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WEB EXPLORATION OF CULTURAL HERITAGE WITH LIMITED ACCESSIBILITY: FIRST EXPERIMENTATION FOR HYPOGEUM ARCHAEOLOGICAL SITES

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ABSTRACT:

The accessibility to hypogeum archaeological sites is still one of the main challenges for the dissemination of Cultural Heritage knowledge, especially in the territories rich of ancient ruins like the Mediterranean area, where modern cities often hide underground ruins of historical settlements making the accessibility of these sites very difficult or even impossible. Digital reconstructions and virtual reality applications result in many cases the only chance to explore these archaeological sites. Terrestrial laser scanning and photogrammetry are the main technologies able now to digitise at a very high-level detail the hypogeum environments, whilst web virtual navigation systems are smart solutions for their dissemination and virtual fruition. However, this approach has some critical issues since the online virtual fruition needs further 3D model elaborations and web design processes. The work aims to develop and implement a web exploration system for the web fruition of hypogeum archaeological sites. The research was carried out on two hypogeum sites in Marsala (Italy), part of the ancient Roman city of *Lylibaeum*. The system was developed using WebGL JavaScript open-source libraries, allowing the construction of a virtual 3D navigation platform accessible on the web. In particular, in this work, the 3D dataset elaboration necessary to solve the limitations relative to the web browsing of complex 3D datasets is investigated and a possible smart solution based on open-source technology is proposed.

1. INTRODUCTION

The fruition of underground Cultural Heritage (CH) sites represents one of the main challenges for exploring and visiting archaeological ruins. In fact, many archaeological sites are settled in the subsoil of modern cities, especially in the Mediterranean area. These sites often present graffiti and ancient reliefs preserved from natural and anthropogenic factors which in other conditions could hinder their conservation (D’Orazio et al., 2020; Baiocchi et al., 2020).

The underground location of these ruins usually preserves the presence of wall paintings thanks to the constant levels of humidity, temperature and air composition. The fruition in situ of these archaeological sites and the visitors’ exploration of the ruins can compromise these conditions with the risk of losing the integrity of the paintings, mosaics etc. (Luvidi et al., 2021).

The digitisation of these underground archaeological sites allows to digitally preserve the original information in terms of geometric and texture information. Recent Geomatics techniques as Terrestrial Laser Scanner (TLS) acquisitions and digital photogrammetry allow to obtain high-detail reconstructions of complex environments, enabling specialists to document underground archaeological sites (Di Stefano et al., 2021; D’Agostino et al., 2022;). In particular, TLS acquisitions are appointed to achieve a better level of accuracy in the geometrical information, whilst digital photogrammetry is ideal to capture the high-detail texture information of the surface decorations.

The digitisation of CH information is not only useful to preserve the geometric information of the environments but in the last decades it has been used for Virtual Reality (VR) and Augmented Reality (AR) reconstructions (Fiorini et al., 2022; Scianna et al., 2020). Indeed, recent advances in computer science were employed for the development of virtual representations based on the digital reconstruction of CH sites. These simulations offer an alternative solution for the exploitation of ancient ruins, preventing in some cases the necessity of a physical visit in the cultural site (Scianna et al., 2021; Fazio et al., 2022). These solutions are based on gaming technologies, and there are many experimentations in museums and monuments, offering the possibility to insert additional information of the cultural sites (popup descriptions, reconstructions in the past, etc.). In the last years many applications have been developed for immersive navigation experiences, AR and VR smartphone applications and web-based solutions.

The digitised dataset with the use of modern Geomatics techniques is the base for the development of VR and AR CH virtualisations, but it needs to be properly elaborated first for this aim. In fact, the main challenge in this context is represented by the management of the huge dataset provided by TLS acquisitions and digital photogrammetric elaborations. The acquisition of CH datasets has no limitations itself, but their digitalisation needs to be strongly simplified in order to be used for virtual fruition requirements. In particular, there is a constant search for setting the right balance between the quality of visualisation and the size of the geometric model (Scianna and La Guardia, 2020). For this reason, the optimisation of the 3D survey dataset for VR and AR applications remains a challenge, especially considering web-based solutions.

The spread of WebGL JavaScript open-source libraries, based on HTML5 standard, revolutionised the world of VR, allowing the web navigation of complex 3D datasets from desktop and mobile devices, with no need to install any apps. The amount of geometric information to visualise in these kinds of applications

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is limited, and for this reason, the integration of digitised datasets provided from TLS and photogrammetric acquisition still remains a challenge. At the same time, the possibility to provide users the opportunity to explore monuments and archaeological sites online using common browsers represents a strategic choice for the dissemination of CH knowledge, especially for sites with limited accessibility like underground archaeological remains.
The work aims to develop a web exploration system for the web fruition of hypogeum archaeological sites. The system was actually implemented for two hypogeum sites of Marsala (Italy), inside the archaeological area of the Roman city of *Lylibaeum*. The sites are the hypogeum of the Sybil and the hypogeum of Crispia Salvia. Both preserve ancient remains as frescoes and paintings and are included in the Archaeological Park of Lilibeo - Marsala. The adopted solution considers the development of WebGL navigation systems based on OpenGL which allow the online virtual exploration of the archaeological sites using a smart and free-from-cost solution. This approach is different from previous work (Tanasi et al., 2021) in which commercial 3D web services were used to display and share 3D models.
The workflow considered the 3D survey acquisition with modern Geomatics methodologies (terrestrial laser scanning and photogrammetry), the 3D modelling of the environments, and, finally, the construction of 3D web environments based on WebGL Javascript libraries to share the 3D visualisation on the web.

2. THE CASE STUDIES

The ancient *Lylibaeum* was a Carthaginian foundation dated back to 4th century b.C. It became a Roman colony in 241 b.C. and until the 3rd century a.D. it had a strategic role in the Mediterranean area. Starting in the second half of the 5th century a.D., the city underwent various vicissitudes which led to the gradual desertion of the original core. Under the Islamic domination in the 9th century a.D., the city was named Marsala, and from the middle 12th century, the settlement developed more and more inland, stepping back from the coast.
The remains of the ancient *Lylibaeum* are still visible in the Archaeological Park of Lilibeo-Marsala, but its actual extension was way over the boundaries of the Park. In fact, many archaeological findings emerged across its boundaries, in the modern town of Marsala, sometimes hidden by buildings or road carriages.
The case studies regard two underground sites: the hypogeum of Sybil, included in the Archaeological Park of Lilibeo-Marsala, and the hypogeum of Crispia Salvia, located inside the modern town of Marsala, nearby the boundaries of the Archaeological Park (Figure 1).

Figure 1. Map of the town of Marsala, with the Archaeological Park of Lilibeo-Marsala and the two hypogea locations.

2.1 The hypogeum of the Sybil

The hypogeum of the Sybil is located in the south-west area of the Archaeological Park. Its first historical mention links the site to a spring of water. In the popular opinion the entire area was the sepulchre of a mythological prophetess (the Sybil whom it was named after) and used for pagan religious rituals related to the presence of water. Probably, the artificial cave was the nymphaeum of one of the Roman villas built in the 2nd century b.C. According to Bonacasa Carra (2002), a document written in 250 a.D. attested the nymphaeum was reused as a baptistery by the first Christian community in the colony. In the 12th century it was turned into a crypt by Cistercian monks whilst an overhead church, dedicated to St. John the Baptist, was built in 1555.
This hypogeum was dug into the limestone bank to a depth of about 4.8 meters from the current surface (it was just about 1.5 meters originally) and is accessible by two entrances from the side naves of the church, albeit nowadays just one of them is currently open and in working order.
A short *dromos* (tracheal passage), preceded by few steps, leads to a circular chamber, covered by a lowered arch dome with an oculus on top, connecting the hypogeum to the floor of the upper parish. In the centre of the main space there is a square basin carved on the pavement, which was used as a baptismal font where the catechumens used to bathe. The basin was fed through a drainage pipe running across the pavement by the water spring arising from a small cavity at the floor level of the northern room, whose shape has an apsidal termination and a crow zone. The water spring is partially hidden by a stone altar built in the 16th century and dedicated to St. John the Baptist, represented in a high-relief statue while holding the Agnus Dei in his arms (Figure 2).

Figure 2. The circular chamber in the hypogeum of the Sybil.

It is clear that the pagan worship of the Sybil, the Christian worship of St. John the Baptist and the use of the site as a baptistery were strictly influenced by the presence of the water table on site (Cusenza and Vecchio, 2006). The entire walls of the hypogeum were covered with frescoes on a lime coat, and the floors paved with mosaics, whose many parts are now missing or deteriorated. The main space was paved by a circular mosaic representing a marine scene with fishes, dated to late 2nd-early 3rd century a.D., according to a theme typical of northern Africa. In the northern room, the mosaic on the floor is datable to the late 4th-early 5th century a.D.. The western room has the most parts of surviving frescoes. A lower band was running along its perimeter, showing few traces of mirrors of false marble. The medium band is developed symmetrically in panels with symbolic pictures; a liturgical shell is painted in the centre of the

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straight walls, surrounded by two lateral baskets full of fruit (*kalathos*), two doves below and some bunches of red roses. Similar features are shown on the apses, where the *kalathos* is flanked by a peacock whilst below a *lilium* is visible between two red playing fishes. The upper band is a ribbon twisted with flowers running along again. Traces of a panel decoration are visible on the ceiling as well. These decorative motifs are typical of funerary paintings and early Christian mosaic cycles of the 4th century a.D. (Lima, 1997).

2.2 The hypogeum of Crispia Salvia

The hypogeum of Crispia Salvia, located outside the perimeter of the Archaeological Park of Lilibeo-Marsala, is famous for the conservation of its fresco wall decorations, in particular the scenes regarding the trespass from life to death. Many tombs of the Punic period were found in that area, which was furtherly used until the Roman-Imperial age. The hypogeum was discovered during the works for the construction of a modern residential building in 1994.
From a dedicatory tile found *in situ*, it is known that the burial chamber was built for Crispia Salvia, a noble woman of the Roman period, by her husband. The high rank of the family was suggested by the richness and the quality of the fresco decorations, and the materials used for the construction of the chamber (Bivona, 2000).
The hypogeum is entirely dug into sandstone ledges down to about 4.7 meters from the soil, and it is accessible from the entrance hall of the modern residential construction built over. Its trapezoidal burial chamber of 25 square meters, housing six tombs and their grave goods, dates late 2nd - early 3rd century a.D.. (Figure 3). The frescoes in the chamber consist of a lower red band running along the tombs at the floor level whilst the perimeter walls are entirely covered by pictorial decorations with figurative scenes, representing the prototypes of the local Paleo-Christian pictorial language (Gaglio, 2004). Heavenly environment is described through coloured floral symbols, where the Christian and Pagan styles merged.

Figure 3. The hypogeum of Crispia Salvia.

3. MATERIALS AND METHODS

The workflow followed for the construction of the web navigation system was based on a 3D survey, where TLS acquisition and digital photogrammetric reconstruction allowed to obtain the necessary 3D dataset. On a first basis, TLS survey allowed to capture the point cloud for underground environments and for the upper and external parts. At the same time, the digital photogrammetric reconstruction, based on Structure from Motion (SfM) approach, allowed to generate 3D mesh of the hypogeum rooms with a high-resolution texture. Both the point cloud and the mesh were simplified to generate 3D datasets compliant with the web visualization. The virtual environments to be visualised on the web were locally prepared considering geometric (polygons and point clouds) and texture information. The web navigation systems were finally created, implementing the 3D dataset in a virtual context and customising the web exploration of the scene (Figure 4).

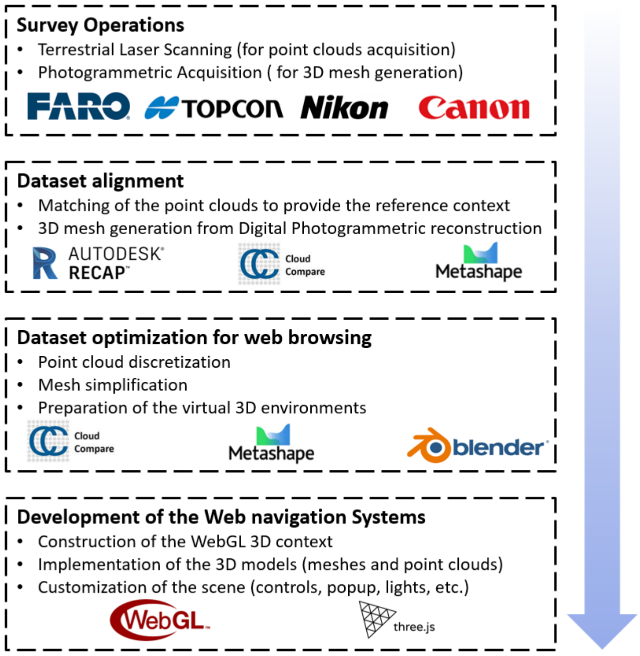

Figure 4. Scheme of the followed workflow.

3.1 The survey of the hypogeum of the Sybil

The survey of the hypogeum of the Sybil was planned to generate a complete laser scanner point cloud from the inner of the hypogeum to the exterior of the upper church. The survey was carried out using a Topcon GLS-2000M, a time-of-flight laser scanner. The instrument, with a distance measuring range up to 350 meters, a scan rate up to 120.000 pts/sec and a single point accuracy of ±3.5 mm (1-150m), provides a vertical and horizontal field of view of 270° and 360°. The laser scanner can recognise the "first pulse" and "last pulse" and offers first/last pulse selection to be taken as a measuring result. This laser scanner can be furthermore used as a total station, measuring each scan position backward and forward through an auxiliary prism (Figure 5).
For the laser scanner acquisition a topographical traverse, made of the vertexes corresponding to the scan positions, was planned. Prior to starting an acquisition from its positions, the prism on tripod was placed in the previous and the following ones, measured topographically by the scanner. This method has been followed considering due to the complicated shape of the hypogeum (Ebolese et al., 2019).
In this way, the automatic alignment of the scans during the post-processing phase was made possible. This traverse started from the hypogeum, continued through the upper church and ended outside, in order to match the different levels. It was made of 16 scan points: 4 of them were planned to acquire the hypogeum rooms entirely, 4 for the dromos and the staircase, 2 for the interior of the church and 6 around its perimeter (Figure 6). All scans were set to a sampling resolution of 12.5 mm at 10 m.
The quality of the TLS captures of the burial chamber was not enough to deliver a useful texture of hypogeum's frescoes and

mosaics, so a close-range photogrammetric survey was performed in order to achieve high-resolution details of the surfaces.
The acquisitions were carried out using a digital Single-lens Reflex Camera (SLR) Nikon D5200 with a 24 mm lens and a resolution of 24 Mpx. A total of 116 images was acquired on a perimetral path along the walls, covering them at different angles. The images were taken from an average distance of about 3 m, resulting an average Ground Sample Distance (GSD) of about 0.5 mm (Ebolese et al., 2019). The lack of natural light inside the hypogeum hindered the photogrammetric acquisition. For this reason, the use of diffuse spotlights guaranteed the uniform enlightenment of the underground environments.

Figure 5. The Topcon GLS-2000M during the survey (from Ebolese et al., 2019).

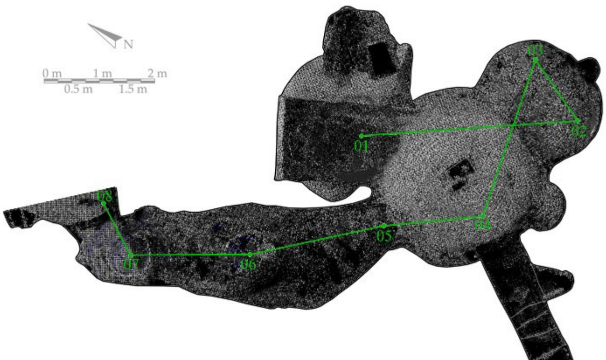

Figure 6. Scanning positions inside the hypogeum.

3.2 The survey of the hypogeum of the Crispia Salvia

The laser scanner survey of the hypogeum of Crispia Salvia was performed considering the burial chamber and its surroundings, until the entrance of the residential building at the ground floor. A FARO Focus 3D S120 laser scanner was used (Figure 7); this device is a phase-shift laser scanner characterized by a distance measuring range up to 120 meters, a ranging error of ±2 mm at 10 m, a measurement speed up to 976000 points/second, and a vertical and horizontal field of view of 305° and 360°.
Data acquisition started from the centre of the cubicle, continued inside the tombs, on the dromos, the stairway, the premises at the ground floor of the residential building and ended in the adjacent external courts for a total of 24 scans.

Figure 7. TLS acquisition of the hypogeum of Crispia Salvia.

All the scans were performed with a large overlap to ensure proper registration.
Also in this case, the TLS dataset acquisition of the hypogeum didn't achieve the necessary level of detail of texture information. The presence of the Roman frescoes demanded, indeed, the integration of a close-range photogrammetric acquisition of the room. A digital 18 Mpx Canon 550D SLR camera was used for taking 222 perimetral acquisitions at different angles and constant intervals of distance. The average camera-to-object distance was 3.5 m; the resulting GSD was of 0.7 mm.
Also in this case, during the image acquisition, a uniform lighting was provided by four led lamps.

3.3 Data processing

The acquired datasets were elaborated to make the digital reconstruction of both sites. The TLS point clouds were registered and merged using Cloud Compare open-source software and Autodesk Recap software. On another side, the photogrammetric reconstruction carried out on Agisoft Metashape software enabled the generation of the textured mesh models of the captured scenes. This step was necessary to obtain a realistic reproduction of the hypogeum environments, granted by the high-resolution acquisition of the surface.
These 3D models, obtained from the digital photogrammetric reconstruction, were then scaled and aligned to the TLS point clouds, taken as main references due to their high-level of detail and accuracy. The 3D digital replicas, now comprehensive of textured meshes and point clouds, constituted the base for the environment to be visualised in the web navigation system.
The presence of frescoes inside the hypogeum rooms needed to be represented in a realistic way, unlike the surrounding environment. For this reason, the triangular high resolution textured meshes were chosen to visualize the hypogeum environments, instead the TLS point clouds were used to contextualize the archaeological sites with their surroundings.
As mentioned earlier, one of the main challenges for the web visualization of 3D complex datasets is their storage size. Both the TLS point clouds and 3D meshes had to be strongly simplified to be uploaded in the web navigation system.
In the TLS point clouds, the consistent geometrical information of the spaces was stripped from unwanted and redundant data through the "filtering noise" command available in Cloud Compare software. At the end of the editing, the final files were sized under 100 MB (Figures 8 and 9).
The number of triangles of the 3D meshes was strongly reduced as well through the Agisoft Metashape software, maintaining a high resolution of the texture information. The final storage size was under 30 MB for each 3D model.

Figure 8. Vertical section of the point cloud of the hypogeum of the Sybil.

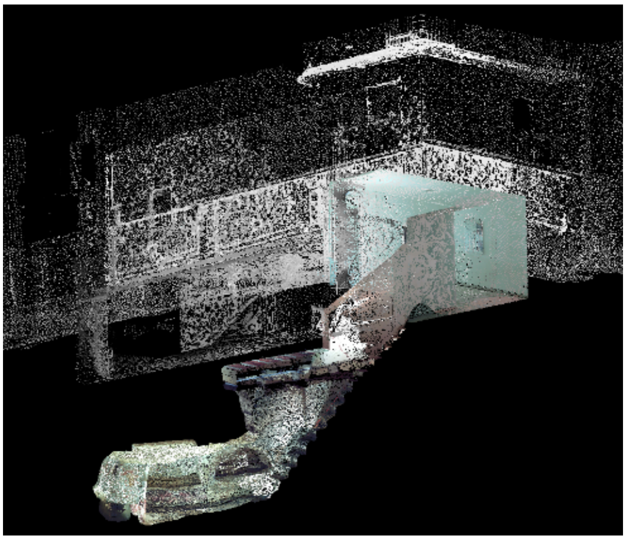

Figure 9. Vertical section of the point cloud of the hypogeum of Crispia Salvia.

In this way, the 3D models were adequately simplified to be visualised on the web. Once resampled, meshes and point clouds were finally processed in Blender open-source software for the final editing.

3.4 Web navigation system

The last step of this work was the construction of the web navigation system. The framework of the web visualization was structured inside an .html file, connected with Three.js WebGL JavaScript libraries. The system was customised inside the .html file, loading the point clouds and the meshes, and setting lights and control systems (necessary to navigate inside the virtual environment). The meshes (as .gltf format) and the point clouds (as .pcd format) were finally loaded into the WebGL environment. The quality of the web visualization was hence tested for desktop and mobile devices, in terms of realism and stability on the web exploration (Figures 10 and 11).

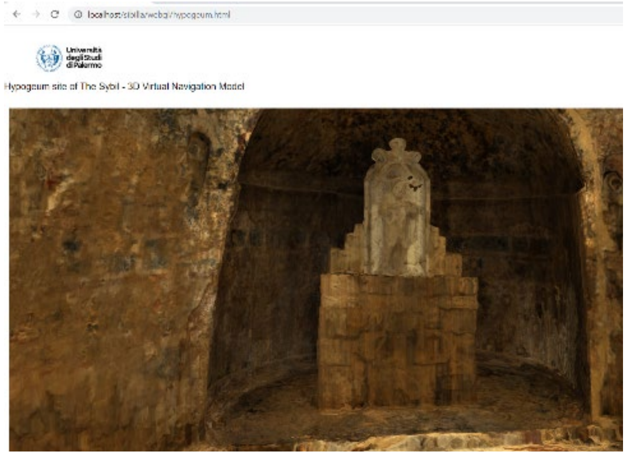

Figure 10. The web navigation model for the hypogeum of the Sybil.

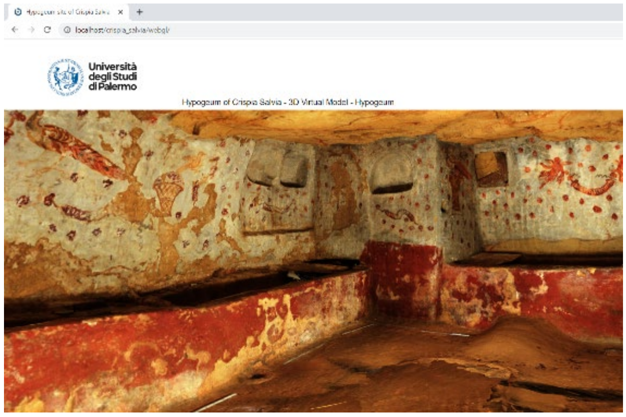

Figure 11. The web navigation model for the hypogeum of Crispia Salvia.

4. DISCUSSION

Considering the acquisition of the dataset, the TLS survey allowed to document the archaeological ruins in relationship with the natural and anthropic context around it. At the same time, the underground location of both archaeological sites complicated the acquisition and registration of the dataset, due to the limited dimensions and the confined spaces of the passages which connected the hypogea to the upper buildings. In particular, the hypogeum of the Sybil is located under the church of St. John the Baptist, and the hypogeum of Crispia Salvia is located under a modern residential building. To solve these issues two different approaches were adopted: for the first one, a topographic approach by the traverse method has been followed, thanks to the Topcon GLS-2000M for scans registration (Ebolese and Lo Brutto, 2020; Lo Brutto et al., 2021); whilst a very redundant acquisition was performed by the FARO Focus 3D laser scanner in the second case.

The geometrical information obtained from the TLS acquisitions was exhaustive for obtaining an accurate digital reconstruction of the real shapes of the spaces, but it wasn’t enough for the virtualization of the environments finalized to the web exploration. In fact, the resolution of the data captured during the TLS surveys didn’t match the expected requirements for an adequate representation of the frescoes inside the hypogeum.

For this purpose, in both the case studies the TLS acquisitions were enriched by a photogrammetric reconstruction of the indoor

environments. The absence of natural light complicated the data capture, and the use of headlights was necessary.
The construction of the web navigation system highlighted the strengths and weakness of the web browsing of CH environments. If on one hand, the web navigation system represents an opportunity to spread the diffusion of CH knowledge with free accessibility and with no software installation needed, on the other hand, this technology still presents some limitations regarding the size of the 3D environment to be visualised. The last versions of Three.js opensource JavaScript libraries allow to upload not only 3D meshes but also 3D point clouds and other kinds of datasets. This opportunity is slightly limited by the web browsers capabilities which still don't allow to upload large files to be visualised on the web. Indeed, if 3D meshes allow to obtain a realistic 3D virtual representation on the web with limited numbers of polygons, 3D point clouds need larger dimensions to render a realistic representation for users.
In the case studies, the web navigation systems of both archaeological sites offer the possibility to visualise the context environment of the hypogeum sites and to visit the chambers inside through a system of popup link connections (Figures 12 and 13). The links were made inside the .html structure of the web visualization, using JavaScript strings. The system was tested using different desktop and mobile devices (PC, tablets and smartphones), in order to choose the best solution for providing a smarter navigation to common users.

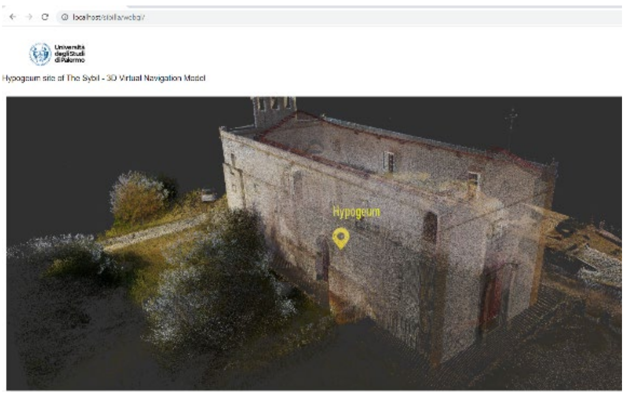

Figure 12. Popup links connection into the navigation model of the hypogeum of the Sybil.

Figure 13. Popup links connection into the navigation model of the hypogeum of Crispia Salvia.

5. CONCLUSIONS

The work has shown a possible solution for providing a free and open-source web navigation tool for the remote fruition of underground archaeological environment for tourists or common users. This choice can be useful to diffuse the CH knowledge in substitution with the real exploration of the archaeological sites, and, at the same time, represents a way to promote the tourism of the entire area, and to share awareness about the local CH.
The integrated use of TLS and digital photogrammetry allows to provide the necessary dataset information for the construction of a virtual web navigation experience. This is particularly advantageous for tourists *in loco*, who can be free from forced software installation for visualising the wanted contents, and, at the same time, is a precious tool to grant a remote web exploration for tourists with reduced mobility. On the other hand, some technological limitations are still challenging. On a first basis, a good internet connection is necessary to have a fast fruition. Moreover, the limited size of the 3D environments to visualize still represents a limitation in terms of enrichment of information requiring also a strong simplification of the digitalized 3D dataset (previously acquired).
In the future, new solutions based on WebGL technologies will solve this conflict, optimising the navigation experience, and, at the same time, offering the possibility to upload more and more geometrical information and contents. Given the continuous improvements of internet connections and web browser capabilities, it will be possible in a while.

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