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WEB-BASED 3D GEOSPATIAL TOOLS FOR DOCUMENTING, PRESERVING, AND SUSTAINABLY MANAGING BUILT CULTURAL HERITAGE: A CASE STUDY OF THE STONE BRIDGE IN BĂILE HERCULANE, ROMANIA

Antrei DELIGIANNIS[1], Panagoula KOPELOU[1], Paul ZDRENGHEA[2], Clara – Beatrice VILCEANU[2], Sorin HERBAN[2], Vassilis PAGOUNIS[1]

[1] University of West Attica, Department of Surveying & Geoinformatics Engineering, Laboratory of Geodesy-Surveying & GNSS,

[2] Politehnica University Timisoara, Faculty of Civil Engineering, Department of Overland Communication Ways, Foundations and Cadastral Survey

Corresponding author: paul.zdrenghea@student.upt.ro

Abstract. *Safeguarding built cultural heritage is vital for maintaining historical identity and ensuring sustainable management practices. The rapid development of geospatial technologies and web-based platforms has opened new avenues for collecting, interpreting, and sharing heritage data in dynamic and user-friendly formats. Cultural heritage constitutes a fundamental and distinctive pillar of Europe's cultural identity, while also representing a critical dimension of sustainable development and tourism policy. This study explores the use of online 3D geospatial tools in the documentation and preservation of the Stone Bridge in Băile Herculane, Romania, a significant 19th-century architectural landmark. Despite increasing awareness of digital heritage's transformative potential, significant challenges persist in embedding these tools within sustainable tourism frameworks—particularly for smaller or underrepresented archaeological sites. By integrating geodesy, 3D modeling, and virtual reality systems (VR), detailed spatial datasets were generated, processed, and published through an interactive web platform. The resulting system allows for high-precision visualization, structural assessment, and ongoing monitoring of the monument, while also encouraging collaborative heritage management by granting open access to specialists, decision-makers, and the wider public. The case study illustrates how digital documentation can strengthen efforts to protect endangered heritage structures and support long-term preservation strategies. More broadly, the research emphasizes the versatility of web-based 3D geospatial technologies as a framework for managing cultural heritage sites in diverse settings.*

Keywords*: Băile Herculane Stone Bridge, cultural heritage; preservation; sustainable management; tourism; virtual tourism; 3D documentation*

INTRODUCTION

In the context of digital communication and globalization, cultural activities play a pivotal role in safeguarding, preserving, and promoting cultural heritage, while simultaneously fostering contemporary cultural production. Such activities encompass a broad spectrum of initiatives related to the creation and dissemination of both tangible and intangible cultural goods. When oriented toward the public interest, cultural activities contribute to the advancement of cultural processes and serve as a foundation for the development of cultural policy [THROSBY,2017, SMITH, 2006]. Moreover, they generate significant benefits for the economic, social, and spiritual dimensions of regional development. The sustainable advancement of cultural activities necessitates innovation, supported by contemporary management practices and development models. In the present era, culture unfolds dynamically within two interconnected and parallel spheres—the physical and the digital—each contributing to the broader trajectory of cultural development. This dual evolution establishes the foundations for cultivating local, regional, and global networks of cultural policy [GANTZIAS, 2010]. The World Heritage List currently comprises 1,248 properties recognized by the World Heritage Committee as possessing outstanding universal value, encompassing both cultural and natural heritage. Among these are 972 cultural sites, 235 natural sites, and 41 mixed properties distributed across 170 States Parties [UNESCO, 2024; EUROPEAN COMMISSION, 2018; JOKILEHTO, 2005]. As of October 2024, a total of 196 States Parties have ratified the World Heritage Convention. The digital transformation of cultural heritage rests on several interconnected conceptual foundations. Cultural sustainability emphasizes the enduring importance of safeguarding cultural resources for future generations, while promoting community involvement and equitable access [SOINI, 2016]. In parallel, the smart heritage framework integrates digital technologies into heritage management and tourism, fostering improved decision-making and greater stakeholder engagement [GIACCARDI, 2012]. Recent developments in digital documentation have greatly broadened the range of tools available to heritage professionals. Technologies such as terrestrial laser scanning (TLS), LiDAR sensors, and UAV-based photogrammetry enable accurate and non-invasive recording of monuments and landscapes [REMONDINO, 2014; FASSI, 2013]. These approaches produce photorealistic 3D models that function as both analytical resources for researchers and engaging communication tools for the public.

Moreover, the integration of these models into Web platforms and immersive environments (such as VR and AR) has revolutionized user interaction with heritage content [KUROCZYŃSKI, 2019; BEKELE, 2018]. These technologies enhance spatial analysis, provide virtual access to sites, and support data-driven conservation strategies. Scholars have underscored their potential to democratize heritage access, particularly benefiting remote audiences and underrepresented communities [CHAMPION, 2015; TAN, 2019]. Across Europe, numerous initiatives have propelled the digital transformation of cultural heritage. Europeana, the EU’s digital heritage platform, has brought together millions of digitized artifacts and multimedia assets from institutions across the continent [EUROPEANA FOUNDATION, 2023]. Projects such as Inception (Horizon 2020), V-MusT.net, and ARtGlass have integrated 3D modeling, semantic web technologies, and immersive storytelling to enrich heritage education and tourism experiences [BRUSAPORCI, 2017; ARTGLASS, 2022]. At the regional level, initiatives like Scan the World, Time Machine Europe, and the Virtual Museums of the Mediterranean showcase the potential of open-access 3D repositories, historical reconstructions, and geospatial storytelling. Nonetheless, much of this progress remains concentrated on high-profile or well-funded heritage sites, leaving many lesser-known yet culturally valuable locations outside the digital mainstream. Addressing this requires scalable, community-oriented digital solutions that not only document cultural assets but also promote participatory planning and inclusive regional development. This need is especially pressing in countries with rich yet underutilized cultural landscapes, such as Romania. This study seeks to bridge this gap through an in-depth case study of the stone bridge in Băile Herculane, situated in Banat, in Caraș-Severin County, Romania. As the whole aarea can be characterized an ancient site, archaeological evidence indicates that the area has been continuously inhabited since the Paleolithic era. The Peștera Hoților (Cave of the Thieves) reveals multiple stratigraphic layers, including one from the Mousterian period, another from the Mesolithic period (late Epigravettian), and several dating to subsequent Neolithic phases, featuring architectural remains from multiple historical periods, The Stone Bridge in Băile Herculane offers an ideal context for combining high-precision digital documentation with community-centered heritage planning. Our approach employs terrestrial laser scanning (TLS), UAV-based photogrammetry, and LiDAR to produce detailed 3D models of the site. These models are then integrated into a Web platform designed not only for heritage visualization, but also to support educational engagement, participatory decision-making, and sustainable tourism management.

CASE STUDY OF THE STONE BRIDGE in BĂILE HERCULANE

The Stone Bridge in Băile Herculane, constructed around 1864 as indicated by an on-site inscription, is recognized as the first bridge of its curved typology in Europe. It remains a significant historical artifact, still displaying the Latin dedication "Ad Aquas Herculis Sacras Ad Mediam." The bridge spans the Cerna Valley, forming a structural link between Hercules Place and Cerna Street.


Figure 1. The Stone Bridge in Băile Herculane

This masonry structure possesses a total length of 36 meters and a width of 10 meters. Its deck is characterized by a slight inclination and incorporates two covered footpaths. The bridge comprises two primary spans, achieved through vaulted construction with individual lengths of 16.5 meters and 12.5 meters, respectively. The primary construction materials are stone and brick, with the superstructure flanked by two spandrel walls built in successive layers of these materials. The bridge is defined by a pronounced curvature with a radius of 35 meters. Its parabolic arch is geometrically optimized, as this shape conforms to the line of pressure for uniformly distributed loads, enhancing its structural efficiency. The bridge is configured as a double-articulated system, rendering it statically determined. A distinctive feature is its roof, constructed from tin sheeting mounted on a wooden framework. This roof system is supported by metal pillars, the upper sections of which are adorned with decorative cast iron ornaments [BADEA, 2015; IOANA, 2024].

Structural analysis of the bridge was performed utilizing both the limit state method, in accordance with Eurocode provisions, and the traditional allowable stress method. This verification confirms that stresses within the initial, uncompromised arch sections remain within permissible limits. However, when accounting for material degradation resulting from corrosion, computational models indicate that the induced stresses surpass the allowable threshold, highlighting a critical vulnerability in the structure's long-term integrity [BADEA, 2015].

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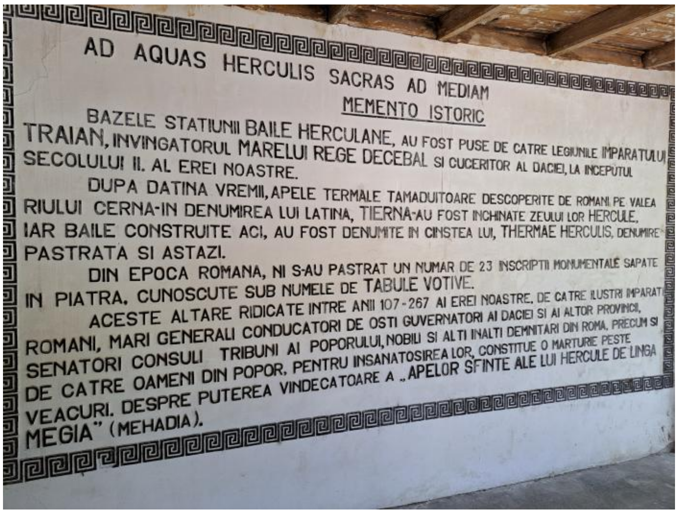

Figure 2. The dedicatory epigraph in Latin

METHODOLOGICAL APPROACH

The proposed methodology (Figure 3) aims to develop an approach that leverages geomatics, combined with historical documentation, to enhance the tourism management of archaeological sites. Central to this approach is the integration of 3D documentation data with historical information about the preservation state of monuments, which—through careful analysis—can support sustainable tourism management.

Figure 3. Sustainable Tourism Management Methodology

The process begins with a comprehensive bibliographic review of all historical and archaeological data related to the Băile Herculane stone bridge. All available information is collected and documented, including details on the current preservation status of the bridge, remaining structures, and areas with ongoing interventions within the area.

Subsequently, detailed digital documentation is conducted using Terrestrial Laser Scanning (TLS) to generate precise 3D point clouds and corresponding 3D models of each monument and site. In parallel, UAV (drone) imagery is captured to ensure comprehensive documentation—particularly important for cultural heritage assets with complex or inaccessible surfaces. The resulting 3D data are georeferenced to facilitate further analysis within the whole area.

The next stage toward Sustainable Tourism Management involves developing a web-based virtual tour platform that integrates all relevant information, including historical data, photographs, structural and material details, degradation assessments and 3D models—organized within a skin. Additionally, a VR application is created to offer an immersive, off-site experience of the stone bridge. A schematic representation of these three information axes is illustrated in Figure 4.

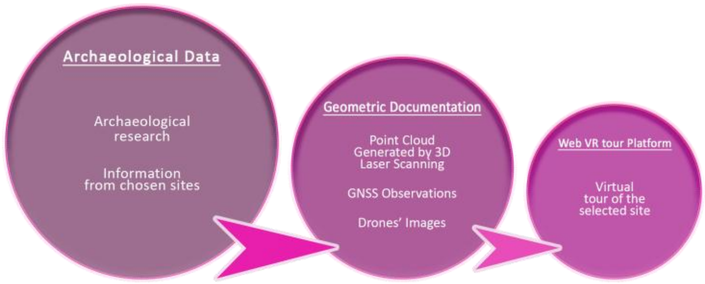

Figure 4. Visual representation of the three dimensions of information within this study

Following the field analysis, it became evident that the bridge contained numerous structurally and architecturally complex elements. Traditional surveying techniques, such as topographic measurements performed with a total station, would have been insufficient to capture the full extent and detail of these features. Consequently, terrestrial laser scanning was selected as the primary data acquisition method, as it enables the generation of comprehensive three-dimensional datasets capable of providing an integrated representation of the bridge.

For this purpose, one of the most advanced terrestrial laser scanners currently available, the Z+F Imager 5024 Supreme, was employed. This instrument is particularly well suited for recording objects situated at short and medium ranges, while also ensuring a high level of precision. The Z+F Imager 5024 Supreme is capable of capturing more than two million points per second, and in combination with the additional TopCAM system, it can also acquire panoramic imagery in as little as 12 seconds (when operating in fast mode). These images are subsequently used to apply true colour to the acquired point clouds. Such capabilities render the scanner highly versatile, making it an ideal choice for documenting intricate structures, including those of cultural heritage value, while simultaneously reducing the amount of time required on site.

Given the efficiency of this device, the survey design of the bridge included 17 scanning stations, strategically positioned to record all accessible components from multiple perspectives. The only exception was one façade of the bridge, which could not be documented due to dense vegetation and restricted pedestrian access. The chosen station layout ensured that all rehabilitated elements of the bridge were captured, with scanning positions placed at short intervals (5–15 meters) to achieve overlapping coverage and detailed observation from several angles.

Owing to this dense station distribution, a scanning resolution of 6.3 mm at 10 meters was sufficient. Even though a single scan at this setting produces a grid in which each point is spaced approximately 6.3 mm apart at a distance of 10 meters, the close spacing of the scanning stations generated significant overlap between individual scans. This overlap resulted in a much denser and more detailed point cloud, providing comprehensive coverage of the bridge's structural and architectural features. At this resolution, each scan required only 52 seconds, with an additional 12 seconds for the acquisition of high-quality panoramic images, leading to a total duration of approximately 64 seconds per station. These settings were applied consistently across all stations except for Stations 1 and 17. For these two positions, a higher resolution and slower scanning speed were selected in order to document with greater accuracy the lateral components of the bridge, including the abutments, piers, and architectural details. Furthermore, Station 17 was placed at a greater distance than the others, necessitating an increase in scan quality to ensure proper alignment with the rest of the dataset.

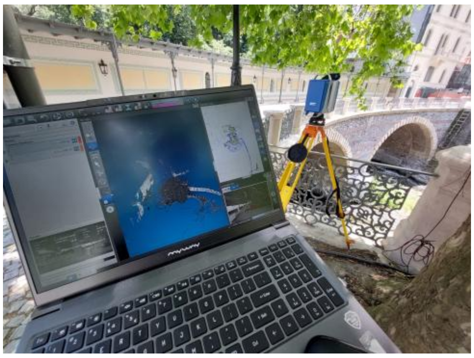

Figure 5. Terrestrial laser scanning of the bridge with real-time data visualization on-site

One of the most innovative features of the Z+F Imager 5024 Supreme is its capability to provide immediate on-site visualization of the acquired data once a scanning station has been completed (see Figure 1). When a Wi-Fi connection is established between the scanner and a laptop, the data are automatically transferred in real time. This functionality offers a significant advantage for fieldwork, as it allows operators to promptly assess the completeness and quality of the collected dataset. In this way, potential gaps or occlusions in the scanned area can be identified on-site, ensuring that additional scans are carried out if required. For instance, in the case of the studied bridge, parked vehicles in proximity to the scanner occasionally obstructed the line of sight toward certain structural elements. The ability to detect such obstructions immediately prevented the omission of critical areas from the dataset. Moreover, the automatic transfer of data directly onto the laptop not only accelerates the documentation workflow but also reduces the risk of data loss. Since the files are stored simultaneously on both the scanner's internal memory and the connected laptop, an additional layer of redundancy and data security is provided.

The company Zoller + Fröhlich GmbH has considerably advanced the field data acquisition process by dividing its processing software, Z+F LaserControl, into two complementary modules: Scout and Office. The Scout module is designed for on-site application, offering not only real-time visualization of the acquired data but also an optimized workflow that enables the automatic registration of multiple scans into a common coordinate system through cloud-to-cloud alignment.

In the present research, focused on the documentation of the Herculane bridge, this functionality played a central role. The scanning strategy was deliberately designed to include relatively short scans with a high degree of overlap, thereby allowing the software to automatically align the point clouds directly in the field. This approach not only facilitated the consolidation of all scans into a coherent spatial framework but also substantially reduced the workload in the post-processing phase. For successful cloud-to-cloud alignment, a high overlap between adjacent scans was maintained, while one station was defined as a reference (for instance, Station 1 serving as the reference for Station 2). The software then automatically reported both the success of the alignment and the associated precision. Where necessary, manual refinement of the alignment could be performed by adjusting two partially overlapping scans before re-running the cloud-to-cloud matching routine.

A further advantage of this approach is that, because each station was aligned immediately after acquisition, the layout of the scanning stations could be monitored live (see Figure 6). This provided continuous control of the station placement relative to the bridge, ensured sufficient overlap between scans, and prevented unnecessary duplication of data. Consequently, the overall efficiency of field data collection was significantly improved, while the accuracy and completeness of the resulting dataset were preserved.

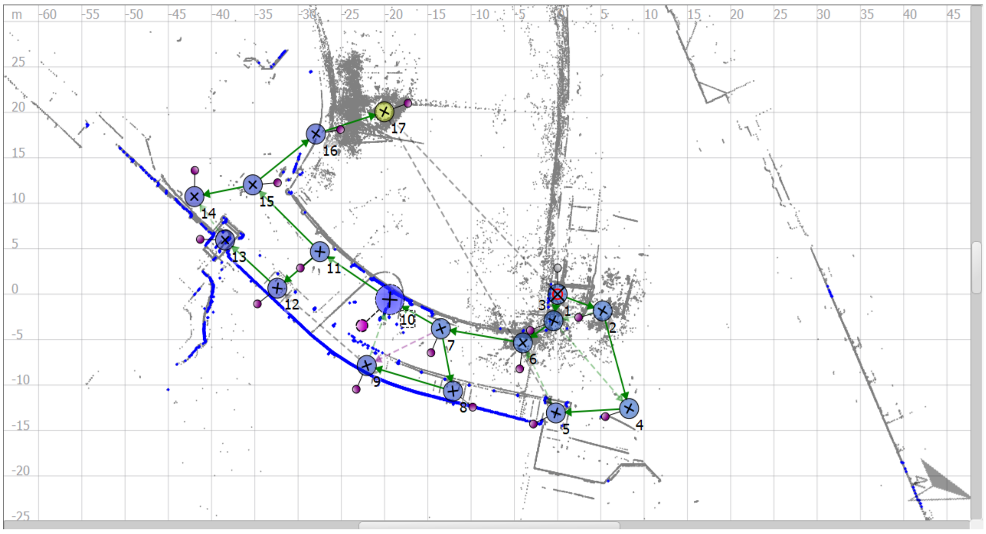

Figure 6. Survey scheme of the 17 scanning stations around the bridge

After the alignment process is completed, a comprehensive report can be generated, providing detailed information regarding both the alignment accuracy and the degree of overlap between consecutive scanning stations. Such reports are essential for assessing the overall quality and consistency of the registration process, as they allow the operator to quantitatively evaluate the precision of each alignment and the spatial relationships between individual scans.

For the 17 scanning stations acquired during the documentation of the bridge analysed in the present case study, the corresponding alignment and overlap data are summarized in Table 1. These values reflect the quality of the field acquisition and confirm the robustness of the cloud-to-cloud alignment procedure applied during the survey.

Table 1

Overview of registration accuracy and overlap between scanning stations

Reference station	Target station	Result of alignment (mm)	Overlap (%)
1	2	**2.9**	27
1	3	**4.7**	33
2	4	**2.8**	39
2	3	**3.5**	28
3	4	**3.1**	21
3	6	**2.7**	36
4	5	**2.5**	46
5	6	**2**	25
6	7	**2.2**	38
7	8	**1.7**	54
7	10	**3.1**	48
8	9	**1.5**	45
9	10	**1.6**	32
10	11	**5**	46
11	12	**1.4**	65
11	15	**3**	40
12	13	**1.6**	41
13	14	**2.6**	28
14	15	**2.8**	47
15	16	**3.2**	38
16	17	**3.9**	23
Average		**2.75**	

As shown in Table 1, the verification process does not assess only the alignment accuracy between consecutive scanning stations, but also includes additional cross-checks with neighboring stations whenever sufficient overlap is available. For instance, Scan 1 was validated not only against Scan 2, but also against Scan 3, ensuring a more robust evaluation of the registration consistency.

The results obtained through the cloud-to-cloud alignment procedure demonstrate a high level of precision, with an average alignment error of only 2.75 mm. Such accuracy confirms the reliability of the registration process and guarantees that the acquired point cloud meets the high-quality standards required for detailed structural documentation.

The Z+F LaserControl software also provides tools for direct measurement of geometric features within the point cloud environment, as well as straightforward data export options. The datasets can be converted into a variety of formats compatible with other specialized applications for point cloud analysis and modeling. For further evaluation, the aligned point clouds were exported in E57 format and subsequently examined in CloudCompare to verify data consistency. After the removal of irrelevant or redundant points, the final dataset comprised approximately 300 million points, each containing fully defined spatial coordinates. This refined point cloud served as the foundation for the subsequent stages of geometric and structural analysis.

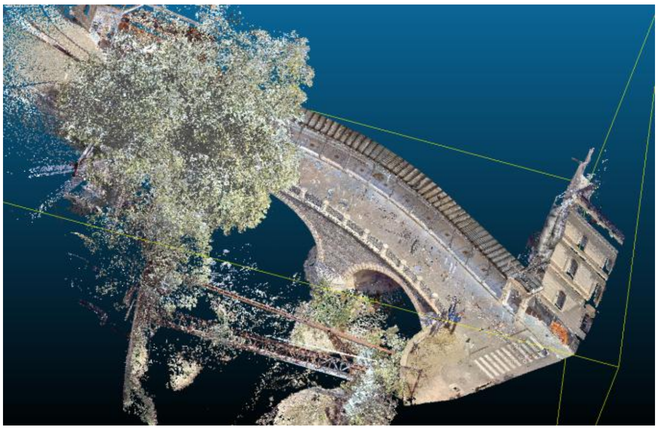

Figure 7. Visualization of the point cloud in CloudCompare

Finally, the UAV DJI Mini 2 was employed for both metric and non-metric purposes. Beyond image capture for measurement and 3D model generation, panoramic images were acquired at varying altitudes (from 40 to 100 meters, in 10-meter intervals) for each monument. Both vertical and oblique images were captured to produce a 3D model and an orthophoto of the stone bridge (Figure 16). The vertical images were taken from a height of 30 meters with an overlap of approximately 50–60%, while the oblique images were captured at 30° and 60° angles to ensure that all monument details were documented.

Figure 8. 30° angle image from UAV

For georeferencing the 3D model and orthophoto, Ground Control Points (GCPs) were employed. Checkerboard targets served as GCPs and were evenly distributed around the monument, with 6–8 GCPs measured per site. Image processing was conducted using Agisoft Metashape, resulting in 3D RGB point clouds and orthoimages for each monument.

The data acquisition process was completed in one day by a team of three surveying engineers experienced in similar documentation projects. Efficiency was enhanced by performing parallel tasks—for example, scanning one site while UAV imaging occurred at another—significantly reducing field time. Favorable weather conditions also contributed to successful data collection. The timing of the survey was crucial as well: it took place in early June, when visitor numbers were relatively low, minimizing the interference of moving people and resulting in cleaner point clouds.

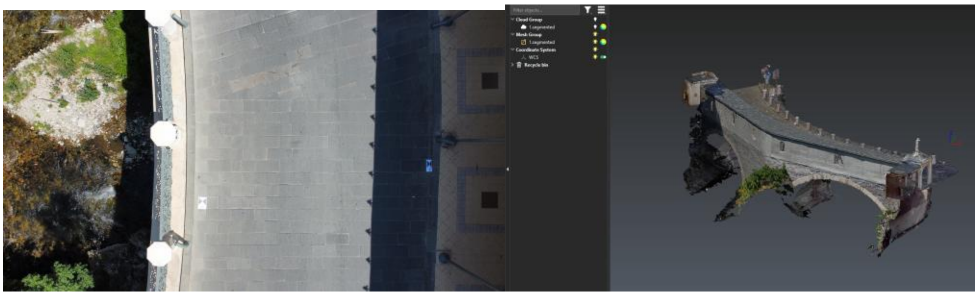

Figure 8. Vertical image from the Stone Bridge (left) and textured model (right)

To minimize potential errors, extensive measurements were conducted. Technically, this involved using dense TLS setups to ensure high overlap and capturing UAV imagery with high overlap ratios and multiple oblique angles, guaranteeing maximum data accuracy and completeness

Figure 9. Orthophoto of the Stone Bridge

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DESIGN and DEVELOPMENT of the WEB PLATFORM

A web-based virtual tour platform was developed to facilitate the systematic documentation and promotion of Băile Herculane, utilizing exclusively the 3D Vista environment. Data were stored in the 3D Vista database and are accessible via a web server designed to support the promotion of Băile Herculane at http://195.130.106.60/ through which the available information can be accessed.

The virtual tour platform 3D Vista enables the development of immersive 360° environments characterized by a high degree of user interactivity. This functionality is achieved through the integration of customizable elements like clickable hotspots, information points, and diverse multimedia assets, including images, videos, and embedded 360-degree videos and 3D models. The platform also provides a suite of advanced features tailored for specific use cases, such as integrated video calling to facilitate live-guided tours and dedicated e-learning tools for the creation of instructional quizzes and training simulations.

The Băile Herculane bridge case study demonstrates the platform's application for cultural heritage documentation and promotion. The visual core of the tour consists of panoramic visualizations and high-resolution images sourced from UAV surveys. To provide historical context, the experience is augmented with integrated archival documentation. A key promotional feature is a photogrammetric 3D model of the bridge, digitally reconstructed from the UAV-captured imagery.

DISCUSSION

For the digital documentation of the Stone Bridge in Băile Herculane, advanced equipment and techniques were employed, both for precise measurement—such as high-resolution laser scanning and UAV-based photogrammetry—and for visualization, using web platforms and VR technologies. This section explores the project's theoretical and methodological foundations, situating it within an international context to highlight its wider significance. The approach rests on two main pillars: firstly, it represents a significant advancement in cultural heritage preservation, and secondly, it aligns with a global trend of integrating immersive digital environments into archaeological research.

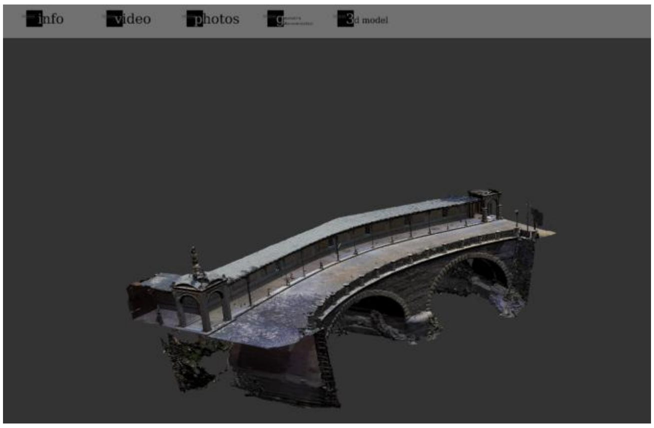

Figure11. Virtual Tour in the Stone Bridge

The 3D model generated for stone bridge is not only highly accurate and interactive, but also introduce innovative ways of representing archaeological knowledge. Platform such as 3D Vista function not merely as visualization tools, but as interpretive mechanisms that enhance historical understanding.

A major innovation of our project was the integration of a VR tour using the MetaQuest 2 headset, extending the platform's capabilities into fully immersive virtual reality environments. This development marks a shift in the pedagogical and experiential dimensions of digital heritage, moving from traditional screen-based interaction to embodied immersion (Figure 21). Through this application, the management and experience of the Stone Bridge in Băile Herculane become almost "tangible" to a global audience.

Figure 12. VR tour test of the Archaeological Park

The platform provides a comprehensive, integrated presentation of the stone bridge, catering to diverse user groups such as tourists, students, researchers, conservators, and engineers. The value of these virtual excursions is particularly noteworthy: they broaden access by overcoming financial and physical barriers. Furthermore, the project demonstrates the potential of immersive virtual technologies to both protect cultural heritage and enhance educational outreach, establishing a benchmark for future digital documentation efforts in archaeology. Collectively, these elements show that the Băile Herculane digital documentation project is not an isolated initiative, but part of broader theoretical and methodological developments in virtual heritage. By positioning Băile Herculane within this international context, we gain a clearer understanding of how immersive technologies can not only preserve the past, but also transform how we engage with, interpret, and share it in the present.

CONCLUSIONS

While digital heritage initiatives are increasingly gaining attention, the focus largely remains on prominent or well-funded sites, often leaving smaller regional locations—despite their cultural significance—outside the digital spotlight. This disparity is particularly evident in efforts to integrate digital tools into sustainable tourism strategies, where less-recognized archaeological sites often face adoption challenges. This issue is especially relevant in countries like Romania, where the cultural landscape is rich yet frequently underutilized.

This study highlights the stone bridge in Băile Herculane, a part of a complex in the valley of the Cerna River, between the Mehedinți Mountains to the east and the Cerna Mountains to the west, Caraș-Severin County, Romania. With its rich history and architectural remains spanning multiple historical periods, Băile Herculane provides an ideal context for combining high-precision digital documentation with community-centered heritage planning. The study details the process comprehensively—from initial historical research and geometric data collection to the integration of results into a Web platform, designed to serve diverse user groups.

Using advanced techniques and equipment, including terrestrial laser scanning (TLS) and UAV-based photogrammetry, high-precision 3D model were produced for the stone bridge within the town. This model achieve an average precision of ±1 cm and serve multiple scientific purposes. Indicative applications include:

- Architectural and structural information: Dimensions useful for architectural analysis, restoration, and preservation projects, including the generation of facade plans, horizontal and vertical cross-sections.
- Material conditions: Orthophotos and 3D models allow for the assessment of monument pathology and conservation needs.

Building on this, a Web platform was developed to promote the monument and the broader area. The platform incorporates elements such as administrative boundaries, road networks, and land cover, and is freely accessible at http://195.130.106.60/BH/index.htm.

The final stage involved the creation of VR tours of the stone bridge, integrated into the platform to enhance not only heritage visualization but also educational engagement, participatory planning, and sustainable tourism management. The platform is a valuable tool for local authorities and the Ministry of Culture to promote the site, as well as for educational institutions, where interactive storytelling and VR experiences offer engaging learning opportunities for all ages.

Additionally, the platform improves accessibility for researchers and the public, providing a virtual archive that allows immersive exploration of the area while minimizing physical wear from tourism. By facilitating remote access, it promotes sustainable tourism, reducing both environmental impact and on-site pressure. In terms of decision-making, the platform can support urban planning, including evacuation planning, path marking, and other management strategies.

The implementation of 3D geospatial documentation via a comprehensive Web platform at Băile Herculane exemplifies the successful integration of heritage conservation with sustainable tourism, offering a replicable model for other heritage sites balancing public access with preservation.

Future work will focus on two main areas:

1. Expansion of 3D models to cover the entire town, providing users with a fully immersive virtual experience beyond the four currently modeled sites.
2. Development of the Web platform and VR experience, including qualitative and quantitative studies on how different user groups (tourists, students, local communities) interact with the platform. Further research may explore mobile-friendly or AR components to enhance accessibility both on-site and remotely, and assess how mixed-reality experiences influence visitor behavior, knowledge acquisition, and cultural appreciation.

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