ACTA IMEKO
ISSN: 2221-870X
June 2024, Volume 13, Number 2, 1 - 7

Documentation and management of complex 3D morphologies through digital technology

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ABSTRACT
Digital technologies offer an effective solution for documenting and managing complex three-dimensional morphologies, particularly in the context of Underground Built Heritage (UBH). Our research explores novel digitization strategies by employing various technological tools for 3D scanning. We focus on a selected case study: the Grotta di San Michele Arcangelo. Range-based techniques using LiDAR-UAV (Light Detection and Ranging set in Unmanned Aerial Vehicles) were used for the cave's exterior, integrated with SLAM (Simultaneous Localization and Mapping) technology was employed for the cave's interior and close-range photogrammetry techniques captured intricate wall decorations. The results yielded precise geometric information crucial for subsequent three-dimensional modelling of architectural and natural spaces. Furthermore, these techniques were integrated to enhance information management, facilitate conservation efforts, and update existing documentation. The resulting comprehensive database is an essential tool for understanding, monitoring, and effectively managing these intricate underground environments.

Section: RESEARCH PAPER

Keywords: Underground Built Heritage (UBH); 3D surveys; Heritage Building Information Modelling (HBIM); data management

Citation: L. Centarti, C. Ferreyra, C. G. Guida, M. Limongiello, B. Messina, Documentation and management of complex 3D morphologies through digital technology, Acta IMEKO, vol. 13 (2024) no. 2, pp. 1-7. DOI: 10.21014/actaimeko.v13i2.1845

Section Editor: Fabio Leccese, Università Degli Studi Roma Tre, Rome, Italy

Received March 20, 2024; **In final form** May 20, 2024; **Published** June 2024

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1. INTRODUCTION

The preservation of cultural heritage represents a fundamental priority to maintain our connections with the past and ensure that future generations can appreciate its value. In this context, Underground Built Heritage (UBH) presents a unique case, since often hosts not only valuable architectural assets but also significant artefacts such as graffiti, murals, or bas-reliefs with immeasurable historical and cultural worth. However, the complex and often inaccessible nature of these spaces poses significant challenges to their management, conservation, and enhancement.

3D digitization emerges as a crucial solution to address these challenges, enabling accurate documentation and detailed visualization of these underground environments. Through advanced 3D acquisition techniques, faithful digital representations can be created. These representations not only facilitate understanding and study but also promote accessibility without compromising integrity. However, 3D digitization is not without limitations and challenges. These include the need for clear quality control and a deep understanding of the potential and limitations of various acquisition methodologies [1].

Simultaneous Localization and Mapping (SLAM) are fascinating and promising technologies for mapping underground structures, speeding up acquisition times, ensuring that the cultural value of these spaces is not compromised while also allowing for their appreciation by the public. In their study, Di Stefano et al. test various portable mobile solutions to ensure accurate and reliable 3D digitization [2].

The digitalization of underground spaces presents an intriguing opportunity, the potential implementation of preventative conservation measures. Effective strategies for their preservation, should balance heritage conservation imperatives with ensuring public accessibility. In these scenarios, preventive conservation strategies rely on defining interventions for technical systems (to restore or improve internal environmental conditions) and operational models for sustainable use (to mitigate stress factors on the Heritage). However, combining these strategies is impractical in underground environments [3]. For example, the research conducted on the UBH spaces of Palazzo Campana in Osimo, Italy, illustrates an innovative approach to conserving such environments. It combines microclimatic characterization through long-term monitoring while defining a quota of acceptable visitor impact. This strategy achieves a balance between heritage preservation and public access, reducing human impact and promoting sustainable enjoyment [4].

Furthermore, comprehensive and detailed 3D digitization of UBH provides decision-makers a valuable tool for effective space management, bridging knowledge gaps. The clear and complete digital representation, enhanced by geological investigations, is crucial not only for preservation but also for their accessibility, as exemplified by Naple's reinvention of the Catacombs of Rione Sanità [5]-[6].

These 3D digitization tools can be used for further modelling techniques using the Scan-to-BIM procedure to create a BIM model (Building Information Modelling), an indispensable tool for precise and informed management. By providing a collaborative platform for professionals involved in the conservation, management, and enhancement of complex morphological spaces, BIM streamlines intervention planning, maintenance, and strategic decision-making, ensuring that every action is taken with full awareness of its impact on the heritage [7]-[8].

The purpose of this research activity, through its application to the Case Study of the *Grotta di San Michele* in Olevano Sul Tusciano, in Campania, province of Salerno, Italy (Figure 1), characterized by the complex combination of natural and built heritage, poor lighting conditions, and difficult accessibility, is not only to showcase the differences in technological tools used for 3D surveying, but also to discuss the pros and cons of these systems, providing the community with best practices and guidelines for 3D data collection using modern available technologies [9]-[10].

Figure 1. Location of the case study, the *Grotta di San Michele Arcangelo, Olevano sul Tusciano* (SA), Italy.

2. CONTEXTUALIZATION OF THE CASE STUDY

During the project, a comprehensive three-dimensional metric survey protocol was defined, which can be reproduced and adapted for application in different subsequent case studies. This was done considering the abundant presence of UBH throughout the Campania region and the need to keep an updated record of it. The department responsible for this task within the Cadastre is the "Cadastre of the Campania Caves", created with the aim of collecting information and maintaining a database for monitoring. These natural cavities are mainly composed of karstic formations, i.e. limestone produced by the erosive action of water. There are currently about one thousand caves registered in the cadastre in the Cadastral Registry of Artificial Cavities in Campania.

High medieval sanctuaries can be counted among the potentially richest heritage sites regarding information about society during those centuries. They were destinations for long-distance pilgrimages and were situated along important routes. These sanctuaries served as meeting points for people from different cultures, places of spirituality, and platforms for ideological expression. They were centres of accumulation and prosperity, significantly shaping the events in the territories where they were established and often influencing settlement dynamics and regional economies.

The Sanctuary of San Michele Arcangelo, located within the studied cave, served as an international pilgrimage centre during the High Middle Ages. It holds a privileged position for investigating the numerous challenges associated with the scarcity or even absence of knowledge and documentation about these spaces.

While it initially emerged as one of the stops along the pilgrimage routes for monks travelling to the Holy Land, this sanctuary stands as one of the best-preserved high medieval settlements in Europe. Its earliest dated records trace back to the 9th century AD. The cave is part of a monastic-sanctuary complex, essentially structured into two distinct functional spaces: the interior sanctuary itself and an exterior area with remnants of defensive walls that block the paths leading to the entrance. Within the cave's interior lies a devotional route, marked by five scattered chapels along a path that extends deep into the stone. These architectural features and the richness of their decorations reveal diverse cultural traditions.

The limited accessibility of the site and the decline of the sanctuary starting from the 13th century allow us to observe it in an almost intact state, revealing its unique features that have prompted the need for protection and safeguarding. In 1996, the World Monuments Watch, a flagship program by the World Monuments Fund (WMF), aimed to draw international attention to endangered cultural heritage due to threats such as negligence,

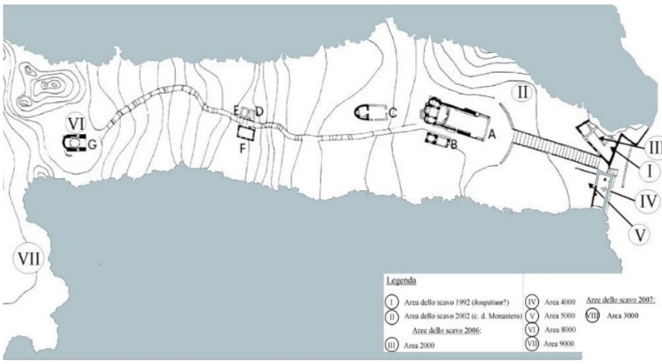

Figure 2. Planimetry of the interior of *the Grotta di San Michele Arcangelo in Olevano Sul Tusciano* by traditional techniques [11].

vandalism, and natural disasters. Advocating for its preservation, the WMF selected the cave as one of the hundred most important monuments in the world, positioning it on the global stage. They developed an emergency conservation plan and launched a fundraising campaign to carry out conservation actions on-site.

In 1998, a conservation project focused on the two main chapels was initiated. The WMF conducted emergency cleaning and consolidation of various decorative elements in the smaller chapel, which were considered the key attributes of the complex. Together with the architectural features of the other chapels, these elements represent the social value that defines it as a world heritage site, reflecting the religion, ideals, culture, and practices of past societies. Out of the seven chapels that once comprised the Grotta di San Michele, only five remain intact. The bas-relief decorative objects and other preserved elements from the WMF project are the sole surviving examples within the complex.

The existing documentation, both graphical and written, combined with data from successive excavation campaigns conducted at the study site between 2002 and 2007, has provided us with reference maps created from surveys carried out using traditional methods (Figure 2). These maps depict the cave's internal structure, serving as a foundation for determining and organizing the collection of new research data.

3. METHODOLOGY

The digitization of UBH environments poses significant technical challenges due to various limitations. These include the lack of natural lighting, which can hinder the precise capture of images, as well as physical obstructions and limited access, which impede the optimal placement of surveying equipment. Furthermore, environmental conditions, such as humidity and the presence of water, can negatively impact the quality of images and the operation of devices. The variability in scale and dimensions of UBH spaces requires flexible planning and execution of surveys to ensure comprehensive coverage and adequate precision. The selection of digitization methods must carefully consider the specific characteristics of the environment and project objectives, considering constraints imposed by geological, geotechnical, and environmental factors. Achieving comprehensive descriptive representation is essential for obtaining precise and reliable data, thus enabling the creation of accurate 3D representations of underground environments [12].

When applying various survey methods, a set of specifically optimized strategies is proposed to address the uniqueness of the case. These strategies are divided into two stages: data collection, which involves surveying and individualizing the capabilities and

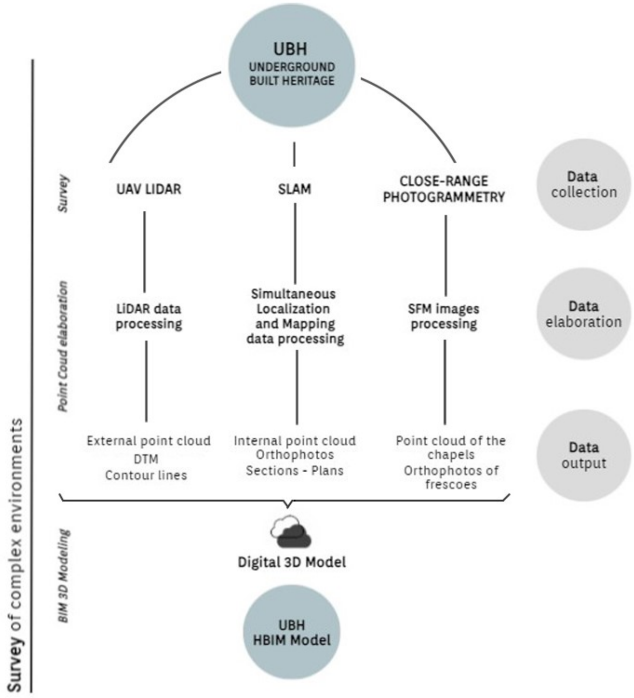

Figure 3. Methodology of the proposed digitization of the UBH.

characteristics of the instruments used. Data is collected and managed, resulting in graphical documents that serve as the basis for further work and define the scope of the research and data integration, where in this second stage, integrated information systems are established. New information is generated and paired with semantic digital models, incorporating data of diverse nature and disciplines.

Today, the availability of 3D information has significantly increased, thanks to various technologies that span remote sensing techniques from macro-scale to micro-scale [13].

Different levels of approximation were employed adopting a multiscale perspective with a data integration strategy. This approach guided researchers from a simple initial observation to a precise object measurement. Initially, at a territorial scale, the physical-natural environment outside the Cave was surveyed using a UAV (Unmanned Aerial Vehicle) LiDAR; at an intermediate scale, the space between the landscape and the built architecture was analyzed using a dynamic laser scanner with SLAM (Simultaneous Localization and Mapping) technology; finally, at the detailed scale, the frescoes on the walls of the chapels were documented using Close-Range Photogrammetry. These three levels provided a comprehensive understanding of the cave, resulting in a thorough knowledge of the case study as the primary outcome (Figure 3) [14].

3.1. UAV LiDAR survey

Regarding the external environmental data acquisition, a UAV quadcopter, the DJI M300, equipped with an RTK GNSS receiver, was used as the platform to mount in LiDAR sensor, the DJI Zenmuse L1. With a maximum range of 450 meters and velocity of 480,000 pts/s, Measurement accuracy H: 10 cm @ 50 m, V: 5 cm @ 50 m. The Zenmuse L1 features a Livox Lidar module, a high-precision IMU, and a 1-inch CMOS camera on a stabilized gimbal. This configuration efficiently captures details of complex structures and provides particularly accurate reconstructed models. From processing the data of the survey campaign, a point cloud containing a total of 60 million points was obtained, captured in approximately 35 minutes. The integrated point cloud includes RGB information obtained through the integrated camera, with centimeter-level precision thanks to the high-precision IMU and the incorporation of GNSS data [15]. The resampled point cloud density was set to 10 points per square meter using the Cloud Compare software. The LiDAR data was utilized for the morphological description of the territory [16]-[17].

3.2. SLAM based survey

Systems employing SLAM algorithms to create three-dimensional models require careful acquisition planning. The quality of the raw data generated through the SLAM approach largely depends on how the acquisition campaign is conducted. The site of interest was thoroughly examined in advance to identify critical areas and address potential obstacles [18].

For the internal survey of the cave, the GeoSLAM ZEB Horizon was utilized. One of the main benefits of implementing this device was the speed of data acquisition, owing to the characteristics of the Time of Flight (TOF) sensor installed in the tool, capable of measuring up to 300,000 points per second in return mode, with a maximum range of 100 meters. The instrument proved suitable for capturing the geometry of the surrounding environment, architecture, and its context, ensuring an acceptable level of precision (± 3 cm) during data collection.

To achieve a comprehensive definition of the morphology inside the cave, five specific paths were carefully predicted. This was necessary due to the complicated and winding paths of the cave, as well as the challenging surfaces that made it difficult to collect data quickly. Additionally, given the complexity of the case and the difficulty of the path, it was consider limiting the acquisition of each path to a maximum of 15 minutes for optimal data management. These paths were planned to ensure sufficient overlap between acquisitions, which is crucial for effectively aligning of the data sets. Moreover, the inclusion of the entrance area in the survey was imperative to facilitate a precise alignment with the georeferenced LIDAR cloud data, as the drone used in this survey was equipped with an nRTK GNSS system, making it the only georeferenced dataset. This careful planning was necessary to achieve comprehensive coverage and reliable data integration under environmental and technical constraints.

The total acquisition time was approximately 90 minutes for a surveyed area of 1 km deep, resulting in a filtered point cloud of around 45 million points. The acquired data were imported into GeoSLAM Connect software and subjected to automatic processing using the SLAM algorithm. A moving temporal window in the raw data was utilized to locate the scanner and calculate the trajectory, based on data from the inertial measurement unit (IMU) and feature detection algorithms.

3.3. Close-Range Photogrammetry survey

The generated point cloud serves as the foundation for subsequent close-range photogrammetry of the interior of the cave. The photogrammetric capture was influenced by the type of heritage and its underground location, which created limitations due to the lack of natural light and the confined space.

Photographic images were acquired using a Nikon D3200 camera within the cave sensor APS-C (23.2 x 15.4 mm, Pixel Size 3,9 μm). These images were necessarily taken using controlled self-timer mode, with the camera mounted on a tripod and with a specific photography lighting Kit.

The processing was carried out using Agisoft Metashape version 2.0, following a classic workflow. This process produced the required orthophotos with maximum resolutions on the order of 1.5 mm per pixel [19].

The main characteristics of the surveys carried out using various technologies, instruments, and levels of detail result in the post-processing phase, where they are integrated into a multiscale point cloud representing the complex morphology and internal architecture of the cave. This non-invasive digital acquisition of metric-formal data can be used as a source of information for the registration and cataloguing of UBH (Figure 4).

4. RESULTS

By adopting a hierarchical multiscale and multitemporal approach, preliminary results were obtained through the integration of the first two methodologies in the case study. By contrasting the LIDAR and SLAM point clouds, we analyzed the height disparities between the interior and exterior of the cave, identifying planes of geological discontinuity. This analysis enabled the geolocation of potential fracture hotspots and sediment deposits. These activities were possible due to the

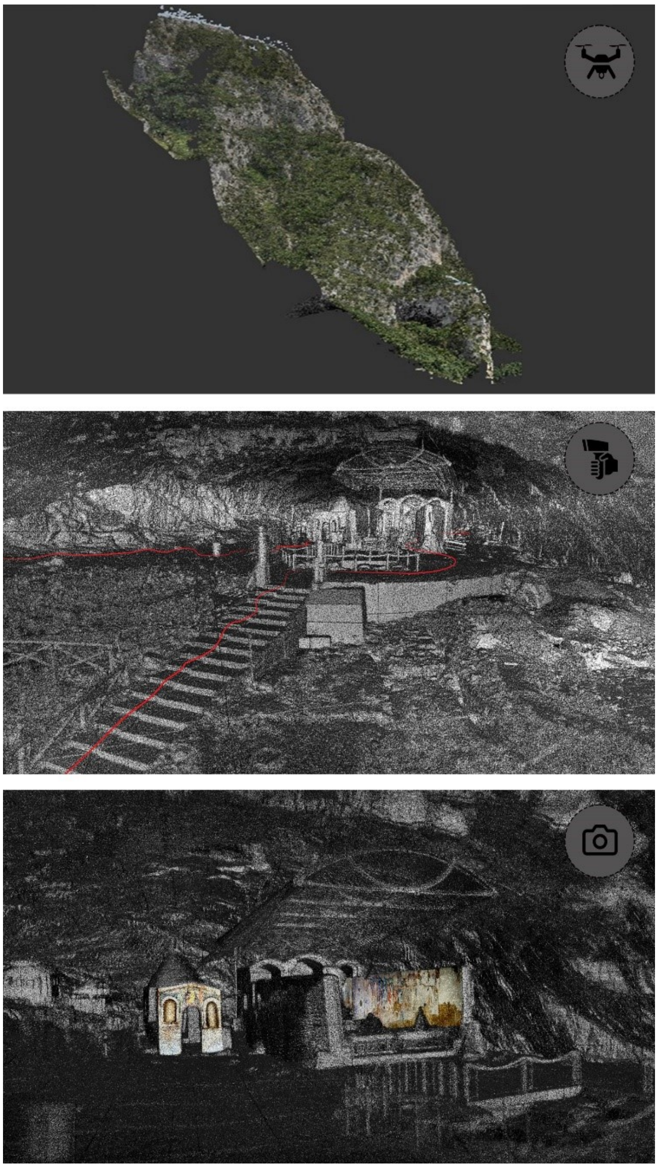

Figure 4. Preliminary results: LIDAR point cloud (top), SLAM point cloud (centre), and Photogrammetric point cloud of UBH case study (bottom).

collaboration with C.U.G.RI. - University Centre for research on major hazards. Consequently, attention could be focused on areas requiring immediate safety measures, as well as those necessitating active monitoring systems due to geomorphological evolutionary trends. These measures aim to mitigate risks associated with deposit usage, safety concerns, soil/subsoil rehabilitation, and structural and environmental monitoring [20].

In order to define an effective system for preserving this significant episode of Campania's UBH and to enhance its management, the proposed approach was HBIM (Historic Building Information Modelling). To genuinely enhance the value of the UBH, an HBIM model was developed from the integrated SLAM and Close-Range Photogrammetry point cloud data [21]. This methodology was applied to both the natural environment and the built heritage, promoting interoperability among various sectors, and facilitating interdisciplinary interventions required for its preservation [22]. Autodesk Revit was originally designed for new construction projects, but it needed several adjustments to be suitable for HBIM in complex heritage contexts. Initially, the natural heritage - the interior surface of the cave - was modelled using a new workflow adapted for complex environments, which interoperated across different software platforms. For the integration of point clouds into the Autodesk Revit environment, Recap was used. The different point clouds were imported, appropriately decimated according to the reference scale. A decimated Lidar cloud was added, from which vegetation was removed using a specific algorithm in Cloud Compare. Within Recap, the cave cloud was divided into different regions, separating the inner surface of the cave into two parts to optimise data management. In addition, eight subregions were created, corresponding to each chapel and the entrance portal. This segmentation allowed for faster and more efficient geometric modelling. In addition, by taking advantage of the cloud visibility settings imported into Revit, it is possible to turn on or off the display of specific subregions or to view the entire internal point cloud, i.e. to perform appropriate analyses concerning the lidar cloud. Adopting colourimetric filters introduced by the software greatly facilitates the visualisation and critical interpretation of data. It is important to determine the level of development (LOD) of the HBIM model, as this directly affects its effectiveness in preserving historical accuracy, allowing for precise interventions, and ensuring sustainable management of the heritage. In this complex case study, a LOD C was chosen to represent the natural space, which strikes a balance between providing enough detail and keeping the model manageable while also taking into account the modelling objectives and the needs of interested parties. The interior point cloud, imported through Recap, was sectioned every four meters to generate cross sections in the cave, outlining the natural profile in each. These profiles were then assembled to create a 3D surface.

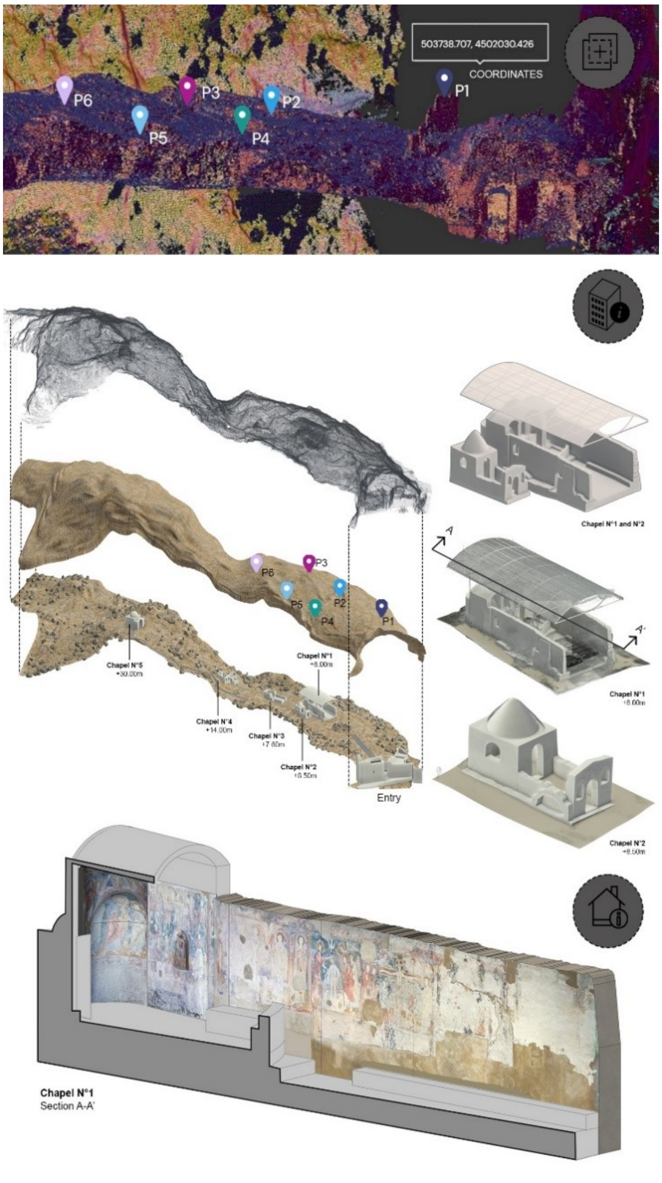

Figure 5. Integration of LIDAR and SLAM point clouds from both the interior and exterior of the cave. Accurate georeferencing has enabled the identification of six critical points using geographic coordinates (top). HBIM modelling process of the natural environment and surrounding architectural structures (centre). Section of the main chapel, where close-range photogrammetric material has been imported and managed using Autodesk Revit (bottom).

Subsequently, the architectural elements of the cave's interior were modeled, with chapels components represented as parametric elements. In order to ensure the preservation of the frescoes and maintain the built heritage, an LOD F was selected. This was made possible using data enrichment with structural information, component details, and decorative elements obtained via close-range photogrammetry, which allows for detailed and accurate documentation of the frescoed surfaces.

It is essential for the model to include alphanumeric data categorized into fields related to the description, documentation, and conservation of the UBH.

After completing the geometric modelling in Revit, an accuracy evaluation was conducted to determine the reliability of the modelling. The Level of Accuracy (LOA) was analyzed according to USIBD standards. Two different tools were used for this evaluation: Autodesk plugin called Point Layout for built heritage, which established an LOA 30 (geometric displacements between 0.005 and 0.015 meters), and Cloud Compare software for natural heritage, selected at an LOA 10, due to the geometric complexity involved with natural environments. These analyses helped assess the accuracy of the modelling by calculating the deviations between the modelled surfaces and the point cloud data, highlighting the specialized accuracy requirements for built and natural heritage scenarios. After verifying the accuracy of the HBIM model, an add-in called Datasmith Exporter from Epic Games was utilized. This add-in includes a functionality known as Direct Link, facilitating real-time synchronization of the Revit-generated model with the Twinmotion visualization tool. A 3D immersive software capable of producing high-quality images, panoramas, and standard or 360° VR videos. Images were generated from various points within the cave, enabling the identification of internal structures and natural heritage morphology. Additionally, a video showcasing the cave's interior was created, providing viewers with a virtual tour and the ability to control camera movements and rotation.

Converting the data into semantic models enriches digital simulations and provides an alternative avenue for accessing heritage sites. This enables a broader audience, including visitors and tourists, to immerse themselves in virtual environments and explore these spaces remotely. Additionally, this accessibility extends to individuals known as "weak users" who may have difficulties physically accessing these sites. Furthermore, it offers the opportunity to showcase heritage on an international scale, expanding the audience and attracting new users. Ultimately, this approach aids in preserving cultural memory and paves the way for advancements in the realm of digital representation (Figure 5).

HBIM technology is pivotal in managing heritage properties by maintaining a dynamic and comprehensive information repository. Designed for continuous updates, the HBIM model supports the integration of new data from advanced scanning technologies into the existing georeferenced framework. This process, involving the alignment of new data with the shared coordinate system, ensures consistency and enhances the model's accuracy. Additionally, the model's structure allows for the modification and addition of information layers without compromising existing data, keeping the HBIM as a living document vital for ongoing management and future explorations. This capability streamlines long-term property management, facilitating efficient access, sharing, and handling of conservation data. The platform supports crucial tasks such as assessing conservation status, generating reports on degradation, and planning restoration protocols. By enhancing data accessibility for stakeholders and creating a flexible documentation system, the HBIM model becomes an invaluable tool for interpreting indicators necessary for the conservation, management, and protection interventions of the UBH [23]-[24].

5. CONCLUSIONS

Through the conducted research, the transformative potential of integrating multiscale acquisition technologies in the documentation and preservation of underground cultural heritage has been illustrated. The synergistic adoption of these methodologies has allowed for a detailed and comprehensive 3D model of the subterranean space, providing a solid foundation for accurate analysis and informed decision-making by various stakeholders involved in the decision process [25].

The ability to query the model by different professional figures underscores the importance of an accessible and manipulable digital representation, facilitating an in-depth understanding of the physical and structural characteristics of the cave. This multidisciplinary accessibility not only enhances collaboration among professionals but also contributes to more effective and targeted site management, enabling conservation interventions based on concrete data and detailed analysis. The conversion of the 3D model into a BIM model represents a further step forward, extending the model's value beyond mere documentation and analysis.

The HBIM model finds promising application in the field of cultural heritage conservation and enhancement. By providing architects, conservators, and other professionals with a dynamic and interactive tool for heritage planning and management, the model facilitates the simulation of restoration interventions, assessment of potential impacts, and efficient coordination of critical information. Ultimately, promoting accessibility to this model not only affirms the scientific and cultural value of the site but also opens up new possibilities for public and educational enjoyment of underground heritage [26].

ACKNOWLEDGEMENT

We extend our deepest appreciation to Santiago Fernandez and Rocio Lamas for their invaluable contributions to the modelling of the cave, which served as the focal point of their dissertation research in the master's degree in building engineering-Architecture, presented at the University of Salerno and developed in collaboration with the Universidad Nacional de Córdoba, Argentina. The authors also express their gratitude to the C.U.G.RI. - University Centre for research on major hazards (consortium between the University "Federico II" of Naples and the University of Salerno), and the Municipality of Olevano sul Tusciano for their collaborative efforts and generous support throughout the project dedicated to the study of the *Grotta di San Michele Arcangelo*.

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