Digital technologies as sensory and cognitive bridges

The Metaverse Lab at the "Infiniti Mondi" House of Emerging Technology in Naples

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The Metaverse Lab of the "Infiniti Mondi" House of Emerging Technology in Naples aims to establish a center for research and training in the Cultural and Creative Industries, focusing on emerging technologies in Heritage Science.

Fig.1 - External façade of the Real Albergo dei Poveri. Metaverse Lab. Credits@S.Giugliano@CNRISPC

The laboratory offers the public a multisensory and multidimensional experience, showcasing diverse applications related to Science, Art, Archaeology, Technology, Tourism (Figs. 1-2).

The Metaverse Lab, located at the Real Albergo dei Poveri of Naples comprises four distinct components or "experiential islands": 1) Online Metaverse: a web-based experience for single or multiple users focusing on archaeological artifacts and sites; 2) Augmented Metaverse: a single-user augmented reality experience that allows exploration of items via a tracking device; 3) Touch Metaverse: an immersive experience using head-mounted displays and haptic devices for user interaction; 4) Immersive Metaverse: a panoramic visualization featuring interactive storytelling using tangible interfaces and motion sensors.

For the project, 19 case studies have been designed, developed, and installed in each "island". The scope of these case studies is to show a pluralistic view of "metaverses" in the context of Cultural Heritage. Rather than presenting a singular and monolithic vision of the Metaver(sic) domain, we highlighted a constellation of digital and virtual environments, each with its own affordances and narrative uses but still interconnectable and integratable —an approach that we argue is more coherent with the multi-layered and holistic nature of Heritage Science.

By combining methodological research with concrete applications across Science, Art, Archaeology, Tourism, and Sport, the Lab aims to demonstrate how immersive and multisensory environments can enhance cultural heritage narration, stimulate new modes of engagement, and offer replicable models of innovation for museums, creative industries, and cultural tourism for different audiences.

OBJECTIVES

The Metaverse Lab is driven by two primary objectives that define its innovative mission. First, it seeks to integrate various forms of digital media by

utilizing cutting-edge technologies, thereby providing users with a dynamic and immersive experience (hybridization of media). Second, it aims to design engaging user experiences based on a Phygital approach, which serves as a sensory, perceptual, and cognitive bridge between the digital and physical realms, enhancing the readability of cultural content. The Lab's initiatives are guided by a structured workflow inspired by the FAIR principles, emphasizing the reusability of data, software, and narratives. The Lab follows principles of Universal Design to ensure clarity, simplicity, and accessibility for diverse users; although some solutions are not open-source, the initiative prioritizes accessibility and encourages potential reuse. The spatial organization strictly complies with European accessibility standards, including EN 301 549 (2021), the Web Accessibility Directive, the European Accessibility Act, and relevant ISO guidelines for usability and technological user interfaces.
The Lab develops and tests solutions in Virtual Reality (VR), Augmented Reality (AR), Mixed Reality (MR), and Extended Reality (XR). It offers a range of experiences, from small-scale applications to expansive multi-projection settings. Various solutions have been implemented, addressing both hardware and software aspects, with a primary focus on content reusability. Here, we will focus solely on the archaeological case studies, demonstrating how technologies are integrated with archaeological data and narrative.

FOCUS ON THE UNDERWATER BAIAE'S CASE STUDY AND ITS ARCHAEOLOGICAL REMAINS

The submerged Roman city of Baiae serves as a prime case study for integrating digital technologies and innovative storytelling to reinterpret and safeguard its unique heritage within the context of the Metaverse Lab. This unique site, which functions as an underwater archaeological park located in the Gulf of Pozzuoli, one of the wider Phlegraean Fields Archaeological Park, is the result of bradyseism, a geological phenomenon that causes notable vertical ground movements due to volcanic activity, ultimately leading to the gradual flooding of the region. In Baiae, more than elsewhere, it seems that natural elements have shaped history: bradyseism, solfataras, and naturally occurring heat and vapors—once used to power bathing facilities and a variety of natural thermal springs—have contributed to the city's renown since antiquity. Agrippa's construction of the Portus Iulius marked the rapid transformation of the coastline. Baiae attracted the Roman elite and emperors Caligola, Claudio and Nerone, rapidly evolving from isolated seaside villas to a densely built landscape of luxurious residences and thermal complexes, as those of Marius, Pompey the Great, Julius Caesar, and Licinius Crassus. In the centuries that followed, Baiae's fame became linked to the reported death of Emperor Hadrian in 138 CE, who had traveled there in search of a cure for his illness (bibliography is huge: lastly, see Pagano *et alii* 2023). With the fall of the Roman Empire between

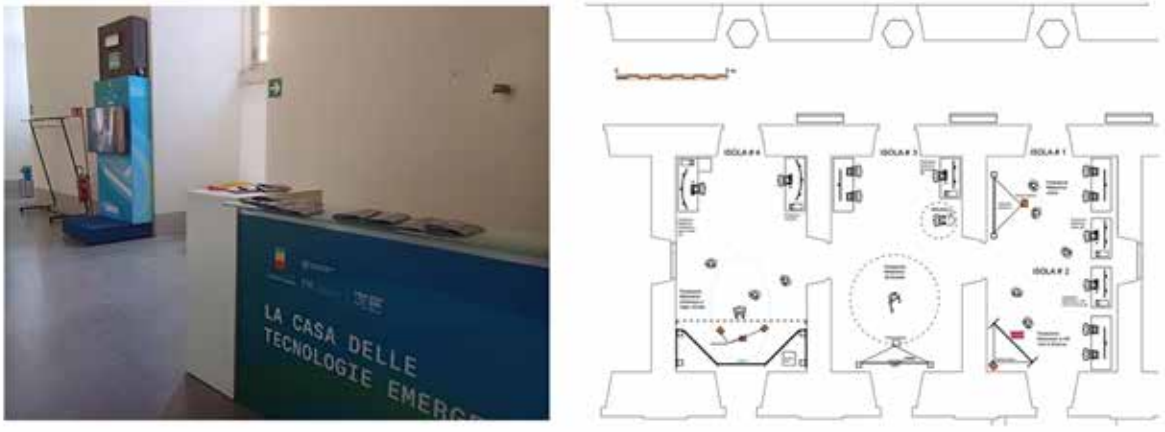


Fig. 2 - Corridories and corners of the Real Albergo dei Poveri, Top view of the Metaverse Lab areas and setup. Metaverse Lab. Credits@S.Giugliano@CNRISPC

the 4th and 5th centuries CE, bradyseism once again shaped the fate of the area: the gradual sinking of the earth's crust caused villas and thermal complexes to be submerged by the sea. Paradoxically, the submersion of archaeological remains also shielded them from modern urban and industrial development, allowing for their preservation. In recent decades, collaborative research and conservation initiatives have enabled the study, restoration, and enhancement of these underwater remains (*Conference* 2025).

In addition to the submerged archaeological site of Baia, which is being studied by the CNR-ISPC in collaboration with the Ministry of Culture (see *infra*), research has also focused on the *fistula plumbea*, an ancient lead water pipeline from Pisoni's Villa, combining heritage investigation with interactive technology (Fig. 4). Discovered in 1924 during early excavations, it remains in its original position in the villa's courtyard (Di Fraia, Lombardo, Scognamiglio 1988; Lombardo 1997). This modest artifact not only helps identify the villa as part of the wealthy Pisones family but also connects us to early Imperial Roman history, characterized by power struggles and intrigues.

The *fistula* consists of three sections joined by two welds, measuring approximately 6.25 meters in length and 6.6 × 7.8 cm in diameter. Its significance lies in three clear relief stamps with the inscription L(uci) PI-

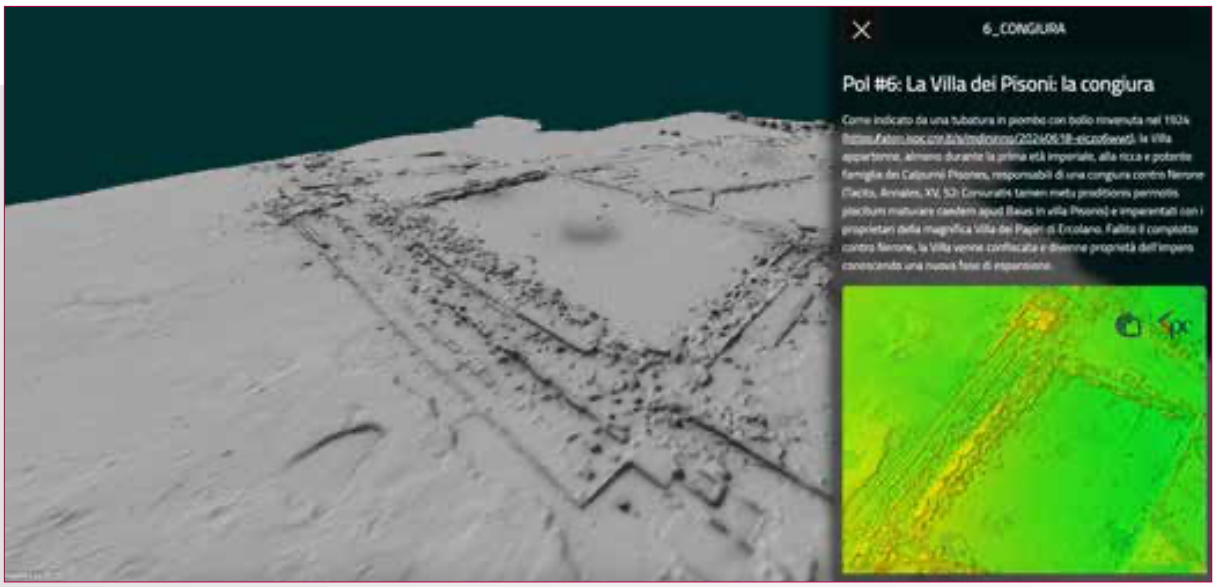


Fig. 3 - Screenshot of the ATON visualization of the submerged Baiae site for the "Infiniti Mondi" project. Credits@CNRISPC.

Fig.4 - Screenshot of the ATON visualization of fistula plumbea for "Infiniti Mondi" project. Credits@CNRISPC.

SONIS, dating it to the early 1st century CE, coinciding with the villa's original construction. While the names on *fistulae* stamps don't always indicate the building's owner, the lack of a nomen gentilicium and Tacitus' reference to a villa owned by Gaius Calpurnius Piso suggest a link to this aristocratic family. However, the exact familial connection between Lucius Calpurnius Piso and Gaius Calpurnius Piso, a key figure in the conspiracy against Emperor Nero, remains uncertain. Little information is known about his personality and motivations for joining the conspiracy. However, he played a key role alongside figures like the poet Lucan and Seneca, Nero's former tutor. The plot was uncovered due to betrayals, leading to Piso's choice to take his own life. Tacitus recounts the events with dramatic intensity, emphasizing the significance of material culture in history.

Tools and technologies applied: Aton, Zspace

The Baiae site has been utilized as a framework for three distinct experiential "islands" of the Metaverse Lab, each contributing unique forms of interaction, archaeological and advancements in software development.

The first one, developed for Island 1 "Online Metaverse," offers a 3D reconstruction of the submerged archaeological remains, informed by an ultra-high-resolution acoustic remote sensing survey of the underwater park, conducted by the CNR ISPC (Violante *et alii* 2023; Violante, Gallocchio, Pagano 2025). This survey employed an integrated approach, incorporating multibeam echosounder bathymetry, shallow-water seismic imaging, and electrical resistivity tomography, which collectively facilitated the creation of detailed 3D reconstructions of the site. The marine surveys generated a high-resolution mesh model that was imported into Blender. Ambient occlusion (AO) maps were created for each segment to visualize small-scale surface details, simulating the interaction of light with different topography, thus improving the perception of underwater structures.

The optimized 3D model was exported and integrated into the ATON Web3D platform, an open-source framework constructed on Node.js and Three.js, designed, developed, and coordinated by CNR ISPC. This platform enables the creation of Web3D/WebXR applications for exploring and interacting with cultural heritage objects and three-dimensional scenes in an online environment, including interaction models, annotations, immersive experiences, and real-time collaboration (https://osiris.itabc.cnr.it/aton/) (Fanini *et alii* 2023).

Users can navigate this virtual environment and explore the sunken villa, intricate mosaics, and harbor structures through simple mouse clicks or smartphone taps, facilitated by the ATON 3D visualization framework. The 3D model of Baiae has been uploaded and enriched with informative points (PoI), providing users with the opportunity to uncover the narrated history of the archaeological site. These experiences can be accessed both online and offline, directly from the main facility, where dedicated desktop stations ensure optimal engagement with

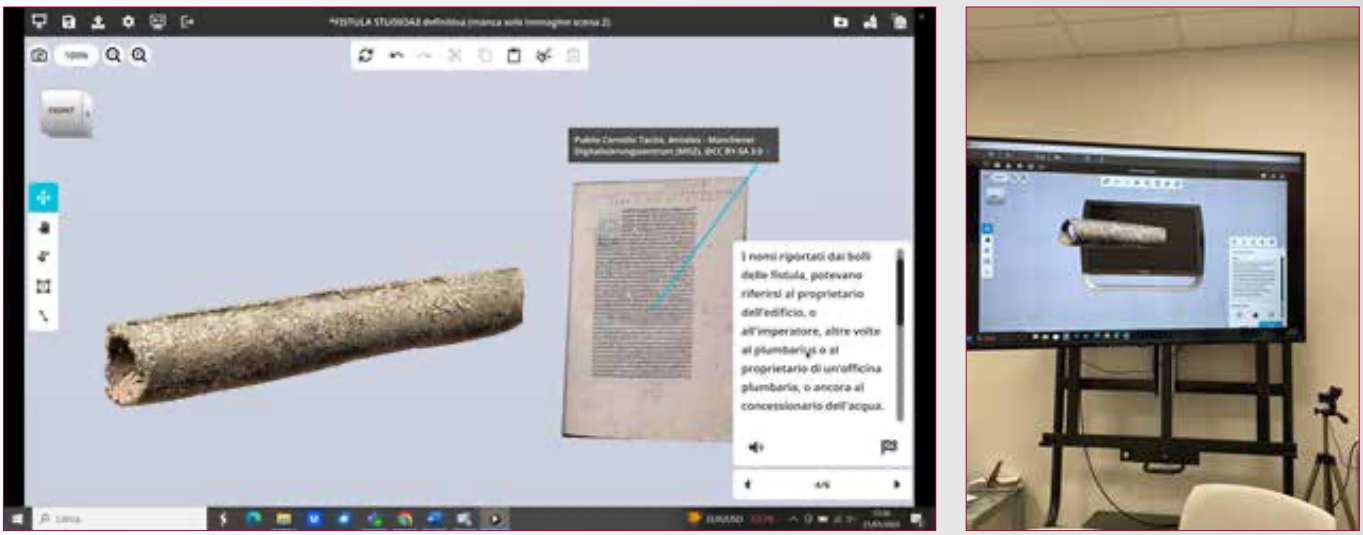
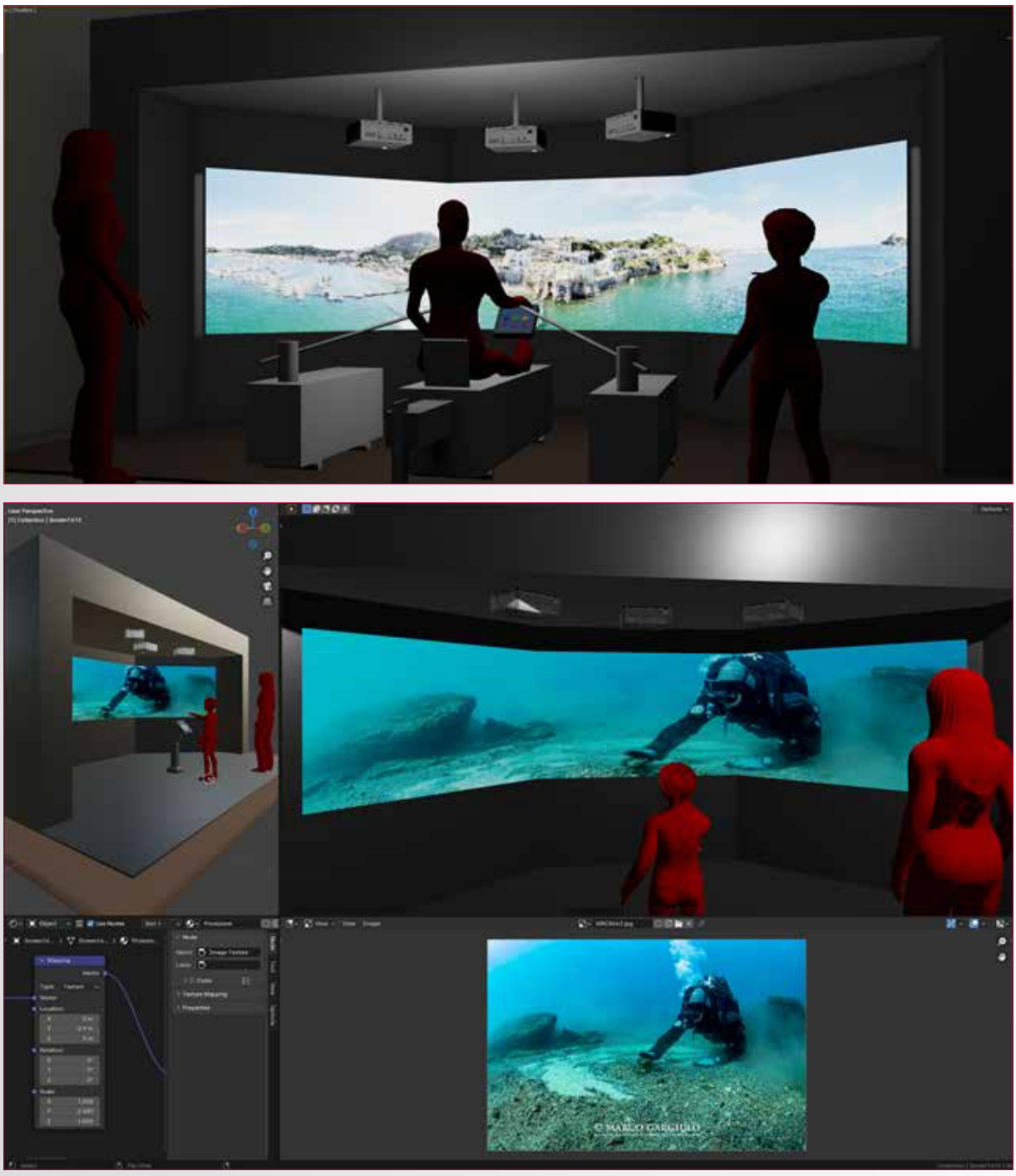


Fig. 5 - Screenshot of the zSpace visualization of fistula plumbea for the "Infiniti Mondi" project. Credits@CNRISPC.

the provided content. Here is the final output for public dissemination: https://aton.ispc.cnr.it/s/dhilab/20240624-2ex9pyngo.
The same workflow is applied to the *fistula plumbea*, findable at this link: https://aton.ispc.cnr.it/s/mdininno/20240618-eiczo6wwt.
Another exciting opportunity is to engage with and explore the lead pipe of the aqueduct within the Island 2 "Augmented Metaverse". This area is powered by the zSpace commercial system (https://zspace.com/), which encompasses three essential components: a PC unit (either a desktop or an All-in-One device), a stylus or pencil, and passive polarized glasses. The central unit features a three-dimensional display equipped with four infrared sensors, which allow the software to accurately calculate the position and orientation of both the stylus and the glasses. This innovative design enables the glasses to function as tools for both visualization and interaction. As users move



Figs. 6 - 7 - Physical setup of Island 4 at Real Albergo dei Poveri with "Moving Baiae" on view, for "Infiniti Mondi" project. Credits@CNRISPC.

around the unit, the scene adapts dynamically to changes in perspective, creating a highly realistic and engaging experience. The stylus serves as an intuitive interaction device, empowering users to engage directly with three-dimensional content and enhancing the overall immersive quality of the experience.

From a commercial perspective, zSpace, distributed in Italy by L'ABCD Edutainment, effectively integrates AR and VR to offer users the opportunity to participate in interactive three-dimensional experiences, ensuring accessibility on all-in-one computers and laptops (Fig. 5).

Baiae is fully appreciated in the Island 4 - "Panoramic Metaverse". Users can navigate the gulf of Pozzuoli using a rowing machine simulator that replicates the arm movements used in Paralympic rowing, adapted for this project, culminating in a virtual experience that immerses them in the seabed. Users can explore Baiae's submerged landscapes through high-resolution, life-sized projections that accurately recreate the coastal and underwater environments (figs. 6 and 7).

The interactive experience installed in the Metaverse Lab, named "Moving Baiae", enhances engagement through multiple input methods, including motion-based interactions, mobile device integration, and remote PC control.

This simulation provides an intuitive and physically engaging way to interact with the submerged ruins, emphasizing the connection between movement, spatial awareness, and digital exploration.

The experience is divided into two parts. First, users row along the Gulf of Baiae, encountering four virtual buoys that activate video-audio narratives about the landscape, bradyseism, and views from the Aragonese Castle, including the ruins of the Baths of Baiae. The fourth buoy at Punta Epitaffio signals the transition to the second phase, an underwater tour of the submerged ancient baths (Lombardo 2009) and Emperor Claudius's nymphaeum-triclinium (Lucignano, Esposito 2010), featuring statues from the Aragonese Castle museum and replicas

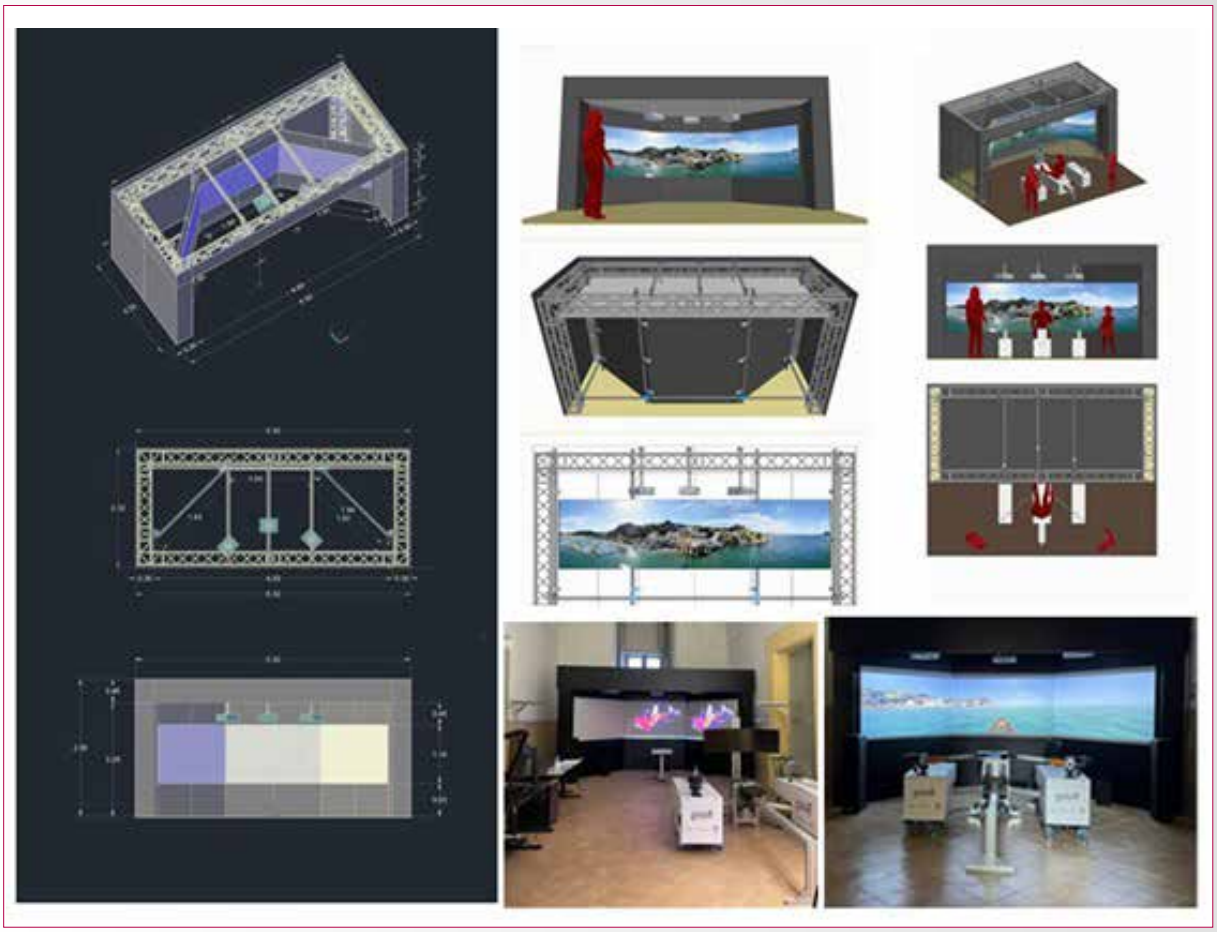


Fig. 8 - Technical prospectus of Island 4 for "Infiniti Mondi" project. Credits@CNRISPC

at the original site. Users then explore the Villa of the Pisoni, where 3D images of the luxurious villa emerge as sediments clear (Davidde *et alii* 2020).
The system is built using both open-source and commercial tools, allowing integration with various interactive elements, such as the rowing simulator. It is programmed with the VVVV visual programming language, ensuring seamless connectivity with peripheral devices like Stream Deck controllers, magnetic panels, motion sensors, and content types (videos, infographics, images).
Furthermore, the system facilitates communication with external PCs, enabling remote control, potential content updates, and live streaming demonstrations.

FOCUS ON THE MANN MUSEUM'S SELECTION OF STATUES

Two notable statues from the MANN (Museo Archeologico Nazionale di Napoli) were showcased on Island 2 "Augmented Metaverse". Selected from the museum's collection, these statues help illustrate daily life in the Vesuvian cities and the artistry of Roman homes, highlighting images of childhood in Roman times and the restoration of Pompeii's gardens. The statues are now part of the "*Domus. Gli arredi di Pompei*" exhibition. Specifically, the statues—depicting a child frightened by a toad and a child holding a hare—originate from the garden of the House of Camillus in Pompeii, are dated to the second half of the 1st century CE, and originally functioned as ornamental fountain spouts. The statues have lost mostly their polychrome surfaces over time due to natural degradation, but the children seem to preserve pigment in the hair, eyebrows, and pupils. That is the reason why these captivating sculptures were meticulously analyzed, alongside the entire assortment of the collection, as part of an in-depth research initiative conducted by the CNR ISPC, in the European project "PERCEIVE - Perceptive Enhanced Realities of Colored Collections through AI and Virtual Experiences" (https://www.ispc.cnr.it/it_it/2023/01/25/perceive/).
Tools and technologies applied: Artec and Zspace
The statues are prominently displayed on Island 2 of the MetaverseLab, utilizing the innovative zSpace software. This powerful software enables users to engage with a meticulously crafted high-resolution digital 3D model, which is generated through advanced techniques such as photogrammetry and laser scanning. In this case, it was employed, prominently featuring the Artec Leo scanner, known for its precision and efficiency in capturing intricate details. The scanner features a two-in-one optical system, an integrated supercomputer, advanced sensors, and VCSEL light for optimal scanning. Its advanced technology captures detailed textures, adapts to lighting, and provides precise texture-to-geometry mapping.
The resulting 3D model was imported into zSpace, where geometric accuracy was preserved. However, color discrepancies appeared; specifically, the texture displayed golden hues that did not align with the statue's actual coloration. To address this, the Metaverse Lab developed a new pipeline for zSpace aimed at improving asset texturing using Studio A3. This collaboration between ABCD and CNR ISPC to update and code modifications approach optimizes workflows and promotes innovation and collaboration for future projects.
Hybridization of media and content reusability
One of the central outcomes of the Metaverse Lab lies in the capacity to merge different media, technologies, and narrative models into a coherent and reusable ecosystem of cultural experiences. Hybridization in this context does not simply mean layering digital over physical, or combining immersive technologies with traditional narratives; rather, it refers to the creation of a flexible design space where content can flow across platforms, devices, and modalities. This cross-fertilization ensures that a single digital asset can be adapted, repurposed, and experienced in multiple environments, from web-based XR frameworks to immersive installations and mobile applications. Such reusability supports long-term sustainability, maximizes the value of digital heritage datasets, and strengthens interoperability across diverse cultural and technological domains.
However, the Metaverse Lab stresses how the content is the key to user engagement (Pagano *et alii* 2016). Users want narrative-driven environments where they can take on roles, which helps them connect emotionally and sensorially. A standardized, collaborative content production pipeline was tested alongside digital system development. In the pipeline, narratives and metadata were developed in parallel with digital applications. This iterative

process ensured that technologies were shaped around historical accuracy, while storytelling adapted to technical affordances. Case studies across the different islands, such as Baiae's 3D models in ATON, the *fistula plumbea* in Zspace, or the immersive rowing simulator, demonstrated how validated content could be repurposed across platforms, supporting both scientific rigor and audience engagement. The model highlights that cultural accuracy, not technology alone, must guide digital heritage, offering a scalable and adaptable workflow for future projects.

On Island 1, the Aton platform identified twelve Points of Interest, allowing users to explore content by reading or listening, in any order and along personalized paths. This non-linear approach supports personalized pathways of engagement and accommodates diverse learning styles and levels of user autonomy. The narrative complemented by a curated set comprising images, 3D reconstructions, architectural plans, and interpretive structure follows a progression from the general to the specific, beginning with the broader historical and cultural context—Baiae in ancient literary sources, its historical landscape, and its contemporary configuration—and gradually focusing on specific archaeological features that can be explored both through in situ underwater immersion and via a virtual navigation of a 3D digital reconstruction.

Similarly, zSpace has proven to be an effective platform for the exploration of two 3D models of the marble statues. The narrative focused on describing the two sculptures, their iconography, and the archaeological context of their discovery, highlighting the symbolism of gardens in Roman domus architecture.

For both Baiae and the statues, the narrative language was intentionally accessible yet precise. It aimed to engage audiences without oversimplification or excessive rhetoric. The audio narration of the case studies was made available within the zSpace environment. Automated voice-over was used instead of professional actors to support accessibility and gender equality. Two phases of manual revision ensured acceptable pronunciation, intonation, stress—especially for Italian technical terms and Latin—and overall fluency. However, automated voice-over technology cannot yet match professional narration in emotional depth, efficiency, or quality.

CONCLUSION

Case studies illustrate how advanced visualization, multisensory interaction, and narrative design can foster both user learning and scholarly dissemination. The practices outlined serve as exemplary models of interdisciplinary collaboration and narrative use in digital archaeology, showcasing their scalability and adaptability for various projects and audiences. Central to this model is the richness and philological accuracy of the content: all narratives must be based on scientifically validated data and the latest research.

As a creative hub, the Metaverse Lab supports cultural and creative industries, startups, and the professional development of students, promoting upskilling and reskilling for Heritage Science professionals amid technological advancements.

This underscores the essential relationship between research and the protection, enhancement, and management of archaeological cultural heritage.

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Bibliography

Conference (2025): Conference on Underwater and Coastal Cultural Heritage of Campi Flegrei, Archaeological Museum of Campi Flegrei (Castle of Baia), Italy (14th May 2025), unpublished.

Davidde Petriaggi, B., Stefanile, M., Petriaggi, R., Lagudi, A., Peluso, R., & Di Cuia, P. (2020). Reconstructing a Submerged Villa Maritima: The Case of the Villa dei Pisoni in Baiae. Heritage, 3(4), 1199-1209. https://doi.org/10.3390/heritage3040066

Davidde Petriaggi, B. et al. (2024), Nuovi dati sulle ville di Baia dalla ricerca archeologica subacquea, Villae maritimae del Mediterraneo occidentale, in: Ciucci C. et al. Publications de l'École française de Rome https://doi.org/10.4000/120w2

Di Fraia, G., Lombardo, N., Scognamiglio, E. (1988). Contributi alla topografia di Baia sommersa, in Puteoli, IX-X, 1985-1986 (1988), 211-229.

Esposito, A., Lucignano, A. (2010). Ninfei marittimi imperiali nel Golfo di Napoli. In Bollettino di Archeologia online 2010. https://bollettinodiarcheologiaonline.beniculturali.it/wp-content/uploads/2021/09/2_LUCIGNANO_ESPOSITO.pdf

Fanini, B., Ferdani, D., Demetrescu, E., Berto, S., & d'Annibale, E. (2021). ATON: An open-source framework for creating immersive, collaborative and liquid web-apps for cultural heritage. Applied Sciences, 11(22), 11062. https://doi.org/10.3390/app112211062

Hassenzahl, M. (2010a). Experience Design: Technology for All the Right Reasons. Morgan & Claypool Publishers.

Jashemski W.F., Gardens of Pompeii, Herculaneum and the Villas Destroyed by Vesuvius Hardcover, 1979.

Lombardo N. (1997). Un nuovo documento epigrafico dalla villa dei Pisoni a Baia. https://www.reteissa.it/mare/pisoni.htm

Lombardo N. (2009). Baia: le terme sommerse a Punta dell'Epitaffio. Ipotesi di ricostruzione volumetrica e creazione di un modello digitale. In Archeologia e Calcolatori 20, 2009, 373-396.

Pagano, A., Pietroni, E., & Poli, C. (2016). An integrated methodological approach to evaluate virtual museums in real museum contexts. ICERI2016 Proceedings, 310-321.

Pagano F., Del Villano M., Mermati F. (2023) Toccare terra: approdi e conoscenze. Primo convegno di archeologie flegree, Parco archeologico dei Campi Flegrei: Museo archeologico dei Campi Flegrei nel Castello di Baia, 14-16 dicembre 2021. Sesto Fiorentino (FI) : All'insegna del giglio.

Parco 2019: Il Parco della ricerca, brochure del Parco Archeologico dei Campi Flegrei, novembre 2019. https://pafleg.cultura.gov.it/getFile.php?id=808

Violante C., Gallocchio E., Pagano F. (2025), First results from sub-seafloor archaeological investigation in the submerged Roman site of Baiae (Naples, Italy) using Parametric Echo Sounder (PES), in: Baika K. et al Harbour Cities I, Sidestone Press Academics, Honor Frost Foundation Research Publication, in press.

Violante C., Gallocchio E., Pagano F., Papadopulos N. (2023), Geophysical and geoarchaeological investigations in the Submerged Archaeological Park of Baia (south Italy), Proceedings of IMEKO Int. Conf. on Metrology for Arch. and Cult. Herit., Rome, 886-891.

Abstract

Il paper illustra una parte del Laboratorio Metaverso della Casa delle Tecnologie Emergenti "Infiniti Mondi" di Napoli, un centro per la ricerca e la formazione sulle Industrie Culturali e Creative. Il laboratorio, coordinato dal CNR ISPC, adotta principi FAIR e dell'Universal Design, promuovendo accessibilità, narrazione scientifica e coinvolgimento sensoriale, supportando lo sviluppo di competenze e l'innovazione nella valorizzazione del patrimonio culturale; offre esperienze immersive e multisensoriali in realtà virtuale, aumentata e mista integrando tecnologie e casi studio interdisciplinari. In questa sede, in particolare, si approfondiranno i casi di studio archeologici e come siano state integrate tecnologie, narrative e metadati.

Keywords

Restoration; scientific investigation; XRD; FTIR; EDXRF; compressive strength; chemical analysis; conservation principles.

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