IS2 inside museums: the case of the “Adria” rattle’s interactive installation

Giulio Pitteri
Department of Information Engineering
University of Padova, Italy

Andrea Franceschini
Department of Information Engineering
University of Padova, Italy

Nicolò Merendino
Computational Media and Arts
The Hong Kong University
of Science and Technology (Guangzhou)

Antonio Rodà
Department of Information Engineering
University of Padova, Italy

***Abstract*—Many museums are increasingly employing interactive installations, such as virtual reality experiences and digital reconstructions, to enhance the presentation of their collections, particularly in relation to ancient musical instruments. However, these digital experiences often do not convey the physicality and tangible qualities of the instruments themselves. In addition, there is a growing demand among institutions for solutions that allow visitors to engage with the acoustic dimensions of these artifacts in a more immersive and accessible manner, including the ability to experience sounds from instruments held in other museums.**

The project centered on the rattle preserved at the Adria National Archaeological Museum was developed in response to these needs. It aimed to create an interactive installation within the museum, featuring an electronic replica of an Etruscan rattle dated to the third to fourth centuries BC. This replica was constructed using a microcontroller-based system housed within a 3D-printed shell, which was modeled from a scan of the original artifact. The device is capable of reproducing sampled sounds of the original instrument and is paired with an interactive touchscreen display that offers contextual information and a digital twin of the artifact. The replica communicates wirelessly with the display through Wi-Fi and has access to an online database of audio samples recorded from other musical instruments housed in museums across the region.

Although not intended as a perfect visual reproduction, the outer shell was enhanced with tactile reliefs that replicate the original decorative motifs and equipped with haptic feedback features to ensure accessibility for visitors with visual or auditory impairments.

***Index Terms*—Internet of Musical Things, Microcontrollers, Interactive Installations, Digital Musical Instruments, Computational Ethnomusicology**

I. INTRODUCTION

Technologies such as 3D scanning, audio sampling, and, more broadly, comprehensive data collection have become essential tools for knowledge preservation in both the cultural heritage and computer science domains. However, many institutions are still not fully exploiting the potential of these technologies. The project presented in this paper operates at the intersection of these two fields, investigating how contemporary technological solutions can enhance engagement with museum exhibitions. In addition, it explores how a distributed network of electronic devices can support new approaches to the study and interpretation of historical contexts and soundscapes.

In this paper, we present an Internet of Sounds (IoS) system designed to offer an engaging experience centered on an ancient rattle that is currently housed in a museum in Adria, Italy. The paper begins with a concise overview of the current state of research in relevant fields. We then propose a conceptual framework for the development of projects situated at the intersection of the IoS and the enhancement of historical and cultural heritage. Following this, we detail the design process of a specific interactive installation of the Adria Rattle, also known as *Sonaglio di Adria*. Finally, we offer a preliminary evaluation of the design process and the results achieved through the practical application of the proposed framework.

II. BACKGROUND

In this section, we outline the two research domains that form the basis of our study. We begin with a brief overview of the application of technology in projects related to cultural heritage. Subsequently, we investigate the Internet of Sounds and its relevance to the context of our work.

A. Technology as a mean to enhance Cultural Heritage

For a few years, museums and cultural heritage institutions have begun to employ connected technologies inside their respective contexts, particularly those centered around sound and music. The Internet of Things (IoT) offers new options to engage visitors while preserving intangible artifacts, and to create augmented experiences that surpass traditional exhibition formats. IoT has found fertile ground in museum environments, often rich in soundscapes and historic narrations, which can benefit from technologies that can capture and interpret acoustic data[7]. For example, audio devices embedded in art galleries can monitor noise levels to help preserve fragile artifacts, while smart speakers can provide personalized audio guides that adapt to the location of a visitor. More specifically, some museums have begun to experiment with soundscapes and dynamic audio environments to recreate the acoustic soundscape of historical settings, such as a medieval market or a battlefield. These applications not only improve the visitor experience, but also contribute to the conservation and interpretation of intangible cultural elements[5].

B. The Internet of Sound

In parallel, the Internet of Sound (IoS) introduces a more performative and expressive dimension to cultural heritage[1, 3, 20]. Smart musical instruments, wearables, and interactive sound installations are being used to revive musical traditions and visitor engagement[9, 17, 21]. In virtual museums, for example, digital twin technologies have been employed to simulate historical music performances, allowing users to interact with reconstructed instruments and sound environments[22]. An interesting case in this line is the use of digital twins to preserve and showcase Kunqu Opera, a classical Chinese art form, by means of immersive platforms that combine audio archives, 3D modeling, and ChatBot-like avatars. These systems not only are useful for documenting musical heritage, but they also invite users to co-create and reinterpret it, bridging the gap between past and present[26].
The integration of IoS into cultural heritage settings is not merely a technological novelty: it reflects a deeper need for a shift toward multisensory experiences and inclusive storytelling. Projects like meSch (Material EncounterS with Digital Cultural Heritage)[1] have demonstrated how tangible smart exhibits can be designed to respond to visitor's behavior, delivering audio descriptions that are more engaging and contextually relevant. These initiatives enable curators to think about layered experiences, where sound becomes a medium of connection, interpretation, and memory[14, 25].

III. Framework for IoS systems in cultural heritage related projects

Building on the research mentioned in the previous section, we propose a framework for the development of projects at the intersection between the IoS and projects that target cultural heritage.

The formulation of our framework started from assessing what the institutions demands were, in particular what their needs were in terms of data recording and accessibility, visual and tactile interactions and feedback, and general structure in terms of number of devices and their capabilities. After gathering all their suggestions, we designed a general logic block diagram for a generic museum installation oriented at cultural heritage exhibitions, together with a standard format for the data transmitted and received by the various components. This diagram assumes that the installation makes use of an electronic device called tangible replica, which allows users to interact with the main part of the installation but also has some functions on its own, like in case of an installation about an ancient musical instrument, it can track the user gestures and play back the sounds the original instrument would have made.
This requires the transmitted data format to store different kind of information, from spatial orientation to generic actions and sound data, and to this purpose, the easiest choice is to use the Open Sound Control (OSC) protocol. This protocol allows the data to be sent as simple text messages, eventually containing the audio data path to retrieve it, and the various events can be stored both in the tangible replica's cache and sent to the installation's main computer to be relayed to an online database, which can in turn be explored using a graphical user interface such as a dashboard.
Using this structure, the audio data sent to the tangible replica to be played can either come from pre-recorded samples from the original instrument, or either be obtained from a physical simulation of the acoustics of the instrument itself, called Physical Modeling Simulation, which can generate the sound on the fly starting from the physical data sent by the device, and then relay the audio back to the tangible replica. This block diagram is shown in Figure 1.

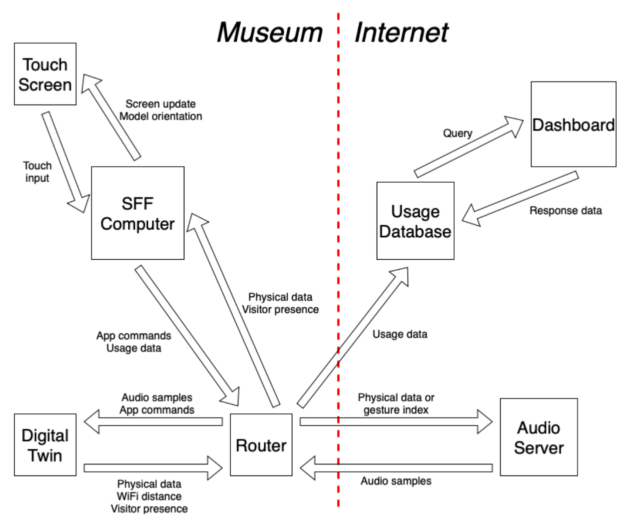

Fig. 1. Diagram of the general structure and data flow of an installation.

IV. Project description

Following the formulation of our framework, we collaborated with a relevant cultural institution to implement the theoretical insights proposed. To this end, we now present the development of a specific case study.

A. The Adria Rattle

This research presents the development of an installation project centered around the archaeological object known as the "Adria Rattle," a ceramic artifact discovered in proximity to a child's grave in the northern Adriatic region[6]. The ceramic rattle, or sonaglio, dating from the fourth to third century BCE, was discovered in the necropolis of Ca' Cima near the grave of a child. This globular object, characteristic of the High Adriatic Ceramic tradition, is flattened at the poles and internally hollow, containing small elements that produce sound when shaken. Its surface is decorated with

[1] https://www.suggesto.eu/en/progetto-mesch

diluted black-reddish paint: a continuous band encircles the body at its widest point, from which radiate lines on both sides: 12 reddish rays descending from the upper apex on one face, and 6 or 7 blackish rays from the lower apex on the other. Irregular transverse impressions, probably made with a roulette tool, are scattered across the surface. The clay is a warm camel color, consistent with regional ceramic practices.

The rattle was most likely a funerary offering, placed by the parents as a symbolic gesture of mourning and remembrance. Although it may have served as a toy during the child's life, its presence in the grave suggests a deeper ritual significance, possibly intended to maintain a sensory link between the living and deceased. The museum has also emphasized the sonic and emotional dimensions of the rattle through guided visits and sound-based experiences, strengthening its role not only as an artifact, but as a cultural and affective object embedded in ancient mourning practices.

B. The team

The project presented here is the result of a collaborative effort by a multidisciplinary team composed of researchers and professionals from a diverse range of fields. Central to this initiative was the involvement of archaeologists whose expertise ensured the historical and contextual accuracy of the material. Equally integral to the project was the active participation of the management team of the Museo Archeologico Nazionale di Adria, whose institutional support and curatorial insight played a crucial role in facilitating access to key artifacts and interpretive resources. In addition, the project benefited from the contribution of computer scientists and designers specializing in Digital Musical Instruments (DMIs), whose work enabled the integration of interactive and sonic technologies into the interpretive framework. This convergence of archaeological, museological, and digital design competencies underscores the project's commitment to fostering innovative, research-driven approaches to cultural heritage interpretation.

V. Initial Data Collection

In line with modern archaeological practices[8, 24], prior to the design phase, the archaeologist team performed a series of tasks to collect data from the rattle on its characteristics. These operations mainly involved capturing images, creating a 3D model, and recording sound samples of the object.

A. 3D scanning and photography

The first imaging of the rattle was made using a structured light 3D scanner, which is a device capable of obtaining the external three-dimensional shape of an object by projecting light patterns, such as grids or stripes, onto its surface. The accuracy of these scanners varies depending on the projected pattern size and the optical quality of the device, going as low as 10 micrometers. The scanner used for the rattle captured details up to 300 micrometers, enough to have a detailed image of all the decorations and the surface defects while keeping the model to a reasonably small memory size. This kind of imaging also allows us to obtain a surface texture representing the true colors of the object, the same colors an observer would see under uniform white illumination, without the need to put the object inside a white box.
The following imaging analyses were performed to explore the inside of the rattle, and the first was carried out using an X-ray machine, obtaining views of the artifact from the sides and the top. These first images allowed us to confirm that the rattle contained four sphere-shaped elements, arguably made of the same material as the rattle's enclosure, and also to evaluate the thickness of the enclosure in different parts of the object. They also showed an opening on the top half of the instrument where the shaking elements were inserted and closed afterwards, and it can also be seen from them that the rattle was not made by joining two half shells together but was instead manufactured from the bottom moving upward and finally closed at the top.

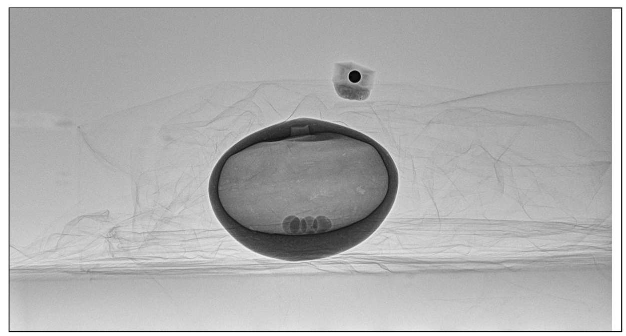

Fig. 2. RX image of the rattle taken from the front side.

The last imaging of the rattle was performed using a computed tomography scan, in which multiple X-ray measurements taken from different angles were processed by a computer to obtain cross-sectional "slices" of an object in all three directions. One of the main differences between this kind of imaging and a classical X-ray scan is the possibility of combining all the slices to build a three-dimensional model of the insides of the rattle. This model confirmed the presence of the four elements inside and was used to obtain a more accurate measurement of the thickness of the enclosing layer, in particular to assess where the most delicate spots on the surface were. This model will also be invaluable when making simulations to find the resonant modes of the rattle's cavity, a crucial step in trying to reproduce the sound generation of the instrument from a physics point of view.

B. Audio Sampling

Being an artifact that maintains its integrity, the rattle is currently capable of producing sound, so the natural step in this direction was to sample it. The recording was made in an anechoic chamber, a room designed specifically to remove all possible sound reflections from the walls, as well as from the floor and the ceiling. In this way, the only sound recorded is the one coming from the instrument itself without any reverberation or echoes added to it, which can be added in a second phase to evaluate the sound effect inside different kinds of environment. A professional microphone was used so that no particular frequencies were enhanced and the sound was sampled at the highest sample rate (192 kHz) and highest bit depth (24 bits/sample). To cover all different sound emissions, the rattle was shaken in three separate ways: one by flipping it from top to bottom, one by shaking it vertically and horizontally, and one by rolling it on its side, and each way was performed with different movement intensities. The entire process was also recorded on video to have a reference of the particular movements made to produce each sound, and the resulting recording was then split into individual audio fragments, tagged by movement type and intensity level.

Fig. 3. Image of the audio recording process inside the anechoic chamber.

VI. Project development

In this section, we discuss the development of the system. The following paragraphs outline the co-design process that informed the selection of the specific components to be included. We then provide a detailed account of the design and implementation of each element of the system.

A. Co-design process

Following the initial phase of data collection, our efforts shifted toward the design and development of the installation itself. To guide this process, we adopted a co-design approach[2, 19], engaging a range of stakeholders involved in the broader funded project.

The choice to employ a co-design approach stemmed from a desire to incorporate diverse perspectives, accounting for both conceptual and practical considerations deemed significant by each participant. By fostering collaborative dialogue, the design process aimed to align with the shared values and expertise of the group, ensuring that the final result would be contextually grounded and functionally robust.

Three focus groups were organized as the primary format for the co-design sessions. These sessions aimed to explore and clarify several key dimensions of the installation:

- The definition of specific components of the system
- The balance between aesthetic experience and informational content
- Practical constraints concerning installation setup and long-term maintenance

Each session began with a presentation of the available design options, followed by a structured round of commentary from all participants. These discussions were supplemented by real-time sketching, which served to visualize potential configurations and facilitate a collective understanding of design possibilities.

B. Outcomes of the Co-Design Process

The collaborative sessions culminated in the formulation of a detailed design brief, which outlined a dual component system: a **tangible interface** and an **interactive screen**.

- The tangible interface was conceived as a multifunctional element: it would play the audio recording of the rattle, provide a tactile representation of the rattle and its interaction, and serve as a control device for engaging with the interactive screen.
- The interactive screen was intended to display a rendered 3D model of the rattle and, upon user interaction, provide detailed technical and historical information about the artifact.
- Importantly, the focus group emphasized that the tangible interface must not overshadow or replace the original rattle, which would remain displayed in a separate exhibit case. Participants expressed a strong preference for prioritizing knowledge transmission over creating a dramatic or overly narrative presentation of the provenance of the object. They also underscored the importance of highlighting the technological advances in contemporary archaeology.

Further discussions addressed spatial configuration, with an emphasis on visitor experience, accessibility, and preservation of the installation. Practical concerns such as prevention of theft, durability, and the potential to collect data on user interaction were also integrated into the final design considerations.

C. Installation Design

Once the co-design session provided an exhaustive overview of what was needed to produce an effective system, the development team (authors of this article) proceeded with the actual design of the system. The design process consisted of selecting electronic components and **designing a circuit**, **[**embedding strategy] to store the circuits in a tangible interface, designing a **[**tangible interface], designing a **Graphical User Interface**, and, lastly the team worked on the final **installation setup**. The following paragraphs detail the processes mentioned above.

1) Electronics Design: The choice of electronic components used was made to ensure enough resources to maintain connectivity, process sounds, and a reasonable power-on duration while maintaining a limited battery space occupation. Considering this, the chosen microcontroller was one of the ESP32 family[10], which guarantees enough space for code and dynamic memory (1.3 MB) while maintaining moderate power consumption when fully operating ($\sim$ 100 mW). Moreover, the battery duration can be optimized by properly setting the microcontroller in a deep sleep state when certain conditions are met.

The other components chosen are a 3W amplifier connected with a 4 Ohm speaker, an SD reader module to fetch the audio fragments stored locally on a SD card, an accelerometer and a gyroscope (IMU) to measure both the orientation and the linear acceleration of the device, a LiPo battery, and a boost module to charge it. Later, an NFC reader module was added to detect when the device was picked up by a visitor by reading a tag placed on top of the device's resting platform, so that when the device is far away enough, the tag can no longer be read. Upon a consideration emerging during the focus groups sessions, we also added a vibration motor to provide haptic feedback when the device is shaken. Table I summarizes the complete list of components. The protocols used to communicate with the sensors are the following: I2C for the IMU and NFC reader, SPI for the SD card reader, and I2S for the audio amplifier.

Component	Description
Esp32 Wroom Dev Module	Microcontroller
MPU6050	I2C Accelerometer and Gyroscope
MAX98357	Audio Amplifier
PN532	I2C NFC tag reader
LiPo Rider Plus	Battery charger and voltage converter
LP953450	1800 mAh LiPo battery
MCABS-274-RC	4 Ohm mini speaker
WPM458	Haptic motor module

TABLE I
TABLE SUMMARIZING ALL ELECTRONIC COMPONENTS USED FOR THE RATTLE'S TANGIBLE REPLICA.

2) Optimization of the circuits: The next step in the design process was to choose how to connect the electronic components and to place them in a disposition suitable to fit them inside the rattle's printed shell. The choice was made to adopt a clam-like solution, with the components distributed between two PCBs designed specifically for this prototype, one for each half of the shell, interconnected with a ribbon cable connector. On each board, the components were placed to ensure minimum space occupation and leave enough space for both the board screws and the shell screws. Each board was placed in its half of the shell with the components facing down, while the battery was housed in the space between them.

One challenge faced was deciding the device's behavior when charging through its USB port, particularly if the device should turn on automatically when charged or charge without turning itself on. The choice was made as follows: the device should turn on when charging but stay on only if placed on top of its resting platform; otherwise, it should turn itself off using a software switch. To achieve this a particular circuit was realized between the device's external USB port, the battery charger, and the microcontroller, thus detaching the USB port used to charge it from the real USB port of the micro, and using a pin to sense when the device is connected to a charger and another pin to turn it off by pulling the base of an npn transistor to 0 Volts.

3) Tangible Interface Design: Having obtained an accurate three-dimensional representation of the rattle's surface, the next step was to use it to make a 3D plastic shell for the tangible replica[18]. Given the high number of vertices of the model obtained from the 3D scanner, the first step was to decimate it to reduce the number of faces and remove most of the surface defects on the original, such as small holes and bumps. After that, the texture was remapped to separate the decorations from the base color of the rattle, which allowed us to manipulate the model in a separate way where the decorations were placed. This operation was critical in obtaining a relief version of the shell, in which the decorations were extruded outward, and this was done to allow visually impaired visitors who cannot see the decorations on the original rattle to feel the same decorations on the tangible replica's surface.

To allow the tangible replica to be easily serviced, the shell was printed in two halves kept closed using four screw holes, together with a front hole exposing the micro USB port for both recharging and programming, and twelve small holes on the bottom to allow the sound from the internal speaker to go out of the shell. Eight other smaller screw holes are placed inside the shell to keep the two electronic boards in place, and the external screw holes are finally covered with rubber lids.

Fig. 4. Screenshot of the initial view of the application displayed on the touch screen. The rattle's model moves when the tangible replica is moved by a visitor

4) Graphical User Interface: With the tangible replica ready, the final step was to program and assemble the remaining parts of the museum installation. They consist of a 32-inch touch screen, a sound bar, and an Intel small form factor computer, together with a router that provides a WiFi network and Internet access, and a wooden platform for the tangible replica to charge and house an NFC tag used to detect when the device is picked up. The screen is used to display an interactive application, programmed using the Godot 3D engine and linked with the tangible replica[23], with expandable sections explaining the instrument's history, the analysis made using imaging techniques, and the realization process of the twin itself. The main screen of the application shows the expandable sections and the 3D model of the rattle obtained with the 3D scanner, complete with its texture, and the model itself can be rotated when the visitor picks

up the tangible replica. While the model on screen rotates, the tangible replica keeps track of the various movements, and when it recognizes a specific gesture, it plays the corresponding audio fragment chosen from a subset of all the sampled audio, modulating its volume using both the gesture velocity and the acceleration detected.
All communication between the tangible replica and its companion application is done through the WiFi network using the OSC protocol, in which simple text messages embedded in UDP packets are transmitted[11, 12]. The tangible replica sends IMU data and the presence or absence of the NFC tag, while the application sends reset and turn off commands. One aspect from the museum point of view, being that this device is freely pickable by the visitors without any attached cables, is to ensure that nobody steals it, and to achieve this the tangible replica periodically measures the WiFi signal power, so that when it becomes lower than a given threshold it sends an OSC alert message to the application that warns the museum with a loud acoustic sound.

5) Installation setup: Once the components outlined above had been successfully designed and tested, the project advanced to the installation phase. This stage was carried out in close collaboration with museum staff, whose insight and logistical support proved invaluable throughout the process. Although minor adjustments were made to the initial setup to accommodate specific institutional requirements, the overall implementation went smoothly and without significant complications. Fig 5 shows the setup of the installation.

Fig. 5. The finished installation placed inside the museum. On the right is the display of the original object.

6) Opening and feedback: The interactive installation was subsequently integrated into the permanent exhibition setup of the Adria National Archaeological Museum. From a technical perspective, the system functioned reliably, with no significant issues reported during the eight hours of continuous observation. Following this session, an informal interview was conducted with the museum director to gather initial feedback. The director reported that the installation operated effectively and observed that visiting students interacted with it consistently and with a high level of engagement. While the overall response was positive, the director also noted the occurrence of minor glitches, which, although infrequent, merit further investigation and refinement in future iterations of the system.

VII. Inter-museum Database

The Adria rattle project is an example that demonstrates how ancient musical artifacts can be recontextualized through digital innovation. It is part of a larger national research line that spans museums in the northeast regions of Italy to explore the historical, scientific, and ethnomusicological aspects of musical artifacts. This effort is more than a simple task of cataloging objects: its objective is to grasp a more defined knowledge of the cultural impact of music among the ancients by collecting archaeological documentation, scientific imaging, and contextual interpretation.
The main focus of this research is the development of an inter-museum database, a digital archive designed to store all the information retrieved from these objects. This includes archaeological reports and photos, high-resolution scans and imaging, virtual 3D models, and acoustic data. Given that one of the project's main goals is to create a shared cultural interconnection, this database has also been made accessible to other institutions, such as museums and their visitors, and in this way visitors' experience can be improved and enhanced. Visitors can see different artifacts and compare them with similar examples from other collections, explore internal structures through interactive virtual imaging using digital twins, and locate objects within a broader historical and geographical context.
This database was not created just for this research as an ad hoc archive, but as an incremental resource aligned with the FAIR methodology, archiving information in a way that makes data searchable, accessible, internally linked and reusable, aligning with the more general principles of Open Science. This means that each entry is carefully documented with rich metadata, assigned persistent identifiers, and stored in formats that support human and machine readability. Such guidelines not only make reproducibility easier, but also allow museums to increase each other's work, creating a dynamic ecosystem of knowledge exchange.
Building on the example set by the Adria rattle installation, the creation of similar digital twins for musical artifacts in other museums opens the possibility for a networked museum experience, where each replica is not limited to its physical location and original artifact. Being connected to the Internet, these installations can be seamlessly linked across institutions, allowing visitors to engage with and explore musical objects preserved in other museums, all from within the installation they are currently visiting. This network allows museums to become an entry point for visitors to a broader cultural scenario, where geographical boundaries give less constraints, and

the visitor's experience is enhanced through virtual proximity to otherwise inaccessible heritage.

A. *Bank of Sounds*

A particularly innovative aspect of the database is the Bank of Sounds, which captures the sampled sounds of ancient musical instruments that are still playable. These recordings are made in a controlled environment, namely an anechoic chamber, using professional-grade microphones to ensure fidelity and eliminate ambient interference. For instruments too fragile or fragmented to produce sound, researchers may employ physical modeling simulations to reconstruct their acoustic behavior. These simulations are too computationally intensive for embedded devices and are therefore processed on external servers, while microcontrollers in tangible replicas capture user interactions and relay them for sound generation. This architecture transforms each tangible replica into a node within the Internet of Sound, capable of responding to visitor gestures and producing personalized auditory experiences.
The benefits for museum visitors are quite interesting. Through interconnected installations, a visitor inside one museum can engage with the digital twin of an object in another, experiencing its sound and story as if it were physically present there. This not only improves access, but also broadens the boundaries of cultural participation. Moreover, by adhering to the FAIR principles, the project ensures that these experiences are not just for their current moment. The data behind them are formatted for longevity, transparency, and reuse, making them available to educators, researchers, and technologists who wish to reproduce or improve the work. In this way, the convergence of the IoS technologies with Open Science practices marks a change in cultural heritage. It invites institutions to move beyond static displays toward interactive and data-driven storytelling. It challenges researchers to think about not only preservation but also accessibility and reproducibility. And, most importantly, it allows visitors to become active participants in the cultural context, engaging with history through sound, interaction, and shared digital memory.

VIII. Conclusions

This article offers three primary contributions to the ongoing discourse at the intersection of technological innovation and cultural heritage. First, it introduces a conceptual framework for projects that merge the Internet of Sounds (IoS) with cultural heritage initiatives and demonstrates its applicability through the development of a site-specific interactive installation. This contribution aligns with current debates on the role of technology in improving public participation in heritage artifacts, particularly in the domain of ancient musical instruments [16]. Second, the paper illustrates the potential of IoS applications in the field of modern archaeology. It highlights the methodological compatibility between the two domains, notably through shared practices such as 3D scanning and audio sampling, thus demonstrating how archaeological data can be effectively integrated into IoS systems [15]. Third, the study positions IoS as a tool not only for interpretation but also for data collection. Furthermore, from the day the installation was set up and connected inside the museum, it started to collect usage data from visitors using it. This data is useful to assess whether visitors tend to use the tangible replica when approaching the installation and how their use of it changes over time. From a simple plot in time of the orientation, for example, we can understand how many times in a day the object is picked up by someone and what kind of movements the visitors like to do more often, and coupling this data with the acceleration data we can also join together the various types of gestures with their movement's intensity. An example of changes in orientation during a time interval is shown in Figure 6. By fostering interactive visitor participation, the installation enables the collection of meaningful usage data, thus contributing to ongoing research on museum visitor experience, audience engagement, and digital strategies for cultural promotion [4, 13].

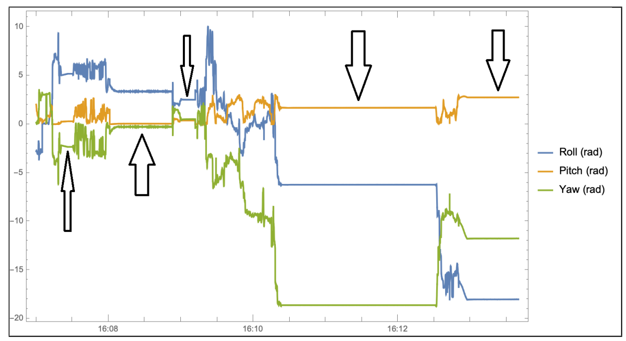

Fig. 6. Time plot of the tangible replica's orientation in terms of its Roll, Pitch and Yaw angles. The intervals where the angles don't change are when the device is at rest and are highlighted by arrows.

A. *Limitations and future works*

The framework was successfully applied to this installation and it was well received both by the institution and by visitors; however, it still presents many aspects that can be improved. Moreover, we still need to gather more data produced by the installation over a broader period of time, in order to assess more accurately visitor's usage trends and effectiveness to engage visitors not used to museum experiences.

This kind of assessment can also be improved by adding the information of distance from the tangible replica's platform by measuring the power of WiFi signal, which although not very accurate, it can give an estimate whether visitors like to stay close to the installation's screen or if they like to play with the device in a more open space.

Further improvements can be aimed at visually or hearing impaired people, noticing that while they are able to feel the rattle due to the relief decoration on the outer shell and are able to feel the sound thanks to the haptic feedback, they have to be initially aware of the presence of the tangible replica, and a solution to this can be made by coupling by proximity the installation with the audio guides provided by the museum to relay a message alerting visually impaired visitors of the device presence.

IX. Acknowledgments

This work was partly funded by the MusE project (Musical Ecosystems of Ancient Northern Italy (XIII B.C. - VII C.E.), PRIN 2022 DD 104, project code 2022W2CBXS), and by the TeMA project (Musical Evidence from Antiquity in the Tri-Veneto Region: A Survey, Repertoire, and Promotion of Their Cultural Heritage, 2020 - Prot. BIRD204753).

The authors thank the Museo Archeologico Nazionale di Adria for their support and for providing access to their collection and exhibition spaces. The authors also thank TMB SpA for access to their production plant in Ceregnano, Italy, and for their technical expertise in conducting imaging analysis on the Adria rattle.

A. Contributions by authors

The contributions to the work presented in this paper were distributed among the authors as follows. Author 1 was responsible for the design of the core components of the system, including electronic circuits, the programming of the Tangible User Interface (TUI), and the development of the main structural framework of the system. Author 2 led the design and implementation of the graphical user interface (GUI), ensuring its usability and integration with the overall system. Author 3 focused on optimizing the TUI design and also facilitated the focus groups that informed various stages of the system's development. Author 4 provided supervision throughout the project and played a key role in guiding the writing and organization of this article.

References

[1] Luigi Atzori, Antonio Iera, and Giacomo Morabito. The internet of things: A survey. *Computer Networks*, 54(15):2787–2805, 2010.

[2] Ingrid Burkett. An introduction to co-design. *Sydney: Knode*, 12:12, 2012.

[3] Anita Choudhary. Internet of things: a comprehensive overview, architectures, applications, simulation tools, challenges and future directions. *Discover Internet of Things*, 4(1):31, Dec 2024.

[4] Luigina Ciolfi and Liam Bannon. Engaging with cultural heritage: a hci perspective. In *Cultural Heritage Communities: Technologies and Challenges*, pages 29–52. Routledge, 2017.

[5] Ashraf Darwish, Aboul Ella Hassanien, and Vaclav Snasel. *IoHCT: Internet of Cultural Heritage Things Digital Twins for Conservation and Health Monitoring of Cultural in the Age of Digital Transformation*, pages 1–21. Springer International Publishing, Cham, 2022.

[6] Rita Deiana and Alberta Facchi. Il sonaglio in terracotta della tomba n. 39 dalla necropoli preromana di ca'cima ad adria (ro): prime considerazioni dalle analisi multispettrali. *Suoni e strumenti musicali nel mondo antico: per un sistema disciplinare e metodologico integrato.-(Studia archaeologica 0081-6299; 265)*, pages 169–176, 2024.

[7] Elizabeth M. Astorga González, Esteban Municio, Maikel Noriega Alemán, and Johann M. Marquez-Barja. Cultural heritage and internet of things. In *Proceedings of the 6th EAI International Conference on Smart Objects and Technologies for Social Good*, GoodTechs '20, page 248–251, New York, NY, USA, 2020. Association for Computing Machinery.

[8] NB Hahulina, LI Maslikhova, and SV Akimova. Modern technologies applied to archaeological research in voronezh region. In *IOP Conference Series: Earth and Environmental Science*, volume 272, page 032037. IOP Publishing, 2019.

[9] T. Irava, M. Georgescu, and P. Lungu. Managing sustainability in the internet of musical things: a bibliometric and literature review of iot integration in the music sector. *Management of Sustainable Development*, 17(1):17–32, 2025.

[10] Aman Jagwani and Victor Lazzarini. Interactive audio toolkit: Creating sonic experiences and installations with low-cost, low-power microcontrollers. In *Symposium 2024 (UbiMus 2024)*, page 54, 2024.

[11] David Johnson, Daniela Damian, and George Tzanetakis. Osc-xr: A toolkit for extended reality immersive music interfaces. In *Proceedings of Sound and Music Computing Conference*, pages 202–209, 2019.

[12] Sebastian Madgwick and Thomas Mitchell. x-osc: A versatile wireless i/o device for creative/music applications. In *SMC Sound and Music Computing Conference*, volume 2013, 2013.

[13] Manuel Martinez, Ana Fernandez-Marciales, and Marta Zorrilla. Iot and smart badges to track visitor behaviour in cultural spaces. *Electronics*, 13(20):3977, 2023.

[14] Edoardo Micheloni, Niccolo' Pretto, Federico Avanzini, Sergio Canazza Targon, Antonio Rodà, et al. Installazioni interattive per la valorizzazione di strumenti musicali antichi: il flauto di pan del museo di scienze archeologiche e d'arte dell'università degli studi di padova. In *Atti del XXI Colloquio di Informatica musicale. Proceedings of the XXI Colloquium of Musical Informatics*, pages 203–208, 2016.

[15] Elisa Micheloni, Luca Simeone, and Paolo Borin. Progettazione e sviluppo di un sistema interattivo per la valorizzazione di uno strumento musicale antico. In *Convegno Nazionale AIxIA*, 2020.

[16] Elisa Micheloni, Luca Simeone, Alessandro D'Aloia, Giorgio Poletti, Laura Piovan, and Paolo Borin. Installazioni interattive per la valorizzazione di strumenti musicali antichi: il flauto di pan del museo di scienze archeologiche e d'arte dell'università degli studi di padova. In *IX Congresso Nazionale di Archeometria AIAr*, 2022.

[17] Stefania Serafin, Cumhur Erkut, Juraj Kojs, Niels C. Nilsson, and Rolf Nordahl. Virtual reality musical instruments: State of the art, design principles, and future directions. *Computer Music Journal*, 40(3):22–40, Sep. 2016.

[18] Ricardo Simian. 3d-printed musical instruments: lessons

learned from five case studies. *Music & Science*, 6:20592043231210653, 2023.
[19] Marc Steen. Co-design as a process of joint inquiry and imagination. *Design issues*, 29(2):16–28, 2013.
[20] Luca Turchet, György Fazekas, Mathieu Lagrange, Hossein S. Ghadikolaei, and Carlo Fischione. The internet of audio things: State of the art, vision, and challenges. *IEEE Internet of Things Journal*, 7(10):10233–10249, Oct 2020.
[21] Luca Turchet, Carlo Fischione, Georg Essl, DamiáN Keller, and Mathieu Barthet. Internet of musical things: Vision and challenges. *IEEE Access*, 6:61994–62017, 2018.
[22] Luca Turchet, Mathieu Lagrange, Cristina Rottondi, György Fazekas, Nils Peters, Jan Østergaard, Frederic Font, Tom Bäckström, and Carlo Fischione. The internet of sounds: Convergent trends, insights, and future directions. *IEEE Internet of Things Journal*, 10(13):11264–11292, July 2023.
[23] Pierrick Uro, Florent Berthaut, Thomas Pietrzak, and Marcelo Wanderley. Decoupling Physical and Virtual Spaces for New Collaboration Strategies in Co-Located Mixed Reality Instruments. In *NIME 2025 - International Conference on New Interfaces for Musical Expression*, Canberra, Australia, June 2025.
[24] Marin Vodanović, Marko Subašić, Denis Milošević, Jacek Tomczyk, Mislav Čavka, Željka Bedić, and Mario Novak. Modern technologies and artificial intelligence in archaeology and bioarchaeology. *Bulletin of the International association for paleodontology*, 17(1), 2023.
[25] Yanan Wu, Yiyuan Huang, Wenchen Guo, Xiao Li, Zhirui Chen, Zheyu Feng, Yubin Zhu, and Guoyu Sun. Multi-sensory interactive experience design of museum musical instrument collections. In Hirohiko Mori, Yumi Asahi, Adela Coman, Simona Vasilache, and Matthias Rauterberg, editors, *HCI International 2023 – Late Breaking Papers*, pages 420–437, Cham, 2023. Springer Nature Switzerland.
[26] Changman Zou, Sang-Yong Rhee, Lin He, Dayang Chen, and Xiaofei Yang. Sounds of history: A digital twin approach to musical heritage preservation in virtual museums. *Electronics*, 13(12), 2024.