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3D modelling for the historical reconstruction of an archaeological site: the temple of Iuvanum

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Abstract – **This paper proposes an integrated methodology for the 3D reconstruction of ancient structures, based on the geometric analysis of archaeological remains and the use of historical sources. The case study that analysed is the archaeological site of Iuvanum (Italy), with particular focus on the reconstruction of temples, within the Lip3D project - Living forever the Past through a 3Digital world. The approach adopted allowed the development of realistic, historically and architecturally consistent 3D models, contributing to the enhancement and understanding of the site. The integration of geometric survey and historical documentation proved crucial in filling the gaps due to the fragmentary state of the existing structures, offering a plausible reconstruction of a place of great historical significance.**

I. INTRODUCTION

The 3D reconstruction of archaeological sites is a fundamental tool for understanding and enhancing historical heritage. Thanks to 3D modelling techniques, it is possible to reconstruct the original appearance of structures that have been reduced to ruins, allowing us to explore how they looked in different historical periods. Furthermore, 3D modelling offers an important form of digital preservation, useful for documenting and preserving evidence of the past, especially in the case of sites at risk of deterioration or destruction.

In this context, the use of advanced sensors and geomatic techniques, such as Terrestrial Laser Scanners (TLS) and Unmanned Aerial Vehicle (UAV) photogrammetry [1], have revolutionised the surveying of archaeological sites, offering extremely accurate and non-invasive tools for spatial data collection and subsequent documentation phases [2]. These technologies allow the morphological characteristics of the terrain and emerging structures to be mapped with extreme accuracy, providing a solid basis for historical analysis, virtual reconstructions, and conservation interventions [3,4]. In particular, the use of UAVs has taken on a central role in the surveying and 3D modelling of archaeological sites, thanks to their ability to quickly acquire high-resolution aerial images. Using specific photogrammetric processing software based on Structure from Motion (SfM) and Multi View Stereo (MVS) algorithms [5], these images can be transformed into accurate point clouds representing the morphology of the terrain, visible structures, and the landscape context with a high level of detail. Furthermore, the models generated can be used in virtual environments, augmented reality applications and immersive visitor tours, expanding the possibilities for scholars, students, and the general public to enjoy and appreciate the site [6].

In the field of 3D reconstruction, Kanun et al., 2021 acquired a photographic dataset using the Parrot Anafi unmanned aerial vehicle to create a 3D model of the Monumental Tomb of Aba, Turkey. The data obtained, in addition to being useful for a series of geometric measurements, will serve as a support model for any future restoration work [7]. Fiz et al., 2022 illustrated the potential of using UAVs for geometric documentation, three-dimensional modelling, 3D printing and image analysis with NGB, Red Edge and thermographic cameras at various heterogeneous archaeological sites [8]. Guo et al., 2022, in the field of ancient architectural cultural heritage, demonstrate a method of 3D reconstruction of ancient buildings integrated with TLS and oblique photogrammetry for the processing of a three-dimensional model of the interior and exterior environments of an ancient building. The authors evaluated the results obtained compared to the traditional survey method, demonstrating the improvement of the proposed method and its value in the field of restoration and protection of ancient architectural cultural heritage [9]. Pepe et al., 2024 developed a method to obtain a 3D model transforming the point clouds into parametric objects; this method includes 3D surveying (TLS), feature extraction, semi-automatic geometric reconstruction with Rhinoceros/Grasshopper and BIM implementation [10]. In the field of model virtualisation, Calisi et al., 2023 demonstrate the efficiency of integrating different surveying techniques not only for 3D representation but also for the creation of a realistic digital twin, aimed at providing an immersive VR experience. In fact, to develop a digital twin of optimal quality of archaeological remains, TLS surveying was integrated with high-resolution textures obtained from images acquired by UAVs [11].

Therefore, taking these works into consideration, this manuscript aims to develop a methodological approach capable of obtaining 3D models representative of an archaeological site as it appeared in the past, based on the acquisition of accurate spatial data from UAV platforms. This model provides a solid, georeferenced basis on which to develop, through advanced 3D modelling techniques, a virtual reconstruction of the site as it was in the past. This reconstruction is not based solely on the data collected, but also on historical, archaeological, and architectural sources, to restore a three-dimensional model of the ancient architectural and spatial layout of the site.

II. METHOD

The method adopted for archaeological site analysis is based on the integration of historical information with the study of the geometries of architectural remains, particularly temples, to reconstruct and better understand the layout and evolution of these sacred buildings.

Historical sources, such as ancient texts, documents from previous excavations, and iconographic descriptions, are used to provide a chronological and cultural context to guide the interpretation of the structures found. Analysis of the geometries of the remains, through 3D surveying techniques and digital modelling, provides an accurate representation of the original forms and their transformation over time. The use of modern technologies, such as photogrammetry and laser scanning, makes it possible to obtain high-resolution three-dimensional models, which are then compared with historical reconstructions and architectural theories related to the temples under examination.

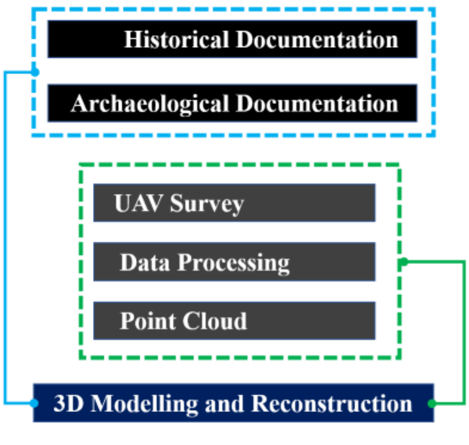

Fig. 1. Methodological approach pipeline

This interdisciplinary approach fosters a deeper understanding of the design and construction of religious buildings, offering new insights into the interpretation of culture and ritual practices related to worship in antiquity. Figure 1 summarizes the workflow of the several task that must be implemented to obtain the 3D reconstruction of old structures.

III. CASE STUDY

A. Archaeological site

The archaeological site of Iuvanum is located in the municipality of Montenerodomo, in the province of Chieti, Italy as shown in Figure 2.

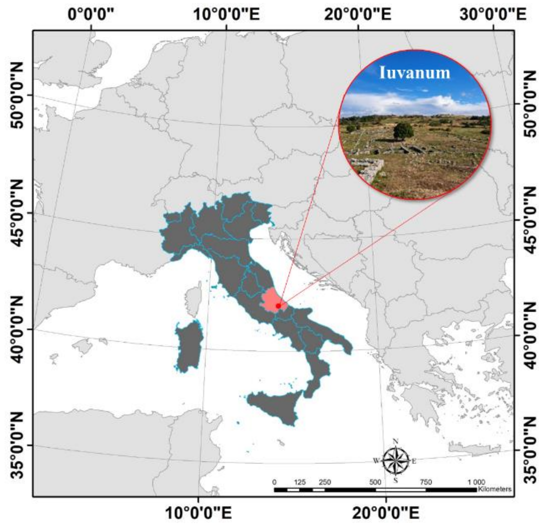

Fig. 2. Iuvanum: location and picture of the archaeological site.

The selection of the study site was derived from the identification of a case study within the Lip3D - (Living forever the Past through a 3Digital world), funded under the Digital Europe program. The project aims to explore and enhance cultural landscapes using advanced digital technologies, with a focus on 3D acquisition and modelling, spatial analysis, and dissemination of results from an open science perspective. The case study identified represents a significant context both for its cultural value and for the application potential of the digital methodologies tested within the project.

The origins of the Iuvanum site (Figure 3) date back to the Bronze Age; its name is thought to derive from a sanctuary dedicated to Iuventas, the goddess of youth, or from the fact that the centre was initially inhabited by *iuvenes* (young people). Within the site, it is possible to recognise some architectural elements such as the forum, the temple, the church, and the theatre. In particular, the acropolis houses two Samnite temples built during the 2nd century BC. The first temple was built on a high square podium covered with stone slabs with a central staircase and four columns with Doric capitals. Later, the sacred area was enlarged with the construction of a second smaller temple, also on a podium, with a single cell preceded by a pronaos with steps. Around the year 1000, the Benedictines built an abbey using stones from the ancient city and the temple, which became the foundations of the new religious building.

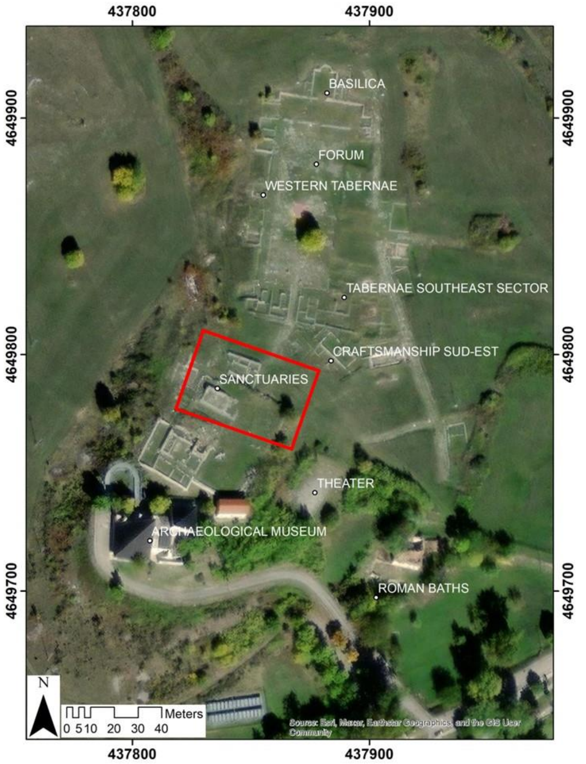

Fig. 3. Aerial image of the archaeological site of Iuvanum (Italy).

From an archaeological point of view, has evolved over time, reflecting the transition from a local community to a Romanised centre, with the construction of public buildings such as the forum, temple, basilica and theatre, which attest to its political, administrative and religious importance. Stratigraphic studies and analysis of the architectural and material remains have made it possible to identify the main phases of the site's development, from its origins in the Samnite period, through Romanisation, to its gradual decline in late antiquity. Three main historical phases can be distinguished: Samnite settlement, Roman settlement and medieval settlement.

The first phase concerns the original settlement of the Samnites, particularly the Carricini tribe, with traces dating back to the Bronze Age (between 2300 BC and 950-800 BC). During this period, two temples were built side by side on a high podium on the hill, along with a small theatre to the south-east of the hill, below the temple area, and a sacellum at the rear of Temple B.

The second phase concerns the Roman settlement, following the Social War (90-88 BC), when the forum, or commercial and political centre of the Roman city, was built, along with the paved square surrounded by porticoes and tabernae, served by paved roads that also connected it to the complex. To the south, along the eastern road, at the current limits of the urban remains, the baths were also built-in late antiquity.

The third and final phase, the medieval period, dates back to around the 12th century, when the church and Cistercian monastery of Santa Maria di Palazzo were built.

B. 3D survey

During the documentation and study activities carried out at the archaeological site of Iuvanum, a photogrammetric survey was carried out using a combination of Unmanned Aerial System (UAS) and Global Navigation Satellite Systems (GNSS) technologies, with the aim of obtaining an accurate, three-dimensional representation of the temple area. The aerial survey was carried out using a Parrot Anafi, a lightweight and compact UAS equipped with a 21 MP camera with 3-axis stabilisation. The flight mission was planned to ensure complete coverage of the area, combining nadir and oblique images. The flight was carried out under uniform lighting conditions, reducing harsh shadows and improving the radiometric quality of the shots. The high overlap between the photographs (approximately 80% along the flight direction and 80% across) ensured the robustness of the alignment process and the accuracy of the model. A total of 163 images were acquired, taken at an altitude calculated according to the camera and focal length, in order to achieve a Ground Sampling Distance (GSD) of 0.5 cm per pixel. This level of detail made it possible to capture even the smallest features, such as traces of emerging walls or slight variations in ground elevation.

In addition, a terrestrial survey was conducted using GNSS technology, which is essential for ensuring the metric georeferencing of the data. The Emlid Reach RS2+ model was used for the GNSS survey. This equipment consists of a multi-band RTK GNSS receiver equipped with a high-efficiency 4G HSPA modem capable of independently transmitting NTRIP corrections. It ensures an accuracy of 4 mm+0.5 ppm (H) and 8 mm+1 ppm (V) in static mode, while in RTK mode it ensures an accuracy of 7 mm+1 ppm (H) and 14 mm+1 ppm (V).

Eight Ground Control Points (GCPs) were positioned inside and around the excavation area. This approach made it possible to obtain planimetric and altimetric coordinates with a margin of error reduced to a few centimetres, significantly improving the spatial accuracy of the final products derived from the photogrammetric process. The acquisition mode was NRTK using the infrastructure of the permanent stations of the Abruzzo Region and using VRS30 correction. The images acquired by UAV were then processed using Metashape software, which allowed the generation of high-density three-dimensional models and detailed point clouds as shown in Figure 4. The Total Error of the photogrammetric process was about 0.01 metres and a dense point cloud of about 3 million points was generated.

Fig. 4. Point cloud obtained using Metashape software.

From the point cloud it was possible to build the mesh and the orthomosaic with a good spatial resolution in order to ensure a level of detail suitable for morphological and architectural analysis of the temple remains.

C. Develop of 3D model

For the 3D reconstruction of the two temples at the archaeological site of Iuvanum, several historical sources were consulted and analysed in order to identify proportions, architectural orders and styles characteristic of a specific historical period and the population living at that time [12-14]. In fact, with regard to the architectural order, and in particular with reference to Temple A of the archaeological site analysed, the presence of columns with a base departs from the classical Tuscan style (characterised by the absence of a base) and is closer to an Italic Doric style with local influences. This suggests that the temple followed a Samnite variant of the Doric order rather than the pure Tuscan style.

By analysing in detail, the orthophotos processed from the photogrammetric survey, it was also possible to measure the diameter of the column remains (0.85 m) present at the archaeological site and establish their dimensions as shown in Figure 5.

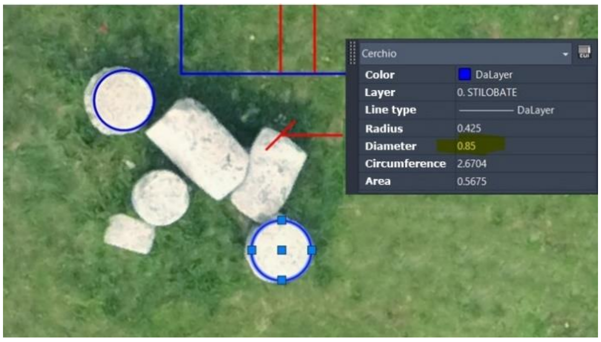

Fig. 5. Overlaying vector with orthophotos

As for the elevation, i.e. the podium and central access staircase of the temple, by analysing the orthophotos and comparing the data with previous studies on other archaeological sites similar in style and proportion, a height of 2.50 m was determined. This assumes a podium covered with cladding slabs and a staircase with 10 steps of 0.25 m (Figure 6a). As for the dimensions of the columns, a ratio between the height and diameter of the shaft of 7:1 was assumed, following the Tuscan order. This resulted in a column height of 5.95 m. For the base of the columns, consisting of a double torus section, considering a ratio of 1:2 based on the diameter of the shaft, a value of 0.43 m is obtained, with a diameter of 0.23 m for the lower section and 0.20 m for the upper torus. Generally, the base has a diameter that can be at most twice the diameter of the column shaft; therefore, the size of the column base is 1.30 m. The dimensions of the capital have also been estimated based on the styles and proportions of the period of construction. In fact, in the classical Greek Doric order, the capital tends to be flatter (close to half the diameter of the shaft) and is approximately equal to the radius of the shaft. The width can be determined according to classical proportions in which, generally, the abacus of the capital has a width equal to approximately 1.33/1.50 times the lower diameter of the column. Considering also that the thickness of the abacus is approximately 1/3 of the height of the capital, and that of the echinus to about 2/3, the dimensions of the capital elements are obtained, as shown in the Table 1 below. The four columns, spanning a total front width of 12.60 m, are generally spaced at a distance equal to 1.5/2.5 times the diameter of the shaft.

Table 1. Dimensions of the structural elements of the column and capital.

Capital height	0.42 m
Capital width	1.28 m
Abacus thickness	0.14 m
Echinus thickness	0.28 m
Column spacing	2.30 m

As regards the entablature, considering that this is not a pure Doric style, as it is an Italic temple, the proportions of the architrave and frieze do not follow Doric proportions, where they are more or less the same height. In the case analysed, the architrave is lower than the frieze, also based on assumptions made about the architectural order in late Hellenistic Doric architecture. Therefore, assuming that the frieze and architrave are 1.5 times the diameter of the column, a cornice 1/2 the diameter of the column and the frieze approximately 1.5 times the size of the architrave, the dimensions of the architectural elements are obtained. In particular, the frieze and lintel complex has a total size of 1.27 metres. The cornice measures 0.43 metres, while the lintel alone measures 0.51 metres.

Finally, the frieze measures 0.77 metres (Figure 6b).

The pediment, on the other hand, is variable, generally between 1/4 and 1/3 of the width of the façade. Based on a comparison with other archaeological sites from the same era and built by the Italic Samnites, a value of 3.15 m has been hypothesised (Figure 6c).

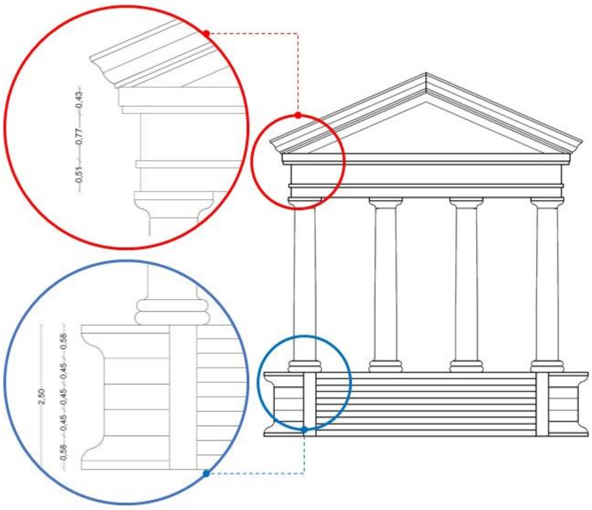

Fig. 6. Hypotheses and dimensions of the temples at the archaeological site for 3D modelling: podium and central entrance (a), friezes and architrave (b), total height (c).

Regarding Temple B, due to the lack of measurable remains of the central access staircase, its width was determined after locating and sizing the cell walls, with which the staircase parapets are aligned. Subsequently, the height of the podium (2.05 m) and the staircase configuration, consisting of 10 steps with a rise of 0.20 m each, were estimated. In reference to the dimensions of the columns, unlike the previous case, no remains or data regarding their diameter were found.

Therefore, proportions were calculated relative to the temple's front width, and by applying the same reconstruction principles used for Temple A. In fact, for Temple B, the frieze and lintel together measure 1.27 metres, while the cornice measures 0.43 metres. Considering the elements individually, the lintel measures 0.51 metres, while the frieze reaches 0.77 metres. The columns have a diameter of 0.56 metres and a total height of 3.85 metres. The base of the column measures 0.28 metres, with a width of 0.84 metres. The capital, on the other hand, has a height of 0.28 metres and a width of 0.84 metres. Inside, the thickness of the abacus is 0.09 metres, while that of the echinus reaches 0.19 metres. Finally, the intercolumnium, i.e. the distance between one column and another, is 1.56 metres.

The features and dimensions assumed for the remaining structural elements of Temple B, such as the entablature and pediment, were established by applying the same reconstructive theories used for Temple A. This approach led to an estimated total height of 10.00 m for Temple B.

IV. RESULTS

The methodological approach described above led to the modelling of the two temple buildings in Rhinoceros. Using this software, it was possible to model the structures and architectural elements of the archaeological site using photogrammetric survey data and historical and archaeological information from the documents analysed. Figure 7 shows the results of the 3D modelling of the two temples at the archaeological site analysed. The reconstruction hypothesis was developed on the basis of principles and assumptions considered necessary to fill the gap in initial information regarding the metric dimensions of the elements in elevation and the classification of possible decorative motifs. Some construction elements were simplified from an ornamental point of view (e.g., in the mouldings). Therefore, the presence or discovery of new finds in the museum or further archaeological studies could allow the model to be refined and improved.

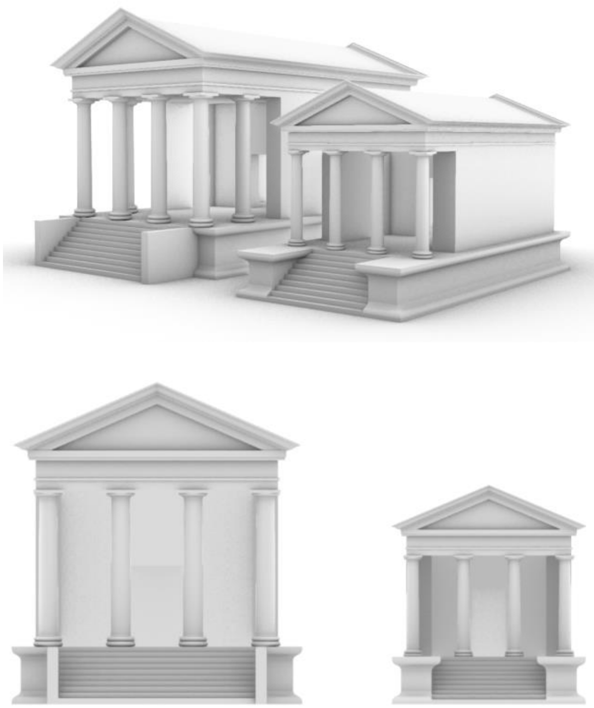

Fig. 7. Visual Details of the three-dimensional modelling of the temples.

V. CONCLUSION

The 3D reconstruction of the two Temples of Iuvanum allowed to provide a coherent and scientifically based vision of the sacred building, contributing significantly to the enhancement of the archaeological site and the understanding of its original architecture. The integration of geometric data, field surveys and historical sources has represented an effective methodological approach to fill the gaps due to the fragmentary nature of the preserved structures. The use of digital tools and 3D modelling has made it possible not only to visualize the appearance of the temple in antiquity, but also to hypothesize construction phases and architectural modifications that would otherwise be difficult to intuit through a simple reading of the archaeological remains. Furthermore, the model obtained is configured as a useful educational and dissemination tool, accessible to scholars, students, and the general public. Furthermore, this paper underlines the importance of interdisciplinary collaboration between archaeologists, architects, and specialists in digital modelling, highlighting how innovative technologies can concretely support research in the field of cultural heritage. The Iuvanum case study could be a point of reference for future reconstructions of ancient buildings with similar characteristics and conservation issues. Future developments include the implementation of a virtual Building Information Modelling (BIM) model of the Temple of Iuvanum, which would allow the 3D model to be associated not only with geometric information, but also with historical data, materials, construction techniques and chronological phases. A virtual BIM of this type would open new possibilities for research, management, and conservation of the archaeological heritage, facilitating comparative analyses, structural simulations, and digitally assisted restoration interventions.

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