

THE GEOMETRIC DOCUMENTATION OF THE GREEK CULTURAL HERITAGE SITES PARTICIPATING IN THE TRIQUETRA PROJECT

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EXTENDED ABSTRACT

I siti del patrimonio culturale, su scala globale, sono a rischio a causa dei cambiamenti climatici, dei processi geologici e delle condizioni ambientali estreme, che portano a una loro graduale degradazione. La documentazione geometrica sistematica del nostro patrimonio culturale è una procedura fondamentale che costituisce la base per gli sforzi di conservazione e le misure di mitigazione del rischio. Prodotti fotogrammetrici di altissima precisione svolgono un ruolo essenziale in questi interventi, grazie alle rappresentazioni geometriche dettagliate dei siti culturali, che supportano il monitoraggio a lungo termine, la pianificazione della conservazione e studi di valutazione del rischio molto precisi. Utilizzando modelli di *mesh* 3D, ortomosaici e modelli digitali di superficie (DSM), ingegneri, conservatori, ricercatori e tutti gli *stakeholders* interessati possono esaminare da vicino lo stato attuale dei siti culturali, rilevare eventuali cambiamenti nel tempo (a condizione che siano disponibili prodotti di documentazione geometrica passata) e mettere in atto strategie di conservazione mirate.

Questo articolo presenta la documentazione geometrica di tre importanti siti archeologici in Grecia: Aegina Kolonna, la Città sommersa e il patrimonio culturale costiero di Epidauro Antica e il santuario di Kalapodi. Questi siti costituiscono i siti pilota del patrimonio culturale greco del progetto di ricerca europeo TRIQUETRA, essendo di grande importanza archeologica e, allo stesso tempo, esposti a diversi rischi ambientali, tra cui erosione costiera, sommersione, danni da gelo e degrado dei materiali. La documentazione è stata realizzata nell'ambito del progetto TRIQUETRA, il cui obiettivo principale è affrontare i rischi legati ai cambiamenti climatici e ai pericoli naturali che minacciano il patrimonio culturale, attraverso un set di attrezzi innovativa e un sistema di supporto alle decisioni (DSS) per l'identificazione, la quantificazione e la mitigazione dei rischi.

Per documentare questi siti, è stata impiegata una combinazione di tecniche fotogrammetriche. Ad Aegina Kolonna, sono state utilizzate la fotogrammetria con droni (UAV) e rilievi a terra per documentare il sito archeologico e il paesaggio circostante, sempre più interessati dall'erosione costiera e dall'esposizione a scavi a lungo termine. Nell'Antica Epidauro, il patrimonio costiero è stato rilevato tramite tecniche UAV LiDAR e basate su immagini, mentre i resti sommersi della Città Sott'acqua sono stati registrati usando fotogrammetria subacquea e rilievi con ecoscandaglio *multi-beam* (MBES), affrontando rischi quali l'innalzamento del livello del mare, la bio-erosione e le attività umane. A Kalapodi, dove i danni da gelo rappresentano un rischio importante per la stabilità strutturale, sono stati effettuati rilievi a terra con tecniche UAV LiDAR e basate su immagini per documentare lo stato del sito e supportare una pianificazione conservativa adattata al clima.

I set di dati raccolti durante queste campagne sono stati elaborati utilizzando *workflow* fotogrammetrici consolidati, tra cui il *matching* di immagini, la ricostruzione 3D tramite *Structure from Motion* (SfM), la generazione di nuvole di punti dense, la ricostruzione di superfici tridimensionali, la mappatura delle texture, la creazione di modelli digitali di superficie (DSM) e ortomosaici. I risultati fotogrammetrici finali rappresentano dati fondamentali per monitorare i cambiamenti strutturali, condurre analisi ambientali e guidare le decisioni sulla gestione dei siti e le misure di conservazione specifiche. Questo studio, insieme al lavoro più ampio realizzato nell'ambito del progetto TRIQUETRA, dimostra quanto sia importante un'acquisizione continua di dati e, soprattutto, una collaborazione interdisciplinare, per garantire la protezione dei siti del patrimonio culturale per le future generazioni. La fusione dei risultati provenienti da diverse discipline, come topografi, ingegneri civili, geologi, ingegneri chimici, oceanografi, meteorologi e climatologi, è essenziale per creare un quadro sostenibile volto a salvaguardare i siti archeologici, specialmente in un'epoca di crescenti sfide legate ai cambiamenti climatici.

ABSTRACT

In the light of threats including climate change, geological degradation and extreme weather conditions, the geometric documentation of cultural heritage sites plays a crucial role in their preservation. Photogrammetric techniques enable the production of highly accurate 3D models, orthoimages, and digital surface models (DSMs), which facilitate both site monitoring and conservation planning. This article presents the photogrammetric documentation of three archaeological sites in Greece, namely, the archaeological site of Aegina Kolonna, the Sunken City and the coastal cultural heritage of Ancient Epidaurus, as well as the sanctuary of Kalapodi. The geometric documentation of all three sites was conducted within the framework of the TRIQUETRA EU-funded project, through ground surveys and UAV-based photogrammetric techniques, either independently or in combination with underwater photogrammetry workflows, in order to capture the geometry of the cultural heritage sites and their surrounding environments. The produced results include 3D dense point clouds, 3D textured mesh models, DSMs and high-resolution orthomosaics. The generated datasets support detailed structural assessments, vulnerability analyses and risk assessment studies, providing a fundamental basis for protection efforts of the archaeological sites of interest.

KEYWORDS: *geometric documentation, 3D model, cultural heritage, UAV-based photogrammetry, underwater photogrammetry, LiDAR*

INTRODUCTION

The geometric documentation of cultural heritage sites is a fundamental process for their preservation. In the face of threats such as climate change, geological degradation or extreme water/snow/ice, accurate photogrammetric products, like 3D models, orthoimages and digital terrain/surface models (DTMs/DSMs) of cultural heritage sites play a vital role for their conservation and monitoring. Advanced photogrammetric techniques can serve as a critical tool for capturing precise records of cultural heritage sites, facilitating conservation planning and promoting public awareness and engagement with our cultural heritage.

This paper focuses on the geometric documentation of three prominent archaeological sites in Greece, as part of the TRIQUETRA project: in Aegina, Epidaurus and Kalapodi. TRIQUETRA is a research project funded by the European Union, that aims to address climate change risks and natural hazards threatening cultural heritage, through an innovative toolbox for risk identification, quantification and mitigation (IOANNIDIS *et alii*, 2023). Its primary objectives include the creation of a knowledge base platform for climate impacts and mitigation measures, the development of systematic approaches for assessing emerging risks, advancing technologies for quantifying threats and raising public awareness to involve citizens in cultural heritage preservation. Key activities of the TRIQUETRA project involve

a new flash LiDAR for 3D mapping of underwater cultural heritage and erosion monitoring, novel spectroscopic sensors for water quality estimation, the refinement of climate and risk quantification models and the integration of remote sensing techniques. The basic outcome of the project is the development of a multi-hazard impact assessment platform, which functions as a decision support system (DSS). The TRIQUETRA project was launched in January 2023 and will conclude in December 2025, including validation testing at eight pilot sites.

The geometric documentation of cultural heritage has evolved significantly over the years, from traditional surveying and photogrammetric techniques to automated workflows. Photogrammetric techniques have seen important advancements, while deep learning is now being integrated into traditional processes, like image matching and 3D reconstruction, hence improving accuracy and automation in cultural heritage documentation (VERYKOKOU & IOANNIDIS, 2025). Early efforts were the foundation for integrating several different data acquisition methods to enhance the accuracy and completeness of the geometric documentation products. The importance of combining multiple data acquisition techniques for the geometric documentation of cultural heritage sites is addressed by GEORGOPOULOS (2017), who provides a comprehensive overview of data acquisition methods, emphasizing both passive and active techniques for accurate geometric documentation. The need for high-quality data collection processes, to ensure the reliability of the resulting 3D models of cultural heritage sites for preservation and analysis is emphasized by MAVROMATI *et alii* (2019). In their study, KASAPAKIS *et alii* (2024) discuss the application of photogrammetry in cultural heritage, highlighting its effectiveness in creating accurate 3D models for documentation and preservation purposes. Also, the integration of reality capture technologies, such as 3D scanning and photogrammetry, with large-scale 3D printing has been explored as an innovative approach for the preservation and reproduction of historical and cultural heritage (GARCIA-ESPINEL *et alii*, 2024). A comparative analysis of different software packages for 3D modeling of complex geometries of cultural heritage sites is presented by VERYKOKOU *et alii*, (2021), where an overview of image-based and scanner-based 3D modeling techniques that may be applied for the geometric documentation of cultural heritage sites is given by VERYKOKOU & IOANNIDIS (2023).

In recent years, numerous geometric documentation applications have been reported in literature. Examples include the holistic 3D digital documentation of the Saint Neophytos Enkleistriotis Monastery in Paphos, Cyprus, through a comprehensive approach that integrates various data acquisition methods, to capture both the tangible and intangible aspects of the monument (IOANNIDES *et alii*, 2016); a multi-scale 3D modeling framework for damaged cultural heritage sites (VERYKOKOU *et alii*, 2016); the creation of

detailed models of the Saint Martyrs Constantin Brâncoveanu and His Sons wooden church in Oradea, Romania, via photogrammetry and 3D scanning techniques (HERMAN *et alii*, 2020); a holistic 3D documentation approach applied to heritage monuments in Rhodes, Greece combining geodetic, photogrammetric, and laser scanning data acquisition methods (TAPINAKI *et alii*, 2021); the generation of high-resolution 3D models for the multi-level documentation of the Meteora UNESCO site in Greece through photogrammetric and surveying techniques (IOANNIDIS *et alii*, 2022), integrated in a web-based framework with a responsive 3D viewer, data retrieval mechanisms and VR/AR functionalities (BOUTSI *et alii*, 2023); the geometric documentation of the Mehmet Bey Mosque monument in Serres, Greece, using a multi-sensor approach integrating terrestrial laser scanning and photogrammetry (TSIACHTA *et alii*, 2024); the digital documentation of the ambulatory of the Cathedral of Santiago de Compostela in Spain, using Structure from Motion (SfM) photogrammetry (PEÑA-VILLASENÍN *et alii*, 2024); the 3D documentation of the Clock Tower in Tirana, Albania using terrestrial laser scanning (LLABANI & ABAZAJ, 2024). These examples demonstrate the variety of methods and technologies that can be used for the digitization and the preservation of cultural heritage sites.

Moreover, COLUCCI *et alii* (2024) showed how spatial and geometric data support risk assessment and vulnerability assessment of cultural heritage sites, by integrating geometric documentation into an INSPIRE-based 3D GIS framework for cultural heritage. Furthermore, Building Information Modeling (BIM) has become a useful tool for cultural heritage documentation, allowing the integration of both semantic and geometric data. CRISAN *et alii* (2024) proposed a methodology for transforming 3D point cloud data into intelligent BIM models, enhancing the conservation, documentation and management of cultural heritage sites. These studies illustrate the continuous effort to use geometric documentation results for the scope of cultural heritage preservation.

Moreover, the geometric documentation of underwater cultural heritage sites is the focus of many recent studies. Critical aspects of all stages of image-based underwater 3D modeling processes are discussed by SKARLATOS & AGRAFIOTIS (2020). CALANTROPIO & CHIABRANDO (2024) show the effectiveness of underwater photogrammetry to create high-resolution 3D models of submerged archaeological sites. Additionally, the use of advanced technologies, like ultra-high-resolution multibeam echo sounders (UHR MBES), has been shown to improve the mapping of archaeological remains, as presented in the study by ABATE *et alii* (2024). Several examples of 3D modeling underwater cultural heritage sites through marine remote sensing and photogrammetric techniques have been reported in literature, such as the recent applications of documenting underwater cultural heritage sites in Malta for the creation of a virtual museum (GAMBIN *et alii*, 2021); 3D reconstructing

the M/S Helma wreck in Norway (DIAMANTI *et alii*, 2021) and the Christoforos Shipwreck in Greece (COLLINA *et alii*, 2022); documenting the underwater heritage of the Methoni Bay, Greece (LEVY *et alii*, 2023); and reconstructing a cluster of cannons in the Gulf of Patras, Greece (LABRIANIDIS *et alii*, 2024). MANGLIS *et alii* (2021) propose a roadmap for the sustainable valorization of accessible underwater cultural heritage sites, using augmented reality and virtual reality technologies, while the significance of shipwreck archaeology is highlighted by BRIGGS & CAMPBELL (2023). All these studies demonstrate the continuous advancements in underwater 3D documentation techniques, thus contributing in preserving underwater cultural heritage sites and enhancing their accessibility.

PHOTOGRAMMETRIC DOCUMENTATION

This section presents the geometric documentation workflow followed for each site, detailing the site characteristics, data acquisition methods, photogrammetric processing steps and final results. Firstly, the documentation of Aegina Kolonna is presented, followed by the Sunken City and coastal cultural heritage of Ancient Epidaurus, and finally, the Sanctuary of Kalapodi is described.

Aegina Kolonna

In this section, the geometric documentation of Aegina Kolonna is presented, including a description of the site, data acquisition, photogrammetric processing and the final results.

The site

Aegina Kolonna is a major archaeological site at the northwest tip of the island of Aegina in the Saronic Gulf, Greece. It was one of the major hubs of the Aegean Bronze Age. The site lies next to the shore and opens to the sea on the west side, which is characterized by a steep cliff. The prehistoric settlement consists of an inner area and suburbs on the eastern side. The site was abandoned around 1200 BC and later occupied as a necropolis during the Iron Age. It continued to flourish from the Archaic to Roman times. From the 6th century AD until around AD 1000, the site was home to a large Byzantine settlement. Aegina Kolonna has been the subject of archaeological excavations since the 19th century. Since 1966, the University of Salzburg has undertaken annual research and restoration campaigns (PARIS LONDON UNIVERSITY OF SALZBURG, 2025).

Since the 1970s, the site has undergone several restoration and consolidation efforts. The walls of the inner suburb were restored and consolidated mostly during excavations in the 1970s and 1980s. However, the outer suburbs and the western area remained largely unprotected until 2015. Due to extensive excavations since the late 19th century, many prehistoric to archaic walls in the outer suburb have been exposed for decades, leading to underwashing of walls and foundations. The deep excavation cuts, combined with high-standing walls, have posed significant stability concerns.

In 2011, a new extensive restoration campaign was initiated under the direction of K. Sporn and architect A. Tanner (SPORN *et alii*, 2017), focusing on the suburbs with scientific analysis. Since 2015, the restoration program has prioritized backfilling and consolidating the walls using various scientifically approved mortars. A particular challenge is the western area of Kolonna, which includes a sacred site overbuilt by Byzantine cisterns and houses. This area was excavated in the early 2000s and partially backfilled. However, it remains highly vulnerable to winter storms and constant wave action caused by the heavy maritime traffic between Aegina and Athens (with commercial ferry boats operating every half hour alongside heavy private traffic). Each year, the archaeological zone deteriorates, especially in the west, due to soil ruptures and the ongoing risk of collapse.

To address these issues, TRIQUETRA technologies are being employed to measure geological hazards related to ground instabilities and to protect the cliffs from wave action and precipitation. Specific geophysical campaigns are being conducted at the site.

The work plan followed within TRIQUETRA includes a thorough analysis of the factors contributing to the site’s ongoing deterioration. It is crucial to differentiate between natural wave action, waves produced by ship traffic and changes in current behavior. Additionally, climate studies are conducted to assess precipitation patterns over past decades. Methodologically, the project incorporates photogrammetric processing and remote sensing imagery analysis, as well as chemical and physical studies of the endangered cliffs. This approach facilitates the identification and quantification of risks and the implementation of risk mitigation strategies. Proven methods, along with those developed within TRIQUETRA, are applied to minimize risks and develop long-term strategies for protecting the cliffs from further damage.



Fig. 1 - Images from the photogrammetric campaign in Aegina Kolonna, led by the Lab. of Photogrammetry, NTUA within the TRIQUETRA project

Data acquisition

The Laboratory of Photogrammetry of the National Technical University of Athens (NTUA), led the photogrammetric documentation of the Aegina Kolonna site, producing a detailed 3D model, point cloud, DSM and orthomosaics. The photogrammetric survey was conducted on June 25, 2024 (Fig. 1). This documentation was implemented within the context of the TRIQUETRA project, with the aim to support long-term monitoring of the site and inform preservation strategies.

For the aerial data collection, a DJI Mavic 3 Enterprise drone was used to capture 945 vertical aerial images, covering the entire site, providing an overview of the site’s topography (Fig. 2a), to ensure high-resolution documentation of complex structures such as slopes, walls, and intricate features, 4,900 oblique aerial images were captured at lower altitudes (Fig. 2b). Representative oblique images are shown in Fig. 3. Additionally, a DJI Mavic 2 Pro drone was deployed to capture 930 images of areas surrounding the Kolonna, as well as areas within the archaeological site and the museum facades (Fig. 4).

Concerning the ground survey, 15 pre-marked Ground Control Points (GCPs) were placed around the site and measured in the Greek Geodetic Reference System (GGRS ‘87) using a Leica

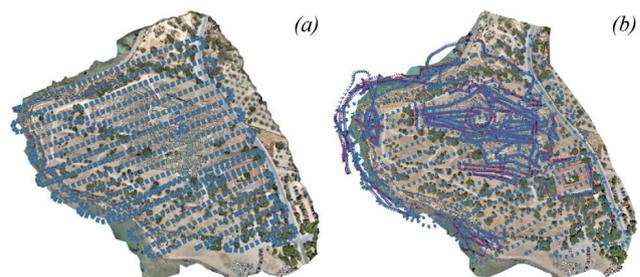


Fig. 2 - Distribution of the UAV vertical aerial images (a) and the whole set of UAV vertical and oblique images (b) over the 3D model of the entire area surrounding the archaeological site of Aegina Kolonna



Fig. 3 - Representative oblique images showcasing the slopes, walls and other site details of Aegina Kolonna



Fig. 4 - Distribution of images captured by the DJI Mavic 2 Pro drone around Aegina Kolonna along with the sparse point cloud



Fig. 5 - Distribution of the GCPs measured in the archaeological site of Aegina Kolonna superimposed on the orthomosaic of the site

1200 GNSS receiver. The NTRIP RTK method was employed to receive corrections from the MetricaNet GNSS permanent stations network. Additionally, 10 characteristic points within the site were measured to further improve georeferencing accuracy. The distribution of the GCPs is illustrated in Fig. 5.

Photogrammetric processing

The photogrammetric processing was implemented using the Agisoft Metashape Professional software, following a multi-view 3D reconstruction workflow.

The first step included the estimation of the interior and exterior orientation of all 6,694 images and the computation of the coordinates of a sparse point cloud containing ~2.4 million points, consisting of the automatically extracted tie points. This process includes the steps of automatic identification of overlapping images, image matching and feature tracking as well as the main process



Fig. 6 - Dense point cloud of the archaeological site of Aegina Kolonna

of Structure from Motion (SfM). Georeferencing was conducted using 15 GCPs, while additional check points were used to validate positional accuracy. The georeferencing achieved a root mean square (RMS) error of ~4 cm for GCPs and 6 cm for check points.

The stage of dense point cloud generation followed. This stage involves (i) performing dense image matching for selected pairs of overlapping images with known interior and exterior orientation parameters, thus producing a set of depth maps for the reference images, and (ii) converting them into 3D points, by projecting them into space to reconstruct the dense point cloud.

3D surface reconstruction was the next step. This process involves generating a polygonal mesh model using the dense point cloud.

Texture mapping was the final stage, for producing a high-resolution texture to the 3D mesh, using the oriented images.

In addition to producing 3D geometric documentation products, the photogrammetric workflow led to the production of high-resolution orthomosaics along with a digital surface model of the site.

Results

The 3D documentation of Aegina Kolonna resulted in the production of high-accuracy photogrammetric datasets, which support archaeological analysis, conservation planning as well as risk assessment within the TRIQUETRA project.

The produced dense point cloud consists of ~61 million points (Fig. 6). It preserves fine details of the archaeological

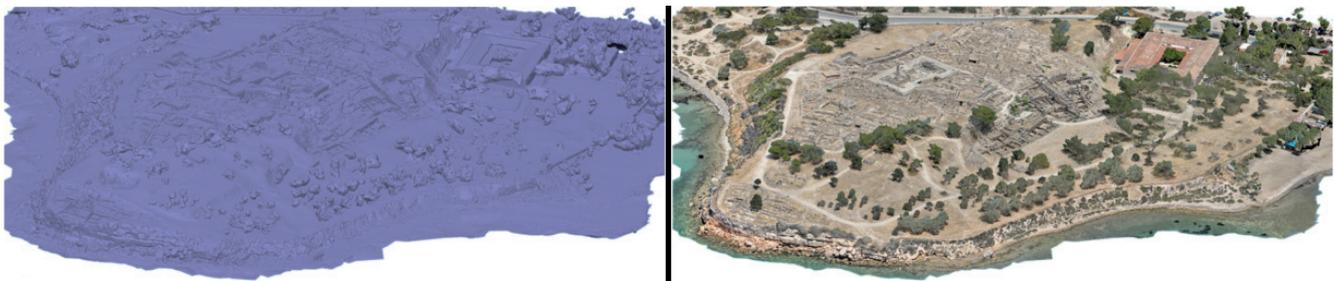


Fig. 7 - Views of the 3D model of the archaeological site of Aegina Kolonna without texture (left) and with texture (right)

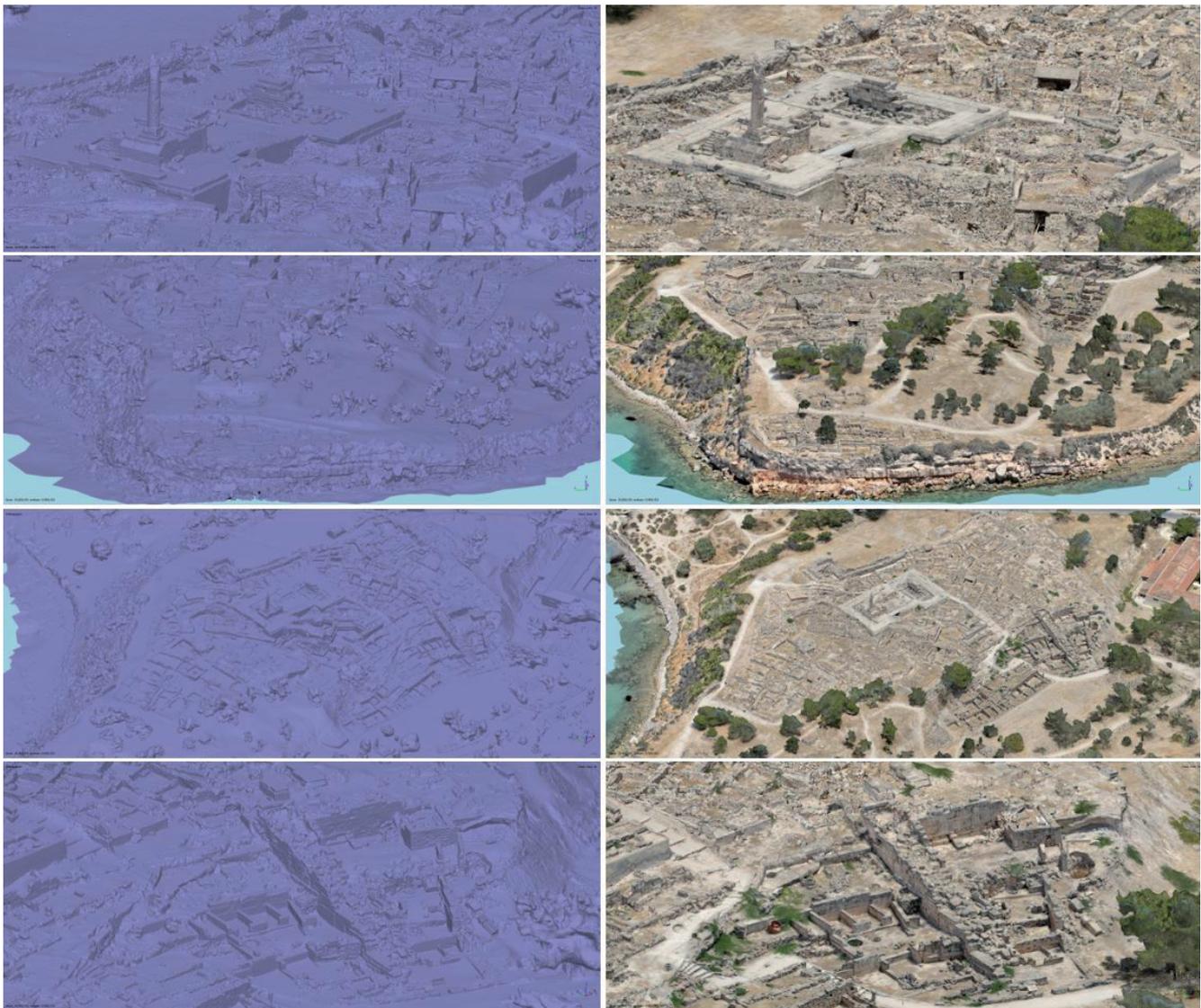


Fig. 8 - Views of part of the 3D model of the archaeological site of Aegina Kolonna without texture (left) and with texture (right).

site and serves as a critical dataset for archaeological studies and conservation efforts, enabling precise measurements and the detection of changes over time.

The generated high-resolution 3D textured model accurately

depicts the geomorphology and architectural details of Aegina Kolonna. The 3D mesh model consists of ~9.9 million vertices and 19.8 million faces. The textured rendered to the model led to a detailed visual representation of structural elements of the study

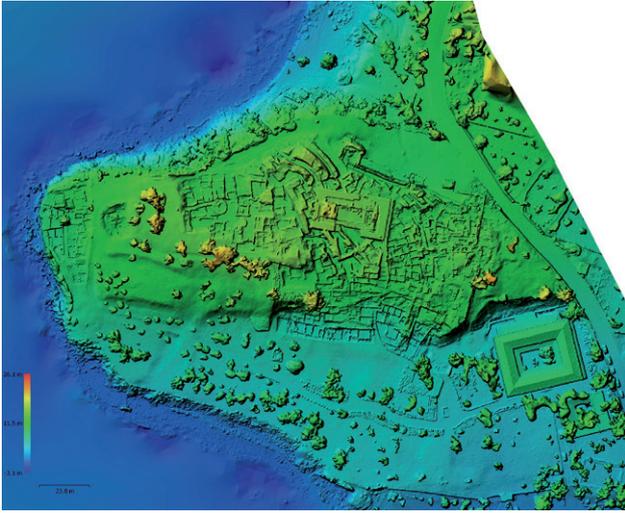


Fig. 9 - DSM of the archaeological site of Aegina Kolonna

area. The 3D model captures not only the main archaeological site, but also the surrounding terrain, providing a valuable resource for future monitoring of structural integrity and environmental changes. Views of the non-textured and textured 3D model are illustrated in Fig. 7 (entire model) and Fig. 8 (zoom-in views).

Furthermore, a DSM was generated, allowing for detailed terrain analysis. The DSM, produced at 1 cm resolution, accurately captures the elevation variations across the site. The elevation values range from -4 m to 26 m, reflecting both the natural topography and the structural remains of Aegina Kolonna. The DSM enables hydrological and topographical assessments, contributing to the evaluation of erosion risks and water runoff patterns. Fig. 9 shows the produced DSM.

Finally, high-resolution orthomosaics were produced for detailed planimetric analysis of the site. Specifically, orthomosaics with a ground sampling distance (GSD) of 1 cm and 2.5 cm were generated. The orthomosaics refer to the GGRS87 / Greek Grid (EPSG::2100) coordinate system and serve as a valuable tool for GIS-based analyses. The generated orthomosaic with a GSD of 1cm is illustrated in Fig. 10.

The photogrammetric documentation of Aegina Kolonna provides a dataset of high geometric accuracy, allowing for structural assessments, archaeological analysis and conservation planning. The 3D textured model of the site enables detailed visualization and monitoring of the site's architectural features, while the produced dense point cloud and DSM contribute to environmental assessments and long-term preservation strategies. Moreover, the generated 2D products (orthomosaics) along with the 3D outputs support archaeological mapping and aid in site management.

Beyond their immediate applications, the generated datasets can serve as the basis for future monitoring of the site, through application of change detection methods that may support

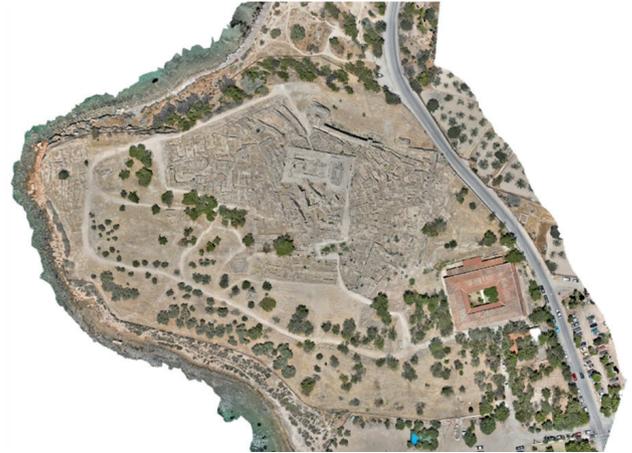


Fig. 10 - Orthomosaic of the archaeological site of Aegina Kolonna

conservation efforts. What is more, the integration of the generated products into the TRIQUETRA Knowledge Base Platform can enhance risk assessment by providing accurate spatial data for evaluating the structural stability of the site and assessing environmental threats. The 3D photogrammetric products also form the foundation for the Digital Twin of Aegina Kolonna, enabling further applications such as the Augmented Reality (AR) app of the TRIQUETRA project for citizen engagement.

The sunken city of Ancient Epidaurus and its coastal heritage

In this section, the geometric documentation of the Sunken City of Ancient Epidaurus and its coastal cultural heritage is presented, including a description of the site, data acquisition, photogrammetric processing and the final results.

The site

Ancient Epidaurus comprises a cultural heritage site of highly significant underwater and coastal remains dating back to the 12th century B.C. The Sunken City is located in the bay of Agios Vlasios, near Ancient Epidaurus. Bio-erosion is one of the most significant risks affecting these underwater and coastal archaeological findings. The Sunken City and the surrounding coastal heritage are slowly deteriorating due to water exposure and microorganisms. Additionally, sea level rise poses a severe threat to coastal archaeological remains, while coastal erosion is another major risk. Flooding on the coastal land, sediment deposition, and embankment construction for port development further endanger the site. Damage is also caused by illegal mooring of tourist boats, while exposure to chemicals, seismic activity and potential vandalism represent additional threats. Systematic conservation and promotion efforts have already begun, alongside ongoing excavations across the site.

The 3D modeling of CH sites, particularly underwater antiquities, presents significant challenges due to the complexity

and specific conditions of the aquatic environment. The detailed 3D survey of underwater and coastal CH resources in Ancient Epidaurus, combined with literature reviews and archaeological studies, will serve as the knowledge base for the TRIQUETRA DSS. These efforts aim to: (i) prevent further deterioration of the site due to overtourism, natural hazards and human-induced threats, (ii) ensure structured protection of the CH site and (iii) develop sustainable tourism strategies and propose restoration solutions for the site.

Cutting-edge data collection techniques in surveying, photogrammetry and remote sensing have been implemented. The authors worked closely with the local municipality, the Archaeological Service of the area, the Marine Antiquities Service, local guides and travel agents. High-accuracy photorealistic 3D models of the coastal and underwater antiquities were generated. For the coastal part of Ancient Epidaurus, a combination of aerial and close-range photogrammetry, terrestrial laser scanning, and aerial LiDAR was used. For the underwater part, hydrographic multi-beam sonar surveys and underwater photogrammetry were employed.

A common reference network was established for all reality capture surveys, ensuring accuracy at every step. A key focus of this work is the detection and monitoring of changes, damage, or deterioration, with a systematic approach to identifying changes at an early stage to allow for timely interventions. All collected survey data were uploaded to the TRIQUETRA online platform for further processing, analysis and collaboration. The high-accuracy 3D survey of Epidaurus antiquities and their surrounding area will serve as a reference framework for scientific research and for integrating the outcomes of the project.

Data acquisition

The Laboratory of Topography (LabTop) of the School of Rural and Surveying Engineering of the Aristotle University of Thessaloniki (AUTH) undertook the photogrammetric documentation of the underwater and coastal CH resources in Ancient Epidaurus, aiming to capture the geometry of the cultural heritage assets of the Sunken city and the surrounding coast for assessing areas vulnerable to environmental and structural risks. The data collection mission in Epidaurus was conducted from May 13th to May 16th, 2024 and its goal was to collect data of four different types (Fig. 11), *i.e.*, aerial LiDAR data, aerial images, underwater images and multibeam SONAR data. Implementing and measuring GCPs was also a prerequisite for some of the above-mentioned surveys.

A DJI Matrice 300 RTK UAV was used for the aerial LiDAR survey, in combination with DJI's L1 LiDAR sensor. Matrice 300 RTK integrates dual GNSS sensors and antennas and can fly with survey grade accuracy, but also geotags the images with survey grade accuracy. For this to happen, the controller must be connected to either a network of GNSS



Fig. 11 - Images from the campaign in Epidaurus, led by the Lab. of Topography, AUTH within the TRIQUETRA project

reference stations via NTRIP or to a base GNSS receiver casting NTRIP. The second scenario was used for all cases in Ancient Epidaurus. L1 according to the manufacturer has an accuracy of 5cm, a 20Mpixels camera for coloring the point clouds captured, integrated gimbal and IMU and records triple return for each pulse, so it can penetrate even heavy vegetation and capture ground points underneath. The coastal area of Ancient Epidaurus was surveyed in five autonomous flights. Three of these flights utilized the terrain-follow function due to significant height variations in the terrain, while the remaining two flights did not use this function, considering the height differences in those areas to be insignificant. The Digital Elevation Model (DEM) files needed for the terrain-follow function were created from data provided by the national



Fig. 12 - LiDAR point cloud derived from 5 LiDAR flights in Epidaurus

cadaster and uploaded to the flight controller. Throughout the five flights, a total of 340 million points were collected, with a spatial resolution of approximately 170 points per square meter. The resulting LiDAR point cloud is illustrated in Fig. 12.

The same UAV was used for capturing aerial images (Fig. 13), for the photogrammetric survey of the area. Again, five flights were conducted, three with the terrain-follow function and two without. In total, 4,949 vertical images were captured during the five autonomous flights. To capture the excavation area in greater detail, two additional flights were carried out: one involved manually capturing vertical images at a lower altitude, and the other involved manually capturing oblique images of the excavated ancient ruins. Together, these two flights contributed an additional 668 images to the dataset. All the necessary flight permits from the Hellenic Civil Aviation Authority, were granted well in advance.

For the underwater photogrammetric survey of the “Mansion” at the south bay of Epidaurus, a variety of cameras and scuba diving equipment have been used. The reason for that is that due to the very shallow depths in most parts of the mansion, a big, heavy camera system with lights would be very difficult to operate. Additionally, the mansion’s ruins were overpopulated by the venomous urchin species “*Diadema Setosum*”, requiring the divers to avoid contact with the ruins under any circumstances. Finally, a method previously employed by LabTop was adapted for these conditions: two GoPro Hero 11 Black cameras were mounted on a 1.20m rod, rigidly fixed at both ends. In addition, two underwater lights each producing 21,000 lumens, were attached to the rod, which was then secured under a diver’s buoy. With this configuration, the cameras were capturing slightly unsynchronized (thus the “pairs” of images cannot be used as a rigid camera system) images (Fig. 13) in timelapse mode every 2 seconds and the diver stayed safely on the surface navigating the buoy in the same pattern that drone surveys are conducted in dry land. The two cameras with their ultra-wide lenses were able to capture images with enough overlap for photogrammetry even in depths of less than 0.5m, which was the case in several parts at the Epidaurus submerged mansion. In total 13,529 images were

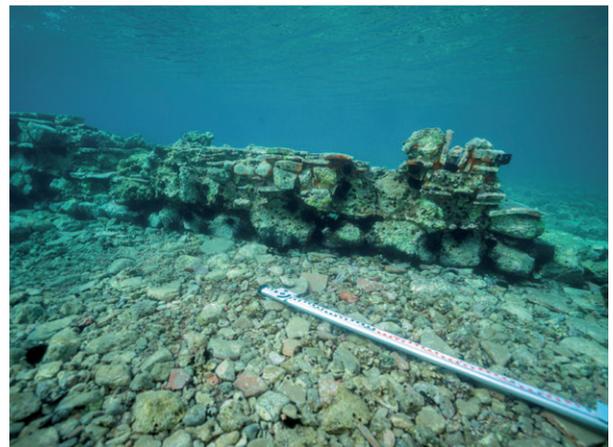


Fig. 13 - Images captured with the UAV (up), GoPro camera (middle) and Hasselblad X1D II (down) in Epidaurus

captured from the two cameras and an additional 308 images of details were captured with a medium format Hasselblad X1D II in a waterproof housing (Fig. 13). The sensors on the GoPro cameras are 1/1.9” and a resolution of 27Mpixels, while X1D II has 50 million effective pixels and was combined with a 21mm lens,

which is equivalent to 15mm in full frame format. The medium format camera was used in parts where the depth was enough to operate it properly and combined with the regular carbon fiber arms and the 21.000lumens underwater lights.

Finally, the multibeam SONAR (MBES) survey, used an R2Sonic 2020 unit, equipped with Sound Velocity Sensor (SVS), an Applanix IMU unit (SurfMaster) and dual GNSS receivers (Trimble). The units had an internet connection to the NTRIP service provided by MetricaNET and for tide compensation, RTK-tide was used, thus the system was compensating tide in real time using the corrections from the GNSS RTK receivers. The unit was attached to a small polyethylene boat for fast deployment and ease of transfer. The draught of the MBES transducer bracket did not allow the boat to operate in depths shallower than 2m, so the north and the south bay were surveyed with this configuration. A total of 81 million points were captured at the south bay, and an additional 81.5 million points were collected at the north bay, where the ancient port was located. The point density at these sites was approximately 700 points per m².

For the GCPs, an EMLID RS2+ GNSS receiver was used, with a connection to the NTRIP service provided by MetricaNET, 24 GCPs were implemented with waterproof printed targets on Teflon material and measured in GGRS'87. Some of those GCPs were also in the shallow waters around the roman mansion. For the deepest parts of the underwater photogrammetric survey (aprox. 2m depth), scale bars were used to further improve the results of the processing and add another way of inspecting the outcome of the underwater survey. The GCPs distribution is illustrated in Fig. 14.

Data processing

LiDAR sensor raw data are downloaded in a proprietary format that is initially processed in DJI's Terra software. Terra calculates adjustments for the trajectories, colorizes the point cloud and produces a file in LAZ format and a corrected trajectory file in SBETxxx.OUT format for each flight. Following Terra, those files are then imported to Terrasolid UAV software. The initial processing step in Terrasolid involves running a strip alignment to enhance accuracy between consecutive strips of captured data. The software then reduces the overlap to create a point cloud with uniform spatial resolution and also reduces noise. Finally, a classification algorithm is executed to classify ground points and create a DTM. The processed point cloud with the corresponding classes is then exported in LAZ format and the DTM is exported in Geotiff DEM format. The spatial resolution of the DEM file was reduced to 0.5m for easier further processing.

UAV photogrammetric survey data were processed in Agisoft Metashape software, following a similar methodology to that used for Aegina Kolonna. Both the images and the control points were imported to Metashape. All the images were aligned, and this stage created a sparse point cloud of 8.6 million points.



Fig. 14 - Distribution of the GCPs measured in the archaeological site of Epidaurus superimposed on the orthomosaic of the site

Subsequent steps included dense matching and 3D modeling, which eventually produced a 3D model comprising approximately 150 million triangles. The total RMS of the alignment was 6.1cm. Then, the model was textured, using a texel size of 15mm. Finally, an orthomosaic was created and exported in 115 tiles of 8.000×8.000 pixels for easier further processing. The ground Sampling Distance (GSD) of the delivered orthomosaic is 15mm.

Similarly, the images captured by the underwater photogrammetric survey, along with the control points were imported to Metashape. All the images were aligned generating a sparse point cloud of 11.6 million points. The total RMS of the alignment was 5.2cm. Subsequent processes included dense image matching and 3D modeling, which eventually produced a 3D model of approximately 88 million triangles. Then the model was textured, using a 3mm texel size. Finally, an orthomosaic of approximately 20.000×20.000 pixels was created and exported in 4 tiles of 10.000×10.000pixels for easier further processing. For the delivered orthomosaic, the resolution of the texturing stage was also kept, that is a 3mm GSD.

Multibeam SONAR survey raw data were captured as well as processed in the same software suite, Beamworx NAVAQ for capturing and Beamworx Autoclean for de-noising, rejecting outliers and removing unnecessary overlaps. The outcome of the processing is a point cloud in LAZ format and a DEM file in GeoTIFF format (Fig. 15). The suite consists of two more software modules, TrajectEdit to edit and post process trajectories and AutoPatch to perform a patch test in order to adjust the MBES angular offsets.

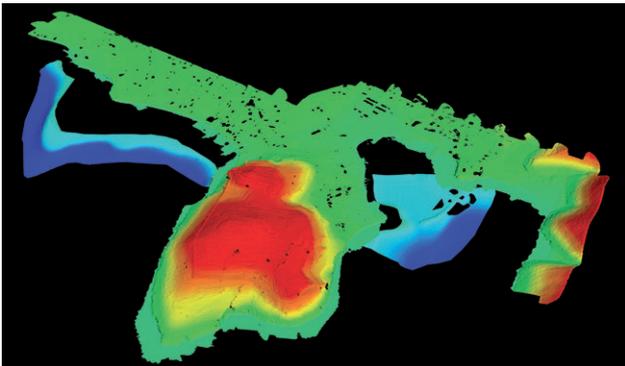


Fig. 15 - View from the DEM model of Epidaurus created from a combination of LiDAR and MBES

Results

The LiDAR survey produced a colored and classified point cloud in LAZ format, both in GGRS'87 and WGS'84 and a DEM model with 0.5m grid in GeoTIFF format. The UAV photogrammetric survey was conducted to generate an orthophoto of the coastal area, with a focus on the excavated area (Fig. 16). The final deliverable from the aerial survey is an orthomosaic of the area in JPG tiles with their corresponding world files in JGW format. The GSD of the deliverables is 15mm, and they were produced both in GGRS'87 and WGS'84. The underwater photogrammetric survey delivered a 3D model of the underwater site of the "Mansion" in FBX format (Fig. 17), georeferenced to GGRS'87, and an orthophoto (Fig. 18) of the underwater site, in 4 JPG tiles with their corresponding world files in JGW format. The ground resolution of the underwater orthomosaic is 3mm. Finally, the MBES survey delivered a point cloud and also generated a DTM in GeoTIFF format. The sampling distance of the DEM file is 0.5m.

The sanctuary of Kalapodi

In this section, the geometric documentation of the sanctuary of Kalapodi is presented, including a description of the site, data acquisition, photogrammetric processing and the final results.

The site

The sanctuary of Kalapodi lies in ancient Phokis, central Greece. Since 1974, excavations conducted by the German



Fig. 16 - View from the detailed orthomosaic, at the area of the ancient theater of Epidaurus and part of the excavation

Archaeological Institute have uncovered two temple complexes and surrounding structures, dating from ca. 1300 BC to 700 AD (BILIS & SOTIROPOULOS, 2024). Since 2018, the southern temple complex has been undergoing restoration by the German Archaeological Institute. In 2021, a hydrological study was conducted to manage rainwater, analyzing materials and their behavior during seasonal climate variations. Frost phenomena pose a constant threat to the site's materials, which, in combination with the vulnerability of the structural materials, contribute to decay issues. Currently, this issue is mitigated through seasonal covering with geotextile and insulation panels.

An integrated methodological model is proposed within TRIQUETRA to protect archaeological remains from frost, a common hazard affecting monumental cultural heritage. The variety of materials and construction methods at Kalapodi is remarkable. The site features natural stone (soft limestone, sandstone, etc.), Roman cement, metals (bronze, iron, copper, etc.) and plaster fragments in the monumental complexes. Applying weather and environmental monitoring techniques will enable the evaluation of climate-related hazards at the archaeological site and guide protection recommendations. Establishing a database of the physicochemical properties of materials, combined with data from previous restoration efforts, is essential.

For the first time, such research is being conducted on the so-called "Spolienbau". Permanent interventions, such as partial coverings or protective installations, are being explored, based on field experience from agricultural practices. TRIQUETRA follows the principles established in previous restoration programs and aligns with the general master plan for site enhancement.

Specifically, the first step within TRIQUETRA was to record microclimatic conditions at the site in detail, followed by documenting the impact of climate on the building materials and, finally, proposing a permanent solution for protecting the

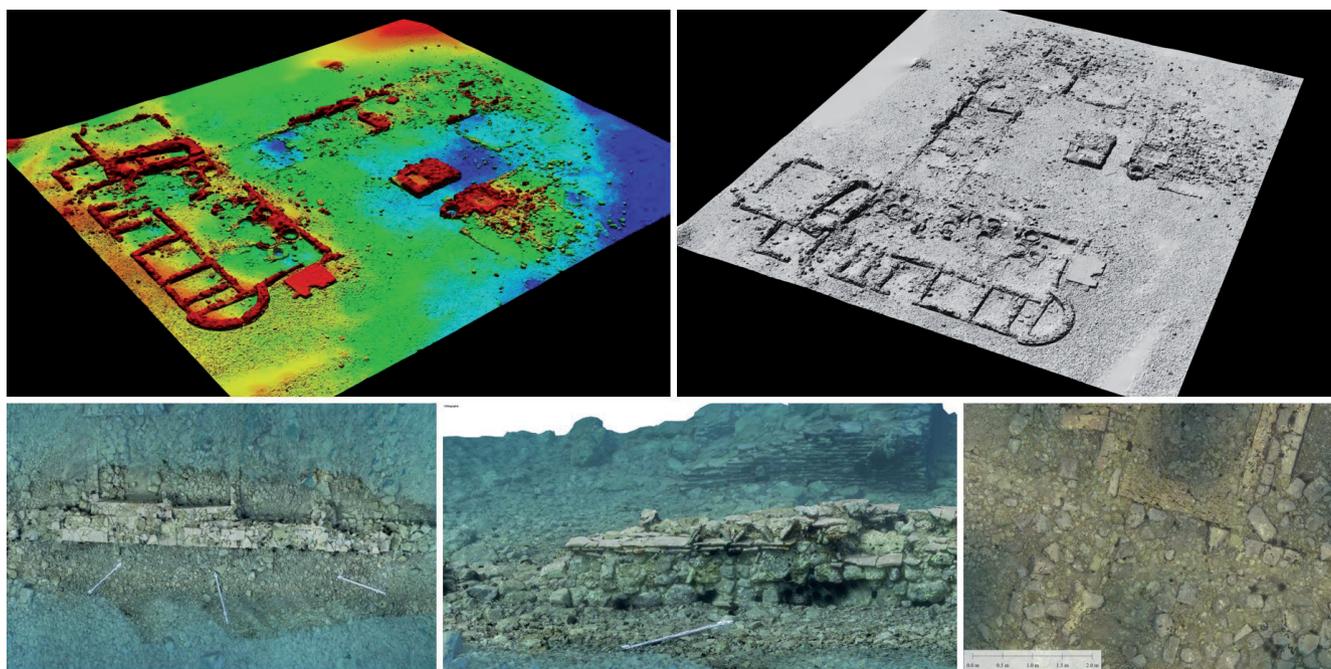


Fig. 17 - General and detailed views of the 3D model of the underwater site of Epidaurus

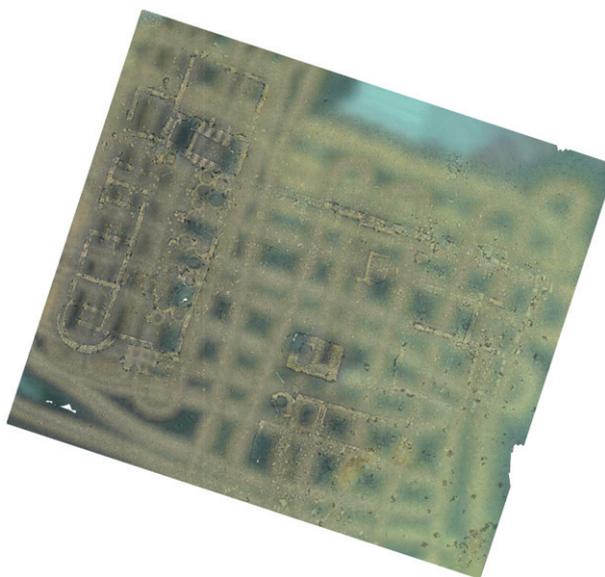


Fig. 18 - Orthomosaic of the underwater site of the "mansion" in Epidaurus

monumental complex from frost. The proposed solution is based on techniques applied to vulnerable agricultural crops (e.g., vineyards), being as discreet as possible to preserve the site's integrity.

A pilot program is being implemented within TRIQUETRA, following the necessary approvals from the German Archaeological Institute Headquarters and Greek authorities (Ministry of Culture, Ephorate of Antiquities). The effectiveness of the solution is being monitored and evaluated. Weather-

climatic and environmental monitoring is necessary to measure the intensity of the frost issue, while material analysis is assessing the behavior of materials under these conditions.

This acquired knowledge will be crucial for the development of effective protection methods and solutions. The project's exemplary character is particularly significant, as it will provide a model for other archaeological sites in Greece and across Europe facing similar challenges.

Data acquisition

The Laboratory of Topography (LabTop), of the School of Rural and Surveying of AUTH undertook the photogrammetric documentation of the ancient sanctuary of Kalapodi, focusing on capturing the geometry and structural details of the archaeological site, assessing material deterioration due to environmental factors and documenting areas vulnerable to frost damage. The data collected contribute to the development of protective measures and risk mitigation strategies as part of the TRIQUETRA project. The mission in Kalapodi, took place on the 1st of July 2024. In brief, the on-site mission included establishing and measuring GCPs, conducting a UAV flight with the LiDAR sensor and conducting two UAV flights with the RGB camera – one autonomous and one manual/oblique (Fig. 19).

Two different types of aerial surveys have been conducted: an aerial LiDAR survey to capture a detailed DTM of the surrounding area of the monument and a photogrammetric survey to capture the area of the sanctuary in detail. A DJI Matrice 300 RTK UAV has been used in both cases. The



Fig. 19 - Image from the campaign in Kalapodi, led by the Lab. of Topography, AUTH within the TRIQUETRA project

drone is equipped with two integrated GNSS receivers for georeferencing the images with a few centimeters' accuracy. An EMLID RS2+ GNSS receiver has been used as a base receiver for the flights, casting corrections over EMLID's free caster service. Both the EMLID receiver and the UAV's controller had mobile network SIM cards installed, to access each other over the internet.

DJI's own L1 LiDAR sensor has been used for the LiDAR mission. The unit includes an integrated IMU and offers an accuracy of 5cm, according to the manufacturer. In a single flight, the L1 sensor captured 56.5 million points, yielding approximately 167.4 points/m² for the surveyed area. The sensor also has the option to capture 3 returns for each pulse, a feature that was used to classify ground points and remove noise to produce the DTM of the area. Finally, an integrated camera captures images during the LiDAR survey, to colorize the produced point cloud, as illustrated in Fig. 20.

For the photogrammetric survey of the sanctuary, a DJI P1 full frame 45Mpixels camera has been deployed, with a 35mm lens. Two flights captured a total of 1,282 images. The first flight was an autonomous one and captured 810 vertical images, while the second one was a manual flight capturing 472, mainly oblique, images. Both vertical and oblique images are illustrated in Fig. 21. The image distribution is illustrated in Fig. 22.

Two new control points were installed within the property of the sanctuary for establishing a base for the total station survey. These were measured and georeferenced to the GGRS'87 system using the same EMLID GNSS receiver connected with NTRIP to "MetricaNET" network of permanent GNSS stations. Starting from these control points, 13 GCPs have been measured using a Leica Geosystem TS10 1" total station. The GCPs were implemented with printed targets on Teflon waterproof material. The checkpoints were permanent control points made of cement, already existing within the archaeological site.



Fig. 20 - LiDAR point cloud of the wider area of the archaeological site of Kalapodi

Data processing

For the LiDAR data, DJI's proprietary Terra software was used to calculate and correct trajectories, remove basic noise and apply color from the images to the point cloud (Fig. 23). The outputs from Terra software include a point cloud in LAZ file format and the corrected trajectory file which is produced from the fusion of IMU and RTK data in SBETxxx.out format. Those files are later processed in Terrasolid UAV software, which is mainly used because of its powerful classification features; additionally, it performs strip alignment (enhanced accuracy), includes better noise reduction techniques, reduces overlaps and builds a DTM.

For the photogrammetric processing pipeline, the Reality Capture software was used. The processing is similar to Metashape with small differences mainly in the reconstruction part. All the 1282 images and the 13 GCPs were imported to the software (Fig. 24). The initial alignment, which determines the interior and exterior orientation of the images through SfM was fast and issue-free, as the images from Kalapodi survey were already georeferenced with adequate accuracy. The produced sparse point cloud consists of 3.2 million points. Additionally, the user should indicate and mark the GCPs on the photos manually, to re-align the photos using the GCPs information, assess the results, mark the GCPs to additional photos or exclude photos from the process and filter possible outliers on the GCPs, which was not the case for Kalapodi. All the photos and all 13 GCPs were used. After the alignment, a reconstruction process took place, which is a combination of dense matching with 3D modeling (that is a key but not significant difference from Metashape's approach), producing the final reconstructed model of the site, consisting of 1 billion triangles. Finally, the model was textured using the P1 images. The projected mean GSD, according to Reality Capture, was under 2mm, but the GSD was rounded to exactly 2mm for the texturing process, which produced 96 textures of 8,192×8,192 for the surveyed area.

The RMS for the alignment was 0.37 pixels (reprojection errors greater than 0.7 had been filtered out during alignment)



Fig. 21 - Representative vertical images (top) and oblique images (bottom) acquired during the survey in Kalapodi.

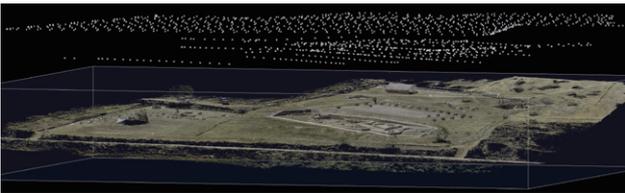


Fig. 22 - Distribution of UAV images along with the sparse point cloud of Kalapodi

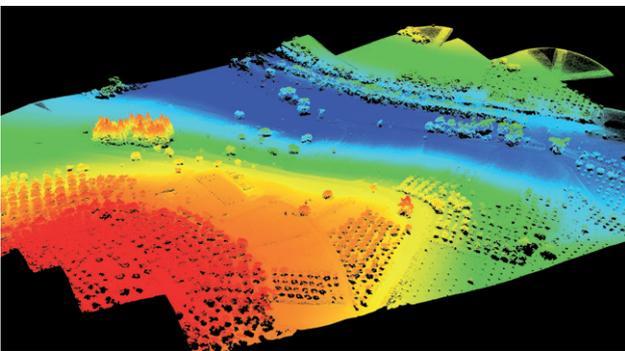


Fig. 23 - View of the LiDAR derived point cloud of Kalapodi with elevation mapping (color scale)



Fig. 24 - Distribution of the GCPs measured in the archaeological site of Kalapodi superimposed on the orthomosaic of the site.

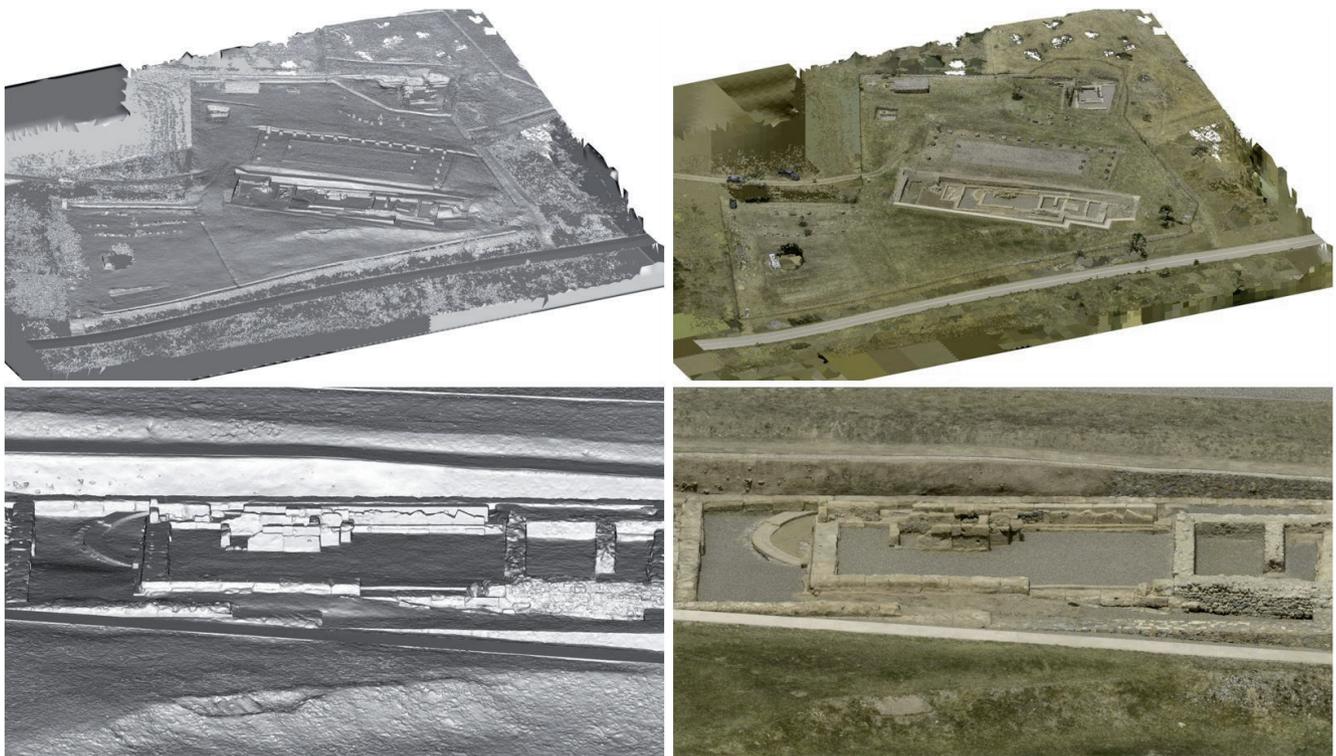


Fig. 25 - Views of part of the 3D model of the archaeological site of Kalapodi without texture (left) and with texture (right)

and the RMS for the GCPs was better than 3mm. Worth mentioning that all the GCPs have been measured from a single total station set-up and the reflector height was set to 0.1m, so in addition to the full frame sensor, its resolution and the short range of the shots, very high accuracy was something to expect. The photogrammetric survey at Kalapodi was conducted to produce a very highly detailed orthophoto and a 3D model of the sanctuary. Reality Capture includes an ortho projection tool, that can produce not only top view orthophotos, but also any other user defined views, including facade elevations and sections. Image renders from the final 3D model are illustrated in Fig. 25.

Results

For the LiDAR survey, the final point cloud has been exported in LAZ file format from Terrasolid UAV. This version of the point cloud includes not only color but also the classification of each point. The final exported DTM was simplified to a 0.5m DEM grid instead of keeping the full resolution, which would make the file difficult to use in simpler software packages, and it has been exported in GeoTIFF file format (Fig. 26). Both LiDAR products have been delivered in GGRS'87 (EPSG 2100) and WGS'84 coordinate systems, after applying the appropriate transformation.

Reality Capture is capable of manipulating and producing

ortho projections from huge models, such as the 1 billion triangles model discussed here. However, exporting those complex models to other software packages, usually raises speed issues. Consequently, the final 3D model was simplified to 50 million triangles while maintaining the original texture resolution. The reduced model was exported in FBX file format, in GGRS'87. The top-view orthophoto was split into 88 smaller tiles of 8000×8000 pixels each, to make it easier to handle. The tiles are kept in JPG format and are accompanied with their corresponding JWG world-file. The top-view orthophoto was produced in both GGRS'87 and WGS'84 coordinate systems (Fig. 27).

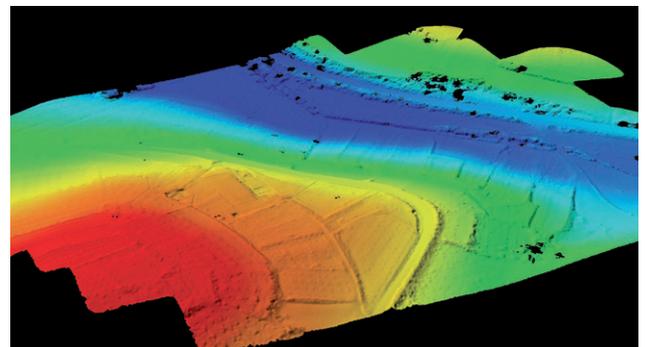


Fig. 26 - View of the LiDAR derived DEM with elevation mapping (color scale).

CONCLUSIONS

The aim of this study was to apply state of the art photogrammetric techniques for the geometric documentation of the three Greek pilot sites of the TRIQUETRA project, namely, Aegina Kolonna, the Sunken City in Epidaurus and its coastal cultural area as well as the Kalapodi site, contributing to their preservation. The main stages of the photogrammetric campaigns consist of data acquisition and photogrammetric processing. The results of the geometric documentation of the three cultural heritage sites are further used and analyzed within the TRIQUETRA project for assessing their structural conditions and monitoring the impact of external factors, like climate change, on these monuments. The produced geometric documentation results are of high importance, so they will be shared with the scientific community and the public, raising awareness of the challenges that our cultural heritage faces under the threat of climate change and natural hazards.

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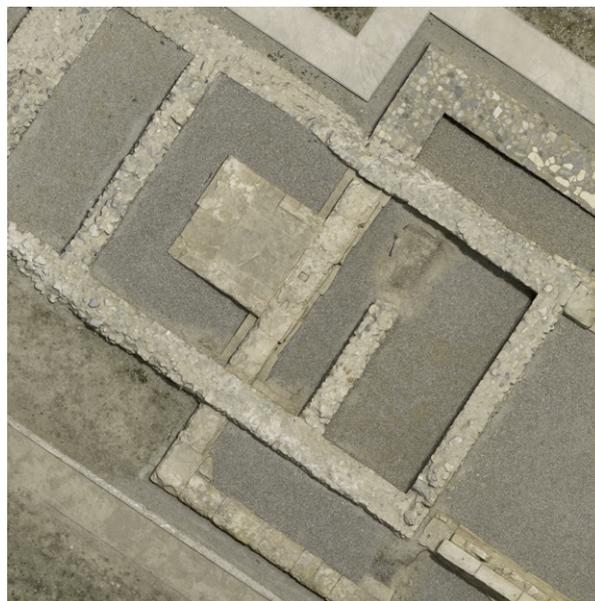


Fig. 27 - Detailed view of the delivered orthomosaic of Kalapodi

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