Multispectral monitoring of the successive phases of the Holy Aedicule rehabilitation

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ABSTRACT

The Holy Aedicule of the Holy Sepulchre, an emblematic monument that has survived throughout the centuries, recently underwent a major and demanding rehabilitation under the responsibility of the National Technical University of Athens Interdisciplinary Team. The requirement for reinstating structural integrity to the Holy Aedicule, for preservation of the values it represents and for achieving a sustainable rehabilitation in a demanding environment, demanded a multidisciplinary approach utilizing multispectral monitoring techniques of the successive phases of the Holy Aedicule, prior, during and after the completion of the rehabilitation interventions. Specifically, a thorough geometric documentation was realized involving laser scanning and photogrammetric techniques, in order to obtain a 3D textured model of the Holy Aedicule, prior to the initiation of the works. At this phase, in parallel a diagnostic study was implemented, regarding the building materials and their decay phenomena, utilizing non-destructive techniques that document the surface of the monument and its state of preservation, while providing prospection of its internal structural layers. This information was crucial for the design of the restoration materials and rehabilitation interventions. The next phase involved dismantling of the exterior stone slabs from the facades. The revealed masonry was geometrically documented, to record the morphology of this internal layer and to optimize the design of the required interventions. The geometrical products verified the non-destructive prospection of the Aedicule. During the strengthening interventions the Tomb of Christ was opened, along with an “observation window” within the Tomb Chamber; their interiors were digitally documented, including materials information. Upon completion of the strengthening interventions (grouting, titanium elements, etc.), the columns were reset and the stone facades were reinstalled, and the Aedicule was “freed” from the British metal frame installed seventy years earlier. The final phase involved an interdisciplinary documentation of the rehabilitated structure.

I. INTRODUCTION

The Church of the Holy Sepulchre in Jerusalem, which dates to 326AD, incorporates the sites where Jesus Christ was crucified, buried and resurrected. The Tomb of Christ is preserved within a small ciborium-type structure, termed the Holy Aedicule, which has evolved throughout the centuries and includes remnants of the original Tomb. The latest reconstruction of the Holy Aedicule was completed in 1810, following a destructive fire. An interdisciplinary team from the National Technical University of Athens (NTUA), after invitation from His All Holiness, Beatitude Patriarch of Jerusalem and All Palestine, Theophilos III, and with the agreement of the other Christian communities who share control of the church, implemented in 2015 an “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”. Based on the results of the NTUA interdisciplinary team study, the project of “Conservation, reinforcement and repair interventions for the rehabilitation of the Holy Aedicule” was successfully implemented in 2017, with the scientific supervision of the NTUA interdisciplinary team (Moropoulou et al, 2017). The present work describes the multispectral monitoring of the successive phases of the Holy Aedicule rehabilitation, and how geometric
documentation, materials characterization and non-destructive testing were merged to support the implementation of the rehabilitation project throughout its various stages.

Specifically, the rehabilitation project involved a) the dismantling and removal of exterior slabs on the main panels; b) removal of disintegrated and incompatible mortars from the revealed masonry; c) consolidation of the interior masonry with grouts; d) resetting and anchoring of exterior columns; e) positioning of titanium frames; f) re-positioning of the stone panels and anchoring of interior marbles; g) conservation interventions on the Onion Dome, the Dome of the Angel, the Dome of the Burial Chamber; h) removal of the British metal frame; i) cleaning and protection of interior and exterior architectural surfaces.

II. METHODOLOGY

A. Geometric Documentation

The methodology implemented for the geometric documentation 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. These data were georeferenced to an already existing local plane projection reference system from previous work of NTUA (Balodimos et al., 2003). Accurate three-dimensional models with the use of photogrammetric and geodetic methods, were produced both for the interior and the exterior of the Holy Aedicule through images and scanned data collection for the reconstruction of the model in actual scale

For the image-based approach, digital image sequences from varying distances were collected using two calibrated professional DSLRs, a Canon EOS-1Ds Mark III full frame CMOS digital camera with 21MP resolution (5616x3744 pixels) and 6.4μm pixel size, and a CANON EOS-6D full frame CMOS digital camera with 20MP resolution (5472 x 3648 pixels) and 6.6μm pixel size. Different fixed lenses with varying focal lengths (16mm, 50mm, 135mm and 300mm) were used.

In addition, laser scanning was also employed, as a 3D data source, but also to document 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 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 distances. It has the ability of collecting one million points per second with an accuracy of 2-3 mm in its space position. For the complete coverage of the Holy Aedicule special scanning strategy was designed, 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. The density of the scans was selected to 1 point every 5 mm, to record all fine details, even those necessary at a later stage (Georgopoulos et al., 2018).

B. Spatial Monitoring System

The Spatial monitoring system is part of SHM systems and provides spatial information for the structure with accuracy of the order of ±1mm (Delikaraoglou et al., 2010; Lambrou et al., 2011; Pantazis, 2015) by using special total stations and reflectorless.

In the case of Holy Aedicule monitoring it was decided to apply two types of spatial monitoring. The periodic monitoring, where measurements of a network take place at specific longtime intervals (every week, every month etc.) followed by detailed data post processing and the successive monitoring, where measurements on targets are carried out at much shorter time intervals (every hour, every 15 minutes, etc.) followed by simpler real-time data processing.

Periodic monitoring offers the following advantages: (i) more accurate and reliable results through integrated least-square adjustment, (ii) the estimation of relative displacements between consecutive time intervals, (iii) the possibility to detect displacements of the site around the monument, and (iv) the spatial vectors of displacement of each measurement point can be calculated and the accuracy and reliability of results can be assessed with statistical checks.

Additionally, the advantages of successive monitoring are: (i) continuous monitoring of spatial information over shorter time intervals, (ii) real-time information on very small deformations of monitored points during restoration works which acts as a warning detector, (iii) outlier detection and relative alarm, (iv) capability of remote monitoring, (v) results are expressed as diagrams of relative displacements between successive time intervals for each point in each direction and scatter plots for the overall assessment of a displacement.

C. Diagnostic Study

A diagnostic study involved the prospection of the internal structure of the Holy Aedicule, which, despite the monument’s importance, was not fully documented in the past. To achieve this, ground penetrating radar (GPR) was used in conjunction with architectural analysis, to elucidate the construction layers of the Aedicule (Lampropoulos et al., 2017) and identify remnants of the original monolithic Tomb. The GPR findings were utilized in the 3D modelling of the internal structure of the Aedicule (Agrafiotis et al., 2017). In addition, other non-destructive testing methods (Alexakis et al, 2018) were used (such as infrared thermography, digital portable microscopy) as
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As analytical testing (thermal analysis, X-Ray diffraction) to study the prevailing decay factors (Apostolopoulou et al., 2018), the state of preservation of the building materials and the Aedicule structure.

III. RESULTS AND DISCUSSION

A. Geometric Documentation Results

On May 2015 916 images were acquired, both for the interior and exterior. On January 2016 the Holy Aedicule was scanned from 58 scanner positions, both for the interior and exterior (Fig. 1, 2).

On 7-13 of October 2016, the facades of the Holy Aedicule were scanned from 50 scanner positions and 2,463 images were acquired (Fig. 3). On 11-15 of January 2017, the facades were scanned from 18 scanner positions and 1,735 images were acquired. On February 2017, the facades were scanned from 28 scanner positions and 389 images were acquired (Fig. 4).

Between 25-29 of October 2016, 860 images were acquired using the CANON EOS-6D full frame CMOS digital camera. The 3d textured models and the orthoimages of the opened Tomb and the observation window were produced applying Image Based Modelling techniques, exclusively (Fig. 5, 6).
The acquisition of data for the documentation of the final phase took place on 5-9 of March 2017, were 1,283 images for the interior and 1,800 images for the exterior were acquired and the Holy Aedicule was scanned from 57 scanner positions, both for the interior and the exterior. The detailed 3d textured model as well as the orthoimages were produced applying the methodology described above (Fig. 7).

From the 3D model of each phase, the production of sections at specific positions was also possible, supported by suitable geodetic measurements (Fig. 8, 9).

The geometric documentation products (such as sections per 10 cm – see Fig. 10, 11) were utilized, in conjunction with information from materials characterization and non-destructive prospection of the internal structure, for the development of the Holy Aedicule Finite Element Model, to study the static and dynamic behavior of the structure, prior, during and after the rehabilitation works (Spyrakos et al, 2019).
The advanced Total Station (TS) Trimble S9 was used for the measurements. It provides accuracy in the distance and direction measurements of ± 0.8mm, ± 1ppm and ±1″.

### 1.1 Periodic monitoring

The periodic monitoring was applied 8 different times from July 2016 to January 2017. A ninth measurement was carried out at the completion of the works in March 2017, in order to be used as reference for the future monitoring of the Holy Aedicule.

The RMSE of the coordinates \( x, y \) and \( H \) of the network points, \( \sigma_{x_i} \) and \( \sigma_{y_i} \) fluctuates from ±0.1mm to ±0.3mm as \( \sigma_H \) fluctuates from ±0.1mm to ±0.2mm. This means that it is a high-sensitivity network, able to detect displacements of 1mm for 95% confidence level.
The TS was set successively at points 1, 2 and 3, from where all visible prisms were sighted. Each prism was sighted at least from two network stations where horizontal angles, vertical angles and distances were measured and registered, in order to formulate the required equations for the least-square adjustment.

In order to achieve maximum required accuracy, the TS height, when it is set at points 1, 2 and 3, was measured according to a special methodology using a digital level and a rod, ensuring instrument height accuracy of $\pm 0.1\text{mm}$ to $\pm 0.2\text{mm}$ (Pantazis et al. 2017).

1.2 Successive monitoring

The successive monitoring started on August 31st 2016. The TS was placed at point 2 of the network. The position of this point (Fig. 13) ensured a clear view of ten network prisms, eight of which are situated on the roof of the Holy Aedicule. These prisms were automatically sighted every 10 or 20 minutes from 7 pm to 7 am every day.

The time interval was defined according to the requirements of the restoration. The TS was connected via cable to a laptop (Fig. 13).

The software Trimble 4D Control was used which enables: (i) communication with the TS, (ii) definition and organization of the monitoring scenario, (iii) registration of measurements, (iv) measurement check and data management, (v) real-time tabular and diagrammatic results presentation (Fig. 14), (vi) decision making. Internet access at the worksite is required for data transfer to any authorized PC worldwide, so that any authorized user can be informed and evaluate the results in real-time.

C. Multispectral input from non-destructive testing and materials documentation

One of the innovations of the Holy Aedicule rehabilitation project in the field of transdisciplinary multispectral modeling and cooperation for the preservation of Cultural Heritage, was the successful merging and cross-utilization of digital data from geometric documentation, materials characterization, structural prospection, architectural and structural analyses, within an integrated core space and multispectral approach (Fig. 15).

Digital documentation of the project did not only focus on the products of geometric documentation and monitoring. It also included information from non-destructive and analytical techniques regarding the type and state of preservation of the building materials, their position, spatial distribution and inter-relation within the Aedicule structure and how these affected the thermohygric and dynamic behavior of the structure.

Specifically, GPR revealed the internal layers of the Holy Aedicule (Fig. 16), which consisted of a main masonry effectively surrounding the remnants of the original Tomb of Christ (Lampropoulos et al, 2017). This masonry was not visible – prior to the initiation of the rehabilitation works - as it was covered with external stone facades, with and interlayer of a filling mortar; the latter was to a large degree responsible for the observed deformation of the external facades, due to swelling of the mortar from rising damp (Moropoulou et al, 2017).
IV. CONCLUSIONS

Through this work, interdisciplinarity was critical throughout all stages of the project. Geometric documentation data provided the basis for all associated technical analyses (architectural and structural). However, the related products, both geometric and finite element models, would not be representative of the actual Aedicule structure, without accurate knowledge of the internal layering and the building materials. The fusion of information from geometric documentation and monitoring, materials characterization, non-destructive prospection, throughout all stages of the project, provided detailed models of the Aedicule, that could analyse the observed deformations and state of preservation, predict the dynamic behavior of the existing structure, and after the implementation of the works, verify the achievement of structural integrity and reinstatement of verticality of the Holy Aedicule. It, thus, highlighted the importance of fusion of information from different scientific fields, in order to accurately assess the state of preservation of cultural heritage assets and their response to environmental factors.

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