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THE CONTRIBUTION OF COMBINED GEODETIC MEASUREMENTS FOR THE PROMOTION OF CULTURAL HERITAGE. THE CASE STUDY OF THE HOROLOGION OF ANDRONIKOS KYRRHISTOS

Abstract:

Virtual tours of monuments become more and more a vital part of the promotion of the culture and therefore tend to be one of the main areas of study in the field of cultural heritage. These representations offer users the chance to tour in areas located far away. In order to create accurate and correct 3D representations of the monument, geometric documentation, using various methods, is essential. In this research, the geometric documentation of the Horologion (clock tower) of Andronikos Kyrrhistos is presented. Both Terrestrial Laser Scanning (TLS) and aerial photogrammetry techniques were used to create the 3D model of the monument. Apart from the architectural plans that were created, going a bit further, a virtual tour of the monument was produced, which can be used by people who cannot visit the place in person.

Keywords: cultural heritage, Horologion (clock tower) of Andronikos Kyrrhistos, Tower of the Winds, geometric documentation, terrestrial laser scanner, aerial photogrammetry, virtual tour, digital twin

ДОПРИНОС КОМБИНОВАНИХ ГЕОДЕТСКИХ МЕРЕЊА И ПРОМОЦИЈЕ КУЛТУРНОГ НАСЛЕЂА: СТУДИЈА СЛУЧАЈА ХОРОЛОГИОНА АНДРОНИКА КИРИСТОСА

Сажетак:

Виртуелне туре споменика постају све значајнији део у промоцији културе и стога представљају једно од главних подручја истраживања у области културног наслеђа. Овакве репрезентације корисницима пружају могућност да обиђу просторе који су удаљени или тешко доступни. Да би се створиле тачне и поуздане 3D репрезентације споменика, неопходна је геометријска документација коришћењем различитих метода. У овом истраживању представљена је геометријска документација Хорологиона (куле са сатом) Андроника Киристоса. За израду 3D модела споменика примењене су технике терестричког ласерског скенирања (TLS) и аерофотограметрије. Осим израђених архитектонских планова, додатно је креирана и виртуелна тура споменика која може бити коришћена од стране људи који нису у могућности да га посете лично.

*Кључне речи**:** културно наслеђе, Хорологион (кула са сатом) Андроника Киристоса, Кула ветрова, геометријска документација, терестрички ласерски скенер, аерофотограметрија, виртуелна тура, дигитални двојни*

1. INTRODUCTION

The digital preservation of architectural heritage using “virtual reality” (VR) applications is a topical issue in contemporary scientific research. It plays an important role in the integrated conservation of historically and culturally significant sites and buildings [1]. It allows users, even from the furthest places of the planet, to explore artifacts, buildings, or even whole cities in an interactive way. Moreover, it facilitates the preservation of cultural heritage, protecting it from natural disasters or human impact. Last but not least, it is a tool for restoration projects. A characteristic example is the recent study of the Notre-Dame Cathedral following the 2019 fire. A detailed digital twin of the monument, was created from laser scanning, photogrammetry, and historical datasets, helping scientists and conservation specialists to collaboratively analyze structural conditions and simulate restoration scenarios within an immersive digital environment. This approach facilitated interdisciplinary cooperation, accelerated scientific investigation, and supported informed decision-making while minimizing direct intervention on the damaged structure, demonstrating the practical value of VR technologies in complex heritage restoration processes **Error! Reference source not found.**. A similar example is the development of the new digital model of the Lascaux Cave, where high-resolution 3D scanning enabled researchers to study environmental conditions and conduct analyses that would be difficult to perform within the fragile physical site. The digital model also supported research, conservation planning, and public dissemination through interactive and multimedia applications **Error! Reference source not found.**. Another example, in the long list of similar projects is the Church of Santa Croce in Ravenna **Error! Reference source not found.**, where researchers used digital twins in order to represent the churches’ different historical, architectural phases.

Furthermore, the social character and the importance of such virtual tours should also be emphasized. Tourism or sightseeing is not something self-evident for everyone. Virtual tours broaden the horizons of people without physical or financial barriers.

A special category of heritage according to UNESCO’S Astronomy and World Heritage Initiative (AWHI) is the Astronomical Heritage **Error! Reference source not found.**. Astronomical heritage tourism is a real and growing form of cultural and scientific tourism. It involves visiting places that preserve humanity’s relationship with the sky across history, science, and culture.

Throughout centuries, the sky was the most important observation object, so people could measure the time, determine their position, or even regulate everyday life, such as agriculture or predicting the weather. In most cases, this observation included buildings and structures (tangible immovable heritage), plans and instruments (tangible movable heritage), or even techniques and rules of use (intangible heritage) **Error! Reference source not found.**. Together with other forms of heritage, the preservation of astronomical heritage is essential to protect humanity’s shared history, identity, and knowledge. These sites, ranging from ancient monuments to archaeological ruins, represent the achievements and the beliefs of past civilizations. They offer connections to our ancestors and help scientists to understand how societies have evolved over time. Without active preservation, cultural heritage is at risk from natural decay, climate change, urban development, mass tourism, and conflict. Protecting these sites is not only about conserving the structures, but also about maintaining cultural memory and educational value for future generations.

Probably the most notable monument of this category is Stonehenge in the United Kingdom, which is believed to have been built in order to represent a calendar year of 365.25 days **Error! Reference source not found.**. On the other hand, the famous city of the Maya, Chichen Itza, had pyramids that were built in a way that were used to track celestial cycles **Error! Reference source not found.**. The same buildings can also be found in Asian Civilizations, like the Angkor Wat temple **Error! Reference source not found.** and, of course, in Ancient Egypt **Error! Reference source not found.**.

However, preserving heritage sites presents significant challenges, particularly concerning problems that arise from tourist activity. While tourism can provide income, excessive visitation may cause physical damage and environmental degradation. This creates a balance between access and conservation: how can people experience the heritage sites, while at the same time preventing their deterioration?

3D virtual tours offer an important solution to this problem and contribute to the sustainable management of cultural heritage tourism. The digital models of a monument can be used for research, restoration planning and disaster recovery. In this sense, virtual tours function as a form of digital preservation, ensuring that detailed knowledge of a site survives even when the structure is under threat.

Concerning Stonehenge, one can find details for its digital reconstruction **Error! Reference source not found.** or even have an interactive virtual tour around it **Error! Reference source not found.**. Same initiatives can also be found for the other aforementioned monuments, like the MayaArch3D project **Error! Reference source not found.**.

In this research, a terrestrial laser scanner (TLS) and a Unmanned Aerial Vehicle (UAV) are combined for the geometric documentation and the creation of a 3D model and the corresponding virtual tour of the Horologion of Kyrrhistos, a famous place of astronomical heritage in the heart of Athens. The paper is structured as follows: Section 2, gives the most important historical and architectural information, essential for understanding the significance of the monument. Section 3, focuses on the case study, describing the field measurements and their process from scratch till the final result. Section 4, describes the procedures for the visualization of the monument. Finally, section 5, concludes the results of the study.

2. HOROLOGION OF ANDRONIKOS KYRRHISTOS - HISTORICAL DATA AND ARCHITECTURAL FEATURES

The Horologion (Clock Tower) of Andronikos Kyrrhistos is located on the northern slopes of the Acropolis at a short distance from the eastern propylon of the Roman Agora, 73m above the sea level (Latitude 37° 58′ 27″ N, longitude 23° 43′ 37″ E). (Figure 1). Also known as “Tower of the Winds” (or “Aerides”, in Greek), is the work of the architect and astronomer Andronikos from Kyrrhos, in Macedonia **Error! Reference source not found.**. Andronikos was an engineer, astronomer, and architect, having gained fame for his sundials and astronomical instruments before he was called to Athens to build the Horologion **Error! Reference source not found.**.

Figure 1. *Orthophoto pointing the location of the Monument* (edited by author in *Windows Paint*).

It is an octagonal tower (3.20 m. long on each side and 13.85 m in total height) standing on a base of three steps, built entirely of Pentelic marble with the exception of the foundations, which were built of “poros”. It has a conical roof, a cylindrical annex on the south side, and two Corinthian porches, one on the NE and one on the NW side **Error! Reference source not found.** (Figure 2).

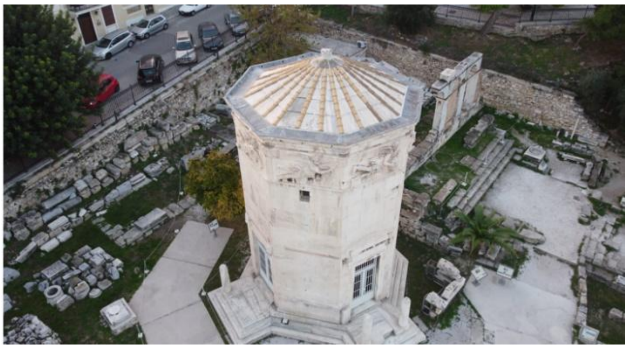

Figure 2. *Views of the Monument (*photography by *authors).*

The engraved lines on the eight exterior sides of the building and on the cylindrical section in the south belonged to nine sundials. The lines represent the hour lines and day lines and were used to determine the time of day and year, respectively, from the shadow created by a gnomon on a dial plate. On the frieze that ‘runs’ the monument over the sundials, the personifications of the eight main winds are depicted, bearing their symbols: Boreas (N), Skiron (NW), Zephyros (W), Livas (SW), Notos (S), Euros (SE), Apiliotis (E), Kaikias (NE) (Figure 3).


*Figure 3. Two out of the eight wind representations (*photography by *authors).*

The fully preserved roof of the building consists of twenty-four slabs and a circular ‘keystone’, on which a Corinthian capital rests and possibly served as the base of a bronze wind vane in the form of a Triton **Error! Reference source not found.**.

In its interior, there was a hydraulic mechanism which, according to the current interpretations, set in motion a “Horologion” or “planetarium” **Error! Reference source not found.**. The holes that were used for mounting the hydraulic mechanism, as well as cuttings that were intended for water supply conduits, but also for fixing the marble parapet that isolated the mechanism, are still clearly visible on the surface of the floor. The mechanism functioned with water pressure, which came from the cylindrical space incorporated into the south side of the monument. The interior of the building is marked in height by three architectural elements: two parallel Ionic cornices and a stylobate, on which eight decorative colonettes stand supporting a two-banded epistyle. The traces of ancient wall painting, such as palmettes, lotus flowers and meander, which are still preserved in places, are particularly significant; blue paint covered the ceiling **Error! Reference source not found.**.

Throughout the byzantine period, but also after the capture of the city by the Ottomans, the monument served as a church, as evidenced by the fragments of frescoes with Christian subject matter (an angel and a saint on horseback), dated at the 13th -14th century, which decorates the northern and the northwestern side of the building’s interior, and also by a documentary source that dates back to the end of the 15th century. In the late period of the Ottoman occupation, the building was also used as a tekke of the Mevlevi Dervishes order; the mihrab niche, carved into the wall on the southeastern side of the ‘horologion’, is directly associated with this use. Inside the monument, the incised graffiti of a Roman ship (2nd - 4th c. AD), as well as the graphite drawings of sailboats that date from later times, are noteworthy. During 1838 - 1839, the Archaeological Society at Athens unearthed the monument in its entirety, which was buried outside as well as inside up to the level of the first interior cornice. Then, in the mid -19th century, metal gnomons were mounted over the ancient incisions of the sundials, based on a study elaborated by the Greek expatriate officer of the French navy Leonidas Palaskas, whereas between 1915 and 1919 Anastasios Orlandos carried out consolidation works on the monument’s roof from which he removed the ‘onion-shaped’ crown that had been constructed at the apex during the Ottoman occupation. It was replaced by the surviving lower part of the Corinthian capital that crowned the monument in antiquity. More recently, in 1976, the Greek Archaeological Service conducted consolidation and conservation work on the roof and the rest of the outer sides of the monument [6]. Further treatments were implemented between 2014 and 2015 in the context of the project of the National Strategic Reference Framework 2007–2013, “Conservation and Valorization of the Horologion of Andronikos of Kyrrhos, at the archaeological site of the Roman Agora of Athens”. This work was undertaken initially by the Ephorate of Prehistoric and Classical Antiquities and then by the Ephorate of Antiquities of Athens, of the Ministry of Culture and Sports **Error! Reference source not found.**.

It is considered the first meteorological station in the world and is mentioned in the works of Pausanias, Vitruvius and other later writers and travelers, such as the Italian scholar Ciriaco de' Pizzicolli (15th century) and the French traveler Comte de Forbin (19th century) **Error! Reference source not found.**. Today, the Horologion of Andronikos Kyrrhistos is protected by the Greek

Ministry of Culture (Ephorate of antiquities of the City of Athens) **Error! Reference source not found.**, **Error! Reference source not found.** and can be visited as a part of the archeological open-air site of the Roman Agora.

3. MEASUREMENTS AND DATA PROCESSING

3.1. FIELD WORK

For the 3D documentation of the monument, several steps were followed. The whole procedure lasted about 8 hours. The measurements were carried out by a team of 1 Surveying Engineer with experience in similar projects and 1 postgraduate student as a part of his diploma thesis **Error! Reference source not found.**. One main challenge was the continuous flow of tourists/visitors, typical for monuments of such importance, that made the measuring processes difficult. That caused delays in the total amount needed.

1.1.1. Total station measurements

A trigonometric network consisting of 4 points was established around the monument, which was measured using a total station and a mini prism. The network was essential for the measurement of the 14 checkerboard targets placed on and around the monument (Figure 4). The targets were necessary for three purposes: ensuring highly accurate registration (alignment) of the TLS scans, linking the aerial photogrammetric data to the TLS coordinate system, and validating the final model's geometric integrity.

*Figure 4. Checkerboard targets on the monument (*photography by *authors).*

1.1.2. Terrestrial Laser Scanner Measurements

Following, laser scanning was performed for the geospatial documentation of the monument since it can capture and depict the geometry, texture, and intensity of the object. For the process, the Leica Geosystems BLK360 TLS was used **Error! Reference source not found.**. The scans were performed in high accuracy (4mm step), and the distance between the scanner and each element of each monument was not more than 15-20m for each setup. The net time of each setup is 6 minutes. The percentage of the scan overlap ranged from 40% to 60%. In many setups, the overlap was even bigger, as most of the construction is visible almost from every setup. This reinforced a strong geometry of the final model. In total 26 setups were performed (Figure 5) and their positions are shown in

Figure 5. *Different setup positions (*photography by *authors).*

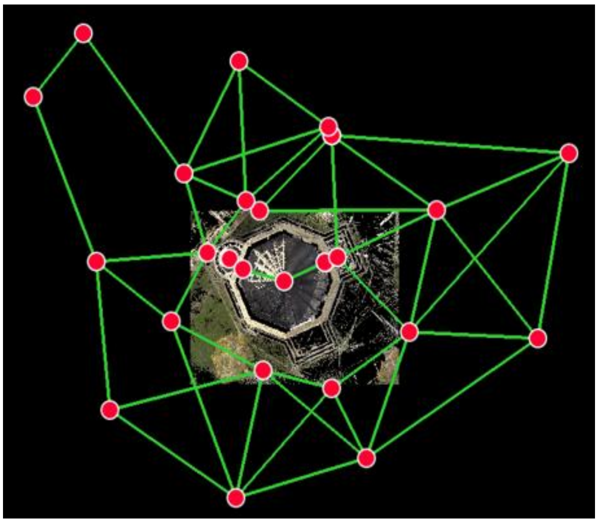

Figure 6. *The relative positions of the setups (*edited by author in *software: Leica Register 360).*

1.1.3. Aerial Photogrammetry – UAV Flight

Subsequently, an unmanned aerial vehicle (UAV) was used. Its role was dual; a) UAV images give better texture to the final model and b) there were parts of the roof that couldn't be documented with the TLS, Moreover, additional images were taken for non-metric procedures (photographic documentation). Vertical and oblique images were taken to create the 3D model and the orthophoto of the monument. The vertical images were taken from ~25 m height with an overlap of approximately 60%. The oblique images were taken at angles of 30º and 60º, so that all the details were visible. Even closer images were taken, especially for the figures that represent the winds. The UAV DJI Mini 2, was used **Error! Reference source not found.**.

3.2. DATA PROCESSING & DIGITAL TWIN PRODUCTION

1.1.4. Point Cloud registration and cleaning

The TLS setups and the UAV images were processed with the corresponding software. From the raw scan files, the alignment was performed using the Cloud-to-Cloud method. This manual approach was preferred over automated registration, as it allowed greater operator control and higher certainty in the alignment of the different point clouds, ensuring they converged into a single, cohesive geometry in a common arbitrary coordinate system.

The final registration report demonstrated the high geometric fidelity achieved, with an adjustment error of 0.007 m and an average Overlap of 51%. The unified point cloud contained noise, primarily originating from moving people, which was manually cleaned. The output of this stage is the final geometrically purified TLS point cloud, ready for fusion with the aerial data.

1.1.5. Photogrammetric Processing & Hybrid model generation

The UAV images were processed and the corresponding point cloud was produced. The subsequent critical step was the geometric synchronization of the photogrammetric data with the high-accuracy TLS data. Using the measured checkerboard markers and assigning the coordinates defined by the TLS local system. The different clouds were transformed, bringing the aerial data into the accurate coordinate system established by the laser scanner. The two synchronized clouds were then combined. This integrated methodology ensures that the geometric rigor of the Digital Twin relies on the TLS, while the visual realism is provided by the images taken by UAV. The accuracy of the final model has a precision of 0.011 m.

Figure 7. *The final hybrid model (*edited by author in *software: Autodesk Recap)*.

1.1.6. Drawings & Orthophoto production

Apart from the 3D model that was used for the virtual tour of the monument, deliverables of the study are also the drawings and the orthophotos of it, with the precision of a scale 1:50;

- Orthophoto of the roof (Figure 8)
- Façade orthophotos and façade plans (Figure 9)
- Vertical and horizontal cross-sections in different directions and heights

These drawings can be used in the future for projects of restoration or preservation of the monument. Moreover, they can also be used for the touristic or cultural promotion of the area.

The great advantage of modern geometric documentation methods is that the user can produce any plan required with no additional measurements in the field. All information is stored and can be utilized in (almost) any future need.

Figure 8. *Orthophoto of the roof (*edited by author in s*oftware: Agisoft Photoscan)*.

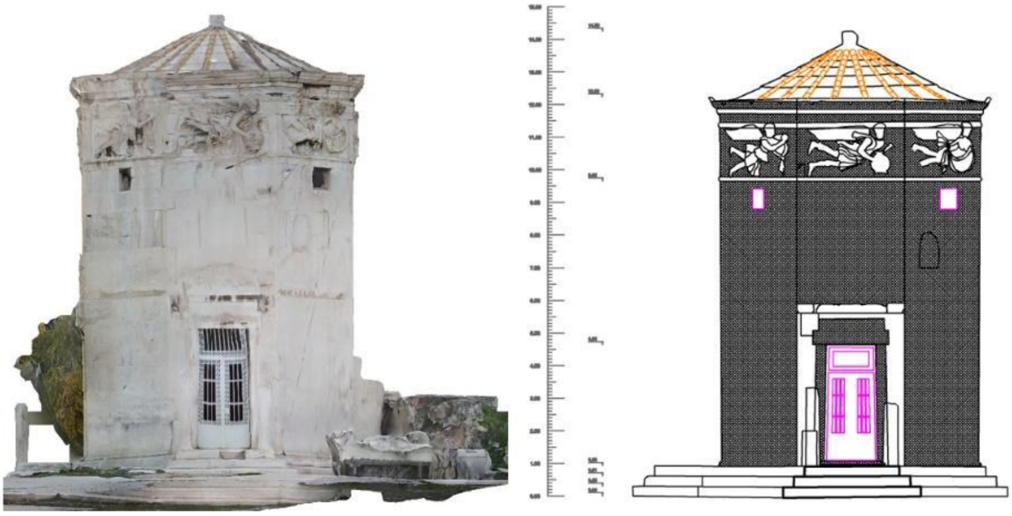

Figure 9. *North-West Façade orthophoto and plan (*edited by author in s*oftware: Agisoft Photoscan)*.

4. VISUALISATION OF THE MONUMENT

4.1. CREATION OF A VIRTUAL TOUR

The point cloud of the monument was imported into the TruView Enterprise, a digital-reality data viewer and collaboration platform developed by Leica Geosystems. It's designed to let users view and navigate through 3D scan data (e.g. point clouds, 3D models) — even if the viewer has no CAD or 3D-modelling experience **Error! Reference source not found.**. Using it, the user can make a virtual tour around and inside the monument and use it to measure dimensions, height differences, angles, or even the temperature of each material during the day of the measurements. Virtual Tour can be reached using the following link: http://195.130.106.58/site/68ca63b785fb572b74eebac8?tab=sitemap

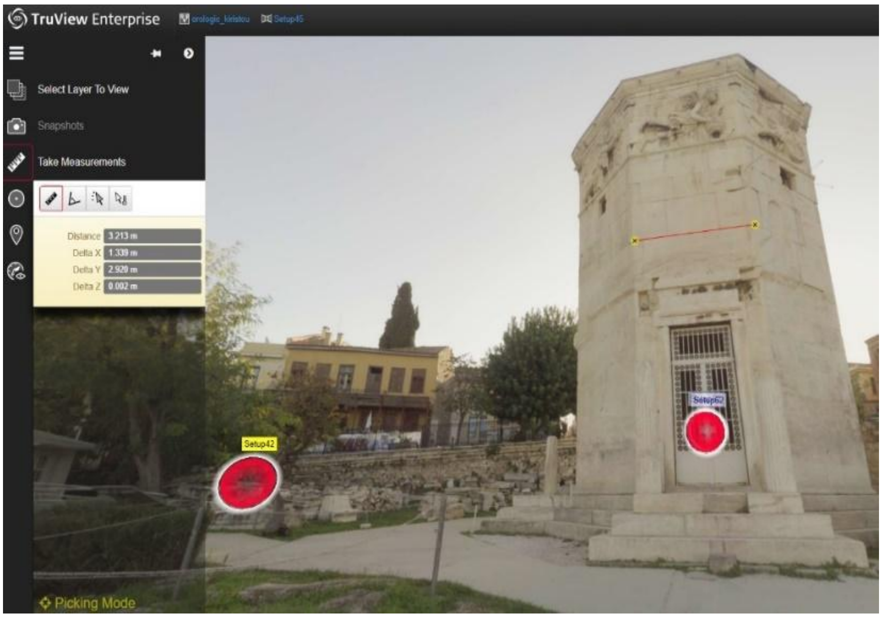

Figure 10. *Figure 10.* *Measuring dimensions within the TruView Enterprise software*

4.2. MIXED REALITY VISUALIZATION

Following the geometric documentation and digital twin production, Mixed Reality (MR) visualization was employed to further exploit the survey-derived three-dimensional dataset. The unified point cloud, produced through the integration of terrestrial laser scanning and aerial photogrammetry, constitutes a high-resolution and geometrically reliable digital representation of the monument, capturing both its exterior architectural features and complex decorative elements. Building upon this dataset, MR was used as an additional visualization layer aimed at enhancing the interpretation, accessibility, and dissemination of the documented cultural heritage.

As described in the previous sections, the geometric documentation of the monument was based on multiple terrestrial laser scanner setups combined with aerial photogrammetric data acquired using an unmanned aerial vehicle. This integrated approach ensured comprehensive spatial coverage of the structure, including architectural details and roof elements that could not be adequately captured through ground-based measurements alone. The resulting unified point cloud formed the core digital asset of the study and served as the basis for all subsequent visualization products, including orthophotos, drawings, virtual tours, and MR applications.

The unified point cloud was transformed into formats suitable for web-based and MR visualization. Initially, the point cloud was converted using the Potree Converter, enabling efficient browser-based visualization through the Potree platform. This approach allows dense point cloud datasets to be accessed via standard internet browsers, providing interactive navigation and basic analytical functionality without requiring specialized software installation. The Potree-based visualization serves as a lightweight and accessible interface for interdisciplinary users, facilitating inspection and interpretation of the survey data.

Figure 11. *Figure 11.* *Interactive visualization of the 3D model using the Potree web-based point cloud viewer*

In parallel, the unified point cloud was further processed to enable MR visualization on smart mobile devices. The dataset was first converted into a surface representation using CloudCompare, transforming the point cloud into a triangular mesh. The resulting mesh was subsequently processed and exported to the GLTF format using Microsoft 3D Builder, producing a lightweight 3D model compatible with mobile MR environments. This workflow follows a software-agnostic and application-free approach, allowing the MR model to be visualized directly through standard web technologies on Android devices, without the development of custom applications or programming.

The hosting of both the web-based point cloud visualization and the MR-compatible 3D model was implemented through a centrally managed server infrastructure, ensuring stable access and broad availability. Using this approach, users can easily access the digital representation of the Horologion of Andronikos Kyrrhistos via a shared link, either for browser-based exploration of the point cloud or for immersive MR visualization on mobile devices. This methodology ensures consistency, reproducibility, and scalability, allowing the same surveying-derived dataset to support multiple visualization modalities.

In addition to point cloud visualization, the survey data were further processed to generate a three-dimensional mesh representation suitable for Mixed Reality visualization on smart mobile devices. The resulting MR model allows users to interactively explore the Horologion of Andronikos Kyrrhistos in an immersive manner, enhancing spatial perception and facilitating a more intuitive understanding of its architectural form, proportions, and structural relationships. Such interaction is particularly valuable for users who are not accustomed to interpreting point clouds or technical drawings, including students, educators, and the general public.

Figure 12. Figure 12. Mixed Reality visualization of the 3D model placed on a tabletop using a mobile phone camera

The integration of MR visualization is directly aligned with the digital twin methodology adopted in this study. While the digital twin provides an accurate geometric reference for documentation, analysis, and future conservation actions, MR visualization extends its value by transforming survey-derived data into an accessible and engaging medium. For cultural heritage management, MR applications offer a non-invasive means of presenting the monument, reducing physical impact while increasing public engagement. At the same time, they support educational activities by enabling experiential learning through direct interaction with accurate survey data.

From a surveying engineering perspective, the MR workflow presented reinforces the role of the surveyor not only as a data provider but also as a key contributor to the interpretation and communication of cultural heritage. The same unified dataset that supports precise drawings and analytical products can be reused for immersive visualization, demonstrating the versatility and long-term value of modern geodetic documentation. Furthermore, the MR-ready models produced through this process may serve as a geometric foundation for future digital applications, such as semantic enrichment or Historic Building Information Modeling (HBIM), should extended documentation or asset management be required.

In conclusion, the application of Mixed Reality visualization to the survey-derived digital twin of the Horologion of Andronikos Kyrrhistos demonstrates how accurate geodetic measurements can be effectively transformed into interactive and immersive representations. By following a reproducible workflow based on point cloud conversion, web-based visualization, and MR-compatible 3D model generation, the study highlights the potential of modern surveying methodologies to support scientific analysis, interdisciplinary collaboration, education, and public dissemination, while maintaining the geometric rigor required for cultural heritage documentation.

5. RESULTS & DISCUSSION

This paper deals with the procedure of the creation of a virtual tour for the promotion of an emblematic monument of Athens, the Horologion of Kyrrhistos. The process is thoroughly described, starting from the early stages, i.e. the geometric data collection till their integration to an application, which offers various options to different kinds of users.

The high value of the Digital Twin methodology is evident when it comes to geometric documentation projects, which in turn lead to applications that aim to promote the cultural heritage of a place. This value becomes particularly apparent when geometric documentation is considered not merely as a recording process but as the foundation for a continuously exploitable digital environment. The Digital Twin approach substantially expands the role of geometric documentation, transforming survey data from a static recording product into a reusable and evolving digital asset. Unlike conventional documentation methods that primarily deliver drawings or isolated 3D models, the Digital Twin integrates high-accuracy geometric information with visualization and interaction capabilities, enabling long-term reuse of the dataset. In the context of the present study, the combined TLS and UAV workflow produced a unified and metrically reliable representation that supports not only documentation but also monitoring, of the monument. This form of presentation allows different levels of engagement, ranging from precise metric analysis required by conservation specialists to explore virtual and mixed-reality environments accessible to non-expert users. As a result, the Digital Twin supports simultaneously to scientific analysis and public dissemination, bridging the gap between surveying outputs and cultural heritage promotion while supporting sustainable heritage management through reduced in-situ interventions and enhanced digital accessibility.

Virtual Reality bridges not only people with historical sites all around the world, but also the present with the past and the future. Integrating the past with state-of-the-art technology, VR ensures that cultural heritage remains alive, accessible and a priceless legacy for future generations.

By employing high-resolution laser scanning and photogrammetry, a precise and interactive 3D model of the archeological site is developed. It should be noted that the use of Virtual Tours can achieve notable success in both heritage preservation and visitor engagement. In this case, the developed model was incorporated into a virtual tour, enabling users to explore the monument remotely with a highly immersive and detailed experience. With this method, understanding and interpreting a monument's preservation state can be improved, offering conservators a digital tool for future work, thus providing the tools to acquire information on a monuments' current state, monitor structural changes over time; while protecting fragile areas from physical intervention Furthermore, a virtual platform can support sustainable tourism management by providing an alternative way that visitors experience the site. Through interactive hotspots, embedded historical details and guided virtual tours, the platform can increase accessibility for a global audience, including scholars, students, and tourists who cannot visit in person **Error! Reference source not found.**.

The significance of these virtual excursions should be highlighted; people's horizons are expanded via virtual tours, which removes both financial and physical constraints. Through high-quality images, 3D models and a VR experience, potential visitors can explore the site remotely and if possible, plan a forthcoming visit. Detailed information about the history, significance and cultural value of the site, enhances visitor engagement and appreciation.

The platform can also be used by the local authorities (e.g. Municipality of Athens) or the Ministry of Culture, as a means of promoting this important historical site. It can also be used for educational purposes for schools and universities. Virtual reality experience can be a creative and interesting way of learning, regardless of one's age.

Also, similar projects highlight the potential of immersive virtual technologies to safeguard cultural heritage and enhance educational outreach, setting a benchmark for future digital documentation initiatives in archaeological preservation.

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