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3D survey and BIM-ready modelling of a Greek Orthodox Church in Athens

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***Abstract* – This paper explores the application of two widely-used digital technologies, Structure-from-Motion (SfM) photogrammetry and Building Information Modelling (BIM), in the case of Byzantine ecclesiastical architecture. SfM photogrammetry was used for the 3D documentation of Agioi Anargyroi Greek Orthodox church in Athens, including exterior and internal spaces, using a combination of ground-based and aerial (UAV-mounted) photography under rigorous survey control. The resulting point cloud dataset constitutes the primary survey record of the building in its current state (as-existing). Finally, a BIM-ready model of the existing structure was proposed as an alternative method for the production of coordinated 2D drawings and facilitating requirements of subsequent development of the project.**

I. INTRODUCTION

In the last decade, Structure-from-Motion photogrammetry (SfM) has been used extensively as a method for 3D documentation of cultural heritage, ranging from large-scale landscapes, historic buildings, monuments, museum objects and artefacts. A growing range of SfM software applications are currently available to an expanding base of users in the heritage sector, corresponding with significant volume of academic research and publications in the field [1][2][3]. The use of SfM photogrammetry (along with other technologies such as laser scanning and close-range scanning) for the digitization of museum collections is becoming ever more widely practiced, as evidenced by the growing output of 3D digital models of cultural heritage objects in web-based 3D viewing and sharing platforms [4]. The relatively low starting costs, versatility and high-quality of visual output (textures) makes SfM photogrammetry an attractive solution for 3D recording of complex historic monuments. This paper looks at the application of SfM for the survey of a significant early example of Byzantine ecclesiastical architecture in Greece.

Building Information Modelling is a technology more widely used in the new-build construction industry. However, in the last five years, the concept of Heritage (or Historic) Building Information Modelling (HBIM) has become of hot topic for research, while in some countries relevant legislation encourages or even enforces the uptake of BIM by the heritage sector (mainly concentrating on construction projects involving historic buildings) [5][6]. Greece has no such legislation at the moment.

Unlike BIM for new-build, where the model develops along with the design and construction phases of a project, BIM for existing buildings (EBIM) and BIM for historic buildings (HBIM) generally requires a significant upfront investment of time and associated costs to create a fully developed as-existing BIM model, which represents not only the geometry but includes also material properties and other information about the various components of a building. The term 'BIM-ready' has been used to describe a 3D model created as an assembly of components in a BIM environment, which represents the geometry of the existing fabric, without incorporating any additional information [7].

II. CASE STUDY

The Greek Orthodox church of Agioi Anargyroi in the neighbourhood of Psyri, Athens, is an 11th century Byzantine building of the cross-in-square type, with significant later alterations (after 1908) [8]. The original form of the building is depicted in a c. 1835 engraving by Stademann, where the tall central tower appears to dominate the area [9]. In the beginning of the 20th century, the parish required additional space, which resulted in alterations of the West façade with the addition of two bell towers and an internal gallery, all in the neoclassical style. The building is listed as a historic monument by the Greek Ministry of Culture [10].

The church consists of external load-bearing masonry walls, with later (20th century) additions of steel H sections bound with strong mortars, which support the internal gallery. The building has suffered structural damage from two earthquakes (1981, 1999); cracks can be observed in several areas, both in the masonry wall and on the domes. This suggested a need for detailed investigation in order to plan consolidation and conservation works.

III. OBJECTIVES

The main objective of the project was the creation of an accurate and detailed 3D record of Agioi Anargyroi (interior and exterior) in its present condition (as-existing). The data will be used by structural engineers for an assessment of the building's structural integrity and defects. Further to that, architectural 2D drawings were required for planning applications for subsequent repair or structural stabilisation works.

Structure-from-Motion photogrammetry (SfM) was selected as the survey method, as it supported the recording of high level of detail (stone-by-stone) and high-quality visual output.

The delivery of 3D models was not part of the brief, however the creation of a BIM-ready model of the existing structure was proposed as an alternative method for the production of coordinated 2D drawings and facilitating potential requirements of subsequent phases of the project. The project was used as a case study to investigate whether BIM-ready modelling could be a viable tool under the constraints of a commercial project, as applied to buildings of Byzantine-style ecclesiastical architecture in Greece.

IV. SURVEY

Structure-from-Motion photogrammetry was selected as a suitable method for producing a 3D record of Agioi Anargyroi, aiming for a complete point cloud with overall positional accuracy of 1-2cm. This method also allowed the production of a 3D model with high-quality textures covering both exterior and interior surfaces, especially important considering the Byzantine-style wall paintings (hagiographia) that cover most interior surfaces. SfM photogrammetry allowed the combination of a metrically accurate 3D record and high-quality photographic documentation of surfaces, resulting in a complete record of the building in its existing condition (as-existing).

A. Design of control points and photography plan

The network of control points was designed, after an initial inspection of the building and its setting, to fulfil mainly the following criteria:

- Control points should be visible from as many locations as possible;
- Control points should not be coplanar;
- Sufficient number of control points to achieve accuracy requirement.

The photography plan was split into:

- Aerial (UAV-mounted) nadir photography;
- Aerial (UAV-mounted) oblique photography;
- Ground-based external photography;
- Ground-based internal photography.

For this type of work, the following criteria were met for planning photography (image acquisition for SfM photogrammetry): frontal overlap of minimum 70% and side overlap of minimum 60% between adjacent images. A detailed photography plan can and should be created in the case of aerial photography (UAV-mounted), while the strict observation of overlap criteria alone is generally sufficient for ground-based photography. In this case, a detailed flight plan was only possible for nadir photography; Agioi Anargyroi are set in a densely-built area, surrounded by tall buildings, which limited the potential for oblique photography. Therefore, aerial oblique photography did not follow a pre-designed flight path, but was conducted in a free-form way by checking each frame to ensure overlap criteria were consistently met.

Fig.1: Flight path for nadir UAV photography.

B. Establishment of control network and measurement of control points

A survey control network of 12 stations (6 outside, 6 inside) was established and measured by Total Station with forced centring. The control network was subsequently referenced to the Greek National Grid (EGSA '87) using RTK GPS. The accuracy of the control stations was estimated between 4-5mm. A number of photogrammetric control points were placed according to the criteria detailed in the previous section (13 outside and 24 inside), placed on various surfaces and at different heights. Control points were measured by Total Station from the control network stations. The accuracy of control points (error ellipsoids from a least squares adjustment of the network) is depicted in Fig.2. The adjustment of the survey control network was performed in surveying application VERM.

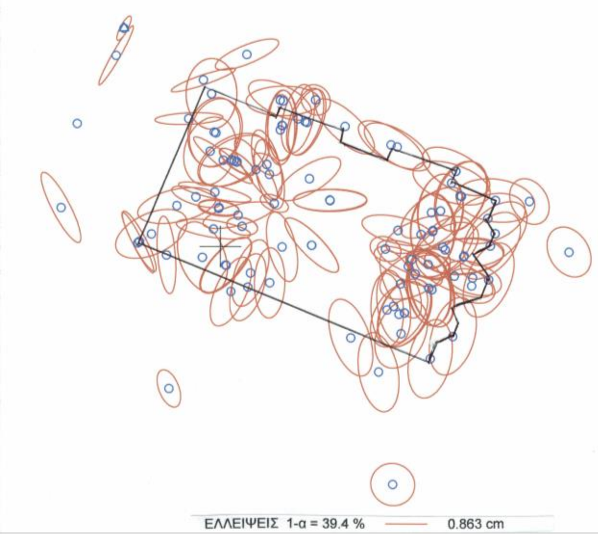

Fig.2: Error ellipsoids for control points (VERM).

C. Photography

A total of 2,314 images were taken from various locations around the site with a SONY NEX5N (16MP) camera. UAV-mounted photography was taken at nadir from 75 locations only, but 2-3 images were taken from each location (subsequently 96 images were used for calculations). The interior of the church was captured at various heights using a custom-built lighting system to counteract the low lighting conditions.

Table 1: Photography details.

Area	Type	Lens	Images
Exterior	Aerial (UAV-mounted); nadir	f=16mm	96
Exterior	Aerial (UAV-mounted); oblique	f=16mm	255
Exterior	Ground-based	f=12mm	313
Interior	Ground-based	f=12mm	1,650

D. Image processing and production of 3D point cloud

All images were pre-processed to correct for lighting variations and contrast. Images were then processed in Pix4D in two groups: exterior and interior. Additional manual tie points were identified in most images, to increase alignment reliability. The total geolocation accuracy of both point clouds was 4.0 and 4.5mm respectively. The results of processing in Pix4D are summarized in Table 2.

The internal gallery above the West entrance of the church had been converted to a storeroom and was full of objects at the time of field work. Free space in that area was minimal, which severely limited possible locations and angles for photography. Similarly, the internal spiral staircases inside the bell towers were very narrow, which again did not allow for sufficient coverage with photographs. Images taken in those spaces (127 total) could not be aligned by the software and were subsequently removed from the dataset.

Two point clouds and corresponding textured 3D meshes were produced in Pix4D. The external point cloud was also used to generate a georeferenced orthophotomap of the wider site, which was exported in DWG format to be used in CAD and other applications. CloudCompare was used for further editing of point cloud and mesh data to create a unified point cloud and a mesh model of the entire building.

Table 2: Image processing results (Pix4D).

Area	Images	Control stations / Control points/ Manual tie points	Accuracy	Point count
Exterior	664	6 / 13 / 10	4.0mm	27,343,541
Interior	1,650	6 / 24 / 33	4.5mm	68,618,559

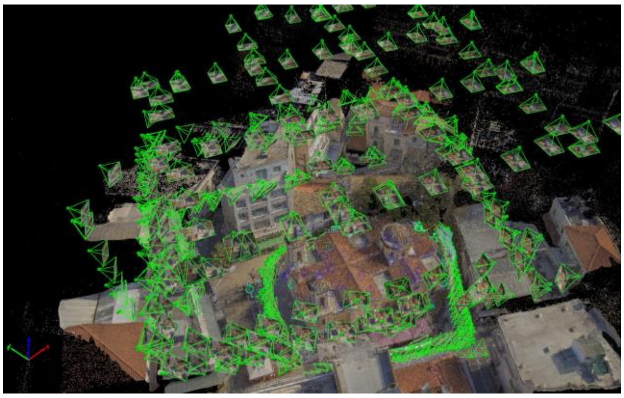

Fig.3: View of external 3D point cloud with camera positions (Pix4D).

Fig.4: View of internal 3D mesh with camera positions (Pix4D).

E. Conclusions on application of SfM photogrammetry

The combination of ground-based and aerial photography (UAV-mounted), can produce a 3D model of building exteriors with almost complete coverage. High-level areas (roofs, tops of walls and parapets), which are impossible to capture from the ground (with photogrammetry, conventional survey methods or laser scanning), were successfully documented using nadir and oblique photographs from a UAV-mounted camera.

Based on experience from this project, the application of SfM photogrammetry was assessed to produce satisfactory results for most internal spaces. However, small and cluttered spaces limit the possible angles for data capture and proved problematic. In such cases, the dataset produced by SfM photogrammetry could be supplemented by other methods of 3D survey, such as laser scanning, or, if not available, by conventional survey methods. Control of lighting conditions, especially for interior spaces, is highly significant. In this case study, the use of a custom lighting rig proved effective in improving low lighting conditions in the interior of the church.

Compared to early attempts, the results of SfM photogrammetry are clearly improved by increasing the number of images used, both with regards to camera alignment and the density of the point cloud produced. Camera alignment and the accuracy of the resulting dataset is improved by increasing the number of measured control points and manual tie points. These must be identified in all photos, where they are visible. Control points must be measured with high-accuracy using a suitable control network.

V. BIM-READY MODELLING

Survey deliverables in this stage of the project were limited to a set of 2D drawings, derived from the point cloud. The process of producing these in a CAD solution, such as Autodesk AutoCAD, is straightforward and involves "tracing" the point cloud with 2D drafting tools in the required views (plans, elevations, sections). In the case of a historic building of this type, this method can result in a set of accurate 2D drawings documenting the existing condition as a limited set of preselected views.

The creation of a BIM-ready model offers some advantages over this methodology: when the model is used to extract 2D documentation, all views are automatically coordinated. Moreover, additional views can be automatically extracted at any time and not limited to the predetermined set of drawings. However, due to the complex and irregular geometries that make up most historic buildings, achieving the same level of accuracy in the final 2D documentation proves problematic. A compromise had to be made between modelling time, file size and model functionality (e.g. using parametric BIM components rather than imported mesh geometry) versus modelling tolerance, i.e. how close the model is to the point cloud dataset, which constitutes the primary survey record.

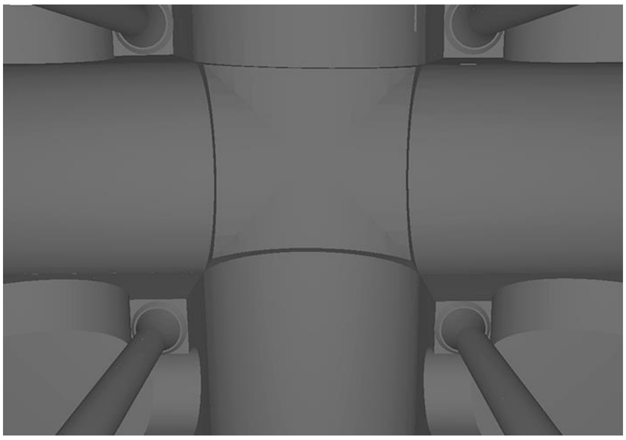

Fig.5: View of vaults over crossing (Archicad).

At this stage of the project, a model was created in Graphisoft Archicad (versions 19-20), which supports point cloud datasets (imported in E57 format). The point cloud was interpreted into an assembly of components, using parametric tools in Archicad. A mixed modelling approach was adopted, which combined simple 3D geometry with a number of repeatable parametric components. For this model, some components from standard BIM content libraries were used (arched windows) and others created from scratch when appropriate components were not readily available (e.g. columns)[Fig.6]. These components can be replaced by more accurate and detailed custom content in future iterations of the model. The archways, vaults and domes were all modelled using 3D geometric tools in Archicad (Shell and Morph), but their use was deliberately limited as much as possible in order to maintain model functionality, given that geometry of this type does not interact with other parametric objects in the same way as true parametric components.

Fig.6: Example of custom object (column, left) and simple 3D geometry (right) created in Archicad.

The model includes architectural features rendered at a basic level of detail and aiming for a modelling tolerance of 5cm. Some features (cornices, decorative friezes) were rendered as simplified forms, but that was sufficient for producing 2D drawings at 1:50 scale. The set of 2D deliverables created from the model were also checked again the point cloud to verify their accuracy.

A. Challenges

Modelling a historic Byzantine-style church in a BIM environment presented several challenges:

(1) Typical components of Byzantine architecture are generally not available in BIM libraries, thus creating the need for custom content creation.

(2) Historic fabric does not typically consist of well-defined geometries due to decay and alterations, which forces a compromise between the use of repeatable components and modelling tolerance.

(3) Complex historic construction systems do not always conform to pre-determined model hierarchies and component typologies, as is the case with complex Byzantine vault systems. Simple geometric forms can be used to represent these structures, preferably using the in-built tools available in a BIM application over importing non-native geometry.

(4) The internal composition, material properties and performance characteristics of historic fabric were largely unknown. Unless in-depth investigations take place, only the creation of a BIM-ready, as opposed to a true BIM model, is possible.

B. Advantages:

(1) The BIM-ready model facilitated the consistency of 2D documentation;

(2) Developing a basic model in a BIM environment presented additional possibilities for visualisation, further development of the project and better communication among a multi-disciplinary project team (surveyor, architect, structural engineer, and client).

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