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ORIGINAL PAPER

3D survey and digital models as the first documentation of hypogeum of S. Saba in Rome

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Abstract
On the Aventine Minor, the oratory of Santa Silvia was home to a community of oriental monks, who, in the first half of the seventeenth century, created a typical Palestinian cemetery with a small monastery that expanded with the growing prestige of the community. The construction of the Basilica of San Saba, above the oratory, was by a group of monks, "the *Benedettini di Montecassino*," who lived there in the middle of the tenth century. The substructure was only recovered in the early 1900s. The study of this architectural structure is particularly interesting because there were no complete surveys and the available documentation, as far as we know, was limited to a graphical plan and section. For this reason and due to the archeological significance, it has been selected as a national research project (PRIN 2010–2011). The research has requested detailed documentation through laser scanning and photographic-based documentation. The goal of the present work is to produce a documentation of the oratory from CAD model to the BIM construction.

Keywords Heritage · LiDAR · Survey · S. Saba · Rome · Panoramas · H-BIM

Oratorio of Santa Silvia in San Saba

San Saba, located on the "Aventino Minore," has ancient origins hidden in its basements: the oratory was dedicated to Santa Silvia, the mother of St. Gregory the Great. It was home to a community of oriental monks who came from the monastery of San Saba, of the same name, in Judea and who were expelled by the Persians and then by the Muslims at the beginning of the seventh century. The monks created a typical Palestinian cemetery, with two orders of burial tombs and a small Byzantine monastery. The area of the tombs expanded with the prestige of the monastery, which, by request of the Roman pontiffs, carried out intense diplomatic activities connecting East and West. A few fragments of remaining frescoes indicate that, in the middle of the tenth century, there was a group of Benedictine monks in *Montecassino*. It is likely that this group of monks began the construction of the basilica above the oratory. Work to recover the basement took place at the beginning of the twentieth century. The floor of the church was completely removed and the excavation was carried out, after which the floor was repositioned, supported by brick pillars. Access to the underground environment is from the porch of the church through stairs on the left. Some roof tiles which have been repositioned on the entrance wall come from the tombs of the oratory and include inscriptions in Latin painted in red. Also visible in the wall are the bases of the two columns that supported the arch of the central door of the oratory in the seventh century.

The oratory of Santa Silvia is a large rectangular hall of 13.5 × 10 m. Now, the continuity of the space is interrupted by the brick pillars that support the new floor of the church's central nave. In the frontal wall, a semi-circular apse is located. Solely in the apse area, there are Roman structures, which belong to the period prior to the execution of the oratory: an *opus reticulatum* wall covered with red plaster and a circular

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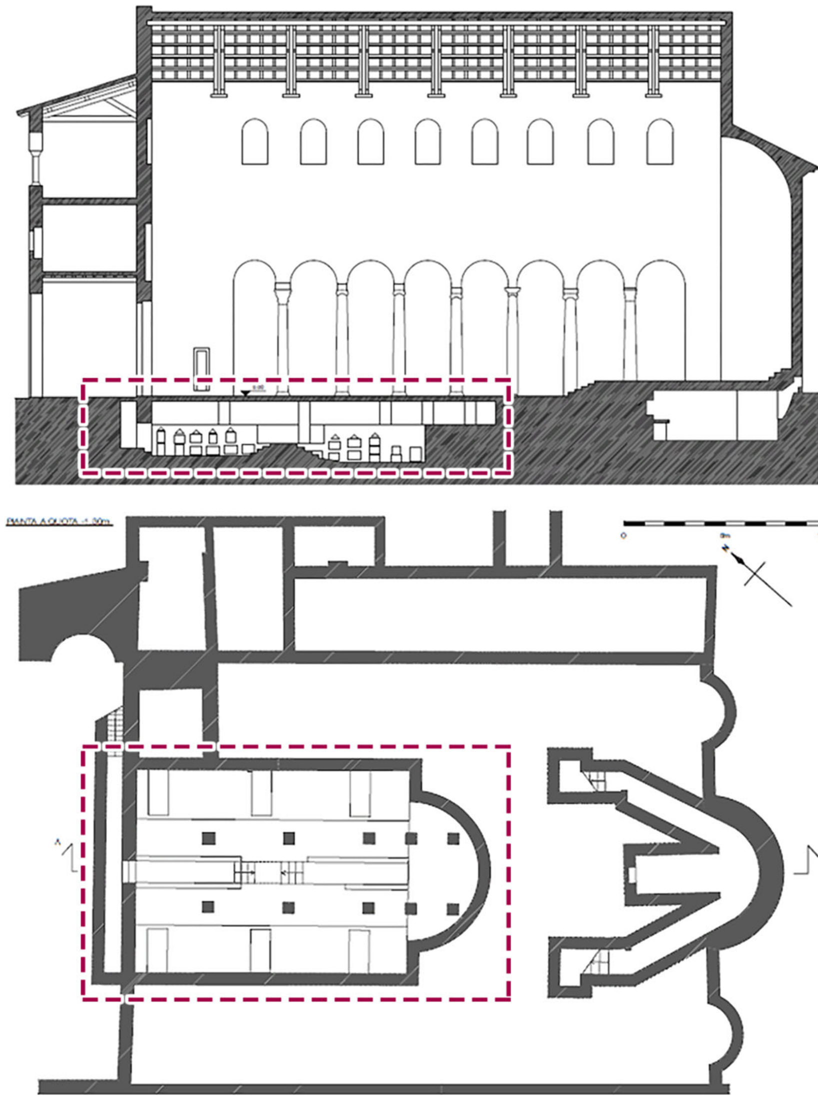

Fig. 1 Sketches of the church of San Saba with the oratory of S. Silvia

basin with the remains of iron extractions. The oratory as it is today dates to the second construction phase from the eighth century, when the original floor was raised 65 cm to cover a cemetery section with a new marble slab floor. The two sides cover cells, “loculi,” closed by bricks. The oldest frescoes represent seven heads of saints (kept in the sacristy) attributable to the oratory of the seventh century and probably made by the same artist. The documentation available until our survey was limited to an approximate plan and section of the Church and its oratory (Fig. 1). As far as we know, no other survey has ever been made to document this structure.

The survey of cultural heritage

Cultural heritage is defined as monuments, group of buildings, or sites which are of outstanding universal value from the point of view of history, art, or science. They are often inadequately documented or maintained and suffering from natural degradation caused by time. They need a detailed description both to preserve the memory of the historical monument and to support technical intervention, such as restoration work or conservative intervention. A 3D model is very significant as it provides a realistic description of the spatial characteristic of the monument. Moreover, when performed at high resolution, it permits an accurate analysis, research, and exploration of the historical monument. Terrestrial laser scanning (TLS), in combination with other digital techniques, such as photogrammetry, and traditional survey methods, is the most appropriate instrument to acquire 3D data for a fast and precise survey of a complex structure. In fact, it is widely used in the field of architecture and cultural heritage (Guarnieri et al. 2017; Barber et al. 2001; Guarnieri et al. 2004; Beraldin et al. 2005; Remondino et al. 2008). Indeed, the 3D cloud points colored with photogrammetric images furnish high-resolution realistic 3D models of the structure.

Fig. 2 Hypogeum of S. Saba in Rome

TLS today is a consolidated technique easy to use even for non-specialized personnel which speeds up the data acquisition. Thus, it has often been used in applications where photogrammetry would have been more appropriate. Elsewhere, TLS is the most correct technique to use such as with the San Saba hypogeum. It is a particularly complex structure (Fig. 2) and has a great deal of detail in a restricted space, which must not be neglected in the survey. A TLS survey was the more appropriate solution, because the information can be easily captured, in particular the geometric data. Furthermore, the analysis of laser reflection intensity would provide an important description of the material (Pfeifer et al. 2008). The San Saba hypogeum, as with many other archeological sites, presents a combination of different ages, and consequently different materials, which were used over the years.

In the design stage of the survey, first, an adequate dislocation of the scan stations, which guarantee complete visibility and avoid any shadows, was planned. Then, the establishment and realization of the reference system in order to permit its integration with potential forthcoming surveys was defined. More specifically, 20 scans were set up in an area of 15 m × 10 m (green rectangles in Fig. 3a), 7 tie points (blue triangles in Fig. 3a) were positioned,

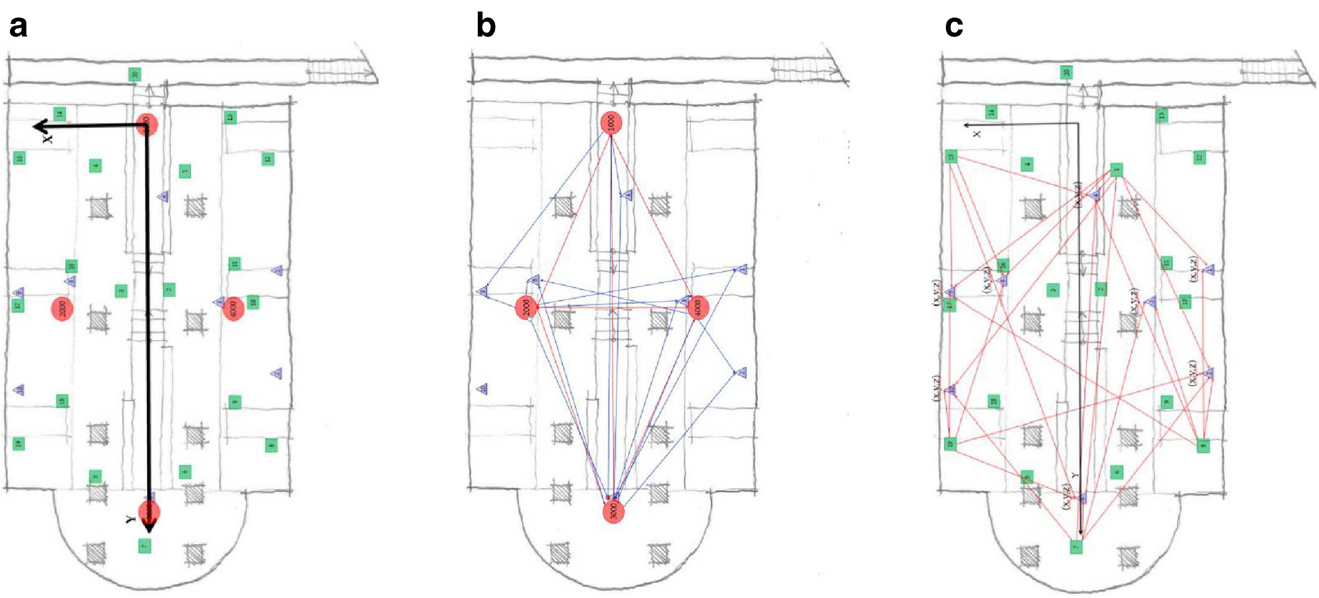

Fig. 3 **a** Reference system, scan stations (green), tie points (blue), and TS stations (red); **b** TS network; **c** laser scanner network

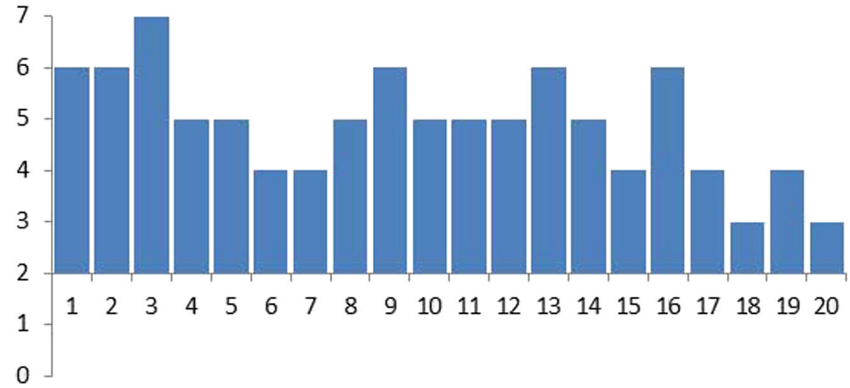

Fig. 4 Number of visible target for each LS station

Fig. 5 Equirectangular projection of a scan

and 3 reference points corresponding to naturally well-signalized points were established. It was not possible to permanently mount any points in the structure.

The coordinates of both tie and reference points were obtained by means of a high-precision topographic network consisting of 4 points (red circles in Fig. 3a) which correspond to the center of the total station (TS).

The reference system originates from one point station and the *y*-axis along the second one (Fig. 3a). In order to georeference the scans in the predefined reference system, at least 3 points must be visible from each scan (Fig. 4).

The network was measured by motorized Leica TM50 TS (angular precision of $\sigma\alpha = \pm 0.5''$ and slope precision of $\sigma d = \pm (0.6\ \text{mm} + 1\ \text{ppm})$). Given the small size of the networks, the station centering error is particularly large; therefore, forced centering systems were used. The observations of slope distance, azimuthal and vertical angle, between the 4 stations and the tie points, were repeated three times in both the telescope positions (face left and face right), using the Leica Automatic

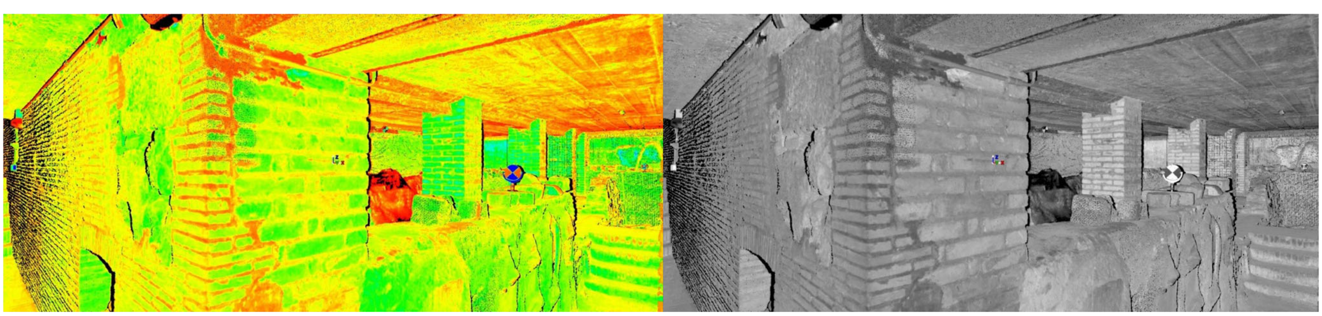

Fig. 6 Point cloud reflectance and black and white visualizations

Table 1 Results of alignment and georeferenced of the scans

	v_x (mm)	v_y (mm)	v_z (mm)
Media	− 0.1	− 0.1	− 0.1
Min	− 4.0	− 7.0	− 6.0
Max	3.0	2.0	2.0
sqm	1.1	1.3	0.9

Target Recognition (ATR) technology in order to achieve more consistent results. The network adjustment is based on a square method and was performed with the scientific software CALGE (Forlani 1986) that estimates the coordinate of an established set of points including their relative accuracy. A mean sqm in *x*, *y e z* of 0.14 mm, 0.4 mm, and 0.15 mm, respectively, and an angular mean sqm of 7.6 cc with maximum value of 8.6 cc for the 4 directions of the stations were obtained.

The scans, using a Leica HDS6000, were performed with a resolution of 10,000 points/360°. Therefore, an angular resolution of 0.036° which produced a point cloud of about 43 million points was set (Fig. 5), while Fig. 6 shows reflectance and a black and white visualization of a scan point cloud.

Subsequently, an alignment and georeference of the 20 scans was performed by Leica's CYCLONE software by creating 120 links (Fig. 3c). A maximum residual of 7 mm (in *y*) and a mean residual of 0.1 mm were obtained as shown in Table 1.

The Leica HDS6000 scans can be georeferenced with a panoramic spherical image generated by image stitching technique. A Canon EOS 450D with fisheye Sigma lens of 8 mm at the same center of the scan station thanks to a spherical head is used. Seven images (6 horizontal as in Fig. 4 and 1 vertical) were acquired (Fig. 7) in order to ensure a good overlap. Once created, the spherical images were mapped following an equirectangular (cylindrical equidistant) projection (Fig. 8).

A point cloud produces a very rich description of the space. The point density is very irregular: the closer a surface is to the scan station, the more points it contains due to the radial projection of the laser rays. Therefore, a first step to avoid an exaggerated high density near the station, but to keep the normal density within a certain limit in the whole point cloud, is to reduce it according to the spatial distance between the points. So, a spatial reduction of a minimum distance can eliminate many points of the total cloud without reducing the density of points which were further than a specific distance from the closest station. In our case, the reduction was important since we carried out many scans to avoid shadows due to the geometry of the space and so that the hidden cells were scanned completely. Moreover, since we used a high scan resolution, the complete registered point cloud of 20 stations would even be difficult to process with a normal workstation. The point cloud was reduced based on a chosen distance of 10 mm to create a final homogeneous and smooth point cloud of 66 million points (Fig. 9).

Graphical drawings are still an interesting and practical representation of the archeological site and obtained using the point cloud as a basis. The production of sections and orthographical views of the point cloud was fundamental as a basis to produce new accurate graphical drawings within CAD programs (Fig. 10).

Modeling of the hypogeum of San Saba

The survey was the basis to produce two types of models and the use of such models is varied. The automatic or semi-automatic reconstruction of a 3D model starting from a point cloud is an interesting step which is normally carried out using algorithms available in commercial and open source software packages. The 3D detailed model helps with the geometrical analysis of the archeological surface where the dimensions and shapes give clear indications of the period and the value of the elements, such as the dimensions of the bricks used and the thickness of the wall layers. This information could be available in a detailed mesh generated from the dense point cloud. The polygonal mesh model creates a visual continuity and eliminates the noise of the point cloud. Different approaches to generating a mesh from a point cloud are available

Fig. 7 Six horizontal photos to compose a 360° panorama using 8-mm fisheye lens in the hypogeum of S. Saba

Fig. 8 Central panorama produced stitching seven fisheye images

in algorithms such as Poisson Reconstruction, Marching Cubes, Ball Pivoting, and Power Crust. In our case, we generated the meshes of some details of the scanned space using the Poisson surface reconstruction (Kazhdan and Hoppe 2013), one of the most diffused algorithms, which produces a noticeable mesh quality (Fig. 11) in a relatively short processing time. The algorithm was used within CloudCompare software (Girardeau-Montaut 2015) (Fig. 11).

The use of 3D CAD models in the cultural heritage field is considered a rich documentation method as well as a geometrical analysis database. Moreover, the demand for another approach is growing quickly with the diffusion of the use of the Building Information Modeling method. Building Information Modeling (BIM) is one of the most promising developments in the architecture, engineering, and construction industries (Eastman et al. 2011). The main difference from a modeling point of view is that, in BIM, model objects are classified and contain non-geometrical properties. Furthermore, BIM modeling software uses a parametric object-oriented modeling approach. Therefore, the objects are simplified geometrically but are rich in attributes. Consequently, a BIM model is semantically readable. The BIM method is being extended to heritage applications such as HBIM (Heritage Building Information Modeling) or B(H)IM (Built Heritage Information Modeling). BIM, by definition, is a method (Eastman et al. 2011) and cannot be limited to a software and one of its most time-consuming phases is the creation of a geometrical model classifying its elements and adding non-geometrical information (attributes) to the objects. The produced model was used in the above-mentioned national research project as the comprehensive representation and documentation of the built heritage (Simeone et al. 2014). Other current research is trying to automate the scan-to-BIM process (Scan2BIM) as demonstrated in the recent state-of-the-art study by Bruno et al. (2018) but no algorithms for complete automatic modeling are available yet.

The building information model was created manually based on the point cloud model. Elements such as pavements and walls were created and aligned to the point cloud according to an acceptable approximation for the objectives of the research. The overlap of the point cloud with the geometrical model in the BIM modeling platform was very useful for a fast

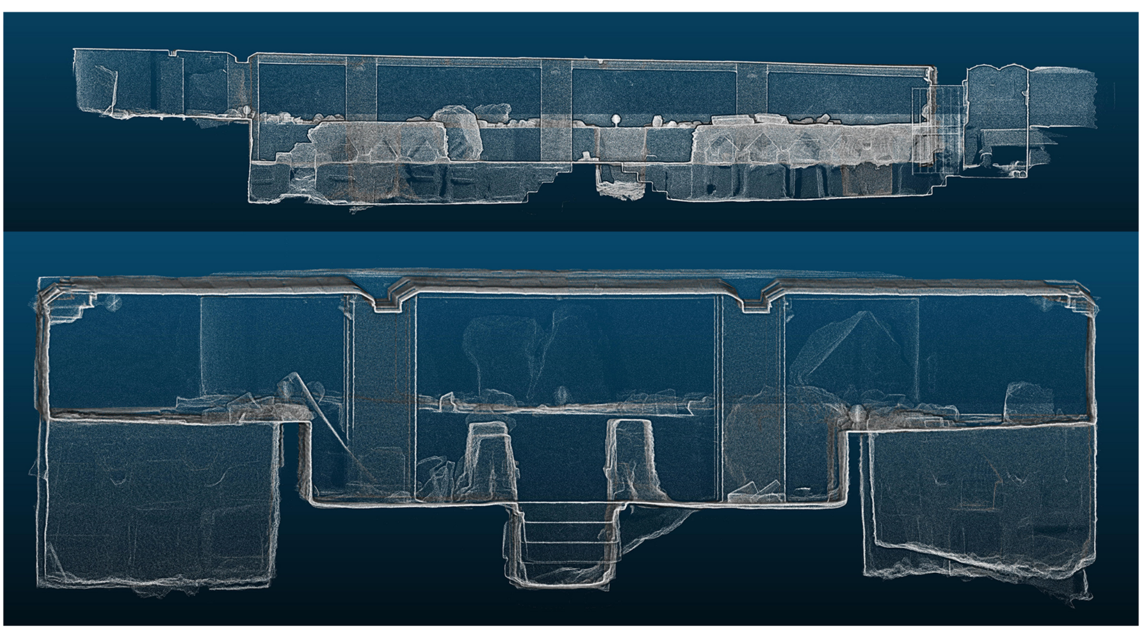

Fig. 9 Two section-views of the point cloud

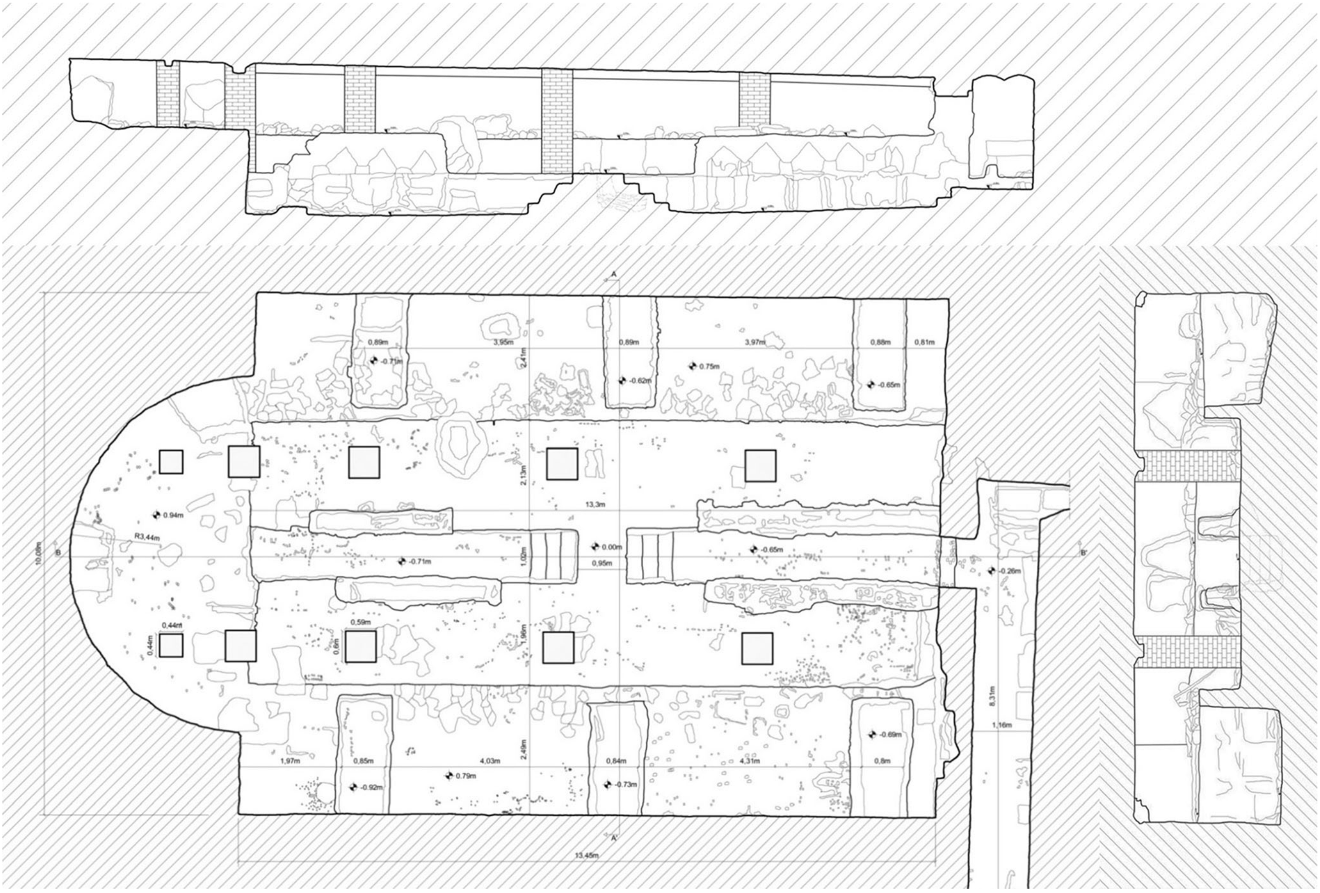

Fig. 10 The produced drawings based on the 3d scan of the hypogeum

construction and easy alignment of the objects to the point cloud (Fig. 12).

Based on the archeological information retrieved from archeological analysis, the model was detailed and enriched with attributes, and the walls were provided with layers in some cases. One of the walls was subdivided according to the visible finishing layer for an in-depth investigation. The use of such a heritage model is intended for the BIM representation where objects are semantically defined (Simeone and Cursi 2017).

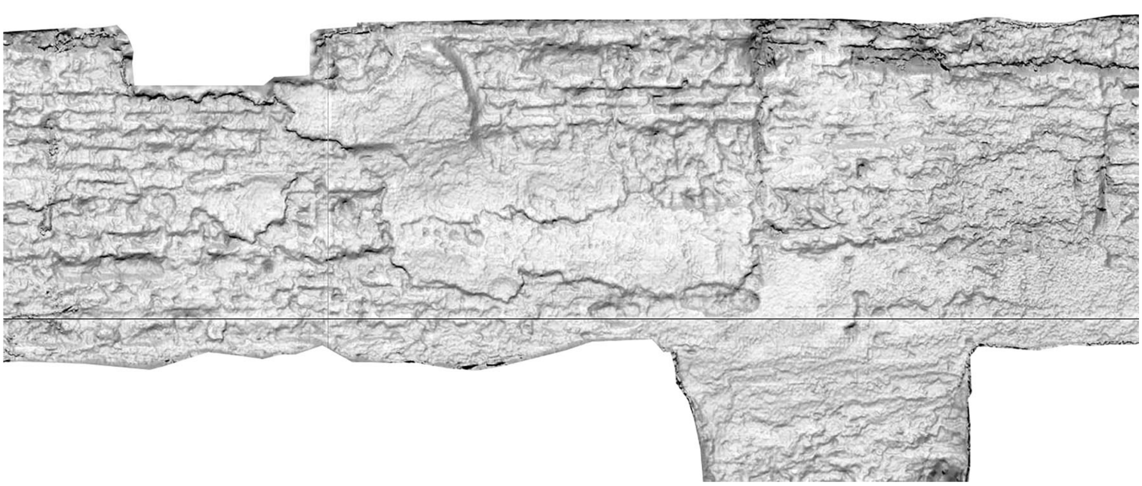

Fig. 11 Part of the north wall of the hypogeum—the conversion of a point cloud to a mesh helps the archeological analyses, which are based on the geometry. The high-resolution scans are used to create very detailed meshes

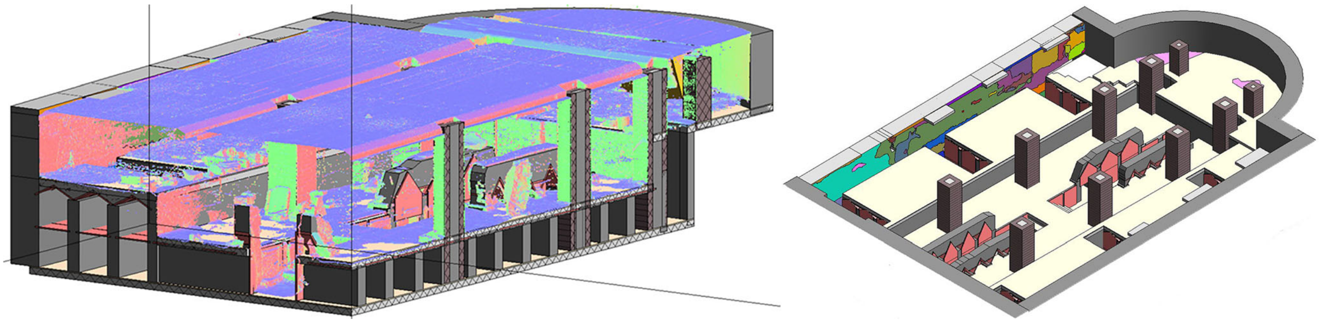

Fig. 12 Scan2BIM, the use of the point cloud within BIM software to produce a building information model, which is able to contain semantic classifications and information such as attributes regarding the historical analysis and additional information of the architectural elements. Left: overlapping point cloud model, right: the model where the northern wall is detailed according to different historical finishing layers

Conclusions

In this paper, we have presented the workflow of the 3D survey of an underground monument; more specifically, the oratory of Santa Silvia in San Saba. The substructure was only recovered in the early 1900s, and no documentation except for a graphical plan and section was available. The particular configuration of this monument, together with the requirements of the archeologist and art conservator, required accurate laser scanning and photographic documentation.

In an environment of about 100 mq, 20 scan stations, which work at a very close distance to the object, were necessary. Moreover, a high-precision network was established to align the scans and reference them in an external reference system. The first result of this survey were graphical detailed plans and section drawings, a BIM model and detailed meshes of parts of the hypogeum according to the art conservator's request. Further analysis of the point cloud about the intensity of reflection value of the scan will be conducted in order to detect the different materials used in different phases.

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