Chapter 9

Five-Dimensional (5D) Modelling of the Holy Aedicule of the Church of the Holy Sepulchre Through an Innovative and Interdisciplinary Approach

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Abstract The Church of the Holy Sepulchre (Church of the Resurrection) is one of the most important historical sites of Christianity. The current Aedicule structure is the result of various construction phases, damages and destructions, reconstructions, and protection interventions, and as such, it serves as an emblematic case study for five-dimensional (5D) modelling. The innovative and interdisciplinary approach adopted for the modelling of the Holy Aedicule of the Church of the Holy Sepulchre utilizes data from the following: (a) architectural documentation: Description of the current form and structure, as well as its evolution through the ages, based on historic documentation; (b) analysis of construction phases: The construction phases were revealed by a ground-penetrating radar (GPR) survey that was implemented within an integrated methodology, which enabled the technique to identify the various interfaces; (c) geometric documentation: Generation of a 3D

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high-resolution model, through an automated image-based method and through using terrestrial laser scanning; (d) materials documentation: A wide range of analytical and nondestructive techniques have been used in order to characterize the building materials and extract data for fusion in 5D modelling; and (e) 5D modelling: visualization of the historic construction phases of the Holy Aedicule of the Church of the Holy Sepulchre. The integrated modelling which, after the above analysis, includes enhanced information covering all aspects of the Aedicule structure, geometry, and materials and forms the basis for the creation of an innovative tool that induces mixed reality (MR) with the focus on the Aedicule's structural evolution (time factor—4D) and on its materials (5D).

Keywords Architectural • Geometric and materials documentation • 5D modelling and visualization

9.1 Introduction

The Church of the Holy Sepulchre (Church of the Resurrection) is one of the most important historical sites of Christianity. Within this Church, the Holy Aedicule is built, which contains the tomb of Jesus Christ. The current Aedicule structure is the result of various construction phases (Fig. 9.1), damages and destructions, reconstructions, and protection interventions [1–4].

The Church dates back to 325 AD, when Emperor Constantine I ordered the construction of a basilica incorporating the tomb of Jesus Christ, within the Holy Aedicule (Fig. 9.1a, by Theo Mitropoulos). The Holy Tomb was carved outside, possibly in a polygonal form, with an entrance on its eastern side (Fig. 9.1a, by Theo Mitropoulos), whereas the interior had a rectangular form and on its northern side the arcosolium. At the start of the seventh century, the exterior surfaces of the polygonal monolithic Aedicule were covered by marble plates, columns, and metal fences to protect it from visiting pilgrims.

The Church of the Holy Sepulchre was damaged by fire in 614 when the Persians invaded and destroyed Jerusalem. The Aedicule's exterior and interior surfaces and decorations were destroyed, including partial destruction of the burial chamber, along its east–west axis (Fig. 9.1b, by Theo Mitropoulos). In 622, Christians were allowed to rebuild churches and monasteries. Modestus, the abbot of the Monastery of St. Theodosius, rebuilt the Church of the Holy Sepulchre and destroyed parts along the east–west axis of the Aedicule which were restored with masonry (Fig. 9.1c, by Theo Mitropoulos). In 1009, the Caliph of Egypt Al-Hakim ordered the complete destruction of the church; the Holy Aedicule is destroyed down to ground level. During the reign of Constantine Monomachus, Patriarch Nikiforos persuaded the Emperor to offer money for the reconstruction of the Holy Sepulchre (1027–1048). Parts destroyed by Al-Hakim were restored with masonry, the Aedicule regaining its former Constantinean plan form, and its exterior surfaces covered with stone plates, enveloped by 12 columns (Fig. 9.1d, by Theo Mitropoulos).

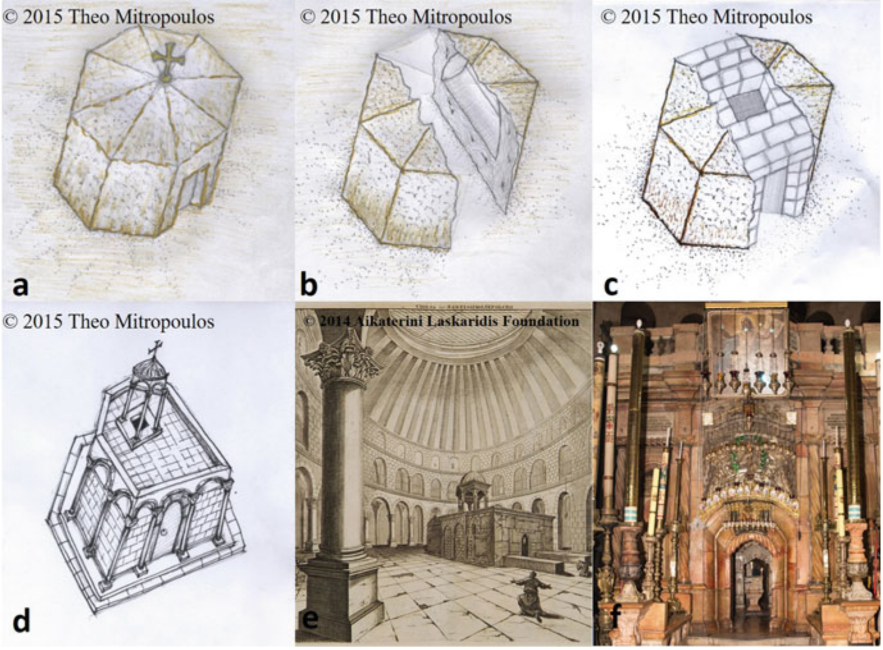

Fig. 9.1 The construction phases of the Holy Aedicule of the Church of the Holy Sepulchre throughout history (© 2014 Aikaterini Laskaridis Foundation, reprinted with permission—© 2015 Theo Mitropoulos, reprinted with permission)

After the arrival of the Crusaders (1099), the Church of the Holy Sepulchre was renovated in a Romanesque style and added a bell tower. A vestibule (Chapel of the Angel) was added at the eastern side of the Aedicule in 1119 (Fig. 9.1e, by Cornelis de Bruyn, 1714). Following various conquerors, Jerusalem fell in 1517 to the Ottoman Turks, who remained in control until 1917.

In 1808, an accidental fire became uncontrolled, which caused the dome of the Rotunda to collapse over the Aedicule, inflicting severe damage to it. According to historic sources [5], the Holy Tomb remained intact, but the Aedicule structure was heavily damaged and buried under the Rotunda dome ruins. After permission, the official architect Nikolaos Komnenos rebuilt the Aedicule in the contemporary Ottoman Baroque style, effectively embedding the remaining core of the burial chamber within the new, larger, Aedicule structure. The restored Church was inaugurated on 13 September 1810 and came into its present form (Fig. 9.1f, May 2015).

Since the 1810 reconstruction, in all external faces except the west end, the marble shell presents a strong buckling. By 1947, the deformation of the external construction of the Aedicule was already as intense as today, forcing the British authorities to take immediate measures in the form of an iron "frame" along the flanks, which through strong wooden wedges prevented any further outward movement of the stones already affected by the buckling mechanism. More recently, the

National Technical University of Athens, after invitation from His All Holiness, Beatitude Patriarch of Jerusalem and All Palestine, Theophilos III, signed a programmatic agreement with the Jerusalem Patriarchate and implemented an innovative research titled “Integrated Diagnostic Research and Strategic Planning for Materials, and Conservation Interventions, Reinforcement and Rehabilitation of the Holy Aedicule in Church of the Holy Sepulchre in Jerusalem”. Within this framework, an array of nondestructive techniques, in conjunction with materials characterization, and architectural and geometric documentation were performed to elucidate the construction phases of the Holy Aedicule, the materials they are composed of, to assess the preservation state of the Aedicule, and to provide basic layering information for the assessment of its current state against static and seismic loads.

9.2 Interdisciplinary Approach: Study Overview

The innovative and interdisciplinary approach adopted to enable 5D modelling of the Holy Aedicule of the Church of the Holy Sepulchre utilizes information and data from the following:

- *Architectural documentation*: Description of the current form and structure, as well as its evolution throughout the ages, based on historic documentation.
- *Analysis of construction phases*: The construction phases were revealed by a ground-penetrating radar in situ survey, implemented within an integrated methodology, which enabled the technique to identify the various interfaces.
- *Geometric documentation*: Generation of a 3D high-resolution model, through an automated image-based method and through using terrestrial laser scanning. The 3D representation of the results of the prospection with GPR for the internal structure of the Holy Aedicule was considered highly useful as it actually enables the 5D representation of the historic construction phases.
- *Materials documentation*: A wide range of nondestructive and laboratory (Analytical) techniques were used for the assessment of the condition and the characterization of the various building materials of the holy monument.
- *5D modelling*: To enable the potential for a 4D modelling, the time factor has to be accounted for, suggesting the historic construction phases of the holy monument. The aforementioned architectural documentation could provide such data validated by the analysis of the construction phases and the geometric documentation. Data fusion from material documentation and characterization will eventually enable 5D modelling.

The typical 3D model is, thus, enriched by the fusion of information from various disciplines, i.e., architecture, civil, surveying, and chemical engineering.

Within this framework, the gamification approach could be adopted transforming the above 5D model into an emblematic case study for smart educational and heritage applications.

9.3 Architectural Form and Structure of the Holy Aedicule

The present form of the Holy Sepulchre, which exists without alterations since 1810, is a result of repair and restoration of the earlier building after the catastrophic fire of 1808. The exact form of the earlier building, also a result of a restoration of an even earlier form, which is closer to the initial form surrounding the Holy Grave Rock, appears in 1609 drawings together with a brief description, a citation on the dimensions and notes [6].

For a better understanding of the structural connection of the new construction with the previous one, Prof. M. Korres, based on newer drawings (made by the National Technical University of Athens), on the ones of 1609, and on his own measurements and observations, composed Fig. 9.2 depicting the present form, the earlier latent construction enveloped by the present building's exterior masonry, and the area of possible existence of the Holy Grave Rock inside the latter.

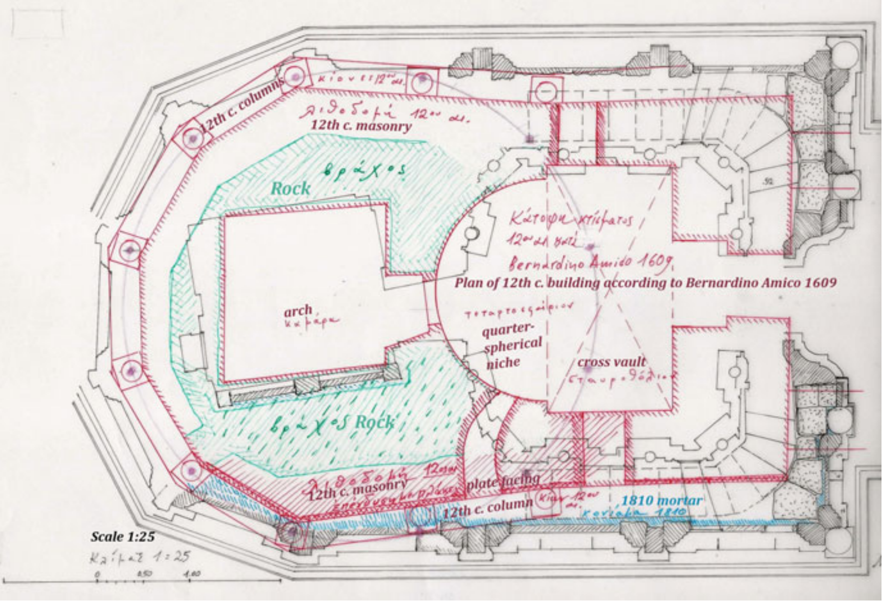

Fig. 9.2 Holy Aedicule, depicting: (a) the present form (*black color*), (b) the earlier latent construction (*red color*) enveloped by the present building's exterior masonry, (c) the potential extent of the Holy Rock (*green color*) inside the Aedicule structure [5]

In the earlier building, the western part, which was polygonal as it is on the present building, instead of being exactly semicircular, was shaped like a horseshoe, and, therefore, it was wider than the other part toward the east. Nevertheless, the sides of the polygon corresponded to 30° arcs, and the columns that existed before them stepped on a circular arc's spokes, on 15°, 45°, and 75° positions north and south of the western semi-axis of the building. To put it in another way, if the aforementioned shape was not interrupted by the east projecting part, it would be a normal dodecagon. In any case, the horseshoe-like form of the building must have been perceived as a result of a merger of a dodecagon and a parallelogram with a west front markedly narrower than the diameter of the dodecagon. So it is most likely that this form was really a product of the attachment of a vestibule in a first regular dodecagon building with columns standing before each of its corners.

Obviously, such a dodecagon cannot be other than the primary dodecagon around the Holy Grave according to the historical tradition. In that initial state, the solid mass behind the 12 columns must have been the carved rock and not surrounding masonry. The lining of the rock with masonry has given the whole, at least externally, the appearance of a building made entirely of hewn stones.

During the drastic overhaul of the building, that is, its extension toward the east, with the result that only the western part remained from the original full dodecagon, a canopy (initially dodeka style) was erected on its roof, almost above the site of the burial chamber, obviously in symbolic accordance to the original form and, in any case, to protect the Holy Sepulchre from the rain falling through the open-air oculus of the dome.

During the 1808 fire, the Holy Sepulchre must have been subjected to a combination of damages, not only because of the violent fall of massive components of the giant wooden dome but also from the thermal attack on the stone, given the combustion of so much material. Obviously, the recovery of the form that existed before the fire was not possible, nor desirable, since, in order to reinforce the construction, very thick new masonry would need to be added almost everywhere externally, and that would drastically alter the original dimensions of the building. Kalfas Komnenos preserved the initial general composition—a dimer internal, a polygonal western end, a circular canopy on the roof—and the repetition of the original external modulation with pilasters or columns that were bearing arches rhythmically projecting from the wall studs. He also used architectural rhythmical elements of his time. He decided to enrich the interior with a drastic enlargement of the vestibule, an increase in the height of the domes, and proper conformation of the surfaces, using rhythmical elements coherent to those on the exterior but, in any case, finer. He apparently pursued some metric proportions to ensure an academic–numerological perfection of the architectural composition and of a certain symbolism: The bulk of the building, that is, without the base and the parapet, has a length of 8.325 m, width of 5.55 m, and height of also 5.55 m. The simple arithmetic connection 2:2:3 of these dimensions is an essential part of the whole architectural concept.

The enlargement of the Aedicule regarding its exterior dimensions, the enlargement of the Chapel of the Angel regarding its interior dimensions, and the reorientation and enlargement of the burial chamber were accomplished by adding new masonry to the exterior of the surviving Crusader building phase one. This would necessitate removal of any surviving lining stones from the previous construction period and carving of the surviving masonry wherever required. Obviously, at elevated heights the masonry would be entirely new, since the previous Aedicule was lower than the newer one and had sustained significant damage due to the fire. In addition, he performed carving of the surviving old masonry, wherever its thickness justified such a laborious approach, to enlarge the interior space. The coexistence of old and new masonries at the interior and exterior of the Aedicule is verified by the ground-penetrating radar prospection of the structure.

9.4 Analysis of the Construction Phases

Ground-penetrating radar (GPR) is an established nondestructive electromagnetic technique that can locate objects or interfaces within a structure. GPR was utilized in order to reveal information about the interior structure of the Aedicule, i.e., the interior layers of its masonries, as well as the assessment of their preservation state and cohesion, in conjunction with macroscopic deformations.

The GPR survey was implemented within an integrated methodology, which was based on the preceding three steps (architectural documentation, geometric documentation, materials characterization) of the overall innovative and interdisciplinary approach, and followed a carefully designed survey matrix, to ensure that the main aims of the GPR survey were achieved without the need for excessively extensive measurements that would distract the religious functions of the Aedicule.

The ground-penetrating radar system used in this survey was a MALÅ Geoscience ProEx system with 1.6 and 2.3 GHz antennae. The MALÅ Geoscience GroundVision 2 software was used for data acquisition. The GPR scans were processed with the MALÅ Geoscience RadExplorer v.1.41 software after application of the following filters: DC removal, time-zero adjustment, amplitude correction, and band-pass filtering. The application of filters enhanced weak peaks and layers that were not readily identifiable in a nonprocessed radargram. The scan after its processing with the aforementioned filters still remains a distance–time graph. The horizontal axis corresponds to the displacement of the antenna over the surveyed surface, whereas the vertical axis of the graph corresponds to the time elapsed between the moment the electromagnetic pulse is emitted from the antenna on the surface, its diffusion within the masonry, its encounter with an interface of materials of different electrical properties, its partial reflection toward the exterior surface, and its detection by the receiver antenna. For the conversion of the scan into a two-dimensional section distance and depth (X axis versus Depth $-$ Z axis), the calculation of the pulse velocities throughout all observed layers is required. Stone blocks of the parapet at the roof and a stone block from the seat outside the entrance to the Aedicule were used as standards to calibrate the pulse velocities for the GPR analysis. Thus, the velocities and dielectric constants were calculated and used in the velocity models of the remaining areas, representing the exterior stone panels and the Holy Rock, as they have a similar synthesis. Based on this calibration, a velocity of $v = 11.58$ cm/ns ($\sigma = 1.02$ cm/ns) was calculated, which corresponds well with that of similar materials of the bell tower of the Church of the Holy Sepulchre [7].

The pulse velocity of the Komnenos construction phase was calculated by adjusting the velocity model in the southern masonry of the Chapel of the Angel, so that the thickness of the masonry measured by a georadar coincides with the actual one. The pulse velocity of the Crusader building phase was calculated by comparing scans from the exterior and the interior and optimizing the velocity model so that common targets coincide spatially. Figure 9.3 presents in a descriptive approach the various layers within the Aedicule structure, as analyzed by GPR. Figure 9.3 is based on Fig. 9.2 and retains the plan of the current structure and the exterior boundary of the eleventh/twelfth-century building (red outlines). The BN3 plane and the longitudinal axis conceptually define the four quadrants A1–A4.

Starting from the southwest quadrant of the Aedicule, and analyzing with the aforementioned methodology, the following internal interfaces were revealed: (a) exterior panel, (b) Kalfas Komnenos construction phase, (c) Crusader construction phase, (d) the Holy Rock, (e) masonry between the Holy Rock and interior

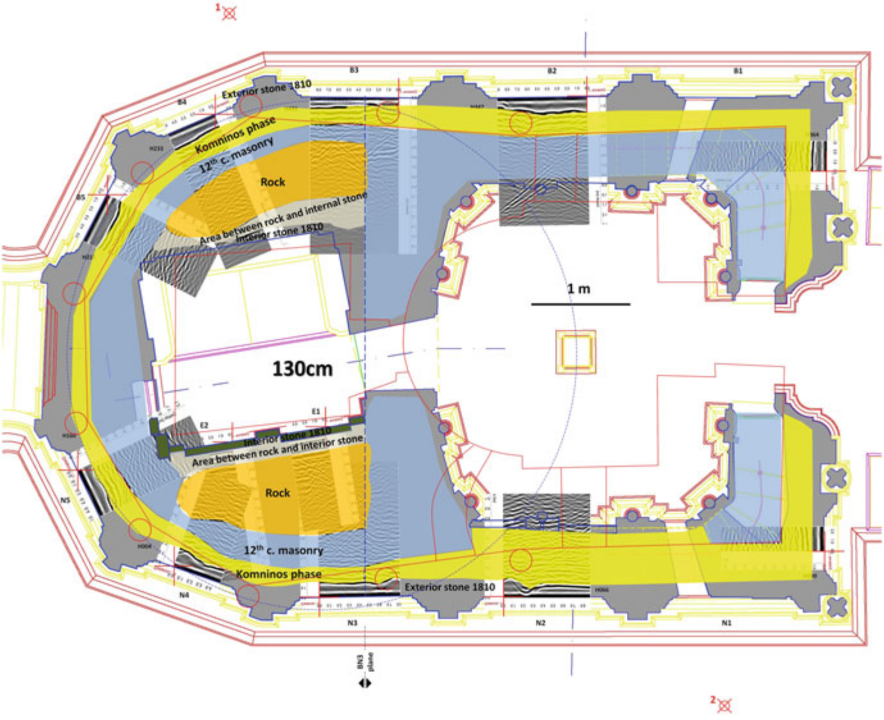

Fig. 9.3 Layering within the Holy Aedicule (cross section at height level 130 cm) as identified by the GPR analysis [5]

panel, and (f) interior panel. The exterior panel has a varying thickness of 10–15 cm. Moving toward the interior, an interface is observed at a depth of 30–40 cm. The layer between the exterior panel and this interface corresponds to the Kalfas Komnenos construction phase and is indicated in Fig. 9.3 as a yellow-colored zone. Moving further toward the interior, the GPR scans reveal the presence of a second interface, at a depth of approximately 50–60 cm. The layer between the red dashed curve—internal boundary of the Komnenos construction phase—and this second interface corresponds to the twelfth-century masonry, i.e., the Crusader construction phase.

The combined analysis of the horizontal and vertical GPR scans at the southern quadrant, both from the exterior (areas N3, N4, and N5) and from the interior (areas E1 and E2), allowed the per-height identification of the boundary of a third internal interface. The volume within this interface is theorized to correspond to the Holy Rock, after its consecutive carvings of its original volume. In Fig. 9.3, the Holy Rock is depicted as an orange-colored area. The GPR analysis shows that the Holy Rock possibly extends to a height of approximately 2 m. Above this height, the GPR scans indicate masonry, possibly constructed after the 1808 fire, although parts of the twelfth-century constructions could not be excluded from being present. Scanning of the interior of the Holy Tomb, it is estimated that the interior panels at areas E1 and E2 have a thickness of 5–6 cm. The area between the Holy Rock and the E1 and E2 panels appears to be masonry with an average stone size of approximately 10 cm.

A systematic differentiation of the horizontal scans in area B3 is observed on a vertical plane BN3 (indicated with a blue dashed line in Fig. 9.3, which is perpendicular to the longitudinal axis of the Aedicule intersecting areas B3 and N3 at their mid-axis. To the west side of this BN3 plane, the construction layers are those described above. To the east side of this plane, the revealed layering is interrupted in respect to its western continuity, regarding the layer corresponding to the twelfth-century masonry, since reflections from the parts of the scans that belong to quadrants of the Chapel of the Angel are present in different depths. The analysis leads to the theorization that to the east side of plane BN3, the structure consists only of masonry, without any rock volume being present in this area. Possibly the interior of the semicircular niche is the result of deep carving and supplementation with a new masonry, so that the area around the entrance to the Holy Tomb obtained its new geometry.

At the Chapel of the Angel, GPR indicates parts of the northern side and the eastern side of the Crusaders' masonry were retained (Fig. 9.3). Deep carving was performed to their interior to facilitate the northward expansion of the Chapel. The old wall was retained—on the north part of the Chapel of the Angel—probably to the full length of the Chapel, up to the façade area [5]. The retained height is probably approximately up to 1.5 m above the interior floor level, corresponding to the height of the entrance of the northern staircase and its first three steps. Above that height, the masonry is most probably entirely new, constructed during the 1810 restoration works. Correspondingly, at the southern part of the Chapel of the Angel, the GPR analysis indicates that retaining of the Crusaders' masonry phase occurs only at the southeastern corner (Fig. 9.3), up to a height similar to the one on the northeastern corner.

9.5 Geometric Documentation

The geometric documentation carried out produced a 3D high-resolution model, through the combination of automated image-based method and using terrestrial laser scanning. Using the final model, it was possible (i) to extract the eventually necessary conventional two-dimensional products, such as, e.g., horizontal and vertical sections, and facades; (ii) to produce suitable visualizations for the support and design of the restoration interventions; and (iii) to virtually visualize the internal structure of the Holy Aedicule in three dimensions.

9.5.1 Data Acquisition

All current measurements and works were based on the important past efforts for the geometric documentation of the Church of the Holy Sepulchre and the Holy Aedicule [8–14].

This present geometric documentation aims at the production of the necessary base material on which the structural and material prospection studies will be based. For the needs of this documentation, it was decided to produce a high-resolution three-dimensional model and to perform specialized highly accurate geodetic measurements for the production of conventional 2D base material on the one hand and for the documentation of the deformations and deviations of the construction today on the other. Due to the peculiarities of the object of interest, and the crowds of pilgrims always present inside and around the Aedicule, most of the works for the data acquisition took place after the closure of the Church. The methodology implemented for the production of the above-described products applied the most contemporary geomatic techniques and specialized instrumentation. Briefly, an automated 3D-imaging methodology based on high-resolution digital images, terrestrial laser scanning, and high accuracy geodetic measurements were implemented.

For the image-based approach, digital image sequences from varying distances were collected using a calibrated professional Canon EOS-1Ds Mark III full-frame CMOS digital camera with 21MP resolution (5616 × 3744 pixels) and 6.4 μm pixel size, aiming to reconstruct the 3D scene of the Holy Aedicule through structure from motion (SfM) and dense image matching (DIM) techniques. These techniques are the state of the art in reconstructing 3D scenes and offer high reliability and high accuracy as a cost- and time-effective alternative to the use of scanners. For this purpose, different lenses with a varying focal length (16, 50, 135, and 300 mm) were used. The image acquisition took place under low natural lighting conditions and during the night, exploiting the existing artificial lighting. No additional light sources were used (flash, studio flash, etc.). Therefore, the use of a photographic tripod was necessary since in some cases, the exposure time was up to 30 s. A total of 3,757 images were captured requiring up to 59.3 GB of hard drive space. However, a selection process was applied in order to ensure a highly accurate result according to the requirements of the study and the significance of the object. Finally, distances were accurately measured on the Holy Aedicule in order to scale the final 3D model. Problems in the acquisition processes such as lighting conditions and camera-to-object relative positioning as well as difficulties in the alignment step and mesh optimization are also encountered without reducing the accuracy of the final results. These problems included, among others, the large distances between the object and the camera, the poor or inadequate lighting, the continuous population of the area by pilgrims, and the smoke from the candles, which create faded areas on the images or unpredictable optical deformations due to the refraction effect caused by the temperature difference in the air.

In addition, laser scanning was also employed, in order to cover the areas where image acquisition was impossible, e.g., the dark and smoked interiors of the two domes of the Holy Aedicule and the two staircases leading to the construction's roof. The two techniques act complementarily to each other. For this procedure the terrestrial laser scanner FARO 3D X 330 was chosen as it is a lightweight third-generation scanner, which uses the phase-shift method for measuring distance. It has the ability of collecting 1 million points per second with an accuracy of 2–3 mm in its space position. It can record points 360° around the vertical axis and 300° around the horizontal axis. For the complete coverage of the Holy Aedicule, special scanning strategy was designed, in order to avoid gaps in the point clouds on one hand and to record all necessary details on the other. For that purpose, it was necessary to acquire overlapping scans from different scan positions. In total, 58 scans were needed, of which 13 were around the Holy Aedicule, 8 on top of its roof, 8 in the two staircases, 10 from the Rotunda gallery, and 19 on the inside. The total number of points collected was 65 million for the outside and 42 million for the inside.

The density of the scans was selected to 1 point every 5 mm, in order to record all fine details, even those necessary at a later stage. The time required for each scan varied depending on the distance of the scanner to the object, a fact which differentiates the total number of points necessary. In any case, the time for each scan was not more than a few minutes.

9.5.2 Data Processing and Results

The creation of the final accurate three-dimensional model from the digital images is a complicated procedure requiring large computation cost and human effort. It includes the already mentioned collection of geometric data in limited space and time, the selection of the images, the 3D point cloud extraction, the creation of the surface, the noise filtering, and the merging of individual surfaces. It is important to note that in such cases, the detail of the surface is very important; thus the noise filtering must be a carefully implemented procedure. The initial data were processed using various software packages in order to produce the final accurate 3D model of the Holy Aedicule. After careful selection of the necessary images and the creation of thematic folders, the radiometric correction of the imagery took place aiming at their quality improvement by minimizing the effects of the shadows and dark areas. Then, the images are imported into the software that implements SfM and DIM techniques. Subsequently, the dense point cloud is exported and imported into another software package in order to be subjected to a time-consuming process for removing outliers. Finally, the processed point clouds are merged and exported again in order to be scaled. The SfM technique for the orientation of the images and the 3D point cloud extraction procedure were realized through the use of Agisoft's PhotoScan® software, which has been extensively evaluated for increased accuracy in prior research internationally and also of the Laboratory of Photogrammetry [12].

For the full coverage of the Holy Aedicule and the creation of a complete 3D model, images were captured from many different locations. It is important to note that for every part of the 3D model, the sparse point clouds consist of 10,000–60,000 points. After an inspection of the alignment results, the generation of the dense point cloud model took place. At this stage, the Agisoft PhotoScan® algorithms, based on the estimated camera positions, calculate depth information for each camera to be combined into a single dense point cloud. It is noted that the dense point cloud of each part of the 3D model of the Holy Aedicule consists of about 35,000,000 points and the entire model of about 280,000,000 points. At this stage the color is attributed to each point based on the images where it appears. In Fig. 9.4, upper left, the outside colored point cloud of the Holy Aedicule is presented.

The processing of the Holy Aedicule point cloud was realized within the Geomagic Studio®, MeshLab®, and CloudCompare® software. To sort out the outliers, several filtering algorithms were applied using various software packages [Geomagic Studio, MeshLab, and Cloud Compare (CC)]. In addition, algorithms were applied in order to make the point cloud uniform in terms of point spacing and to reduce its density. Finally, the processed dense point clouds are wrapped into meshes. Figure 9.4 upper right illustrates the part of the 3D model of the dome, which is one of the more complex parts of the Holy Aedicule. Through the created 3D model, it is possible to identify vulnerable and destroyed areas of the Holy Aedicule with no physical access to them.

The laser scanner data were thoroughly examined for their completeness in situ, i.e., before the departure of the team from Jerusalem. For that purpose, test registrations of the point clouds were performed in order to establish this possibility on one hand and their completeness on the other. After these tests, additional scans were required sometimes from very unconventional scan positions.

The final point cloud registration was performed in the Laboratory of Photogrammetry of NTUA. As the volume of data was huge, it was decided to perform

Fig. 9.4 *Upper left* The colored point cloud of the Holy Aedicule. *Upper right* The 3D model of the dome textured. *Lower* Part of the registered point clouds inside the Holy Aedicule [5]

the registration separately for the inside and outside parts of the Holy Aedicule. For the point cloud registration, at least three points are required. This role was undertaken by the special targets, whose coordinates in the common reference system were carefully determined. Hence after registration the point clouds were also referenced to the common system. The accuracy achieved for the registrations was of the order of 2–3 mm. In Fig. 9.4 *lower*, a sample of the registered point clouds is shown.

For registering and georeferencing the three-dimensional models of the Holy Aedicule which were produced with the methods described to the common reference system, specially targeted points were put in suitable positions on the inside and outside of the Holy Aedicule and also in the surrounding area. In total 38 control points were used.

9.5.3 Inserting GPR in 3D

The 3D representation of the results of the nondestructive prospection with GPR for the internal structure of the Holy Aedicule was considered highly useful as it actually enables the 5D representation of the historic construction phases. For the creation of this innovative 3D model of the internal structure of the Holy Aedicule, as this was interpreted from the GPR data, an interdisciplinary scientific methodology was developed. The methodology applied was specially designed and adapted for this specific application, as it has not been implemented in this way in the past. Finally, the 3D surface model created was incorporated into the existing high-resolution 3D model of the interior of the Holy Aedicule, where its position in relation to the reference system and also to the various details was established. This initial innovative step toward the relation of the GPR data and high-resolution 3D models definitely enables the study of the Holy Aedicule and offers additional data to the experts. In addition, this related model verifies the precision and accuracy of the measurements and observations by the members of the interdisciplinary team.

The contribution of this 3D visualization and relation of the interpreted GPR measurements are very important for this study, as it represents the internal structure of the Holy Aedicule, which is not directly visible. The main aim is to enable the advanced interpretation of the initial GPR observations from the experts and the feeding of the structural study with this invaluable information. For the creation of this innovative 3D model of the internal structure of the Holy Aedicule, as this was interpreted from the GPR data, an interdisciplinary scientific methodology was developed. The boundary lines of the various materials detected were available in 2D sections at 23 known elevations in the form of JPG images. They covered the Holy Aedicule from a height of 0.3 m up to 2.9 m from the internal floor. It was foreseen that these sections had at least two points of reference, which were determined in the common reference system. In this way their georeference was enabled and also they were directly related to the 3D model.

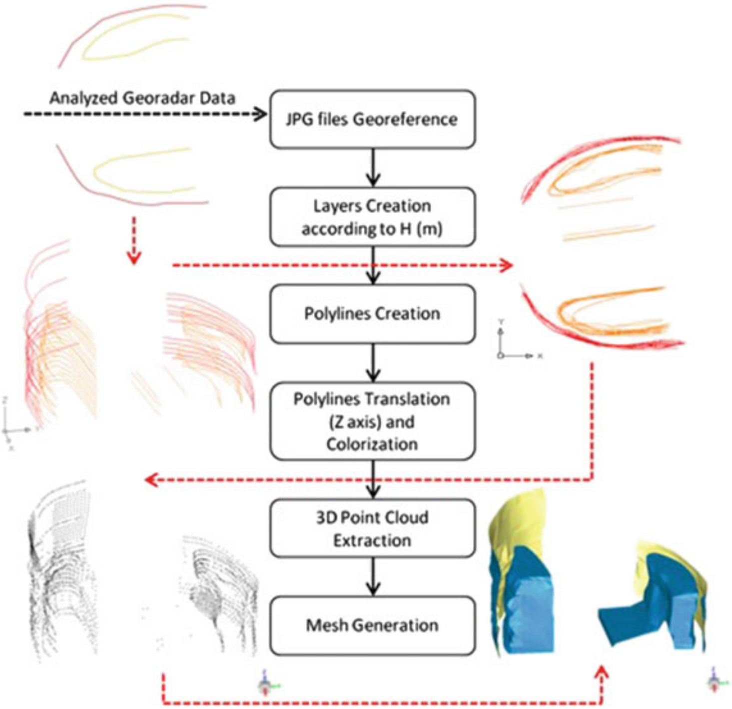

Fig. 9.5 Flowchart of the methodology developed for the creation of the 3D model of the internal structure of the Holy Aedicule

The methodology applied was specially designed and adapted for this specific application, as it has not been implemented in this way in the past (Fig. 9.5). Initially the 23 images of the 2D sections of GPR were georeferenced. Subsequently they were placed in various layers according to their height attribute. They would contain the digitized border lines/2D sections.

Afterward, each of these lines was transferred to its own height. In this way the 2D information was converted to 3D. Then points were extracted from the drawn polylines in a .txt file. This file was imported into a point cloud and surface processing software, where the desired surface is created and is subject to the final processing for its integration and completion with the help of careful interpolation (Fig. 9.6 left).

Finally, the 3D surface model created was incorporated to the existing high-resolution 3D model (Fig. 9.6 right) of the interior of the Holy Aedicule, where its position in relation to the reference system and also to the various details was established. This initial innovative step toward the relation of the GPR data and high-resolution 3D models definitely enables the study of the Holy Aedicule and offers additional data to the experts. In addition, this related model verifies the precision and accuracy of the measurements and observations by the members of

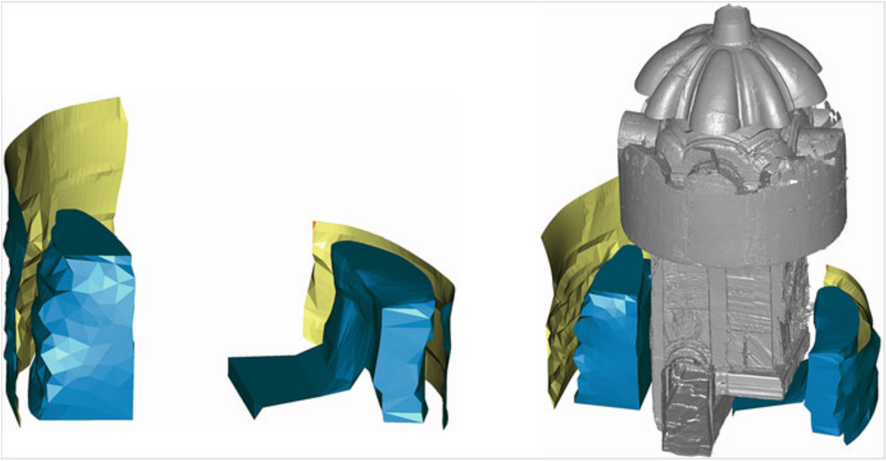

Fig. 9.6 *Left* 3D visualization of the prospection findings. *Right* The scanned 3D model (*gray*) integrated with the 3D GPR data

the interdisciplinary team. However, it needs further investigation, research, and development.

9.5.4 Visualizations from the 3D Model

From the three-dimensional model, it is possible to visualize the Holy Aedicule with simple procedures in order to better understand its structure and for the proposals for its restoration to be based on solid ground. In addition, the eventual restoration works can be better designed and programmed.

Initially a vertical section was implemented to the 3D model. This section appears in Fig. 9.7 left with texture. It should be noted that this texture is originating from the high-resolution images. Corresponding sections can be applied in any position and at any angle. Finally, in Fig. 9.7 *right* a horizontal section at a very low height is presented, in order to highlight the marvelous marble inlays of the Holy Aedicule floor set by the architect Komnenos.

9.6 Materials Characterization

Members of the Laboratory of Material Science and Engineering, School of Chemical Engineering NTUA, conducted an in situ diagnostic study for assessing the extent of material decay and the conservation state of the Holy Aedicule of the

Fig. 9.7 *Left* Visualization of a vertical section from the 3D model with texture. *Right* horizontal section of the 3D model where the floor is shown

Church of the Holy Sepulchre. The present section is part of the study under the title "*Materials & Conservation, Reinforcement and Rehabilitation Interventions in the Holy Edicule of the Holy Sepulchre*" [5].

A macroscopic observation survey over the Sacred Monument reveals the extent of certain deformation of the external facades of the Monument (Fig. 9.8), suggesting detachment of the façade building material from the internal substrate due to that buckling. These deformations could have a great impact on the Sacred Monument's static and dynamic correspondence to loads contributing in a negative way to its longevity. This is the reason why the cause of the effect has to be determined and reversed. To do so, first a nondestructive testing assessment of the materials' compatibility and condition took place making use of the infrared thermography and the fiber-optical microscopy.

In order to determine the materials' decay and the origination of this decay (causes), the need to study the building materials with laboratory techniques arises. Characterization of historic materials is subjected to sampling limitations imposed by the sensitive nature of built cultural heritage—in which the nondestructive techniques present a clear advantage over destructive analytical testing—and refers

Fig. 9.8 External facades deformations

to a range of analyses. In the present study, material characterization measurements will be utilized not only as data for the integrated 5D modelling but also for visualization purposes such as texturing and rendering of visual objects. In particular, optical microscopy measurements are processed and then used for texturing the mesh (UV Mapping) of the historic construction phases' 3D models (4D modelling). Additionally, nondestructive testing and material characterization measurements (infrared thermography, X-ray diffraction, mercury intrusion porosimetry) enable data fusion from heterogeneous datasets.

9.6.1 Sampling

In order to identify the causes behind the external marble masonry deformations, the building materials' preservation state has to be examined with laboratory techniques and make an evaluation of their decay, physical, chemical, and mechanical properties. The extracted samples (building materials: building stones, mortars, plasters) were collected from crucial parts around the Monument. Core samples were also extracted (Fig. 9.9), in order to ensure that building materials coming from all the historic construction phases of the Holy Monument would be included in the study.

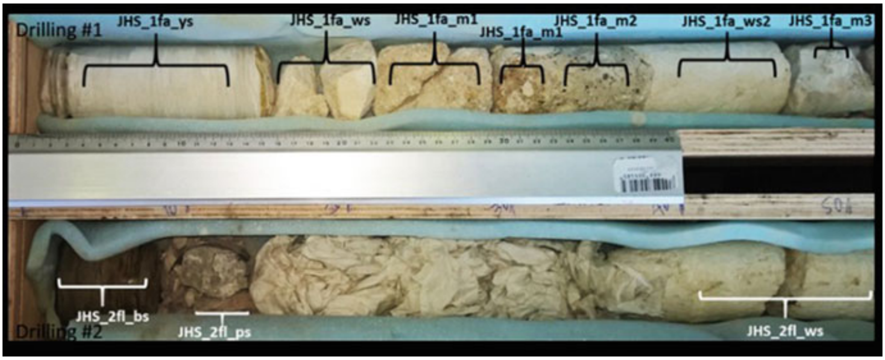

Fig. 9.9 *Upper* Façade core sample: Three building stones and three mortar samples. *Lower* Floor core sample: Three building stone samples

9.6.2 Nondestructive Testing

Infrared Thermography

Infrared thermography measurements were performed for the nondestructive inspection of the architectural surfaces of the Holy Aedicule of the Church of the Holy Sepulchre in order to collect data indicative to: the decay of the building materials, the physicochemical compatibility among each other by identifying defective areas, the presence of nonvisible components inside a wall, and the presence of moisture and the study of its transportation mechanisms. The particular method-technique records the infrared radiation emitted from the testing materials providing their thermal radiation map, which is associated with the microstructure and their surface morphology. The thermal variations of the testing material are recorded and rendered where the different colors correspond to different temperatures.

From the examination of the south façade of the Holy Aedicule, it is verified that the long intervals of the pilgrims burning candles cause strong thermal stresses to the building stone of the façade, apart from the obvious esthetic degradation, due to accumulation of soot and oil deposits. This can be deduced from the higher temperature by 1.5 °C of the building stones neighboring the flame of the candle (Fig. 9.10). The anisotropic heat distribution over the surface of the building stone and subsequently in the deeper layers of the wall via the mechanism of heat induction and the maintenance of that temperature difference at least by 0.5 °C 3 h after burning the candles out proves the topical thermal heterogeneity. The aforementioned action taking place on a daily basis causes corresponding changes in the thermo-hygrometric behavior of the building materials in the masonry, accelerating their deterioration.

Fiber-Optical Microscopy

Fiber optic microscope (FOM) is a nondestructive microscope that can be utilized in situ to acquire magnified, visible-spectrum images. FOM is a microscope system

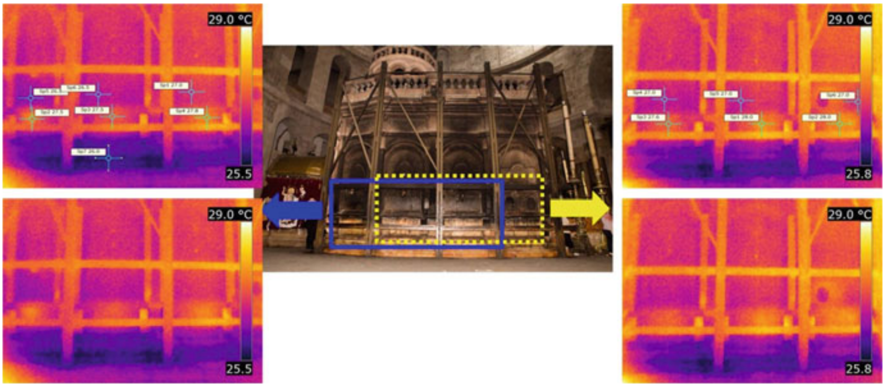

Fig. 9.10 IR-thermal inspection of the south façade of the Holy Aedicule of the Church of the Holy Sepulchre

integrating advanced optics, fiber optics, and digital components. Whereas in traditional optical microscopy a sample is required to be placed at the microscope, with FOM, no sampling is required, and the image can be acquired in situ. In the field of cultural heritage protection, FOM is employed to identify differences in the texture and composition of surfaces, for materials classification (e.g., classifications of mortars) and for the study of the decay phenomena (alveolation, hard carbonate crust, etc.); to investigate the materials' surface morphology; to identify defects in historic building materials, for material characterization; to classify decay typologies for porous stones; to evaluate cleaning interventions, consolidation interventions, and incompatible interventions; and to study the preservation state of mosaics.

A part of the Holy Rock of Golgotha coming from the core sample illustrated in Fig. 9.9, is examined through Optical Microscopy, as illustrated in Fig. 9.11. Macroscopically, has off-white color with visible craters all over its range. The examination with the polarizing microscope (Fig. 9.11 *lower left*) reveals opaque metallic minerals which probably are ferric (Fe) oxides and hydroxides as suggested by the off-orange color revealed from the fiber optical microscope measurements in the same figure.

9.6.3 Laboratory Techniques: Petrographic and Mineralogical Characterization

In order to determine the origin, the micro-texture, and structure of the rocks, the optical mineralogy analysis in thin section is equipped. From the XRD examination (Fig. 9.12, left) of the same sample, it is slightly bituminous and mainly consists of micrite calcite at approximately 98 %. Opaque metallic minerals are also found, as shown from the polarized microscope measurement in Fig. 9.11, which are iron oxides

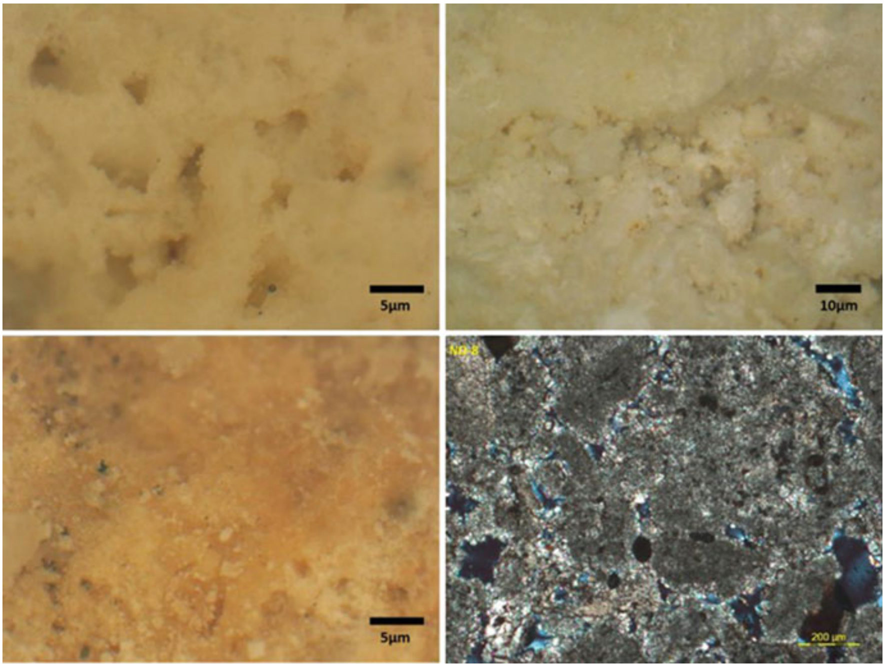

Fig. 9.11 *Upper* and *lower left* Microscope fiber optic measurements using lens 50× (scale 10 μm) and lens 120× (scale 5 μm). *Lower right* Polarizing microscope measurement

at <2 %. This sample is characterized as a micritic limestone. The pore size distribution, as determined from the microstructural analysis with mercury intrusion porosimetry, is presented in Fig. 9.12, right. From the microstructural analysis for the same sample, the measured characteristics were: Specific surface area is 0.256 m^2/g, total porosity 22.37 %, average pore radius 0.005 μm, and bulk density 3.08 g/cm^3.

9.7 Five-Dimensional (5D) Modelling of the Historic Construction Phases

Based upon the sketches of Fig. 9.1 coming from the historic documentation of the Holy Aedicule provided by the Architect of the Technical Service of the Jerusalem Patriarchate, Dr. T. Mitropoulos [2], the visualization of the first two construction phases of the Holy Aedicule has been realized with the open-source computer graphics software Blender. According to the historic documentation, the Holy Tomb was carved outside, possibly in a polygonal form, with an entrance on its eastern side (Fig. 9.1a). In order to represent the real texture of the Holy Tomb, FOM measurements from the Holy Rock of Golgotha sample (Fig. 9.7) were processed and used to create a new "virtual material" within Blender. The mesh

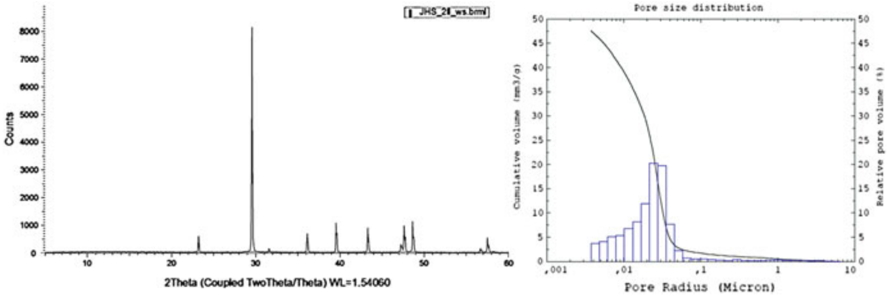

Fig. 9.12 *Left* XRD pattern. *Right* Pore size distribution

Fig. 9.13 The Holy Aedicule—two construction phases (*left* and *right* models) and the demolished state in the *middle*

of the 3D model was unwrapped and the UV mapping of the mesh polygons based upon the “virtual material” previously constructed. The rendered result of the first construction-phase textured 3D model is illustrated in the left part of Fig. 9.13. In order to texture the demolished (by the Persians Fig. 9.1b) part of the Holy Tomb, another processed FOM measurement from a cracked section of the sample used to create one more “virtual material” for texturing the specific area of the rendered 3D model as illustrated in the middle part of Fig. 9.13. Due to the fact that there are no documented information for the masonry building materials (stones and mortars) from the Modestus reconstruction phase (Fig. 9.1a), a random masonry material has been used for texturing the reconstructed masonry as presented (rendered) in the right part of Fig. 9.13. In conclussion, 3D visualization of the first and the second construction phases of the Holy Tomb has enabled the 4D modelling, whereas material data fusion (i.e. texture), realize the 5D modelling.

The 3D models representing the historic phases have been fitted upon the dimensions of the real Holy Rock of Golgotha as they are illustrated in Fig. 9.14. Based on the analysis presented at the end of the previous chapter, the interpolation of the

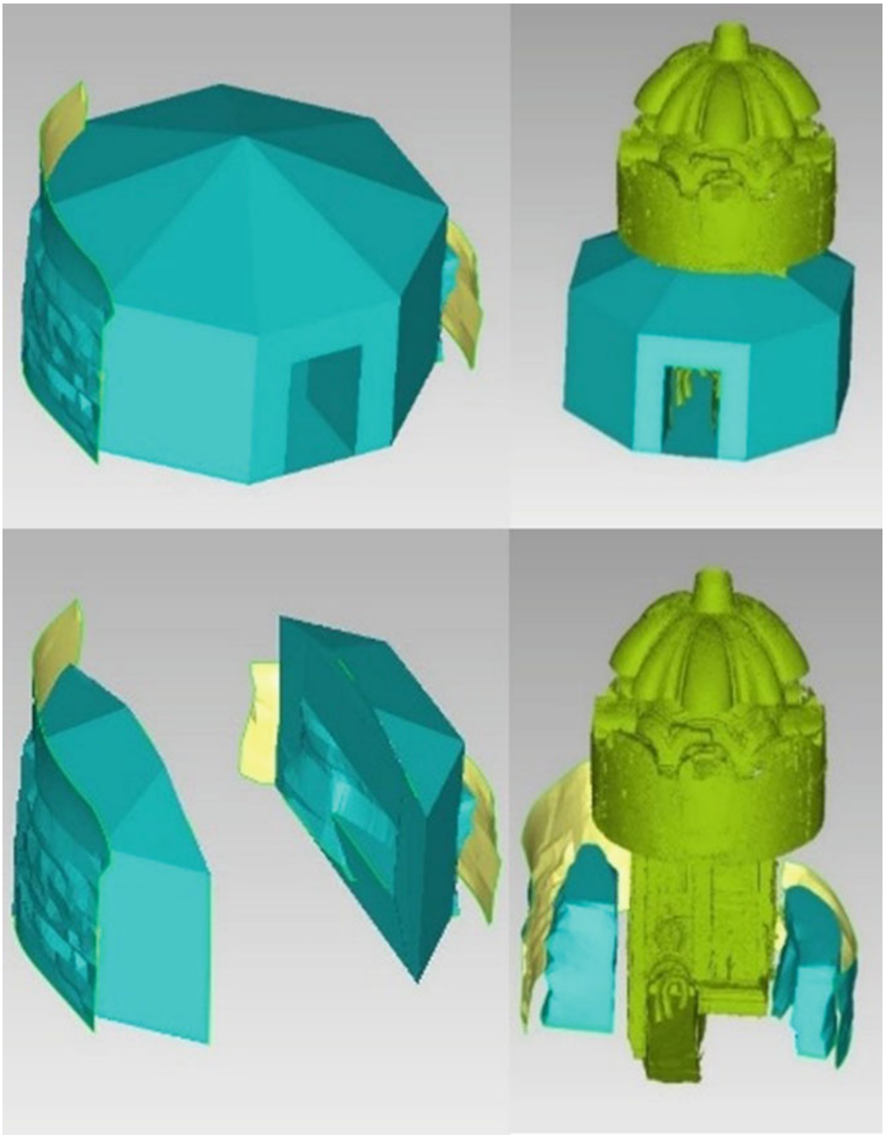

Fig. 9.14 Fitting the 3D models in the real dimensions as estimated by the GPR measurements

GPR measurements in different heights gave an estimation of the real dimensions of the Holy Rock of Golgotha volume over which the historic construction-phase 3D models were adjusted.

The work presented so far contains enhanced information covering all aspects of the Aedicule structure and forms the basis for the creation of an innovative tool that induces mixed reality (MR) with the focus on the Aedicule's structural evolution (time factor—4D) and on its materials (5D). The typical 3D model is, thus, enriched by the fusion of information from various disciplines, i.e., architecture, civil, surveying, and chemical engineering. Within this context, gamification approach can be adopted that can transform the above 5D model into an emblematic case study for smart educational and heritage applications.

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