3D reconstruction of ancient cities: first results of the structures (Tabernae) present in the archaeological site of Iuvanum (Italy)

Massimiliano Pepe[1], Donato Palumbo[1], Oliva Menozzi[2], Ahmed Kamal Hamed Dewedar[1], Vincenzo Saverio Alfio[1], Domenica Costantino[3]

[1] G. d'Annunzio" University of Chieti-Pescara, Department of Engineering and Geology,
Viale Pindaro 42, 65127 Pescara, Italy
massimiliano.pepe@unich.it, donato.palumbo@alumni.unich.it, ahmedkamalhamed.dewedar@phd.unich.it,
vincenzosaverio.alfio@poliba.it
[2] G. d'Annunzio" University of Chieti-Pescara, Dipartimento di Lettere e Scienze Storiche,
Via dei Vestini,31, 66100 Chieti, Italy
oliva.menozzi.unich.it,
[3] Polytechnic University of Bari, DICATECh Department, via E. Orabona 4, 70125 Bari, Italy
domenica.costantino@poliba.it

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Abstract

This article presents a methodology for the 3D reconstruction of ancient cities through the case study of Iuvanum (Italy), integrating archaeological data, historical sources, and advanced digital technologies. The research outlines a multidisciplinary process that combines photogrammetric CAD modeling and texturing advanced software for three-dimensional modelling (Twinmotion). The virtual models obtained cover part of the archaeological site of Iuvanum, and in particular the research focuses on the bases of the remains of the *tabernae* in the archaeological park. The 3D reconstruction characterized by a high level of textural and geometrical accuracy, constitutes a significant contribution to the scientific interpretation of the structures and serves as a reliable instrument for cultural heritage dissemination and public engagement.

1. Introduction

In recent years, the integration of archaeology and digital technologies has revolutionized the way sites of the past are documented, studied, and communicated. Three-dimensional (3D) reconstruction of ancient cities is emerging as a key practice for the preservation, interpretation, and enhancement of archaeological heritage (Pepe et al., 2023; Waagen et al., 2024; Fortuna et al., 2025). Tools such as photogrammetry, laser scanning, Building Information Modelling (BIM), and advanced digital modelling software now make it possible to accurately and immersively restore now-lost or partially preserved urban environments (Arciò et al., 2024; Limogiello et al., 2025). These techniques not only allow the creation of visually realistic models, but also provide a scientific basis for spatial analysis, reconstructive hypotheses, and historical simulations. Digitization and 3D modelling of archaeological sites also offer new opportunities for both the scientific community and the public to enjoy them through interactive experiences in virtual environments, Augmented Reality (AR) and Virtual Reality (VR) applications (Zhang et al., 2023; Menconero et al., 2024; Pepe et al., 2024). The 3D reconstruction of ancient cities allows for an immersive and concrete understanding of often fragmented structures, offering a more complete view of the urban context, daily life, and social organization of past civilizations. From a scientific point of view, these reconstructions provide a tool for comparative analysis and hypothetical verification, useful for archaeologists, architects and art historians. In addition, digital modelling facilitates the integration of multidisciplinary data, allowing simultaneous visualization of material, textual and cartographic sources. From an educational and communicative point of view, 3D reconstruction is an effective tool for disseminating cultural heritage, as it simplifies complex concepts and makes them accessible to everyone. Increasingly central to scientific research, it is the subject of studies that explore its methods, sources, and applications in digital archaeology and cultural heritage enhancement. For example, Kargas et al., 2019 present two approaches to 3D reconstructing 19th-century Nafplio, Greece, using VR and gaming technologies to enhance cultural education, emphasizing the need for collaboration between cultural institutions, academia, and 3D creators while addressing related challenges and opportunities. Ergin, 2023 emphasizes the importance of integrating virtual reconstruction into Cultural Heritage conservation and, through a comparative analysis of fifteen applications identifies effective techniques and software preferences to guide future archaeological reconstruction efforts. The study performed by Arar, 2024 addresses challenges in virtual heritage reconstruction by developing a more user-friendly method using Unreal Engine to integrate sources and improve clarity between original and added elements. Therefore, this article aims to analyse the main approaches, tools, and methodologies used in the 3D reconstruction of ancient cities, with a particular focus on technical, interpretative, and communicative aspects.

2. Method

The aim of the proposed method is to produce a scientifically reliable digital reconstruction of historical environments that remains accessible and engaging to a wider audience. By combining advanced technologies - such as photogrammetry, laser scanning, and 3D modelling - with the critical analysis of historical sources, the method ensures a reconstruction that is both accurate and contextually meaningful. Another aim is to bridge the gap between traditional documentary research and modern digital tools. The integration of historical data with contemporary surveying and modelling techniques allows researchers to fill in gaps where physical evidence is missing or has been altered over time. The proposed method is structured in four main phases. The first involves the analysis of historical sources, which includes the collection and critical study of maps, plans, archival photographs, textual descriptions, architectural drawings, and oral testimonies. The sources are compared to identify consistent elements, discrepancies, or gaps, and then georeferenced for integration with survey data. The second phase consists of photogrammetric surveying, carried out using UAVs to acquire orthophotos and dense point clouds. The data is processed using photogrammetric software to generate high-resolution three-dimensional models. This is followed by 3D modelling in a CAD environment, with the import of historical and photogrammetric data into AutoCAD and Rhinoceros. The datasets are superimposed and calibrated to ensure consistency between sources and surveys, and parametric modelling of the architectural elements is carried out, distinguishing between existing, hypothetical, and documented parts. Finally, in the visualization phase in Twinmotion, the models are exported from Rhinoceros and imported into the software for the application of textures, lighting, environmental context, and animations. The result includes interactive visualizations for scientific communication, education, and heritage enhancement.

3. Case study

The case study concerns the archaeological site of Iuvanum (Italy) within the Living Forever the Past through a 3Digital World (Lip3D) project, funded in 2024 by the European Health and Digital Executive Agency (HADEA) under the Digital Europe Programme. The project focuses on developing a virtual environment for the documentation and enhancement of cultural heritage, with particular emphasis on archaeological sites. The project involves the reconstruction of the site. The city of Iuvanum has a complex plan (Figure 1) and integrates the religious, political, economic, and cultural functions integrated within the urban system (Bradley, 2004).

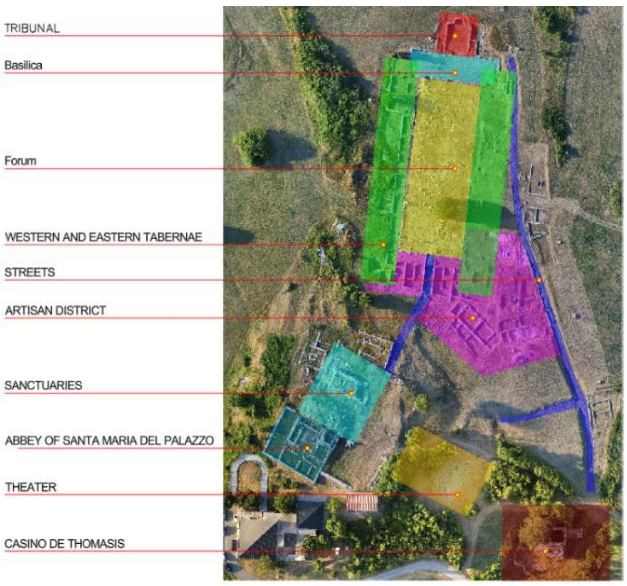

Figure 1. Plan of the archaeological site of Iuvanum with identification of the main areas.

Of particular interest for their historical value are the *tabernae*, which in ancient Rome represented commercial spaces, which were mainly small workshops, sometimes with courtyards and storerooms, which were used for economic and productive activities. On the western, eastern, and southern sides of the square were various spaces, both small and large, which served as public offices, *tabernae*, sacred areas, colleges, and venues for a wide range of activities. Archaeological investigations have revealed the transformations these buildings underwent over time. In particular, rooms R, S, Q, H, G, and P were built on previous structures, deliberately demolished to redefine the city's urban layout. The *vicus* is identifiable in the rooms preserved at foundation level near the *Via del Foro* and partially overlapping with it particularly in rooms I, L, K, O, X, and J arranged according to the topography of the acropolis (northeast-southwest) and subsequently integrated into the urban fabric of the Roman municipality. It is also visible in the spaces defined by structures obliterated during the construction of the Roman city. These structures, aligned along a north-south axis like the later *forum* complex, reveal a settlement pattern much more extensive than initially believed. They consist of two rows of rooms, one facing west and the other east respectively oriented toward the area later occupied by the paved forum (but which was already a large square used as forum *boarium* since the III century BC) and toward the eastern road.

4. 3D survey of tabaerne analysis and 3D reconstruction

The survey was conducted using a UAV platform equipped with a high-resolution camera, specifically a Parrot Anafi. The flight was performed in manual mode, but with a high overlap and sidelap of minimum of 80% to ensure the quality of the photogrammetric process based on the algorithm of Structure from Motion. The flight altitude was calibrated based on the desired scale of detail. During the survey, GCPs (Ground Control Points), detected with high-precision GNSS instruments (Pepe, 2018; Zhong et al., 2025), were positioned on the ground and used as control points for the subsequent accurate georeferencing model. These reference points were strategically distributed across the entire area of interest to ensure uniform spatial accuracy. At the end of the acquisition, the approximately 300 images collected were processed using Agisoft Metashape photogrammetric software, generating a dense point cloud, a georeferenced 3D model, and a high-resolution orthophoto of the entire site. The photogrammetric dataset was processed by setting an appropriate processing accuracy value to ensure detailed reconstruction of the acquired images. In addition, parameters allowing for optimization of the balance between correspondence density and computation time were appropriately set for the alignment phase. The model quality analysis returned a centimetric reprojection error, indicating good consistency between the image point projections and the reconstructed three-dimensional geometry. Table 1 below summarises the main parameters set and the total reprojection error achieved.

Setting	Values
Processing Accuracy	High
Key Point Limit	40,000
Tie Point Limit	12,000
RMSE	0.013 m

Table 1. Setting parameters for the alignment phase and total reprojection error.

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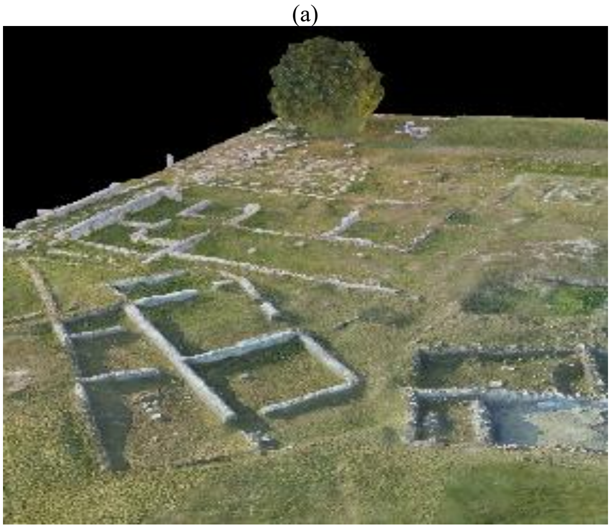
In Figure 2 are represented some of the results obtained through the processing of photogrammetric data; in particular, Figure 2a shows the orthophoto with indications of the rooms of the *tabernae*, while in Figure 2b is shown the 3D-colored point cloud.

(a)



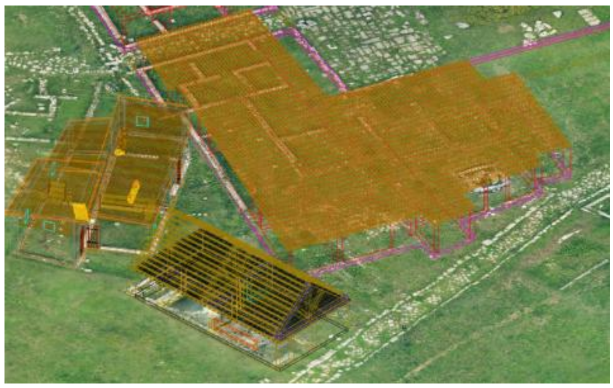
(b)

Figure 2. Representation of the *tabernae*: Orthoimage (a) and 3D Point cloud (b).

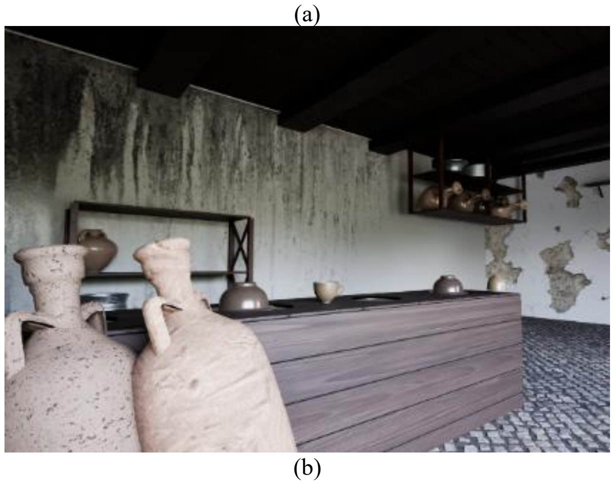
5. Tabernae analysis and 3D reconstruction

The three-dimensional reconstruction of the *tabernae* in the archaeological area of Iuvanum was carried out using a rigorous multidisciplinary approach, integrating historical, archaeological, and technological expertise to produce a model as closely aligned as possible with the site's historical and architectural reality. The entire process began with a solid preliminary phase of documentary research, made possible by direct collaboration with archaeologists and researchers, as well as access to a considerable amount of archival material, including site plans, excavation reports and historical surveys. One of the initial phases of the project focused on analysing proportional relationships throughout the site, with particular attention to the construction modules used in antiquity. Investigations revealed a geometric coherence linking many of the structures to recurring modules. These were based, for example, on wall thicknesses of approximately 50 cm, which appear to have served as spatial organizing units. Other modular references were found in the varying diameters of the columns, measured directly on-site: about 40 cm in the western *tabernae* and up to 56 cm in the basilica. These patterns suggest a clear architectural and functional hierarchy that influenced design choices at the time.

To support this theoretical framework, field investigations were conducted using aerial photogrammetry based on drone surveys. These methods produced a highly accurate 3D model of the current state of the site. Integrating the data from these investigations with historical documentation enabled cross-verification of sources, leading to the development of a two-dimensional site model that aligns precisely with the available archaeological evidence. From this 3D model, plans, façades, and sections were extracted tools that proved essential not only for the reconstruction itself but also for the documentation and deeper understanding of the site. Data processing was carried out in a CAD environment, where a detailed plan was produced and compared with historical sources to ensure consistency and accuracy. Figure 3a shows the three-dimensional modelling supported by orthophotos. The model, integrated with direct surveys and historical documentation, was imported into Rhinoceros to define volumes, heights, and shapes consistent with current knowledge. Modelling in Rhinoceros is a progressive process in which two-dimensional survey data, imported in vector format, provide the structural basis for the three-dimensional model. From these references, surfaces are generated and progressively refined through extrusion, loft, or revolution operations to achieve complex configurations. Subsequently, the model was imported in Twinmotion software for the reconstruction of the surrounding environment, thanks to its advanced rendering and material customization features.



(a)



(b)

Figure 3. 3D reconstruction of the *tabernae* on geospatial data (a) and example of material and lighting application in Twinmotion software (b).

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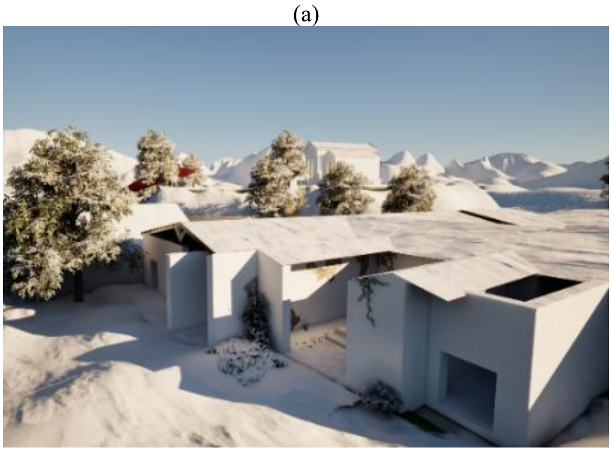
One of the main difficulties concerned the choice of materials (Figure 3b), as the software offers modern textures; neutral materials were therefore chosen, capable of evoking Roman aesthetics without being invasive. The result stands out for its geometric accuracy and historical consistency, but the model remains open to future updates. Excavations, material analysis, and construction studies may provide new data to further refine the reconstruction, making it an effective tool for research, dissemination, and enhancement of the archaeological heritage.

6. Discussion

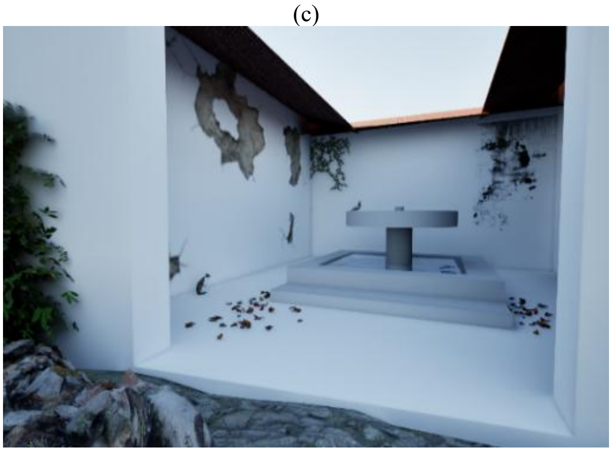
The workflow adopted for the 3D reconstruction of the archaeological site of Iuvanum followed a hybrid approach, combining manual modelling techniques with geometric data derived from in-situ surveys. This methodological choice ensured a balance between scientific rigor and communicative effectiveness, particularly in a context where the preserved remains are only partially intact. The initial phase involved manual modelling guided by historical and iconographic sources. In areas where architectural structures were damaged or missing, a comparative analysis with coeval Roman and Italic buildings was conducted. This allowed researchers to hypothesize original volumes, roof structures, and spatial arrangements such as porticoes, *tabernae*, and temples. Reconstruction was carried out according to philological principles, and hypothetical elements were explicitly marked in the model. Concurrently, geometric features were extracted directly from the remaining structures, using topographic and photogrammetric surveys. The resulting data were processed to generate high-resolution meshes and rendering, which served as a reliable metric base anchoring the 3D model to the physical site (Figure 4).

(a)



(b)

(c)



(d)

Figure 4. Rendered views of the archaeological site: main entrance (a); *tabernae* with snow (b); road leading to the *forum* (c) and room Q with fountain (d).

Continuous cross-checking between digital survey data and manual reconstruction helped ensure spatial consistency and refine the virtual outputs. A major strength of this workflow lies in its modular design: each building was treated as an independent reconstruction unit, allowing for flexible updates in response to future discoveries or reinterpretations.
Moreover, the workflow included a mid-stage archaeological validation process, during which archaeologists and 3D modelers collaborated to assess the plausibility of proposed reconstructions. Despite the soundness of the method, some critical issues have emerged.
Manual reconstruction, although accurate, is time-consuming and influenced by the interpretation of the operators. In the absence of stratigraphic details or fully preserved architectural components, some parts remain hypothetical and should be clearly indicated in the model with distinctive marks such as transparencies or different textures. (e.g., transparency, altered textures).

7. Conclusions

The partial 3D reconstruction and subsequent virtualization of the archaeological site demonstrated the great potential of digital technologies in returning, in an immersive and documented way, fragments of life from the past.
The virtual reconstruction of the *tabernae* at the archaeological site of Iuvanum represents an important example of the application of digital technologies to the valorisation of Roman heritage. This virtual environment now allows for immersive exploration of the *tabernae*, offering a suggestive "return to the

past" experience, useful for both public use and for teaching and research.
Through this reconstruction, it was possible not only to visualize the original appearance of a key part of the urban fabric of Iuvanum, but also to understand the economic and social role of the *tabernae* in the daily life of the Roman city. Finally, the article underlines the importance of multidisciplinary approaches in valorising archaeological heritage, laying the foundations for future developments in education, museums, and participatory practices.
It is important to highlight that the studies concerning the three-dimensional reconstruction of the archaeological area of Iuvanum are still ongoing.
The work carried out so far provides a solid scientific foundation, but further research, documentary analysis, and technological advancements may contribute to enriching the model and improving its historical and architectural accuracy.
Future research prospects are oriented towards expanding and refining the proposed methodology, with particular attention to the integration of more advanced surveying techniques and a greater degree of interoperability between different modelling tools. Further development will focus on the implementation of interactive and immersive digital solutions, aimed both at disseminating results in the scientific field and at engaging a wider audience. Finally, applying the approach to different archaeological contexts will make it possible to verify its versatility and consolidate its validity as a tool to support research, enhancement, and conservation of cultural heritage.

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