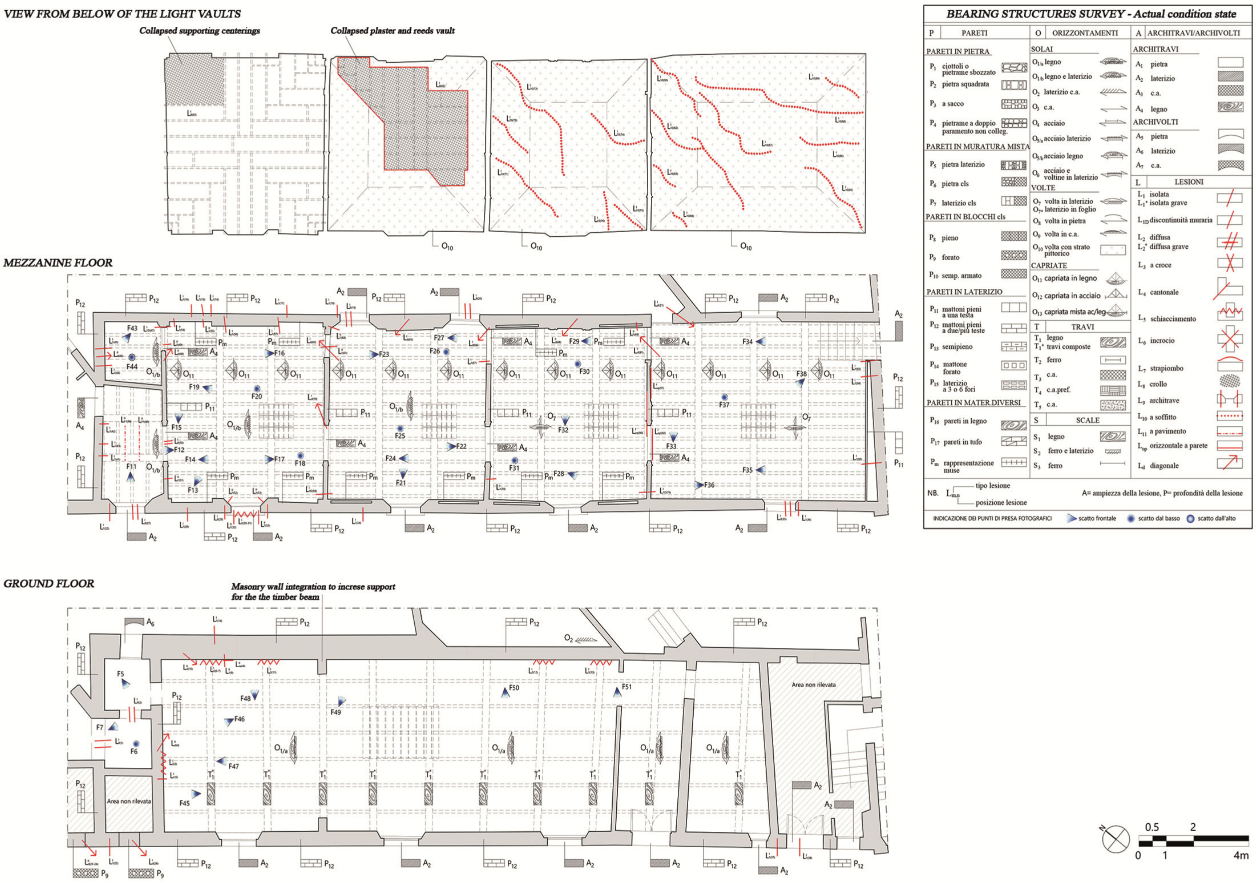

Figure 3. *Sale delle Sibille* minimum unit of intervention, the bearing structures survey and the crack pattern assessment.

dynamic operations (Ferranti et al, 2024). Furthermore, the minimum unit of analysis is defined as a portion of the aggregate typically larger than the specific minimum units of intervention being considered. It usually includes adjacent structural units and is used in the planning phase and assessment of damages and vulnerabilities. This is done to evaluate any interaction effects, such as the impact of pushing systems or vertical or horizontal loads from floors or walls of adjacent structural units.

This analysis identifies the *Sale delle Sibille* as a distinctive structural unit. It comprises the minimum analysis units, four rooms separated by light partitions, composed of timber frames and reeds that support the decorated plastered surfaces. The building's propensity to develop specific damage mechanisms that affect entire sections of it (i.e., macro-elements) is the basis for the vulnerability assessment. The building's geometrical, typological, and mechanical characteristics all contribute to the activation of several potential mechanisms. The interpretative frameworks of the possible collapse kinematics are represented by rotations or translations of masonries, even though deformations are not always concentrated in individual fractures, particularly in low-quality masonry, but rather in large areas (Valluzzi et al., 2023).

Three displacement transducers are installed to monitor the most significant fractures of the crack pattern framework, addressed by the analysis of triggerable damage mechanisms. The sensors' positioning did not necessitate any special protections to prevent potential interference from users, as the pilot site is not accessible for academic activities. The dynamic characterization is also implemented due to the slenderness of the perimeter walls and the presence of partially covered wall painting decorations, which have not yet been the subject to conservation work. Triaxial accelerometers are positioned to facilitate the more accurate identification of the modal parameters of the *Sale delle Sibille*. Consequently, a Tromino tromograph is installed on the ground floor to measure the ground's accelerations and investigate the case study's response to known stresses (Pesci et al., 2011). The response is investigated using three accelerometers and an inclinometer strategically positioned along the southern walls of the mezzanine floor to identify the maximum number of vibrational modes.

Signals are gathered from measurement sources and digitised for desktop presentation, analysis, and storage to monitor the behaviour and integrity of built heritage. The fundamental architecture of a digital data acquisition system includes sensors, measurement transmission hardware, and a computer equipped with a data management software application (Di Giulio et al., 2017). This system, unlike conventional measurement systems, harnesses the power of IoT technologies. It delivers a continuous recording measurement solution that is not only economical, interoperable, flexible, modular, and scalable, but also maximizes the productivity, visualization, and connectivity capabilities of hand-held devices, primarily tablets and smartphones (Colucci et al., 2023).

For maximum design latitude concerning the monitoring system, data acquisition systems available on the market are categorized according to their technological profiles. For operational purposes such as testing, measurement, and automation, it is possible to opt for wired or wireless devices. In such cases, the data acquisition hardware functions as an intermediary between the device and the external environment, converting the analogue signals inputted into a digital format that can be interpreted by the specialised application.

Importantly, the Internet's inherent technology not only enables data transmission but also allows for remote access from any location. This empowers the user to execute operations from a device capable of communicating with the desktop computer station. The Mu.S.A. platform implements wireless data transmission technology, which offered the system architecture increased flexibility and simplicity of installation, in addition to reduced installation and maintenance expenses, in contrast to the capabilities of wired devices, and extended communication range. Due to many factors, including but not limited to the safety of the structures, the treacherous terrain, the financial and time investment associated with each visit, unfavourable weather conditions, and the threat posed by environmental threats, frequent site visits are only sometimes feasible. This created the most challenging situation possible while designing the architecture of the monitoring system. A long-range wireless monitoring system that operates autonomously and requires minimal maintenance has been developed in order to address the shortcomings of conventional infrastructures. Consequently, in accordance with the IoT methodology, data sampling from sensor nodes is conducted directly on the Web, which serves as the facilitating tool for data and information exchange between an object and an intelligent management system. Thus, a comprehensive analysis of this system can be accessed via the Internet (Lo Duca and Marchetti, 2020).

Leveraging the technological advancements facilitated by digital transformation, a real-time and continuous monitoring system has been established with minimal human resource involvement in person-hours. This enables the case study site to experience fewer visits for configuration and maintenance purposes, which has a cost-effective impact on the overall expenses, associated with the monitoring project's implementation, and on personnel involvement.

Following the LV2 level of seismic risk assessment, initially proposed by the 2008 NTC and endorsed by the Guidelines for Cultural Heritage, the Sibille tunnel's seismic vulnerability is addressed, and collapse mechanisms that may be triggered were characterized (MiBAC, 2011). The sensor nodes were intended to be installed in the third and fourth rooms of the gallery. To maintain the integrity of the wall paintings and mechanically secure each sensor to the predetermined location, specialized support was devised by creating an ad hoc prototype from ABS plastic using a 3D printer and preparing a 3D digital model. In order to account for the thermal fluctuations of the surroundings and the expansion of the support, a temperature sensor is connected to the sensor node to compensate for the recorded values. Subsequently, the system is sealed by a final device that manages the network as a gateway, transferring data packets from the individual nodes to the remote data collection server while arranging the whole network. The gateway is outfitted with a LoRa communication module, which enables a wireless connection to the network and is designed to receive nearly constant data transmission. This module can potentially regulate a monitoring system encompassing the entire building department.

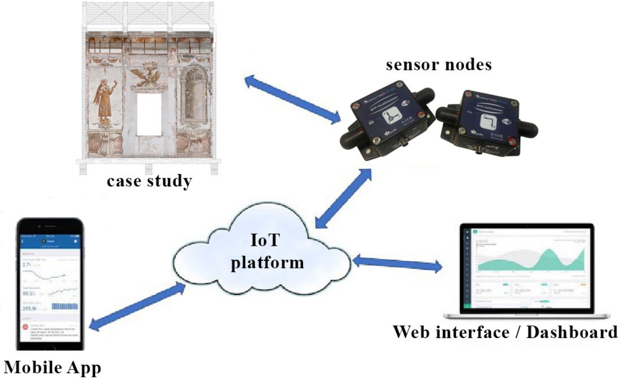

Figure 4. System architecture infographic of the Mu.S.A. project monitoring platform.

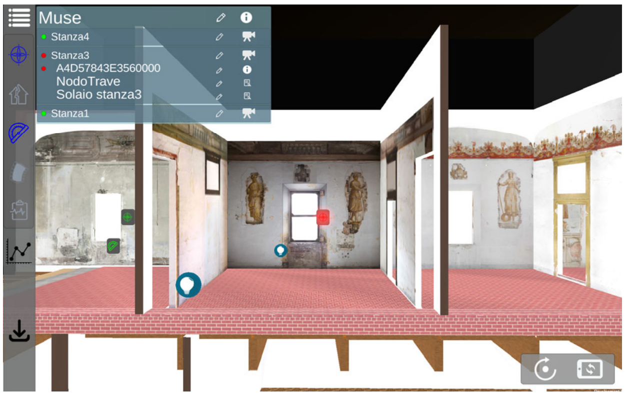

Figure 5. The monitoring control dashboard. A desktop simulation of an alert detected by the ID03 accelerometer,

2.4 The IoT data management of the Mu.S.A. platform

The methodology employed to observe the case study's behaviour adheres to the approach reinforced by the Industry 4.0 paradigm. As defined by the lemma, condition-based maintenance comprises three primary stages: data acquisition, data processing, and determining whether to initiate proactive interventions. Hence, it functions as an operational criterion that influences the development of intervention strategies by utilizing data gathered from the surveillance of structural behaviours and conservation status. Nevertheless, it is thought that this method, which is so meticulously organized, can be expertly supplemented with a wealth of knowledge that monitoring alone cannot provide for on-site operations: that is, the entire body of knowledge that results from the non-destructive and archival investigation, diagnosis, and previous construction site activities.

The Mu.S.A. platform provides a relational database that utilizes entities that represent and provide access to information in the form of images (e.g., digitized archive documents, diagnostic campaigns utilizing video-endoscopies and multispectral images, graphic processing for the characterization of construction techniques, digitization of recordings from prior monitoring) as the logical data structuring model.

With a profound comprehension of the benefits that the Industry 4.0 paradigm can bestow upon a site activity as resistant to innovation as the construction sector, the decision is made to implement an application that, when positioned along the technological trajectory of the worldwide predictive maintenance approach, enhances the strategic and timely organization of environmentally friendly interventions. This strategic value is crucial for ensuring interventions that minimize their impact on pre-existing conditions, and it is in this context, that the software platform is developed.

Utilizing varying degrees of authorization and accessible via an interface subsequent to user registration, the application is developed to display and examine stored data and perform operations on the captured data. A collection of Easy-IoT programming libraries is utilized in its development, which included a server installation. For this study, a package of libraries designed for application development in the Android® environment is adopted, with the understanding that a similar approach could be taken for other established operating

Figure 6. The Mu.S.A. monitoring control dashboard GUI, dataset access via drop-down menu.

systems. The interface, which is user-friendly and adaptable to both desktop and mobile devices, is developed in the Unity Pro® environment to support 2D and, more importantly, 3D functionality to prepare the platform for future implementation in augmented reality. This user-friendliness ensures interoperability, which depends on communication protocols and the capability of different devices to exchange, communicate, and utilize data. The platform provides access to the several data obtained from the sensors and the pertinent characteristics of the image data, categorized into three primary datasets: visual, physiological, and behavioural. The visual data series comprises sampling data obtained from the field sensors. This data is abstracted into a graphical format, enabling the continuous extraction of spatio-temporal information since the surveillance procedure was initiated. The application can be queried to display the data processed in non-destructive diagnostic campaigns by utilizing a series of physiological data. On the other hand, the platform performs initial processing of the behavioural data, which offers an initial indication of the stress condition. This information can then be utilized to develop a predictive approach for data classification using Bayesian logic. One of its most compelling features, the application possesses is the capability to transmit alert messages via email and text message. In order to validate a control test, a warning message was established for a peak acceleration of 50 cm/s^2, equivalent to around 5% of g-force. Following this, an impulse is applied, which disrupted the equilibrium of the monitoring system. As a result, the anomaly is recorded, and the user is notified of the date, time, and temperature, along with the specific accelerometer that recorded the alert and its absolute value. This function is highly advantageous not only for notifying the user whenever the predetermined threshold is surpassed but also for transferring the attributes of the anomaly associated with the stress event to the behavioural dataset through recording a series of alert events. This assists in identifying a behavioural trajectory of the subject under investigation that deviates from his typical conduct. This facilitates the organization of a field inspection activity to identify disruptive factors so that prompt action can be taken prior to their ability to trigger damage phenomena.

3. Discussion: replicability, adaptability and future developments

As part of the preventive approach to the conservation of built cultural heritage, it is crucial to evaluate environmental conditions and the structural behaviour of the subject under investigation. This evaluation provides a trajectory of standard behaviour, enabling the implementation of a timely intervention strategy in a well-defined space and time if necessary. The Mu.S.A. platform, by leveraging the management of sensor-collected data, which can be accessed remotely, in real-time, by a single mobile device or multiple mobile devices, and put into action via a web access application, demonstrates the potential of the Internet of Things technologies in significantly promoting the adoption of a proactive and preventative strategy for the preservation of built cultural heritage.

The paper presents the Mu.S.A. platform, built upon an IoT architecture. It addresses the user's needs regarding data acquisition, cloud processing, and data visualization as they pertain to the built cultural heritage. By providing this information, the platform assists the user in making informed decisions. With an emphasis on the sensor nodes, the most critical component of the system architecture, the findings presented in this work provide an initial sneak peek of the research conducted at the Department of Architecture of the University of Ferrara. As a result, a solution was formulated utilizing the de facto standard LoRa and Sigfox technologies to obtain valid autonomy in situ operations with minimal impact on the architectural system. The selected wireless technology can traverse walls with significant cross-sections and cover considerable distances, which are commonplace occurrences when monitoring intricate structures or open archaeological sites, for instance. As a result, the Mu.S.A. platform is suggested for managing the monitoring infrastructure. When combined with cloud technologies, this creates an open and reproducible system architecture, enabling anyone to implement a comparable infrastructure that is elastic and scalable with regard to storage and computation, accommodating particular workload requirements. In addition, the monitoring platform should include an Augmented Reality front-end application that enables the interactive display of video streams and data collected by the deployed sensor network on a daily basis, during unmanned aerial vehicle inspections, for instance, and offline displaying of the structure's digital twin in an immersive environment. The ability to display historical data stored in the monitoring control dashboard will also be provided.

The future optimization of the monitoring system architecture, based on the Mu.S.A. platform, will be able to scale up the processing and storage resources distributed in a public cloud or on-premises to develop the integration of complex predictive models using the most appropriate data analysis algorithms. This combination of technologies will contribute to a predictive approach in different environments, from the main scenario applied to the conservation of the built cultural heritage to the broader approach to the preventive planned conservation of the diffuse built heritage.

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