

5D Model of the Holy Aedicule of the Church of the Holy Sepulchre through an innovative and interdisciplinary approach.

Prof. A. Moropoulou
*Laboratory of Materials Science
and Engineering, School of
Chemical Engineering, NTUA*

**Assist. Prof. A. Mpakolas,
Dr. E. Delegou,
Dr. K. Lampropoulos,
Dr. P. Moundoulas†,
PhD Cand. Emm. Alexakis,
PhD Cand. M. Apostolopoulou**

Prof. A. Georgopoulos
*Laboratory of
Photogrammetry, School
of Rural and Surveying
Engineering, NTUA*

**Assoc. Prof. E. Lambrou,
Assoc. Prof. G. Pantazis,
PhD Cand. P. Agrafiotis,
Eng. L. Kotoula,
Eng. A. Papadaki**

em. Prof. M. Korres
*School of Architecture,
NTUA*

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, damages and destructions, reconstructions and protection interventions, and as such, it serves as an emblematic case study for the creation of a 5D model.

The site, where the current church is built, has been used as a quarry since Iron Age and in the early first century AD was being used for burials [1 – 4]. During the Jewish-Christian period (AD 33-135), no large Christian buildings were constructed, the early Christians performing their religious ceremonies at Golgotha. In 135, Emperor Hadrian banned - the Christian religion, and renamed Jerusalem into Aelia Capitolina and rebuilt the city in the style of a typical Roman town. The Romans landfilled the area between the Holy Sepulchre and Golgotha and built a Capitolium, whereas at the top of Golgotha a statue of Venus was worshipped.

After the First Council of Nicaea in 325, the first Christian emperor, Constantine the Great, ordered that the temple be replaced by a church. The Capitolium was demolished and the Hadrian landfill was removed revealing the Tomb and Golgotha, with both Holy sites included within the newly constructed building. The new church complex was built at the base of Gareb hill, and to ensure the stability of the building's foundations, Constantine arranged for the rockface to be carved down to the level where the Holy Tomb was located. Constantine's church complex was consecrated on 13 Sept 335 and consisted of five buildings: a) the eastern atrium, b) the Basilica (Martyrium), c) an enclosed colonnaded atrium which included within it the site of Golgotha, d) the Rotunda (Anastasis) which contained the Holy Sepulchre in its centre, and e) the Patriarchate. The Tomb was carved outside, possibly in a polygonal form, with an entrance on its eastern side (Figure 1a), whereas the interior had a rectangular form and on its northern side the arcosolium. At the start of the 7th century, the exterior surfaces of the polygonal monolithic Aedicule were covered by marble plates, columns and metal fences to protect it from the visiting pilgrims.

The Church of the Holy Sepulchre was damaged by fire in May of 614 when the Sassanid army, under Khosrau II, invaded Jerusalem and destroyed the city. The Aedicule's exterior and interior surfaces and decorations were destroyed, including partial destruction of the burial chamber, along its east-west axis (Figure 1b). 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 were restored with masonry (Figure 1c). In 746, the church suffered severe damage due to an earthquake.

On 18 October 1009, Fatimid caliph Al-Hakim bi-Amr Allah ordered the complete destruction of the church, with few parts of the early church remaining. The Holy Aedicule is destroyed down to ground level, but it is unknown to what extent the Holy Rock remained intact. After wide ranging negotiations between the Fatimids and the Byzantine Empire in 1027–28 an agreement was reached. The rebuilding was finally completed by Emperor Constantine IX Monomachos and Patriarch Nicephorus of Constantinople in 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 (Figure 1d). The interior, as during Constantine's phase, remained non-covered. 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 (Figure 1e). 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 to it severe damage. 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 13th September 1810 (Figure 1f).

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 Authority (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 non-destructive techniques were used, 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.

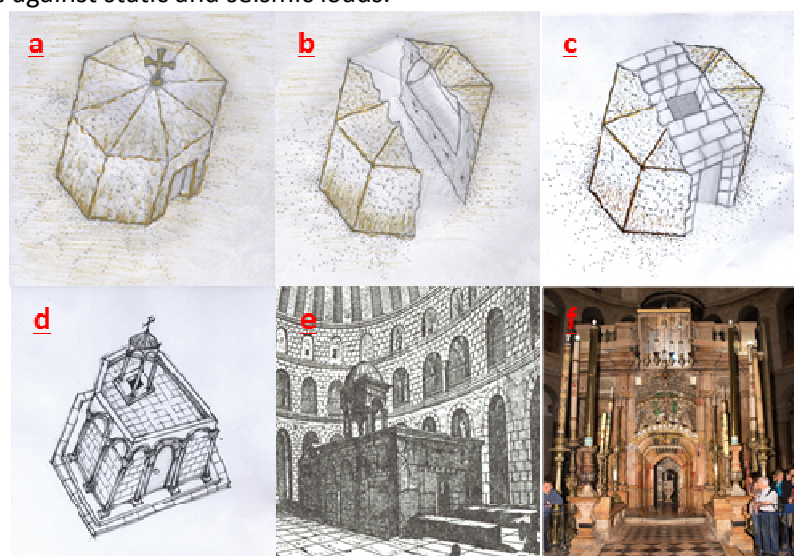


Figure 1. The construction phases of the Holy Aedicule of the Church of the Holy Sepulchre throughout history [2].

2. Interdisciplinary approach

The innovative and interdisciplinary approach adopted for the creation of the 5D Model of the Holy Aedicule of the Church of the Holy Sepulchre utilized data from the following:

- a) Architectural documentation, (scientific responsible: Prof. M. Korres), which described the current form and structure, as well as its evolution throughout the ages, based on historic documentation.
- b) Analysis of construction phases (scientific responsible: Prof. A. Moropoulou): The construction phases were revealed by a ground penetrating radar survey that was implemented within an integrated methodology, which enabled the technique to identify the various interfaces.
- c) Materials characterization (scientific responsible: Prof. A. Moropoulou), which included a wide range of analytical techniques such as microstructural analyses, XRD, mechanical characterization, optical microscopy, and non-destructive techniques such as infra-red thermography, and fiber-optics microscopy.
- d) Geometric documentation (scientific responsible: Prof. A. Georgopoulos) that produced a 3-D high resolution model, through an automated image based method, and through using Terrestrial laser scanning, from which it was possible to extract the eventually necessary conventional two dimensional products, as e.g. horizontal and vertical sections, facades etc. Visualizations from the 3D model support the design of restoration interventions. The 3D representation of the results of the non-destructive prospection with the 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. 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.
- e) Virtual and Augmented Reality (scientific responsible: Prof. A. Moropoulou and Prof. A. Georgopoulos) of the historic construction phases of the Holy Aedicule of the Church of the Holy Sepulchre. Development and applications of latest advances of the enabling technologies of Mixed reality by rendering 3D models with real materials texture and georeferencing them with the 3D model.

The integrated model which, after the above analysis, contains enhanced information covering all aspects of the Aedicule structure, 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 framework, the gamification approach is adopted transforming the above 5D model into an emblematic case study for smart educational and heritage applications.

3. Architectural documentation

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 explanatory notes [6].

For a better understanding of the structural connection of the new construction with the previous one and, therefore, to better understand the distortions of the external structure of the Canopy, 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 Figure 2 depicting a) the present form, b) the earlier latent construction enveloped by the present building's exterior masonry c) the area of possible existence of the holy grave's rock inside the latter. He also composed a new drawing of the facade (Figure 3 Left), which describes the boundaries and the movement of each stone, vertical and horizontal design sections (Figure 3 Right). Their particular value regards the distinction of the boundaries of the structural stones, which are often confused with those of the architectural forms. This allows the description of the deformations. mechanism, where such deformations exist and the interpretation of their geometrical characteristics.

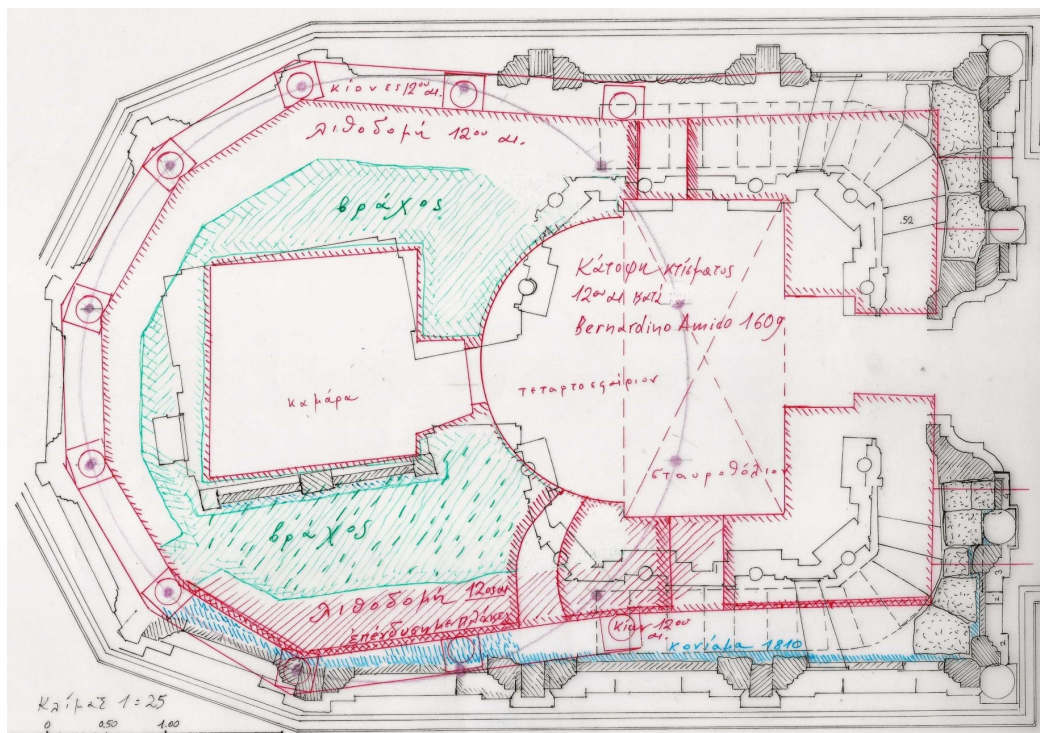


Figure 2 Holy Aedicule, depicting: a) the present form (black color), b) the earlier latent construction (red color) enveloped by the present building's exterior masonry c) the potential extent of the Holy Rock (green color) inside the Aedicule structure [5]

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 behind the 12 columns must have been the carved rock and not surrounding masonry. The lining of the rock with masonry, for the sake of which another carving was probably required, has given the whole, at least externally, the appearance of a building made entirely with 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 circular dodekastyle canopy was erected on the roof of this, 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 giant dome. Initially, the twelve columns of this canopy must have been forming a normal dodecagon, in order to look like the original form of the building that carried these columns. In any case, during the new construction of the 12th century, if not after a later reconstruction of the canopy, even though those columns remained 12, they were put in order as pairs, composing 6 double supports. This exact situation is depicted in the 1609 drawings.

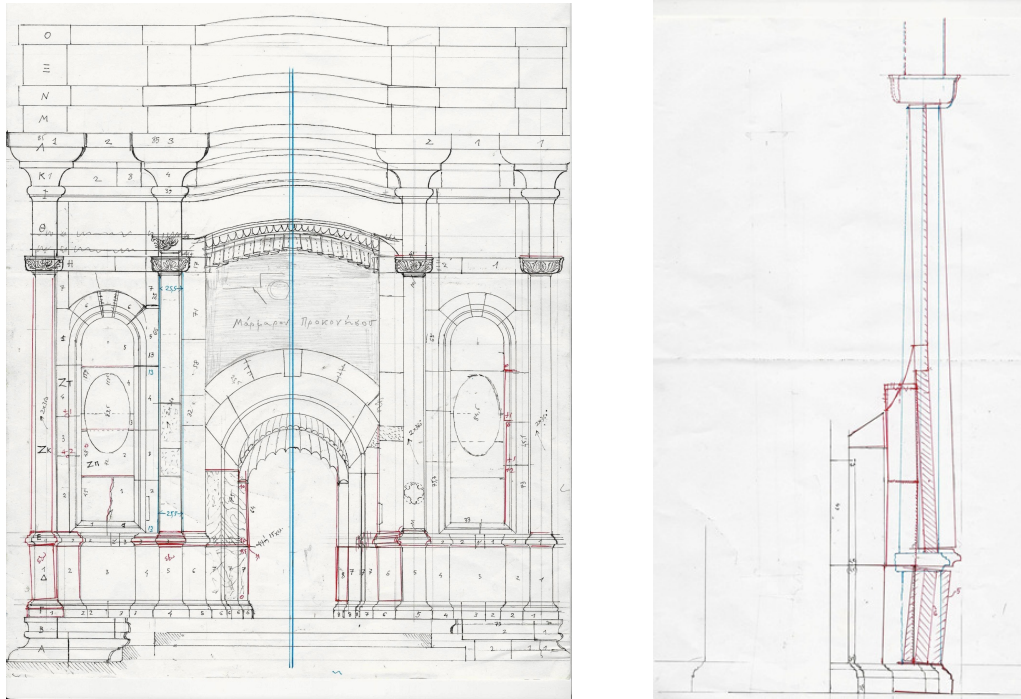


Figure 3 Left: Holy Aedicule: Boundaries and the movement of each stone, vertical and horizontal design sections. Right: Vertical axial section at the location of the main entrance with view to the right of this column. Red color denotes the current state (significant deformation and lifting mechanism of columns and superstructure). Blue color indicates the canonical form and the intended reconfiguring. [5]

During the fire of 1808, 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 dome, which were made of wood, but also from the thermal attack of the stone, given the combustion of so much material. As is known, the sudden increase in temperature causes heavy damage to stone blocks, especially to the larger ones; that is, extensive faulting accompanied by peeling and collapsing fragments, which generally belong in the category of thermal breakage. Given the huge quantity of timber, as well as the combustion and the free fall of huge masses falling from twenty and more meters, the damages on the Holy Sepulchre must have been severe, resulting in the complete loss of its outer surfaces and probably the fall of the groin vault of the chapel of the Angel.

Obviously, the recovery of the form that existed before the fire was not possible, nor desirable, because, in order to reinforce the construction, very thick new masonry would have to be added almost everywhere externally, which would drastically alter the original dimensions of the building. Kalfas Komnenos undertook, planned and accomplished this complex task as follows:

- a) He intended to preserve 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 decided to use architectural rhythmical elements of his time and not the old pointed ones, as everyone else would do in his position, in the East and

- the West (where classicism dominated, while the neo-Gothic style had not yet appeared). Furthermore, he decided to apply the new rhythmological system on the eastern façade too (which had remained for centuries incomplete on the previous building) and particularly in a richer way, that is with columns instead of simple pilasters.
- b) 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.
 - c) He also decided the natural and in particular the chromatic distinction of the marbles that would be used for all the surfaces: red on the exterior, white on the interior, but, exceptionally, also white on the exterior, above the door (where there is also a black stone on the arched lintel (to be checked). This, apart from its obvious advantages –a fervour on the exterior in accordance with the feelings inspired by the Resurrection of the Lord, a chilliness, but also a better visibility in the less lighted interior– provided also a valuable practical advantage: the white architectural elements of the interior, for which Prokonisian marble should be used, could be prepared in Constantinople by the excellent artists there, at the same time with the ones of the exterior, for which the local red stone, equivalent to the marbles, would be most appropriate and would be processed by the best stonecutters of Jerusalem. This would allow a large reduction in time, but at the same time, it would increase the difficulties of coordinating the work (these aforementioned considerations need to be checked based on evidence).
 - d) In order to ensure the result, Komnenos must have prepared very accurate general drawings to scale, indicating all the dimensions on the basis of a procedure of multiple calculations. Certainly, he prepared drawings of all the forms (capitals, for example) and cross sections (mouldings, for example) at natural size (scale 1:1), to be used by the craftsmen. These forms were not others than these that dominated in the urban Constantinople, a peculiar mixture of Central Europe's Baroque style with folk memories of classical architecture and some makeshift findings. He must have also defined, as far as possible, the dimensions based on a metrical system of cubits or other tectonic units and subdivisions.
 - e) In any case, the apparent pursuit of some metric proportions is indicative, to ensure an academic – numerological perfection of the architectural composition as well as of a certain symbolism: The bulk of the building, that is without the base and the parapet, has a length of 8.32,5 m., width of 5.55 m., and height 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 architect Komnenos following these approaches:

- Addition of a new masonry outside of the surviving Crusaders' phase one. This would necessitate removal of any surviving lining stones from the previous construction period and carving of the surviving masonry wherever required, in order externally to blend the existing edifice with the new architectural elements designed by Komnenos and to enhance cohesion between the two masonries. Obviously, at elevated heights, since the previous Aedicule was not only lower than the one designed by Komnenos but had also sustained significant damage due to the fire, the masonry would be entirely new. Characterization of building materials, verified the presence of two types of mortars, corresponding to the two construction phases.
- Carving of the surviving old masonry, wherever its thickness justified such a laborious approach, in order to enlarge the interior space these masonries defined. This approach could be carried out, in certain areas, in conjunction with the aforementioned addition of a new masonry.

The coexistence of old and new masonries at the interior and exterior of the Aedicule, following the 1808-1809 works, is analyzed, as described below, by the use of ground penetrating radar for the prospection of the structure.

4. Analysis of the construction phases

Ground Penetrating Radar (GPR) is an established non-destructive 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 the conjunction with macroscopic deformations. In Figure 4, the basic scan areas of the exterior and interior of the Aedicule are presented. The ground penetrating radar system used in this survey was a MALÅ Geoscience ProEx system with 1.6GHz and 2.3GHz antennae. The MALÅ Geoscience Groundvision 2 software was used for data acquisition. The MALÅ Geoscience RadExplorer v.1.41 software was used for data processing.

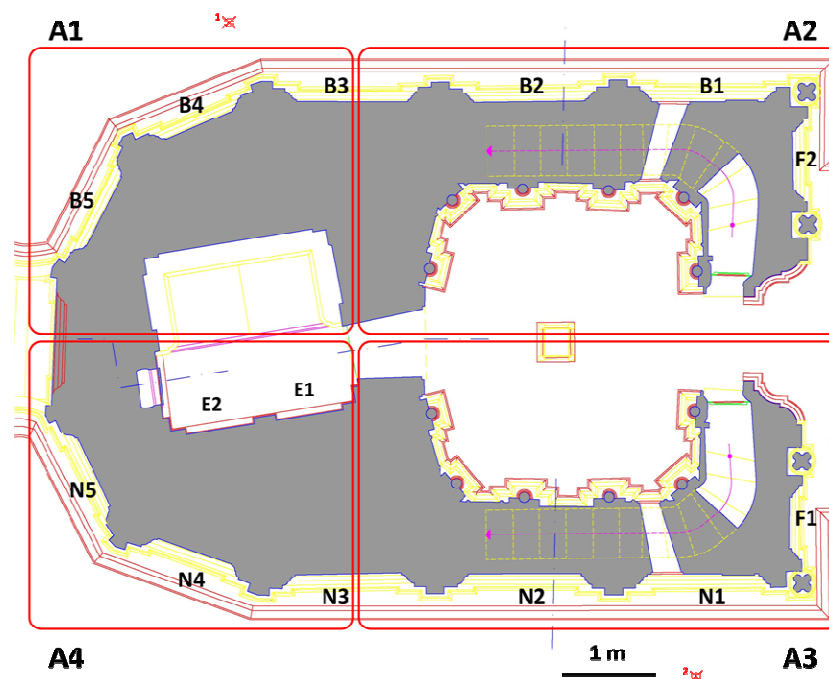


Figure 4 Plan of the Aedicule (at a height of 130cm from the interior floor). The red quadrants represent the basic survey areas. The markings B1-B5 and N1-N5 corresponds to the north and south arch areas at the exterior surfaces of the Aedicule.

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 description of the analysis of the GPR scans is presented in Figure 5, which corresponds to a horizontal scan on area N4 at a height of 130cm above the interior floor level. In Figure 5, the same scan is presented after its processing 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 was the revealing of weak peaks and layers that are not readily identifiable in a non-processed radargram. It is noted that in most cases the background removal filter was not applied, as it

generally eliminated important information from the radargrams. However, in certain radargrams it was applied in order to clarify certain details during data analysis.

It should be noted that the scan after its processing with the aforementioned filters still remains a distance – time graph. Specifically, 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 when 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 towards the exterior surface, and its detection by the receiver antenna. The amplitude of the reflected pulse is attributed with shades of grey, where black and white correspond to maximum intensity of a pulse with positive or negative polarity correspondingly, whereas grey corresponds to zero intensity of the detected pulse. Figure 5B presents with a blue color the palmograph at position X=0,07m from the beginning of the scan, where the various reflections per time lapse (blue line peaks) are visible, and in particular the reflection of the exterior panel / Komnenos construction phase at approximately 3ns.

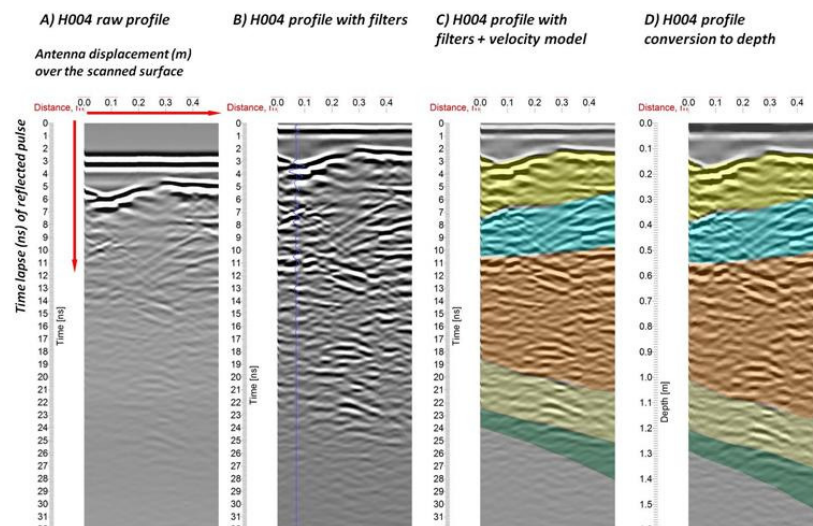


Figure 5 Overall process of conversion of a GPR scan into a graph distance – depth. A) Original scan (raw data) H004 in sub-area N41 of area N4, B) Application of filters on scan H004, C) Identification of masonry layers – velocity model, D) Conversion of time (vertical axis) into depth.

For the conversion of the scan in Figure 5 into a two-dimensional section distance - depth (X axis vs vs Depth – Z axis), the calculation of the pulse velocities throughout all observed layers is required. For this purpose, stone blocks of the parapet at the roof and stone block from the seat outside the entrance to the Aedicule were used as standards to calibrate the pulse velocities for the GPR analysis, with the aid of, the velocities and dielectric constants were calculated and used in the velocities models of the remaining areas, representing the exterior stone panels and the holy rock, as they have similar synthesis. Based on this calibration, a velocity of $v=11,58\text{cm/ns}$ ($\sigma=1,02\text{cm/ns}$) was calculated. It should be noted that the stone ashlar that were used for the construction of the Bell Tower of the Church of the Holy Sepulchre had a velocity of $10,48\text{cm/ns}$, as measured during a previous diagnostic study with non-destructive techniques by the research team of NTUA [7].

For the calculation of the pulse velocity of the Komnenos construction phase, scans in the N2 area were calibrated, where, most probably the masonry consists mainly by stone/marble panels (exterior and interior) and one internal building phase. For the calculation of the pulse velocity corresponding to the Crusaders building phase the fact that reflections of the interior panels were “visible” from the exterior through scan H004.

Moreover, the overlapping of areas within the masonry from various scans at the same height, allowed the optimization of the identification of the masonry layers through the identification of common “targets” and discontinuities, which further refined the pulse velocities values. Following these, Figure 5C and Figure 5D present the application of the velocity model on scan H004. The various layers are identified by the user and are depicted on the scan. From the exterior surface and inwards, the various layers are shown. Grey = exterior stone panel, Yellow = Komnenos construction phase, Blue = Crusader’s construction phase, Brown = Holy Rock, Light Green = Masonry layer between Holy Rock and interior marble panel. Green = Interior marble panel.

Figure 6 presents in a descriptive approach the various layers within the Aedicule structure, as analyzed by GPR. Figure 6 is based on Figure 2 and retains the plan of the current structure, and the exterior boundary of the 11th / 12th century building (red outlines). The BN3 plane and the longitudinal axis conceptually define the four quadrants A1 – A4.

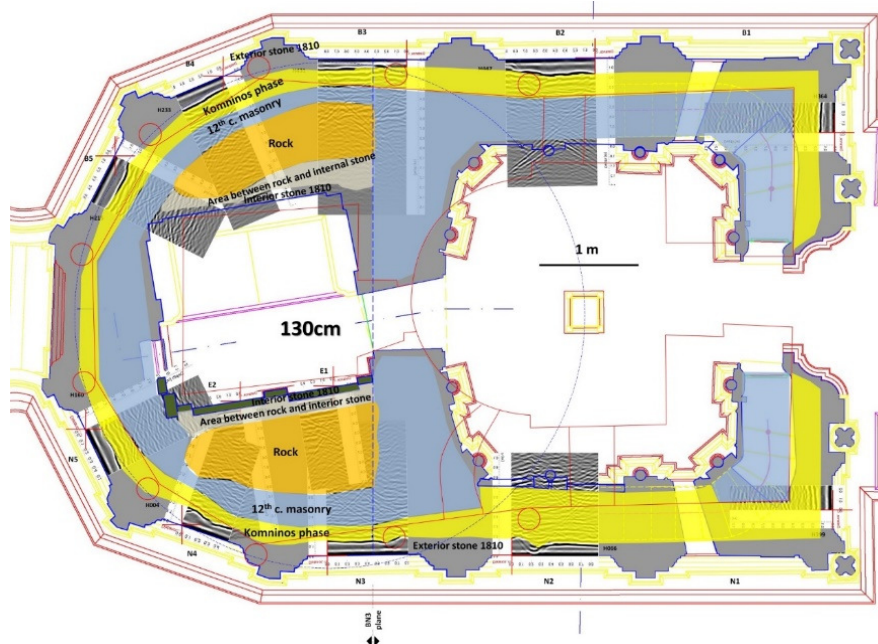


Figure 6 Layering within the Holy Aedicule (cross-section at height level 130cm) as identified by GPR analysis [5].

Starting from the southwest quadrant A4 of the Aedicule, and analyzing with the aforementioned methodology the various detected internal interfaces, from the south exterior towards the interior of the Holy Sepulchre, the following are revealed: a) exterior panel, b) Kalfas Komnenos construction phase, c) Crusaders construction phase, d) Holy Rock, e) masonry between Holy Rock and interior panel, and f) interior panel.

The exterior panel has a varying thickness of 10-15cm, and corresponds to the first zone (0-15cm) at the respective GPR scans of the exterior surfaces. Moving towards the interior, an interface is observed at a depth of 30-40cm. The layer between the exterior panel and this interface corresponds to the Kalfas Komnenos construction phase, and is indicated in Figure 6 as a yellow coloured zone. Moving further towards the interior, the GPR scans reveal the presence of a second interface, at a depth of approximately 50-60cm. The layer between the red dashed curve – internal boundary of the Komnenos construction phase – and this second interface, corresponds to the 12th century masonry, i.e. the Crusaders construction phase.

The combined analysis of horizontal and vertical GPR scans at quadrant A4, both from the exterior (areas N3, N4, 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 Figure 6, the Holy Rock is depicted as an orange-coloured area, whereas a 3-

dimensional model of the Holy Rock was presented in a previous section. The analysis of the presented GPR scans (Figure 7), in conjunction with analysis of respective vertical scans, indicates that the Holy Rock possibly extends to a height of approximately 2m. Above this height, the GPR scans indicate masonry, possibly constructed after the 1808 fire, although parts of the 12th c. constructions could not be excluded from being present.

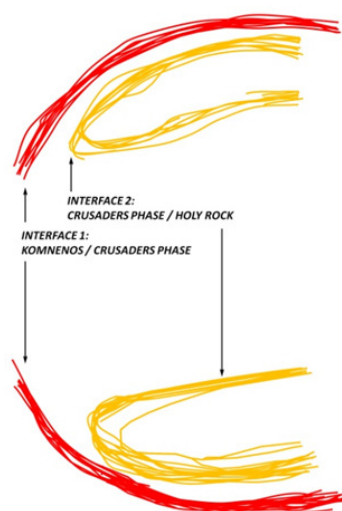


Figure 7 Overlay of interface curves from a height level 30-350cm, as identified by GPR analysis. Red curves correspond to the Komnenos/Crusaders' phases interface; Orange curves correspond to the Crusaders' phase / Holy Rock interface [5].

Scanning of the interior of the Holy Tomb, and in particular areas E1 and E2, and as verified by scans from areas N3 and N4, it is estimated that the interior panel at areas E1 & E2 have a thickness of 5-6cm, both the grey and red marble panels. Behind the panel of areas E1 and E2 an interface at a depth of approximately 20cm is revealed, that corresponds to the north boundary of the Holy Rock, within quadrant A4. The area between the Holy Rock and the panel of areas E1 & E2 appears to be a masonry with an average stone size of approximately 10cm. Regarding the eastern boundaries of the Holy Rock, within quadrant A4, the presence of an interface belonging to a vertical plane (BN3) is indicated, which is perpendicular to the longitudinal axis of the Aedicule and which intersects B3 and N3 at their mid-axis, as will be discussed below.

It should also be noted that the 12th c. masonry appears to have an increased thickness, approximately 30cm eastwards (area n3), in comparison with a thickness of 20cm westwards (area N4, as well as throughout quadrant A1). This observation, in conjunction with a) the slight rotation of the Holy Tomb in respect with the longitudinal axis of the Aedicule and b) the different location, towards the north, of the 8th pillar of the Crusaders phase, in relation to its location at the original dodecagon building, can lead to the theory that the Holy Rock solid volume, or at least whatever remained from its successive carvings, did not have a canonical dodecagon plan in full correspondence with the pillars of the original dodecagon building, but possible had a transverse dimension slightly smaller than the longitudinal one. Therefore, the addition to the Holy Rock of the 12th c. masonry, possibly reinstated the canonical geometry on the apparent volume of the Holy Rock. The revealed layers within quadrant A1 of the Aedicule are the same as that of quadrant A4. The 12th century masonry appears, however, to have a thickness of approximately 20cm, throughout quadrant A1, in contrast to the case of quadrant A4.

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. 63), 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 for quadrants A1, A4. To the east side of this plane, the revealed layering is interrupted in respect to its

western continuity, regarding the layer corresponding to the 12th c. masonry, since reflections from the parts of the scans that belong to quadrants A2 and A3 are present in different depths compared to the depth of reflections from the parts of each scan that belong to quadrants A1 and A4. The analysis of the GPR scans lead 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 semi-circular 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.

Regarding the Chapel of the Angel, and based on the analysis of GPR scans, there are indications that on the northern side and on the eastern side parts of the Crusaders' masonry were retained (Figure 6, Figure 8), on which deep carving was performed to its 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 1,5m above the interior floor level, this 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, GPR analysis indicates that retaining of Crusaders' phase masonry occurs only at the southeastern corner (Figure 6, Figure 8), up to height similar as the one on the northeastern corner.

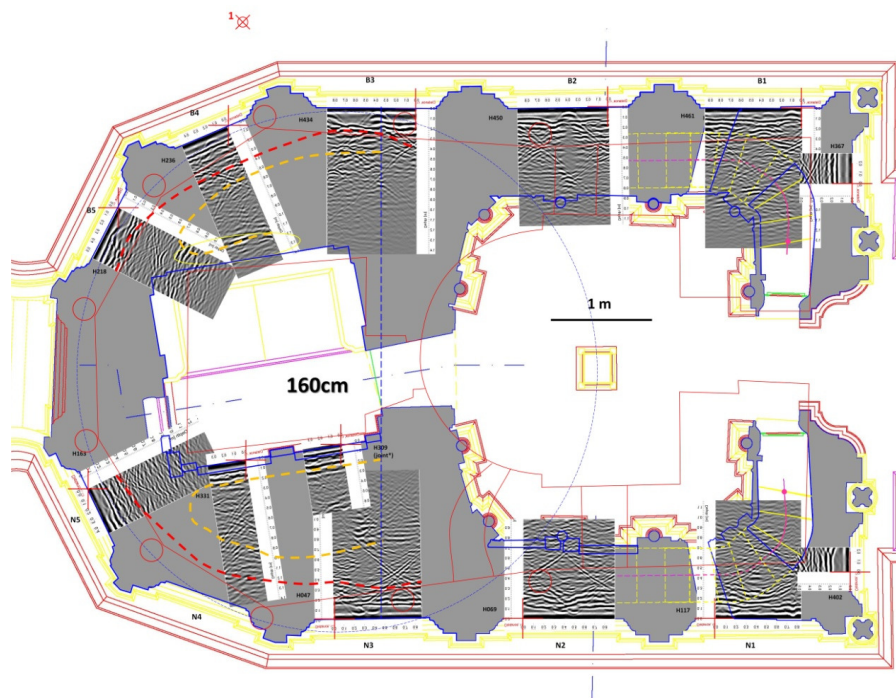


Figure 8 Layering within the Holy Aedicule (cross-section at height level 160cm) as identified by GPR analysis [5]

5. Materials characterization

On May 2015 the members of the Laboratory of Material Science and Engineering, School of Chemical Engineering NTUA visited the Holy Aedicule of the Church of the Holy Sepulchre in order to conduct an in-situ diagnostic study for assessing the extend of materials decay and the conservation state of the Sacred Monument. The present section is part of the study under title *"Integrated Diagnostic Research Project and Strategic Planning for Materials,*

Interventions Conservation and Rehabilitation of the Holy Aedicule of the Church of the Holy Sepulchre in Jerusalem” [5].

A macroscopic observation survey over the Sacred Monument reveals the extend of the certain deformation of the external facades of the Monument (Figure 9), 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 Non Destructive Testing assessment of the materials compatibility and condition state took place making use of the Infra-Red Thermography and the Fiber Optical Microscopy.

In order to determine the materials decay and the origination of this decay (causes), the need of studying 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 non-destructive techniques present a clear advantage over destructive analytical testing – and refers to a range of analyses. For the characterization of the building materials of this study the following analyses has been taken place:

- Mineralogical and petrographic analyses: Optical Microscopy, X-ray Diffraction (XRD), Scanning Electron Microscopy (SEM).
- Analysis of chemical composition: gravimetric and volumetric chemical analyses, spectroscopic methods (Fourier transform Infra-Red Spectroscopy- FTIR).
- Thermal analysis: Differential Thermal Analysis (DTA), Differential Scanning Calorimetry (DSC).
- Microstructural analysis: Mercury Intrusion Porosimetry (MIP).
- Determination of physical - chemical properties
- Determination of the percentage of the Soluble Salts
- Determination of mechanical properties: universal testing machines (stress-strain curves, fracture strength, static modulus of elasticity, Poisson ratio, etc.)



Figure 9 External facades deformations

5.1 Sampling

In order to identify the causes behind the external marble masonries 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 (Figure 10), in order to ensure that building materials coming from all the historic construction phases of the Monument would be included in the study.



Figure 10 Above: Façade core sample: Three building stones samples (JHS_1fa_ys, JHS_1fa_ws, JHS_1fa_ws2), Three mortar samples (JHS_1fa_m1, JHS_1fa_m2, JHS_1fa_m3)
Below: Floor core sample: Three building stones samples (JHS_2fl_bs, JHS_2fl_ps, JHS_2fl_ws)

5.2 Non Destructive Testing

Infra-Red Thermography

Infra-Red Thermography measurements were performed for the non-destructive 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 non-visible 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 pilgrimage burning candle cause strong thermal stresses to the building stone of the façade despite the obvious aesthetic degradation, due to the accumulation of black 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 (Figure 11). 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 hours after burning the candles out, proves the topical thermal heterogeneity. The aforementioned action, taking place in a daily basis causes corresponding changes in the thermo-hygrometric behavior of the building materials of the masonry, accelerating their deterioration. It is clear that the burning candles or/and the oil-lamps being in contact or having close proximity to the architectural surfaces of the Holy Aedicule is prohibitive and is suggested the particular action to take place at a sufficient distance from it.



Figure 11 IR-Thermal inspection of the south façade of the Holy Aedicule of the Church of the Holy Sepulchre

Fiber Optical Microscopy

Fibre Optics Microscope (FOM) is a non-destructive microscope that can be utilised in situ to acquire magnified, visible spectrum, images. FOM is a microscope system 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), for the study of the decay phenomena (alveolation, hard carbonate crust, etc.), to investigate materials' surface morphology, to identify defects in historic building materials, for materials 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.

The FOM measurement presented in Figure 12, has been conducted over part of the Holy Rock of Golgotha coming from the core sample illustrated in Figure 10. Macroscopic, has off-white color with visible craters all over its range. The closer examination with the Microscope shows that possibly there used to be fossils in the sample that has been detached. There are also discernible kind like of fibers in certain parts of the sample and several orange regions are observed which probably are due to oxides and hydroxides of Ferric (Fe).

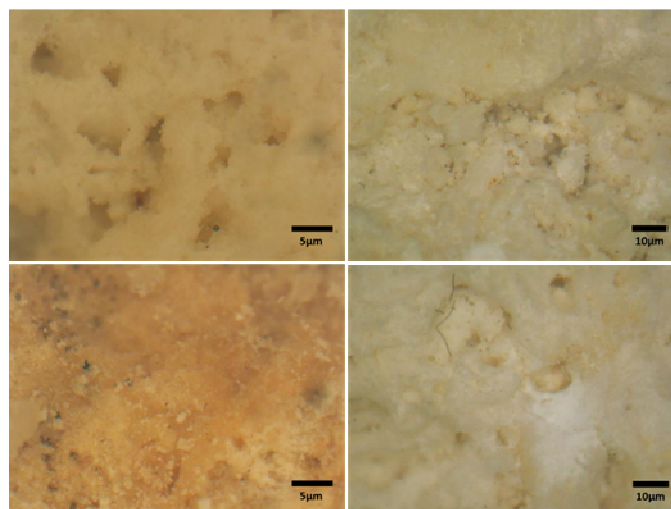


Figure 12 Microscope Fiber Optic Measurements using lens 50X (scale 10μm) and lens 120X (scale 5μm)

5.3 Petrographic and Mineralogical Characterization

In order to understand the origin, the micro-texture and structure of the rocks, optical mineralogy analysis in thin section is equipped. From the XRD examination (Figure 13) of the same sample, the sample is slightly bituminous and mainly consists of micrite calcite at approximately 98%. There are also found opaque metallic minerals, which are iron oxides at <2%. This sample is characterized as a micritic limestone (Figure 14).

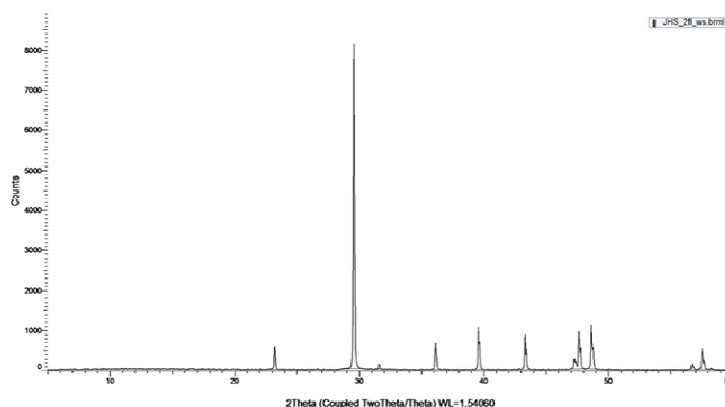


Figure 13 XRD pattern

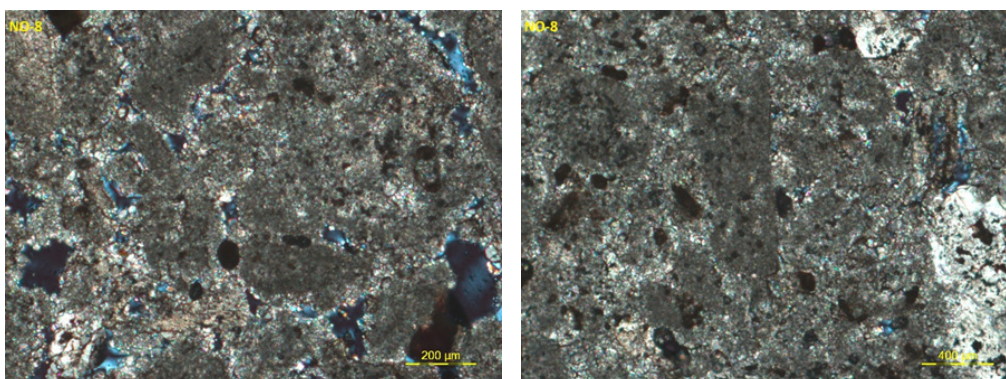


Figure 14 Micritic Limestone JHS_2fl_ws – Polarizing Microscope Measurement

5.4 Analytical-Laboratory Techniques

Microstructural Analysis

The measurement of the microstructural characteristics has been made by the Mercury Intrusion Porosimetry. From the microstructural analysis for the same sample, the measured characteristics were: specific surface area is 0.256 m²/gr, total porosity 22.37%, average pore radius 0.005 μm and bulk density 3.08 gr/cm³. The pore size distribution for the particular sample is illustrated in Figure 15.

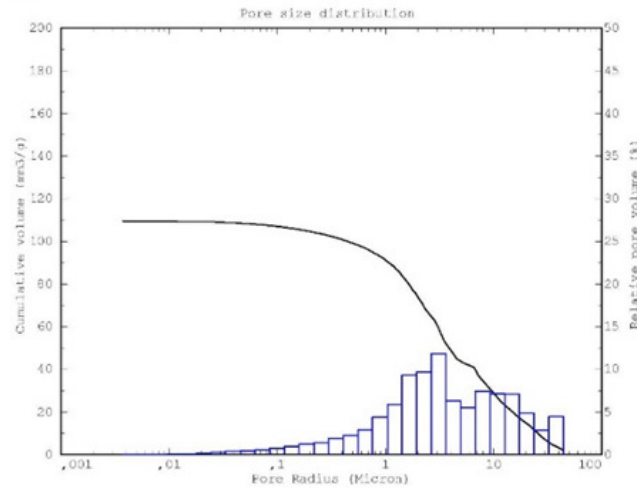


Figure 15 Pore size distribution

6. Geometric documentation

The geometric documentation (scientific responsible: Prof. A. Georgopoulos) carried out produced a 3-D 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, facades etc., (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.

6.1 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 high accurate geodetic measurements for the production of conventional 2D base material on 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, 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 geomatics 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 (5616x3744 pixels) and 6.4µm 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 (16mm, 50mm, 135mm and 300mm) 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

seconds. 3.757 images in total were captured requiring up to 59.3GB 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, 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 of the air.

In addition, **laser scanning** was also employed, in order to cover the areas where image acquisition was impossible, like 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 the distance. It has the ability of collecting one million points per second with an accuracy of 2-3 mm in its space position. It can record points 360 degrees around the vertical axis and 300 degrees 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 around the Holy Aedicule, 8 on top of its roof, 8 in the two staircases, 10 from the Rotunda Gallery and 19 in 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.

6.2 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. Diagram A presents the flowchart designed and adopted for the initial data processing procedure (images and measurements). After the 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 to 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 but also of the Laboratory of Photogrammetry [12].

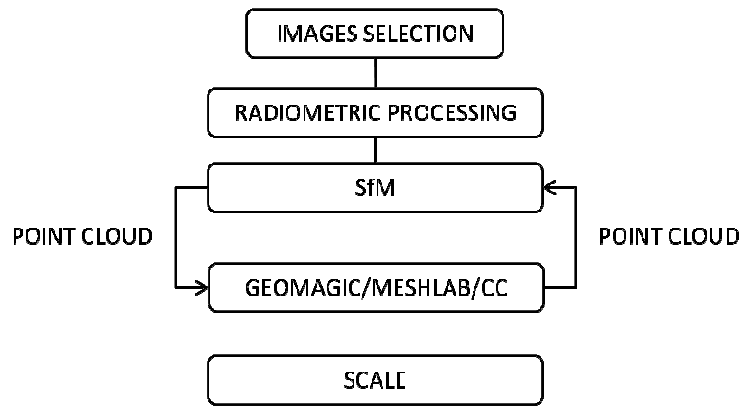


Diagram A Data processing framework

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 to 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

Figure 16 The colored point cloud of the Holy Aedicule

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® και Cloud Compare® software. To sort out the outliers, several filtering algorithms are 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 reduce its density. Finally, the processed dense point clouds are wrapped into meshes. Figure 17 presents 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 not physical access on them.



Figure 16 The colored point cloud of the Holy Aedicule



Figure 17 The 3D model of the dome textured (left) and non-textured (right)

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 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 **Σφάλμα! Το αρχείο προέλευσης της αναφοράς δεν βρέθηκε.** a sample of the registered point clouds is shown.



Figure 18 Part of the registered point clouds inside the Holy Aedicule

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 inside and outside of the Holy Aedicule but also in the surrounding area. In total 38 control points were used.

6.3 Inserting the GPR in 3D

The 3D representation of the results of the non-destructive prospection with the 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 to 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 towards 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 of the members of the interdisciplinary team.

The contribution of this 3D visualization and relation of the interpreted GPR measurements is very important for this study, as it represents the internal structure of the Holy Aedicule, which is not directly visible. 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 form of jpg images. They covered the Holy Aedicule from a height of 0.3m up to 2.9m 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.

The methodology applied was specially designed and adapted for this specific application, as it has not been implemented in this way in the past (Figure 19). Initially the 23 images of the 2D sections of the GPR were georeferenced. Subsequently they were placed in various layers according to their height attribute. They would contain the digitized border lines/2D sections.

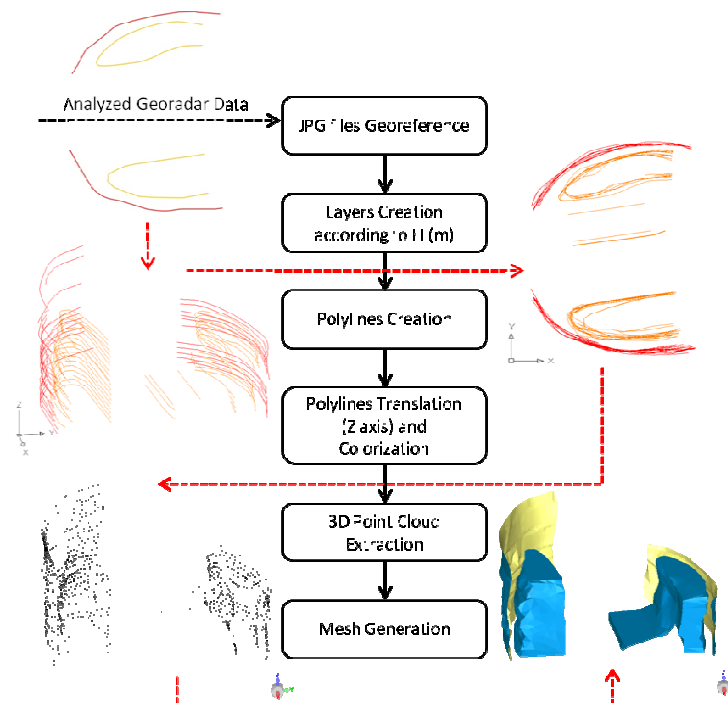


Figure 19 Flowchart of the methodology developed for the creation of the 3D model of the internal structure of the Holy Aedicule

Afterwards, 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 (Figure 20 Left).

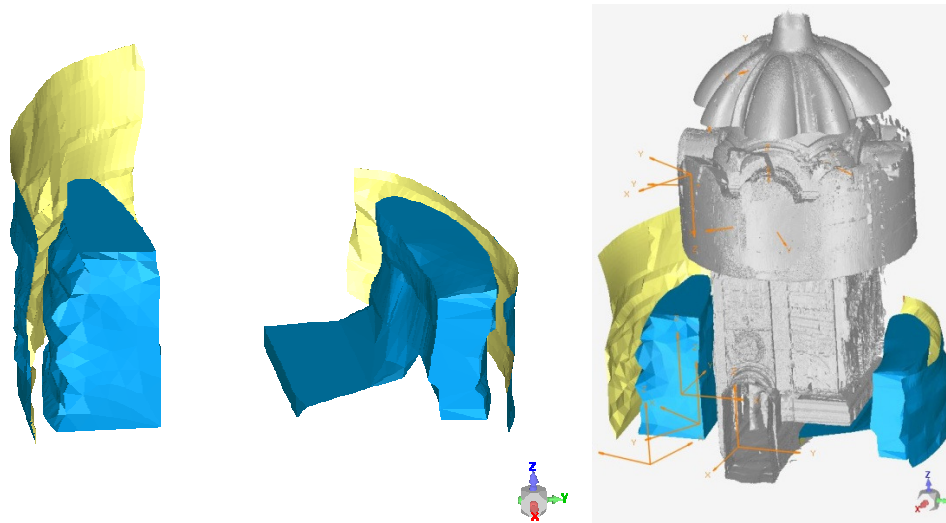


Figure 20 Left: 3D visualization of the prospection findings Right: The scanned 3D model (grey) with the 3D GPR data

Finally, the 3D surface model created was incorporated to the existing high resolution 3D model (Figure 20 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 towards 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 of the members of the interdisciplinary team. However, it needs further investigation, research and development.

6.4 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 Figure 21 (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 Figure 21 (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.



Figure 21 Left: Visualization of a vertical section from the 3D model with texture
Right: Horizontal section of the 3D model where the floor is shown

7 Historic Construction Phases Virtual and Augmented Reality Modelling

Based upon the sketches of Figure 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 realized with the gaming and visualization open source software Blender. According to the historic documentation, the Tomb was carved outside, possibly in a polygonal form, with an entrance on its eastern side. In order to represent the real texture of the Tomb, processed measurements taken by the Fiber Optic Microscope from the Holy Rock were utilized (Figure 22 left). For the representation of the damaged inside part of the Tomb, same type of measurements coming from broken sample of Holy Rock were used for creating the texture (Figure 22 middle). Due to the fact that there are not documented information concerning the building materials of the masonry from the Modestus restoration, a random material texture has been used (Figure 22 right).

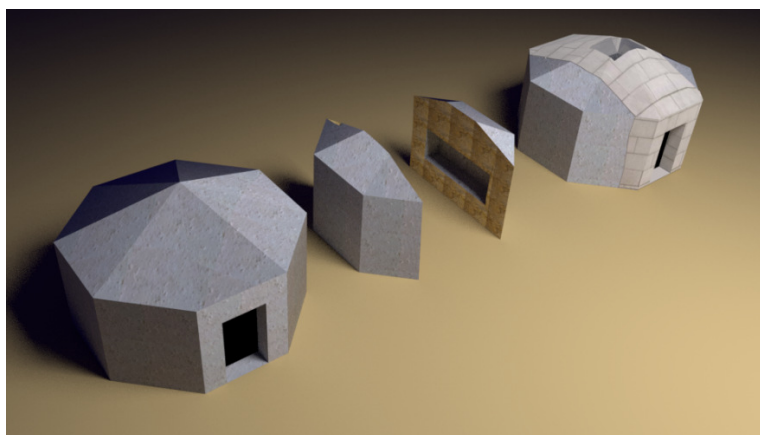


Figure 22 The Holy Aedicule - Two construction phases (left and right models) and the destructed state in the middle.

To bring the 3D models in real dimensions, they had to be fitted upon the dimensions of the real Holy Rock. Such estimations have been made by the analysis presented in the end of the

previous chapter where the interpolation of the GPR measurements in different heights gave a rough estimation of Holy Rock volume. The 3D models representing the historic phases have been fitted upon the dimensions of the Holy Rock as they are illustrated in Figure 23.

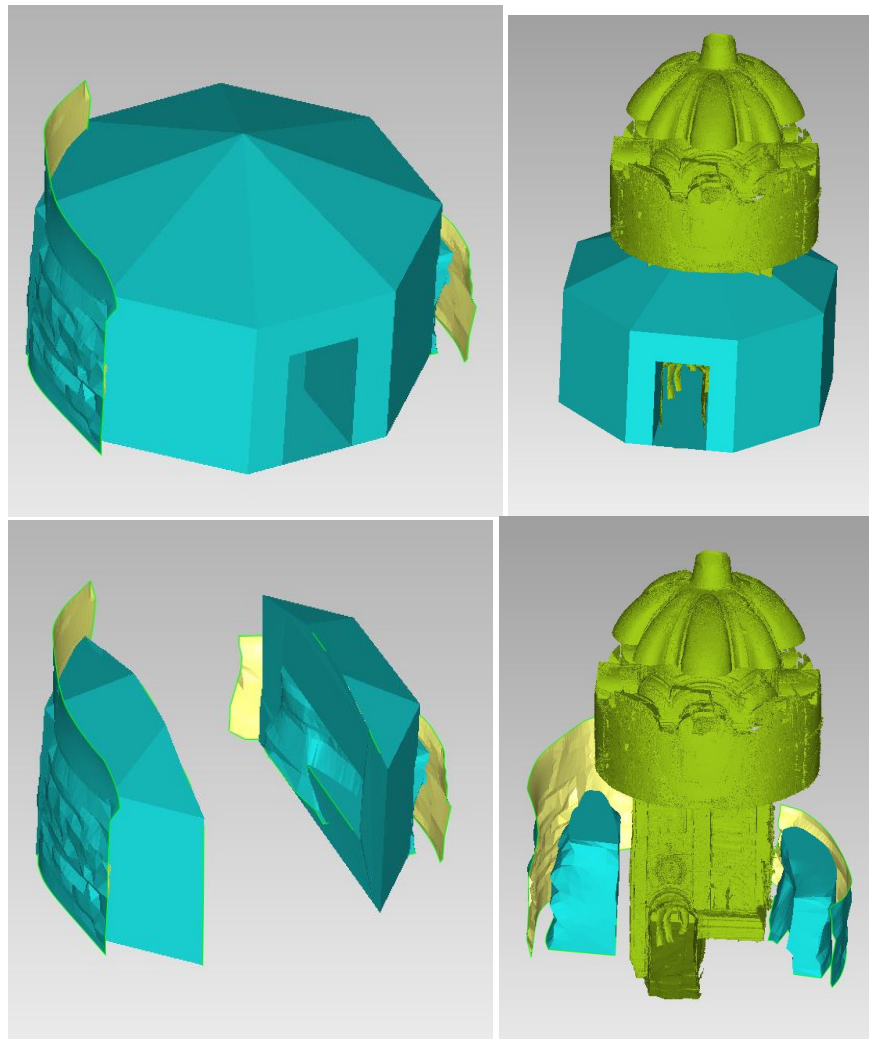


Figure 23 Fitting the 3D models in the real dimensions as estimated by the GPR measurements.

The work presented so far, contains enhanced information covering all aspects of the Aedicule structure, 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.

Acknowledgements

His Beatitude the Patriarch of Jerusalem Theophilos III, that took the initiative to perform the program agreement by NTUA with title *"Integrated Diagnostic Research Project and Strategic Planning for Materials, Interventions Conservation and Rehabilitation of the Holy Aedicule of the Church of the Holy Sepulchre in Jerusalem"*.

His Paternity the Franciscan Custos of the Holy Land, Rev. f. Pierrebattista Pizzaballa, and His Beatitude the Armenian Patriarch in Jerusalem, Nourhan Manougian, that authorized His Beatitude the Patriarch of Jerusalem Theophilos III and NTUA to perform this research.

References

- [1] Lavvas G. The Holy Church of the Resurrection in Jerusalem. The Academy of Athens; 2009
- [2] Mitropoulos T. The Church of Holy Sepulchre – The Work of Kalfas Komnenos. European Centre of for Byzantine and Post-Byzantine Monuments; 2009 (in greek)
- [3] Pringle D. The Churches of the Crusader Kingdom of Jerusalem. A Corpus. Volume III, the City of Jerusalem. Cambridge University Press; 2007
- [4] Simon Sebag Montefiore. Jerusalem: The Biography Paperback, Phoenix; 2012
- [5] "Integrated Diagnostic Research Project and Strategic Planning for Materials, Interventions Conservation and Rehabilitation of the Holy Aedicule of the Church of the Holy Sepulchre in Jerusalem", Scientific Responsible: A. Moropoulou, National Technical University of Athens, 2016
- [6] Bernardino Amico da Gallipoli, Trattato delle piante et imagini dei sacri edificii di Terrasanta, Rome 1609 and Florence 1920 (the first version has better printing)
- [7] K. Labropoulos, A. Moropoulou "Ground penetrating radar investigation of the bell tower of the church of the Holy Sepulchre", Construction and Building Materials, 47 (2013) 689-700
- [8] Biddle, M., Cooper, M.A.R., Robson, S., 1992. The Tomb of Christ, Jerusalem: a photogrammetric survey, The Photogrammetric Record, 14(79), 25-43.
- [9] Balodimos, D., Lavvas G., Georgopoulos, A., 2003. Wholly Documenting Holy Monuments CIPA XIX International Symposium, 2003, Antalya. <http://cipa.icomos.org/text%20files/antalya/133.pdf>
- [10] Corbo, V.C., 1981. Il Santo Sepolchro di Gerusalemme. 3 vols. Publication of the Studium Biblicum Franciscanum 29, Jerusalem.
- [11] Georgopoulos, A., Modatsos, M., 2002. Non metric bird's eye view. International Archives of Photogrammetry and Remote Sensing, 34(5), 359-362, Corfu, Greece.
- [12] Georgopoulos, A., 2015. Photogrammetric Automation: Is it Worth? Proceedings VAMCT 2015, Delphi.
- [13] Lavvas, G., 2009. The Church of the Holy Sepulchre in Jerusalem, Academy of Athens, 2009, 192 p., ISBN 978-960-404-139-8 (in Greek).
- [14] Tucci, G., Bonora, V., 2011. Geomatic techniques and 3D modeling for the survey of The church of the Holy Sepulchre in Jerusalem. Proceedings XXIII CIPA Symposium - Prague, Czech Republic - 12/16 September 2011.