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Three-Dimensional Documentation and Virtual Web Navigation System for the Indoor and Outdoor Exploration of a Complex Cultural Heritage Site

Manuela Aricò [1], Gino Dardanelli [1], Marcello La Guardia [2] and Mauro Lo Brutto [1,*]

[1] Department of Engineering, University of Palermo, 90133 Palermo, Italy; manuela.arico@unipa.it (M.A.); gino.dardanelli@unipa.it (G.D.)
[2] Department of Civil and Environmental Engineering (DICEA), University of Florence, 50121 Florence, Italy; marcello.laguardia@unifi.it
* Correspondence: mauro.lobrutto@unipa.it

Abstract: The spread of new survey strategies for the documentation and 3D reconstruction of complex cultural heritage sites enables the implementation of virtual web navigation systems that are useful for their virtual fruition. In particular, remote indoor/outdoor exploration enhances our knowledge of cultural heritage sites, even in inaccessible or difficult-to-visit states. However, the 3D data acquisition of complex sites for documentation remains a challenge, and the 3D virtual exploration of these datasets is often limited to property software implementations. This work describes the 3D documentation and construction of an indoor/outdoor web visualization system based on the WebGL open-source technology of a complex cultural heritage site. The case study regards the complex of "Santa Maria della Grotta" in Marsala (Italy), which is composed of a church that is located mostly underground and is connected to a human-dug hypogea on the site of a Punic necropolis. The aim of the work was to obtain detailed 3D documentation of the indoor and outdoor spaces through the integration of mobile laser scanning and aerial photogrammetry survey, and to develop a virtual web navigation system for the remote exploration of the site. The indoor/outdoor web navigation system provides users with a simple, web-browser-based 3D visualization, enabling the dissemination of the monuments' knowledge on the web through an economically sustainable solution based on open-source technologies.

Keywords: 3D survey; cultural heritage; mobile laser scanning; 3D modelling; virtual reality; WebGL

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1. Introduction

For cultural heritage sites that are characterized by safety and vulnerability issues, we may face a lack of knowledge and documentation; this can affect their maintenance and costs, especially if they are fragile, scarcely accessible, difficult or impossible to reach, or in a risky condition [1]. The documentation and the valorisation of these sites still represent a dual challenge when it comes to both managing their information and improving and promoting their visibility. The widespread development of surveying technologies which currently provide the most accurate three-dimensional (3D) information for such vulnerable sites has been beneficial to cultural heritage institutions as well [2]. Indeed, the digital models obtained from the integration of heterogeneous, multi-resolution 3D datasets, acquired following geomatics strategies, offer effective, alternative solutions to physical visits through the recent improvement of virtual reality technologies [3–7]. The application of virtual reality (VR) to the world of cultural heritage (CH) and the spread of fast internet connection have recently made way for new scenarios involving the virtual fruition of monuments, museums, and archaeological sites via web applications on standard or multimodal devices [8]. Virtual fruition could be achieved through interactive virtual tours based on 360° panorama photos and hyperlinks to enrich the presentation and knowledge of the real artifact [9]; this is enhanced through the integration of 3D models and Heritage Building Information Modelling (HBIM), which can eventually be linked to Geographic Information Systems (GISs) [10]. However, whenever a virtual reality navigation system requires robust data for documentation and not only for fruition purposes, 3D-reality-based models built from laser scanning (LS) and/or digital photogrammetry data provide the most suitable basis. Therefore, a combination of geomatics and computer graphics strategies—from data acquisition (through integrated survey campaigns), data processing, and data modelling (with the resulting digital model and virtual environment) through to the design of the visualization system (for virtual reality applications)—should be carefully balanced and applied [11].

Data acquisition is the first and fundamental step in the 3D documentation process; the goal of this step is to develop an as-is 3D reconstruction of the captured surfaces, especially when they are defined by composite shapes [12]. For this purpose, the integration of different modern survey methodologies is mandatory. Furthermore, multiple fast acquisition methodologies and approaches are crucial in the case of underground sites whenever the environments are confined or unsafe [13,14]. Limited accessibility is sometimes a major challenge for obtaining complete 3D documentation of monuments and historical sites [15]. One of the most common procedures currently used for the 3D documentation of CH sites is the combination of LS and close-range photogrammetry techniques [16]. LS surveys are applied to a wide range of fields, including architecture, engineering, construction, forestry, urban planning, and environmental monitoring, whenever 3D data capture and mapping are required [17–20]. CH and archaeology also benefit from LS, as it provides the necessary 3D information for the digitization of monumental sites [21]. Photogrammetry (both terrestrial and aerial) enables the automatic 3D reconstruction of objects from images thanks to processes based on structure-from-motion (SfM) algorithms [22].

Despite the fact that integrated surveys guarantee the complete acquisition of 3D information that is sufficient for 3D documentation purposes, the processing and modelling phases are crucial for the generation of a virtual reality environment which simultaneously preserves the original characteristics and downsizes the model [23,24]. For these reasons, to be suitable for virtual reality platforms, the dataset acquired during the survey must be processed and optimized by means of subsampling, surface or solid modelling, and meshing operations [11].

Considering the virtual fruition of the 3D context, recent years have seen the exponential development of several possibilities in the field of virtual reality applications, previously inconceivable in several fields of research [25–27]. These technologies have allowed the development of 3D virtual reality environments of CH sites finalized for valorisation purposes [28–30].

Herrero-Tejedor et al. [31] and Piscitelli [32] provide examples of virtual fruition supported by 3D-reality-based models for more in-depth documentation purposes; the use of integrated surveys in their case studies was, respectively, justified by the exceptionality and the precarity of the sites to be documented. However, in addition to UAV techniques, a 360° camera was used in order to obtain a more realistic and rapid photogrammetric model of the interiors [32]. Some researchers disregarded LS methodologies in favour of exclusive aerial and terrestrial photogrammetry, due to the extension of the sites [33,34], or in combination with other techniques to obtain a multimodal imaging system [35]. Güleç Korumaz and Kilit [21] used panoramic photos from Google Maps to develop their model.

Regardless, the real playability and fruition of this kind of application remain challenging for many reasons. In the case of commercial software solutions, the costs of developing and maintaining the application limit its use. At the same time, the need to download oversized applications or dress-specific devices for virtual reality fruition severely limits playability on the client side (i.e., Oculus) [21,36,37]. On the other hand, the recent development of the Web Graphics Library (WebGL), based on a JavaScript API (application programming interface) [38], has enabled developers to render 3D and 2D graphics directly in web browsers to enable online virtual reality exploration without any further software installation [39,40]. Today, thanks to the power of hardware-accelerated graphics, many open-source solutions based on WebGL technology allow specialists to create visually appealing interactive CH exploration experiences, with the possibility of displaying, exploring, and enjoying digital 3D models inside a virtual generated environment via web applications for smartphones, tablets, and PCs, in a more innovative and faster way [31,33,35,41,42].

Despite the different results of this overview, they are all linked by the following common scopes: offering users the possibility of remotely exploring archaeological and monumental sites even when they are not easily accessible [43,44]; supporting institutions in improving the dissemination of cultural heritage knowledge through the diffusion of virtual reality applications installed in museums and monumental sites [45]; influencing the way cultural heritage specialists manipulate, share, and manage data, moving from classic educational dissemination, documentation, and inventory methodologies towards digital and virtual domains [46].

If the WebGL solution seems to be the best option in avoiding expensive software implementation on the server's side and software installation on the client's side, it must be noted that the limited dimensions of the datasets to be shared and the requirement of scripting skills by developers currently represent the main challenge of this approach; this primary challenge should be overcome in the near future though lightweight solutions [47]. Indeed, an appropriate balance between the quality of the detail of the model to be displayed and the web browsing capability should be achieved, especially when the represented cultural heritage site is intended to reach a wider community of users. It is also important to avoid either redundant or over-simplified information; this will enable us to overcome the risk of unnecessary overload or the loss of spatial perception during navigation [48].

This paper discusses a two-fold focus on the 3D documentation and the construction of the virtual web navigation system for the virtual visualization and the remote fruition of the monumental complex of "Santa Maria della Grotta" in Marsala (Southern Italy). This monumental complex presents a singular conformation, since it consists of a church, which is mostly underground and is connected to an articulated system of hypogea under a Punic necropolis. The relevance and cultural interest of this site from a historical point of view is due to the stratification of the archaeological and architectural remains which characterize the site. It is currently inaccessible to citizens and tourists due to its state of deterioration and poor maintenance, which make it difficult to visit. In addition, the site has never been investigated using modern geomatics approaches that are capable of providing comprehensive 3D data of the complex's unique configuration.

The 3D documentation was based on the data collected during a survey campaign carried out inside and outside the church; the hypogeum rooms and the surrounding area were documented at various levels of detail using Simultaneous Localization and Mapping (SLAM)-based Handheld Mobile Laser Scanning (HMLS) and unmanned aerial vehicles (UAVs). SLAM solutions represent recent control technologies which have been finalized for the localization and mapping of real-time robot positioning [49]. These technologies have recently been applied to surveying applications; by combining SLAM algorithms with LS and an inertial measurement unit (IMU), real-time 3D mapping is enabled [50].

The point cloud acquisition was carried out with an HMLS technology because the main goal of the survey was to document the entire monumental complex. The 3D documentation was finalized to obtain a 3D digital model of the monumental complex that was suitable for valorisation purposes (i.e., web exploration). If on one side, HMLS devices are ideal and more advantageous to be used in both extensive archaeological areas and underground sites because of their ease of use and speed in data acquisition and processing; on the other side, LS solutions allow to obtain lower levels of roughness, enabling the shape recognition of small elements with complex geometries [51,52]. Even taking into account the survey methodologies used, the UAV allowed us to capture the most inaccessible parts of the complex which could not be reached by the other devices (such as the external roof and the highest parts of the church) and to obtain overall photorealistic 3D models. Thus, the integration of different survey methodologies made the detection of the geometric components of the site possible, avoiding the presence of gaps or holes in the results [53,54]. This integrated digital survey, which embraces and encompasses the complexity of such a vast, stratified, and uneven landscape, also provided an opportunity to create a 3D exploration system on the web to improve its virtual accessibility.

A 3D virtual reality exploration model, accessible on the web, was then developed, allowing users to navigate at a multiscale level. To build the web navigation system of the monumental site, the dataset was optimized for implementation in a WebGL environment. In particular, 3D point clouds were clustered and subsampled, and 3D meshes were simplified for web visualisation. Each level of navigation included different parts of the 3D dataset, appropriately simplified for browsing on the web. The construction of the 3D environment was based on open-source Three.js JavaScript graphic libraries. Each level of navigation was developed in a specific HTML file combining the HTML, JavaScript, and CSS coding languages. A system of links within the 3D environments allows users to navigate between the different levels of navigation.

Compared to similar previous experimentations in Marsala by the same authors [43,44], this work achieves a further step of development, creating a navigation system for an extended and articulated environment, combining indoor and outdoor navigation, utilising different control systems, and integrating point cloud and 3D, textured mesh visualization.

With regard to the 3D documentation, the main challenge was the complexity of the spaces to be surveyed, in a site which embodied different historical stratifications distributed throughout indoor and outdoor environments. The integrated survey methods used in this case study provided a rapid solution for obtaining a complete 3D digitization of a complex monument, useful for 3D documentation and valorisation purposes.

At the same time, the virtual fruition of this complex environment on the web was also a challenge, requiring the proper design of the web visualization structure, and consequently the optimization of the 3D dataset for the web browsing. The proposed solution explores the possibilities offered by the world of WebGL, developing a proper framework of HTML pages which integrates different Three.js libraries according to the requirements of each visualization module. The implementation of this open-source system bypasses the use of commercial software, which is good practice for avoiding expensive and unsustainable solutions.

The paper is structured as follows: Section 2 briefly describes the monumental complex with its historical information; Section 3 reports on the materials and methods used in this case study, with a focus on survey operations, 3D models digitization, and the development of the WebGL virtual environment; Section 4 presents the results; Section 5 reports on general considerations on the overall process; concluding remarks and prospectives for follow-ups on the work were reported in Section 6.

2. The "Santa Maria della Grotta" Complex in Marsala (Italy)

The thousand-year-old site of the "Santa Maria della Grotta" complex is located in the modern town of Marsala (Sicily, Southern Italy) (Figure 1). The complex comprises an archaeological area with a stratified sequence of remains from the Punic, Roman, and Medieval periods, including a church which has been partially excavated underground (Figure 2).

The archaeological area consists of a Punic necropolis that is connected to an articulated system of hypogea which converge inside and form the original core of the church. This singular and unusual morphology makes the site particularly suggestive and important both historically and architecturally. The Punic necropolis, dating back to between the 4th and the 2nd centuries B.C., is attested by the remains of burial chambers (Figure 3) and by the skylights found in the hypogea; in addition, there is evidence for pit burials, due to the characteristic vertical-shaft hypogea, with or without chambers, whose depths range from 2 to 10 m.

Figure 1. Location of the complex of "Santa Maria della Grotta" (from Google Maps©).

Figure 2. Aerial view of the church of "Santa Maria della Grotta".

The area underwent its first transformation during the Roman period when it was turned into a stone quarry, due to the rapid expansion of the ancient town. The original Punic hypogea were enlarged and huge craters (called *latomie*) of indeterminate shape were created in the ground. In the 5th century A.D., it returned to its use as catacombs for the local Paleo-Christian community; several tombs, characterized by the presence of typical structures with vaulted recesses (*arcosolium*), were dug out of the abandoned quarries.

In 1097, the first nucleus of the abbey called "Santa Maria della Grotta" was built, partially readapting the underground spaces of the previous catacombs [55]. A tower was also built to signal and guard access to the abbey, which was later transformed into a bell tower [56].

From the 16th century to the 18th century, the church was entrusted to various religious orders, until 1866 when it became property of the state. Between 1712 and 1715, when the church was administered by the Jesuits, the medieval building was redesigned, rearranged, and enlarged to take on its current appearance.

The church remained open for worship until 1968, when an earthquake caused some parts and the bell tower to collapse, making it dangerous [56]. The complex is now part of the Archaeological Park of Lilibeo-Marsala and is currently closed to the public due to its poor maintenance.

Figure 3. The archaeological site of "Santa Maria della Grotta"; the Punic necropolises on the premises of the church are indicated in red.

The site is accessible from the upper Punic necropolis by a four-ramped stairway, leading to the churchyard dug into the lower quarry. According to [55], the complex consists of the central Baroque church (A) connected to three hypogea: one on the northern side (B) and two (C, D) on the southern side (Figure 4).

The Baroque church (A) has a single nave with blinded recessed chapels, a quadrangular presbytery, and a polygonal apse. On the long sides, four doors lead to the hypogeum rooms and two staircases lead to the upper galleries. The walls, made of sandstone bricks which lean against the carved surfaces, are entirely covered with white plaster, which defines the round arches and a double, huge order of Tuscan columns, which support the continuous mouldings around the entire perimeter of the church. The false ceiling is in the form of a boat vault over the central nave; the presbytery has a simple barrel vault with lunettes lit by an octagonal tamboured lantern, while the apse is covered by a five-spoke dome (Figure 5). The extrados of the roof is flat all around, whilst its central part reveals the profile of the boat vault below. A hemispherical dome rises from the presbytery area. The main façade of the church has simple features, such as the main doorway and a rose window, which are without ornamentation [55].

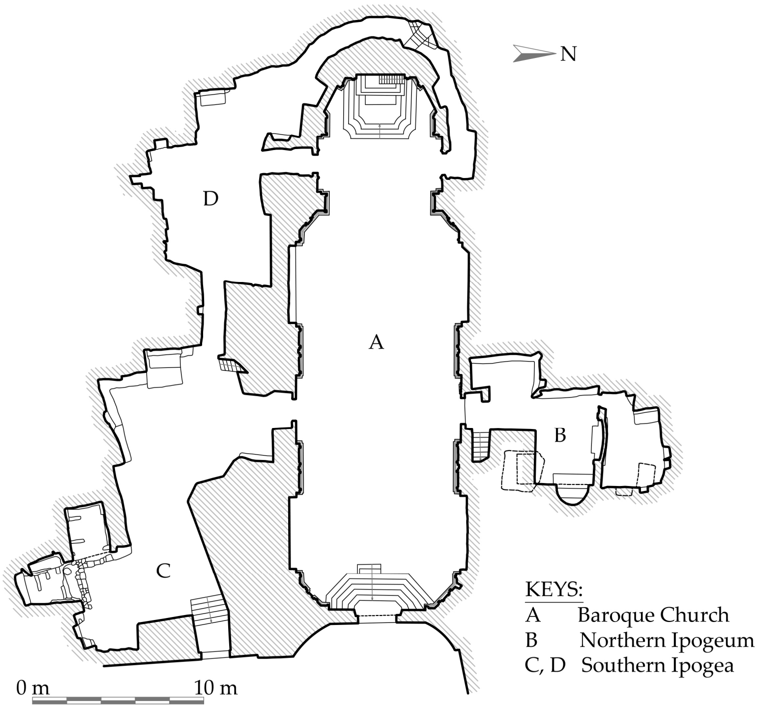

Figure 4. Plan of the complex of "Santa Maria della Grotta".

(**a**)

(**b**)

Figure 5. The internal space of the church of "Santa Maria della Grotta": (**a**) view towards the apse, (**b**) view towards the entrance.

The pre-existing Paleo-Christian hypogea (B, C, D), located to the north and south of the current Baroque church, respectively, were continuously altered between the 13th and 15th centuries by the coenobitic community, which settled in the original medieval core of the building for the purposes of Basilian worship.

Hypogeum B was probably their funerary chapel, as evidenced by an iconostasis and an arcosolium converted into an ossuary (Figure 6). This hypogeum used to be a two-storey room, with the upper floor used as a dormitory, which was destroyed during the Baroque restoration of the church [55]. Hypogeum C was used as a refectory, as evidenced by stratified traces of food found in three arcosolia, which previously housed a family and their burial equipment (Figure 7) [56]. Hypogeum D is connected to C through a straight passage and to the presbytery by an annular passage. These three rooms have some features in common, such as the additional altars and seats which were carved into their perimeter walls, and various series of liturgical frescoes (dating from the 12th to the 17th centuries) that are typical of the Orthodox religion [55]. Some of these frescoes came to us in good condition, such as a line of Basilian Saints, the Martyrdom of St. Stephen, and a Madonna with Child in room B, and another Madonna and St. John in room C. Few traces of other frescoes can still be seen on the walls and in the D hypogeum, but they are in a poor state of preservation; this is either because of the high humidity in the caves or because they were destroyed during the Baroque restoration [55].

Figure 6. The internal space of the coenobitic caves of hypogeum B with traces of frescoes.

Figure 7. The hypogeum C with carved *arcosolia*.

3. Materials and Methods

The process for the 3D documentation of the site and the construction of the virtual web navigation system involves several steps embracing different operations such as 3D survey, 3D modelling, and web development. The complexity of the site in terms of the distribution of the environments represents a demanding challenge both for the 3D acquisition and modelling phase and for the subsequent design and development phase of the web visualization system. Given the complex indoor/outdoor structure of the site, the publication of the 3D environment on the web required the design of an ad hoc visualization structure. The aim was to offer users the possibility of exploring the monumental complex, starting from a general contextual visualization, through an intermediate visualization clarifying the relationship between the church and the hypogeum complex, and ending with a first-person exploration of the interior environment.

3.1. Three-Dimensional Survey

The 3D digitisation of the environment was based entirely on a survey campaign that aimed to record the as-is conditions of the complex. In order to select the best tools and techniques for obtaining the most complete 3D data, some preliminary assessments were carried out. These showed that the peculiar morphology of the site, which alternates between large, unobstructed areas and narrow passages, heavy staircases and dense vegetation spots, ruled out the use of a static LS in favour of an HMLS method. The latter technology allows very large, uneven, and complex structures to be captured quickly, overcoming the registration difficulties associated with static scanning. It also allows easy connections to be made between the internal and external parts.

The device used was a GeoSLAM Zeb Horizon RT (Figure 8), which can acquire up to 300,000 points per second with a maximum range of 100 m, a ranging accuracy up to 6 mm (whenever data are processed through the property GeoSLAM Connect V2 property software), and an angular resolution of 2° in the vertical direction and 0.2° in the horizontal direction. The Zeb Horizon RT is based on SLAM technology and is capable of real-time mobile laser scanner acquisitions in both indoor and outdoor environments. Thanks to its in-built Zeb Vision sensor, it can deliver RGB point clouds. The survey can be monitored via a tablet connected to the system, which displays the acquisition in real time, whilst the density of the stored point cloud depends on the operator's walking speed.

Figure 8. The GeoSLAM Zeb Horizon RT laser scanner.

The entire site was scanned according to three different paths (Figure 9), which were pre-arranged to avoid excessive or redundant information. The first path covered the southern hypogea, the second path was performed on the southern and the northern hypogea, whilst the third one was carried out externally around the churchyard and the upper necropolis. The façade and the nave of the church have been detected in all the paths, to have common features to be overlapped in the processing phase.

Since each path was characterized by a proper local reference system, it was necessary to identify some ground reference points, to improve the alignment of the scans during the post-processing phase. Overall, seven reference points were placed: four inside the church and the hypogea and three outside. An external reference point on the access staircase was chosen as the start and end point of all the paths; in this way, each acquisition was performed as a closed path to ensure better trajectory control. To measure the coordinates of the ground reference points, the device was placed over these points for the time required to register their position (approximately 10 s).

In order to ensure the complete documentation of the site with a photorealistic 3D model of the exterior of the complex and of the interior of the church, and to cover all the surfaces which could not be reached with the HMLS device, a UAV photogrammetric survey was also planned and carried out for both the exterior environment and the central aisle of the church. An ultra-light multi-rotor Parrot Anafi Drone was used; this is characterized by a weight of 250 g, a maximum flight autonomy of 25 min, and is equipped with a 4 K HDR camera that is capable of capturing 21 MP images.

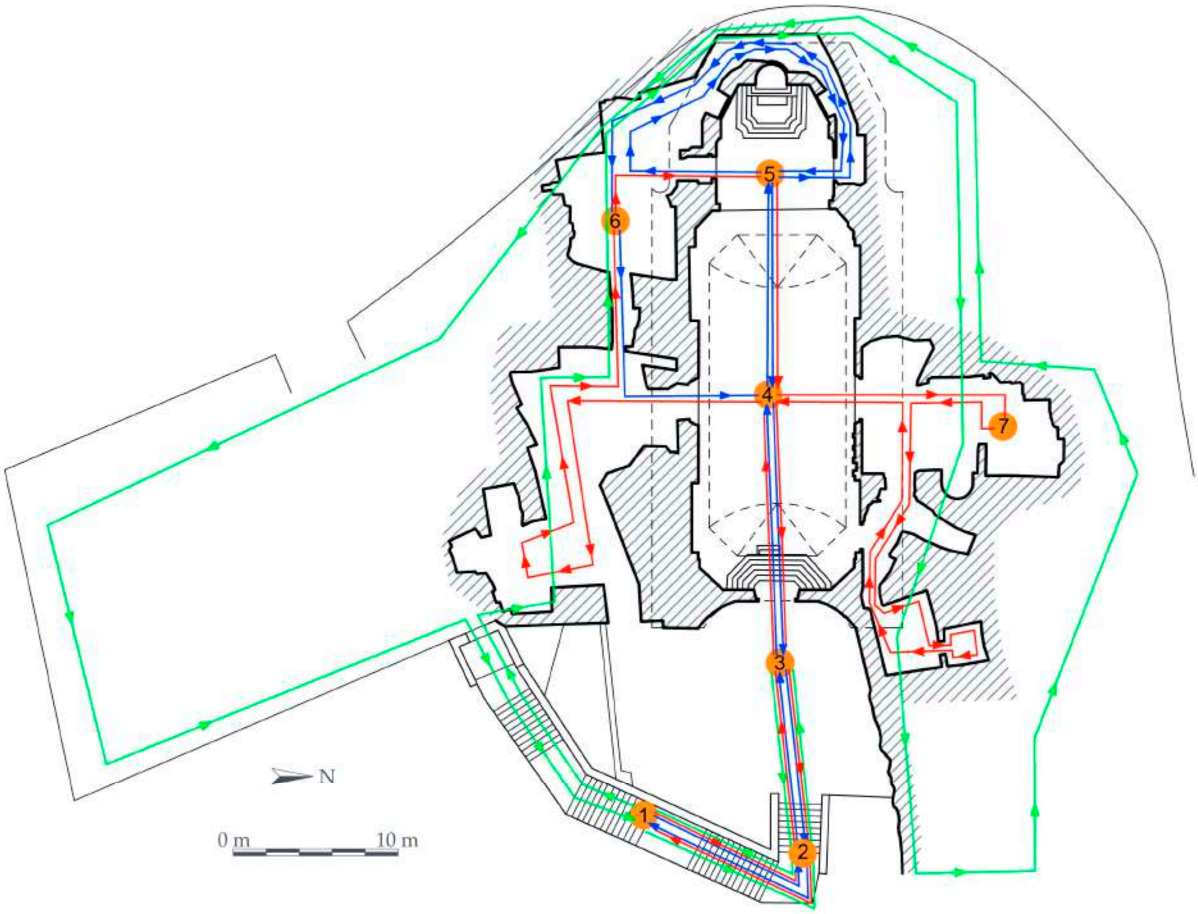

Figure 9. The three paths of the HMLS survey: the blue and the red lines indicate the two paths inside the hypogea, whilst the exterior path is shown by the green line. The ground reference point locations are indicated in orange.

Different image configurations were adopted and executed for the UAV acquisition. For the exterior, two nadiral flights were performed in an automated manner to capture the roof, the dome, and the surrounding landscape; meanwhile, two circular flights were performed around the church at 30° and 45° camera tilt angles, respectively. These flights were planned to ensure the complete coverage of the surfaces and to ensure an adequate overlap among the images. A manual-mode flight was also carried out to capture images of the main façade of the church. As the drone's control system did not allow for an autonomous flight inside the church, a manual-mode flight was carried out for the interior of the church. During this flight, images were taken from different heights and at different angles. The drone survey delivered a total of 405 images: 224 of the exterior and 181 of the interior.

3.2. Data Processing

The three separate point clouds derived from the different paths of the HMLS survey and covering the exterior and interior of the monumental complex were filtered, coloured, and processed using the Stop-and-Go Alignment workflow that is available in the proprietary GeoSLAM Connect software ver. 2.3. This workflow enabled the automatic alignment of the scans using the common reference points that were captured during the survey. The alignment was further improved by performing an additional cloud-to-cloud registration using the common parts of the point clouds. The processing allowed the three-point clouds to be merged in order to produce an overall cluster of almost 360 million points, excluding only those parts which were inaccessible to the operator (such as the church roof). The huge size of the total cluster was a result of its high resolution (a few millimetres), which made it too difficult to manage; for these reasons, the point cloud was segmented from all the redundant information (such as the vegetation) and subsampled for easier computation. A final point cloud of about 127 million points was obtained after a spatial subsampling process carried out with CloudCompare ver. 2.13.1 software, setting a minimum distance of 1 cm between two points. This dataset was sufficient to obtain the complete documentation of the site, which was lacking prior to this survey. A further roto-translation was imposed on this cluster to place it in a convenient local reference system with the X-axis corresponding to the main façade and the Y-axis running along the long side of the church.

Images from the UAV survey of the exterior were imported into Agisoft Metashape ver. 2.1.2 software for automated processing using an SfM approach. Ten ground control points (GCPs), measured with a total station, were used to calculate the exterior orientation parameters, obtaining GCP residuals of about one centimetre. Firstly, a point cloud of the entire external complex of about 40 million points was generated using Agisoft Metashape's dense stereo-matching algorithm (Figure 10); then, a photorealistic 3D model was obtained by reconstructing a polygonal model of about 25 million faces. The photogrammetric point cloud was also imported into CloudCompare and aligned with the HMLS point cloud using an automatic cloud-to-cloud registration procedure, with a scale adjusted to minimize small-scale differences between the two datasets. This cluster was manually segmented to retain only those parts that were related to the church roof, which were missing from the laser scanner acquisition, and to discard the unwanted data. The segmented roof (nearly 1 million points) was merged with the HMLS dataset to deliver a complete point cloud of the entire complex (interior and exterior).

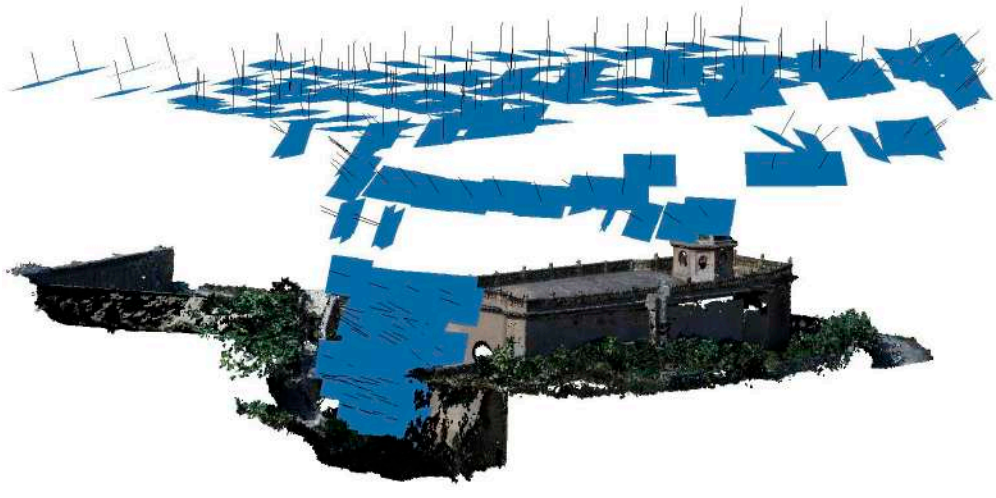

Figure 10. Scheme of UAV survey of the external parts; blue indicates the capture positions of the camera during the flight.

The 181 UAV images of the interior of the church were imported into Agisoft Metashape for processing. Due to the poor lighting conditions of the site, the exposure of these images was not optimal, so radiometric pre-processing was required. The internal dataset was also processed using the standard Agisoft Metashape workflow; some ground control points (GCPs), measured with a total station, were used to estimate the external orientation parameters of the images. The result was a point cloud of approximately 62 million points (Figure 11) and a polygonal model of approximately 10 million faces.

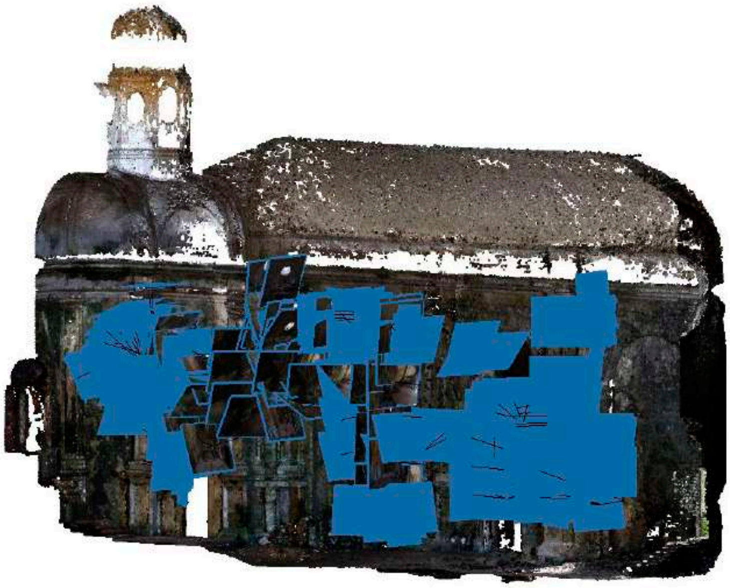

Figure 11. Scheme of UAV survey of the internal parts; blue indicates the capture positions of the camera during the flight.

These outcomes served as a basis for the subsequent web navigation system, which used them for a differentiated visualization, as explained in the next subsection.

3.3. The Development of the Virtual Web Navigation System

The limited data size associated with the 3D geometries for online visualization was the main challenge in building the virtual web navigation system. In fact, each HTML page can host only a limited number of geometries in terms of data size. This meant that the amount of data obtained from the survey was incompatible with remote visualization, and this forced us to carry out an appropriate editing and pre-processing stage. In addition, given the size and complexity of the site, it would have been very difficult to create a single exploration web page to appropriately display all parts of the complex. The adopted solution was to design a multiscale visualization structure organized in modules (Figure 12). Each level of visualization (which characterizes the module) was linked to the previous and the next, ensuring continuity in the user's web exploration experience and a complete visualization of the complex that correctly relates all the existing environments.

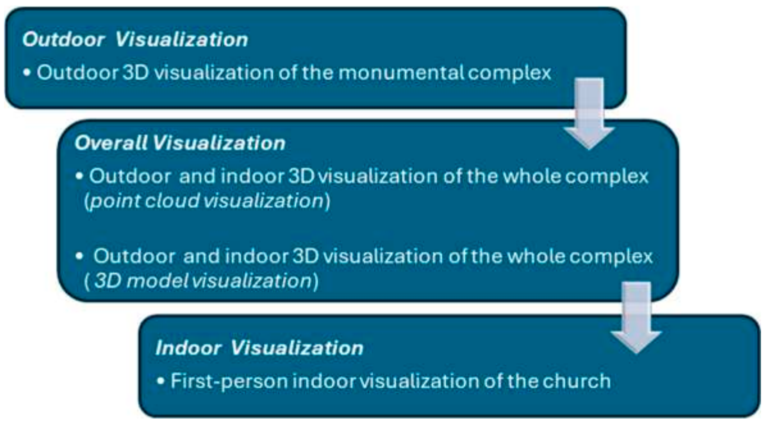

Figure 12. The framework of the modules which compose the virtual web navigation system.

The first module, called "Outdoor Visualization", contains the exterior 3D visualization of the monumental complex at the urban scale of navigation. This module is connected to the next level of visualization through a popup link.

The following module, called "Overall Visualization", allows a user to explore the 3D models of the church and the hypogeum complex together. In contrast to the Outdoor Visualization, the surrounding terrain has been omitted and the geometric information of the interior parts of the entire monumental complex has been added. In this way, users can explore the entire monument, and are able to visualize the relationship between the church and the system of hypogea surrounding it. To achieve this goal, two different types of visualization have been considered in this module: one based on a point cloud, and another based on a 3D polygonal mesh. The possibility of switching between these two different options allows users to acquire a complete understanding of the monumental complex and the spatial distribution of its components. This module is connected to the last module by a popup link, which was placed at the main entrance of the church.

The last module, called "Indoor Visualization", displays the 3D visualization of the interior of the church, offering users the opportunity to visit the entire environment in a first-person mode or through a walking exploration.

3.4. Three-Dimensional Modelling for the Virtual Web Navigation System

The data used to build the web navigation system were based on the datasets as processed in the previous phase. The 3D information, in the form of meshes, textures, and point clouds, was optimized for web browsing navigation purposes. This operation is challenging because the web visualization of complex 3D environments, based on WebGL technologies, is limited by the capabilities of the web browser itself. These capabilities affect the maximum size of the geometric information which can be displayed on each web page. For this reason, the combination of geometric information (number of points for the point cloud; number of polygons for 3D meshes) and texture dimensions should be correctly balanced to avoid browser crashes and, at the same time, to guarantee the quality of visualization during the virtual exploration. Each module hosted different combinations of 3D datasets, depending on the level of information they were designed for (Table 1).

Table 1. Datasets used for the virtual web navigation system.

Module	Object	Type	Format	Number of Data	Size
Outdoor Visualization	External model of the complex	3D mesh Texture	OBJ JPEG	36,616 faces 8192 × 8192 pixels	3.4 MB 13.2 MB
Overall Visualization	Point cloud of the complex	3D point cloud	PCD	1,000,000 points	31.3 MB
	Hypogea and Church	3D mesh	OBJ	106,611 faces	8.4 MB
Indoor Visualization	Indoor model of the church	3D mesh Texture	OBJ JPEG	99,544 faces 8192 × 8192 pixels	10.6 MB 9.1 MB

The Outdoor Visualization module included the 3D, textured mesh of the exterior shape of the church and its surroundings, generated with photogrammetric reconstruction. The geometry of the model, originally composed of 25 million polygons, was reduced to an OBJ file with 36,616 faces. The realistic web visualization of the monument was guaranteed by the highly detailed texture information (8192 × 8192 pixels) of the associated JPEG file (Figure 13).

The Overall Visualization module was composed of two different switchable visualizations: one containing the complete point cloud of the whole complex and another containing the 3D meshes of the church and the surrounding system of hypogea. The point cloud, originally consisting of 127 million of points, was reduced to one million elements in a PCD format. The point cloud information was displayed using a height colour scale, ranging from blue to red (Figure 14). The 3D meshes of the hypogea (which have no texture information of their own and are therefore displayed in opaque colour) were obtained using the Poisson reconstruction tool provided by the Mesh Inspector ver. 2.4 software. The geometric information was contained in an OBJ file with 49,944 faces. The 3D model of the church was created with a 3D CAD modelling process referenced to the full point cloud. The result was an OBJ file with 56,667 faces. The materials of the church and the hypogea system were treated differently in order to better visualize the connections between the environments. In particular, the 3D meshes of the hypogea were displayed as an opaque material, whereas the 3D mesh of the church was adapted in the associated MTL file to create a semi-transparent effect for the surfaces (Figure 15).

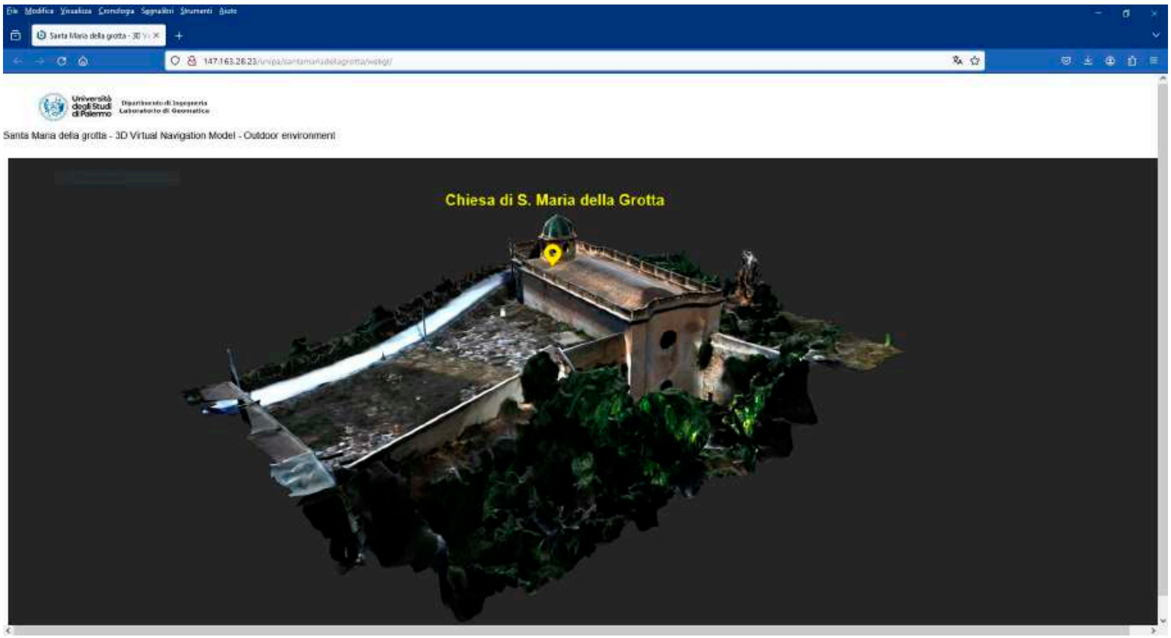

Figure 13. The "Outdoor Visualization" module.

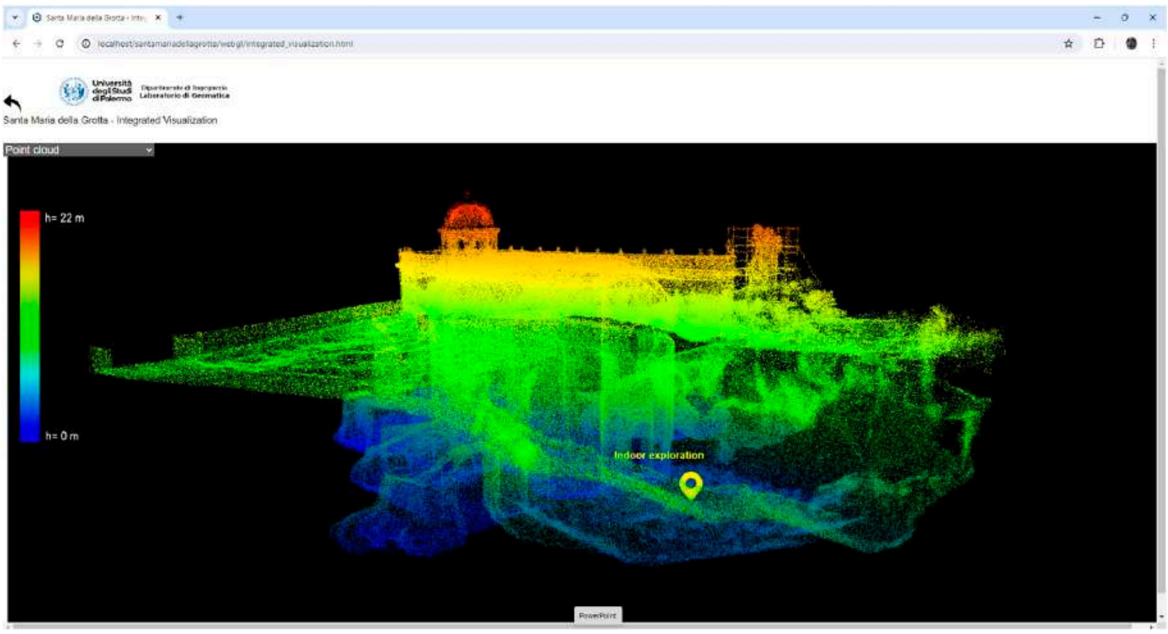

Figure 14. The "Overall Visualization" with the point cloud of the entire complex.

The Indoor Visualization module included the 3D, textured mesh of the interior configuration of the church, generated by photogrammetric reconstruction. The geometry of the model was reduced to an OBJ file with 99,544 faces. The interior realistic first-person web visualization of the monument was obtained from the highly detailed texture information (8192 × 8192 pixels) of the associated JPEG file (Figure 16).

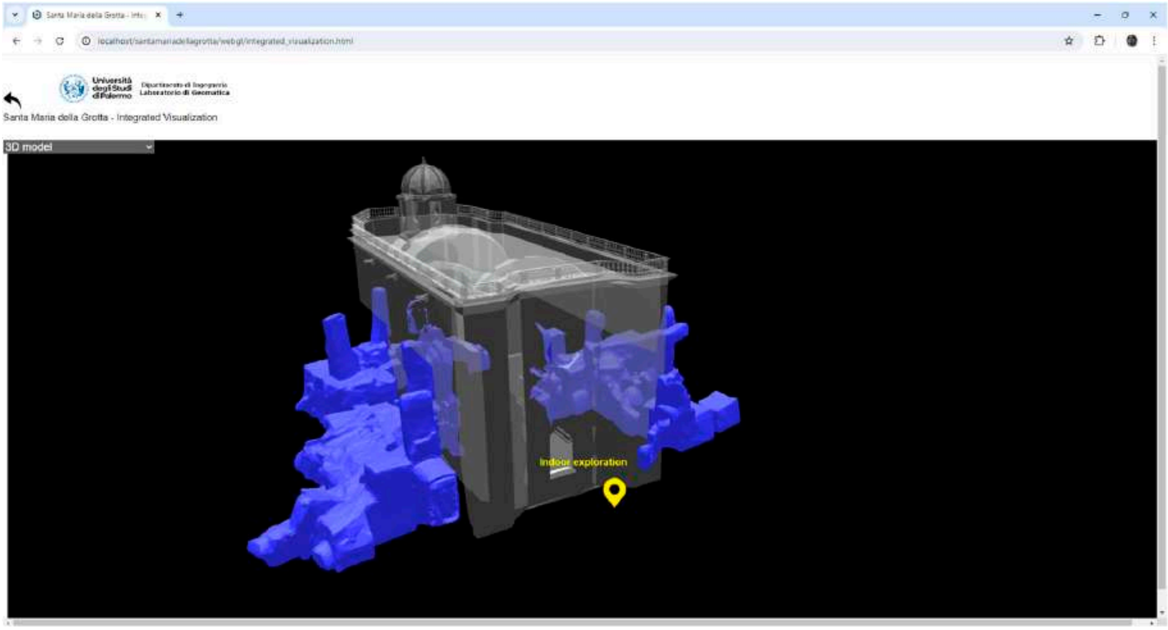

Figure 15. The "Overall Visualization" with the 3D meshes of the entire complex.

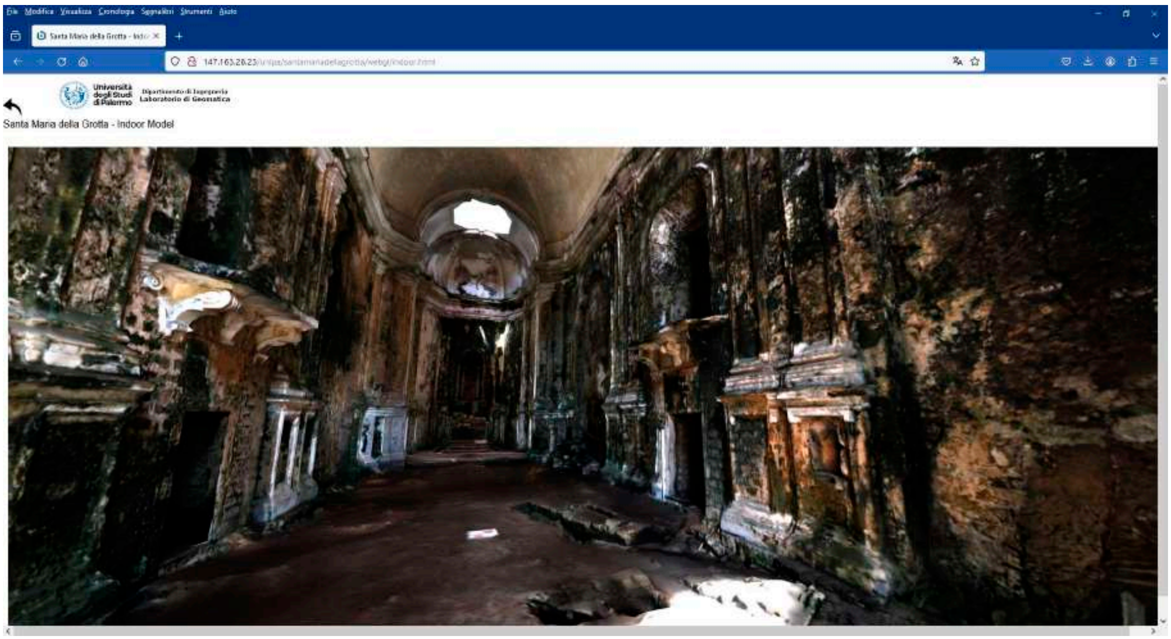

Figure 16. The "Indoor Visualization".

4. Results

The 3D dataset modelled for the web exploration was integrated into a webserver folder, along with the HTML pages hosting the modules. Each module was hosted in a single HTML page following the HTML5 standard [57]. Each HTML page contained the structure of the 3D environment in a JavaScript language and was linked to a system of WebGL libraries, integrated in the webserver folder. The system developed used Three.js open-source WebGL libraries, which provide powerful APIs for creating interactive 3D applications on the web for desktop and mobile devices. The HTML structure, based on a common template, was customized for each module of navigation (Figure 17). Each module was linked to the next one through a system of popup elements, to create an exploration path which takes visitors from the external environment to the internal visualization of the church (Figure 18). The interface was designed with simple navigation controls without visible buttons or command descriptions to allow simple and clear web navigation for users of desktop PCs and mobile devices.

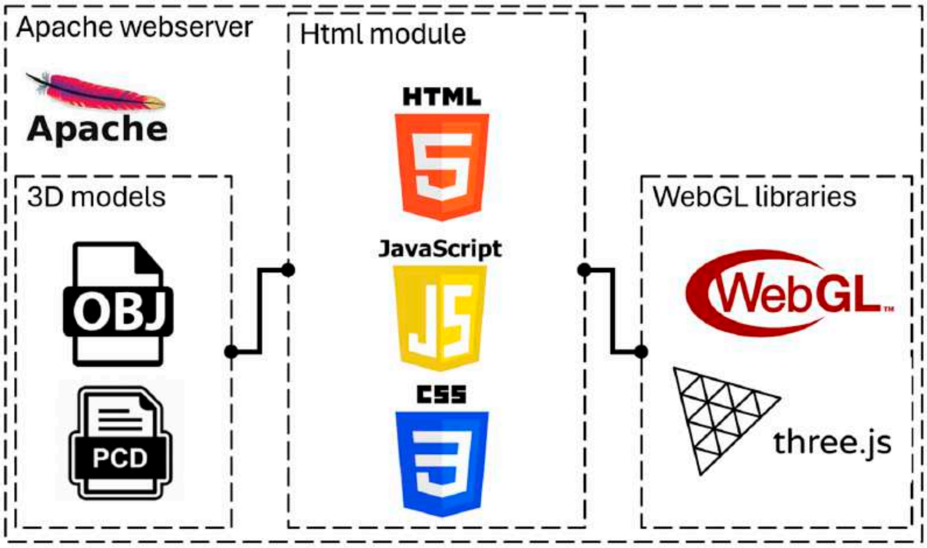

Figure 17. The webserver structure of the system.

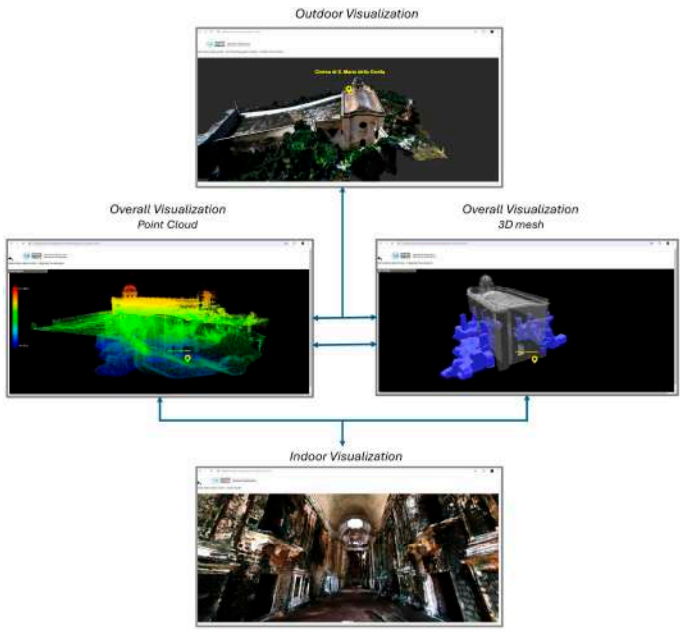

Figure 18. The web navigation path.

The HTML page which hosted the Outdoor Visualization module contained an "OrbitControls" Three.js library, which allowed 3D orbit navigation around the model. It also included the "MTLLoader" and "OBJLoader" Three.js libraries, which are required for the 3D visualization of the mesh. The connection to the next module is managed by a "PointerDown" function connected to a popup link inside a sprite element.

The HTML page which hosted the Overall Visualization module contained, like the previous one, an OrbitControls Three.js library for the orbit navigation and the MTLLoader and OBJLoader Three.js libraries for mesh visualization. It also included a "PCDLoader" Three.js library for point cloud visualization. The HTML structure consists of a switcher structure built into a dropdown menu, which enables switching between the point cloud and the mesh visualizations. The connection to the next module is managed, as in the previous one, by a PointerDown function connected to a popup link inside a sprite element.

Finally, the HTML page which hosts the Indoor Visualization module included a "MapControls" Three.js library; this enables first-person walking navigation of the environment. It also includes the MTLLoader and OBJLoader Three.js libraries, which are needed for the 3D visualization of the mesh.

5. Discussion

This work promotes the simulation of a realistic experience and perception for users through the digitisation of the complex of Santa Maria della Grotta, an area characterized by a singular geomorphic conformation and stratified by historic and anthropic factors.

The added value of this research was based on the achievement of three different goals:

(1) To document, for the first time, the entire complex of Santa Maria della Grotta using the most advanced technologies that are capable of capturing the actual conditions of the site in a complete and effective way and in the shortest possible time.
(2) To use open-source, cost-free, user-friendly VR solutions to enjoy the fruition on the web without the need for third-party installations or special equipment to enhance user experiences.
(3) To allow users to virtually visit the CH site without risk of harm to people or of further degradation occurring in such a fragile environment.

The initial datasets were acquired using different techniques such as HMLS and UAV photogrammetry; these allowed the 3D documentation purposes of the research to be satisfied, with geometric information of the internal and external environments of the site (including the underground caves and the connections to the church and the external quarry and the upper churchyard) that was as complete and exhaustive as possible. These integrated acquisitions were carried out independently of their use in this VR system; once obtained, they can be stored and possibly reused for other applications. In particular, the HMLS was preferred over the static LS acquisitions due to the extremely irregular shapes of the hypogea and the limited spaces between the caves (this was one of the main challenges faced during the survey). On the other hand, the UAV technology made it possible to carry out a rapid survey of the articulated and extended landscape and environments that were inaccessible during the HMLS survey. Once processed, the resulting dataset required a strong simplification process to enable the visualization in the web navigation system. In fact, the amount of 3D information—in terms of number of polygons, number of points, and texture resolution—which can be browsed within a single HTML page is limited. This limitation is now the main challenge of WebGL technology, leading specialists to explore different solutions, depending on the need for virtual web navigation.

Therefore, the workflow followed in this case study integrated 3D documentation methodologies and web visualization strategies to allow a realistic and exhaustive virtual exploration experience on the web of complex CH sites characterized by limited accessibility. Compared to other similar cases of study, this work represents a further step: it enables the exploration and understanding of the spaces of a complex indoor/outdoor CH environment on the web. This has been achieved using a low-cost solution based on the adoption of open-source graphic libraries [31,43,44,58].

Other experimentations cited in this research adopted different solutions—such as Pano VR2 [21], Potree.js [31], 3DHOP WebGL libraries [33] and CodeIgniter [35]—to solve the geometry loading limitations. These solutions allowed the automatic optimization of point cloud visualization, through changing the resolution based on the viewing point; thus, it provides an easy-to-use solution for the geospatial analysis of point clouds [59]. Although this kind of solution can be useful in a simple web browsing solution for geospatial data visualization on the web, it cannot be easily adapted to integrate different data sources (as 3D mesh integration) or different navigation controls.

Finally, Three.js seems to be more suitable for web exploration aimed at dissemination purposes, i.e., for implementation in archaeological sites or museums, allowing visitors to explore the environments on the web with their own devices. In fact, access to the virtual web navigation system can be obtained through simple QR code links, allowing intelligent navigation through desktop and mobile devices.

The use of open-source-based technology allowed us to design and customize a complex 3D environment for web visualization at no cost, while avoiding the need for any application download on the client's side.

With this technology, it is possible to freely customize the visualization of the environment by loading different types of datasets (textured meshes, coloured meshes, point clouds, etc.), the lighting of the surfaces, the user controls, and the connection with links and semantic data (for instance, popup windows). The use of this technology offers the possibility of customising the 3D visualisation system, but it also requires the presence of programming skills in the background of the developer.

Comparing this work with previous, similar experimentations, this system integrates first-person web navigation of complex indoor environments (such as the interior of the church) and allows different types of datasets to load. The limitations of the first-person navigation system, which has not yet been extended to the hypogeum environments, remain a challenge. The lack of texture information in the hypogea environments, caused by the poor light conditions at the site, prohibited the realistic visualization of these spaces with a high level of detail.

The current structure of visualization can be seen as a first step for future developments. In fact, more informative content could be added, such as a gallery of images with textual descriptions of the different environments, to enhance user understanding of the complex during its virtual fruition. The navigational experience in Santa Maria della Grotta could even be linked and integrated with two similar case studies what have been previously arranged for similar cases of hypogeum architectures in Marsala [43,44]; thus, one might create a structured thematic itinerary through these isolated places. This system would spread awareness of the local underground heritage which might otherwise remain neglected. Moreover, this platform is suitable for connection with a sensor network on site and can be used as a digital twin for the real-time analysis and monitoring of the complex on the web; this type of application would be particularly useful for its maintenance and conservation.

6. Conclusions

The process presented in this work enables the 3D documentation of a complex cultural heritage environment and the creation of a virtual web navigation system for the site. This paper addresses the challenge of digitally preserving a complex structure of a monumental area, and makes a 3D virtual cultural heritage site accessible on the web, with a particular focus on monumental complexes with safety and maintenance issues. Using geomatics technologies, especially HMLS and photogrammetry, the study demonstrates the effectiveness of integrating diverse data acquisition methods to develop accurate 3D digital representations of monumental complexes with underground caves. The research highlights the importance of combining geomatics and computer science strategies throughout the data acquisition, processing, and visualization phases, particularly for the development of 3D web navigation experiences based on open-source solutions.

The case study of "Santa Maria della Grotta" in Marsala illustrates the application of these techniques to a complex historical site with underground structures. Through an extensive survey campaign using HMLS and UAV, detailed 3D datasets were obtained both internally and externally. Subsequent data processing and modelling allowed the optimization of digital models that were suitable for virtual reality experiences and web-based navigation. Key findings include the need to simplify datasets for web visualization while maintaining the necessary level of detail, based on a combination of point clouds, textured meshes, coloured meshes, and polygonal models. The development of a web-based navigation system using WebGL technologies enables users to explore the site from a macro to a micro scale, offering a multiscale visualization experience. This system adopts different types of datasets (point clouds, textured mesh, coloured mesh) that are properly combined for each level of visualization; this offers users the possibility of accessing an exhaustive 3D representation of the monumental complex.

Considering the 3D documentation strategies involved, our case study can be useful in the future as a reference for the 3D digitization of complex monumental sites. At the same time, this case study demonstrates how the open-source technologies adopted in the web-based navigation system can be used for the exploration of different types of 3D datasets, based on extensive survey acquisitions.

Overall, the study highlights the potential of integrating advanced survey techniques with web-based visualization to improve the accessibility, understanding, and management of CH sites, paving the way for future developments in digital and virtual heritage.

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