A Data-Driven Approach to support the Sustainability of Cultural Heritage Restoration and Conservation Professionals

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***Abstract*—Conserve and restore cultural heritage increasingly requires sustainable, technology-driven approaches focused on human well-being. This contribution presents an integrated method that combines the Internet of Things to monitor environmental parameters on the heritage site, combined with data on restorers' physical, cognitive, and emotional states. We combine these data sources using Artificial Intelligence techniques to support preventive and well-being-oriented restoration practices, providing visual information through an interactive dashboard where experts can monitor parameters, sentiment levels, and receive support notifications. A case study conducted during the restoration of the Church of the Misericordia in L'Aquila demonstrated the technical viability and practical value of this approach, contributing to interdisciplinary research on conservation methods, technologies, and their long-term impacts.**

***Index Terms*—Preventive Conservation, Monitoring, Restoration, Internet of Things, Smart Cities, Cultural Heritage**

Cultural heritage conservation and restoration are crucial to ensure the longest possible life of our societies' historical and artistic heritage. Among the most complex and delicate cases are architectural assets, such as historic churches, where the challenges of material conservation and the final results of restoration intersect with the need to ensure the safety, effort, and well-being of restoration professionals. Recent digital advancements in environmental monitoring and data-driven decision-making support both technical and human-centered restoration, enabling smart environments that improve visitor experience at cultural heritage sites [1], [2]. Internet of Things (IoT) technology, such as sensors for temperature, humidity, and air quality, is being used to inform decisions regarding cultural heritage sites [3], [4].

However, less attention has been paid to using digital technologies for supporting conservation, restoration, and long-term management activities, which are equally critical for the sustainable preservation of cultural heritage assets. Indeed, restoration practices remain largely focused on the material and structural aspects of cultural assets, with limited consideration for the working conditions of human operators involved in the restoration process. Also, no data are integrated with IoT information on how such environmental conditions can affect restorers themselves. This represents a significant gap, particularly because restoration work often takes place in challenging environments: confined, poorly ventilated, or structurally unstable spaces where bad environmental factors can directly impact physical comfort, cognitive performance, and emotional well-being. Ignoring these dimensions can compromise worker health and safety and may also affect the quality and efficiency of restoration interventions, often delaying the delivery of the final result.

To address this gap, we propose an integrated approach that combines IoT for real-time environmental monitoring with the collection of subjective data from restorers through restoration logbooks generated by voice recording analysis. We analyze both data streams using Artificial Intelligence (AI) techniques, aiming to support more informed, well-being-oriented decision-making for restorers in restoration processes. Results will provide an interactive dashboard where expert activities are temporally aligned with environmental data collected during the same period, enabling a multidimensional interpretation of the restoration context. Also, through AI, for each logbook received, we analyze the sentiment of the restorer during work. This alignment facilitates the identification of correlations between environmental conditions and perceived well-being or difficulties reported by restorers, thus contributing to the design of preventive and adaptive strategies that enhance both conservation outcomes and working conditions. A case study from the restoration of the Church *Santa Maria della Misericordia, in the historical center of L'Aquila*, demonstrates the feasibility and advantages of our method. Findings indicate that the integrated data-driven framework supports more sustainable, human-aware restoration practices and provides valuable data for interdisciplinary research.

I. Methodology and Case Study

This study adopts a mixed-methods approach to develop and evaluate an integrated system for sustainable and human-centered restoration, combining environmental monitoring with subjective data collection from restoration professionals. The methodology is presented in Figure 1 and structured into several main components.

Environmental Monitoring. A network of non-invasive commercial and home-made IoT sensors was developed and

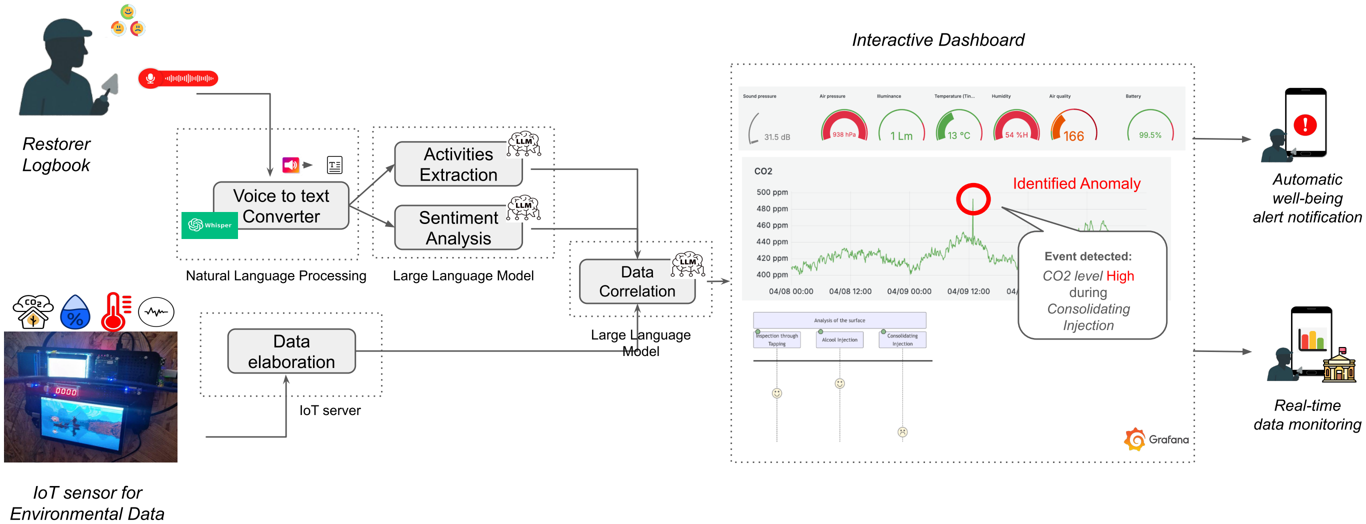

Fig. 1. Data-driven process combining restorer logbook and IoT data to generate an interactive system

then deployed within the restoration site in strategic positions. The sensors continuously recorded key environmental parameters, including temperature, relative humidity, air quality (CO_2, VOC), and concentrations of specific pollutants (e.g., particulate matter). The sensor layout was designed to capture spatial variability across different zones of the site, with particular attention to areas of active restoration.

Voice-Based Data Collection from Restorers. To capture the lived experience and well-being of restoration professionals, we introduced a voice-diary system as a non-intrusive, low-effort data collection method. Restorer are invited to record short daily audio notes describing their daily activities, physical condition (e.g., fatigue, discomfort), cognitive focus, emotional state, and any perceived environmental issues (e.g., poor ventilation, strong odors).

Data Processing and Integration. Restorer data were processed using natural language processing techniques using the automatic speech recognition system Whisper APIs LLM[1]. Following, using OpenAI APIs, activity recognition and sentiment analysis were accomplished to extract structured information on physical, cognitive, emotional, and environmental aspects. Activity and sentiment data were synchronized with the corresponding time-stamped subjective reports to enable correlation analysis. LLM was also applied to integrate the two data streams, enabling both descriptive analyses (e.g., identifying recurrent discomfort patterns associated with specific environmental conditions) and predictive modeling (e.g., forecasting potential risks for well-being or material degradation under certain environmental trends).

Interactive Dashboard. The results are presented in the form of an interactive dashboard, where it is possible to see, for a given time frame, the activities pursued by the restorer with the data collected by the environment for that time. For what concern the sentiment analysis, the audio transcribed by the LLM was elaborated to generate a Mermaid model[2], where it is possible to see the restorer sentiment for each activity.

[1]https://openai.com/index/introducing-chatgpt-and-whisper-apis/
[2]https://mermaid.js.org/syntax/userJourney.html

Also, if real-time environmental data exceeds the threshold or is near it, an automatic alert is sent to the restorer.

The integrated system was piloted over four months during the restoration activities at the Church of the Misericordia, in L'Aquila city. Data were collected from an operator's audio every day, through a Telegram channel, and a sensor node was deployed inside the church in a strategic position to better capture environmental data during work. The result of our analysis shows a preliminary set of activities pursued by the restorer, divided into subactivities and collected into a timeline, together with a sentiment analysis. Results are graphically shown inside Grafana on the right of Figure 1. The outcome of the system supports two complementary modes of use, subject to future developments. *A Proactive mode*, where the system autonomously analyzes patterns and trends to generate recommendations for preventive actions, helping to mitigate risks to both the restorers' well-being and the conservation of materials; and a *Passive mode*, where restoration staff and supervisors can consult the dashboard to retrospectively understand the causes of discomfort or degradation events, facilitating informed decision-making and documentation.

II. Conclusion

This study demonstrated how digital technologies support sustainable, human-aware heritage restoration by monitoring site conditions and restorers' well-being, respecting both the artifacts and those preserving them. The case study in L'Aquila confirmed the potential of our approach to support restorers not just technically, but emotionally and cognitively. Future research will focus on extending the system with a recommended component capable of suggesting preventive actions, personalized interventions, and adaptive strategies to optimize restoration workflows.

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