The Use of UAVs and Photogrammetry for the Documentation of Cultural Heritage Monuments: The Case Study of the Churches in Cyprus

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ABSTRACT: Innovative technologies provide an accurate, simple and cost-effective method of documenting cultural heritage sites and generating digital 3D models using novel techniques and innovative methods. These digital 3D models can then be saved in a central database that can be accessed by end users. The project "Digital unblocking of holy islands" proposes digital service requires the creation of digital infrastructure and its enrichment with culturally digital evidence and data, in order to serve as an information hub for the management and promotion of ecclesiastical cultural heritage. The internal and external digitization of ecclesiastical monuments will be carried out using several methods, including images from Unmanned Aerial Vehicles and photogrammetry. Hundreds of images from the monument will be taken using a UAV with an attached high-resolution camera. The images will then be processed through photogrammetry to provide a digital model of the church. The use of digital technology to document cultural heritage within a structure, creates a dynamic database and valuable resource to better understand the cultural heritage monument, as end-users will be able to access the information from the digital platform at any time.
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KEYWORDS: Remote Sensing, photogrammetry, Cyprus, Cultural Heritage, ecclesiastical monuments, artefacts

1. INTRODUCTION

Digitization of cultural heritage is a multidisciplinary procedure of cultural heritage management in a technological environment, where an object, image, document or a signal is represented by a discrete set of its points or samples [1-3]. Many cultural heritage sites may be inaccessible due to their location and are affected by natural and anthropogenic factors. Therefore, digitizing cultural heritage sites can assist in restoration and conservation efforts, as well as providing the general population with digital access to the site [4,5]. However, there is a decided lack of documentation and technical information in many existing historic buildings [6,7]. 3D scanning and photogrammetry technologies are particularly relevant for accelerating spatial data collection from existing buildings, as well as for rapid intervention conditions are dangerous.

Currently, only 10 percent of the world's historic sites are digitized [8]. The importance of digitizing cultural heritage sites was apparent in the recent fire of the Notre Dame Cathedral in April 2019. Dr Andrew Tallon, was the only person to digitally scan the entire 850-year-old cathedral [8]. His precise measurements, accurate to within five millimeters or 0.1969 inches, are the only modern record of the cathedral just as it was on the day it was partially destroyed, which will prove invaluable to the reconstruction of the cathedral. Tallon created a billion data points with his laser scanners inside Notre Dame by taking panoramic laser scans from 50 different spots, as well as panoramic photographs at each scanning point, which he then used as a background for the scans to create a full 3-D model that will be exactly to scale. [8,9].

Information and Communication Technologies (ICTs) provide researchers with powerful tools to deal with the digital acquisition, storage, conservation, recreation, reconstruction, and representation of CH assets, both tangible and intangible. information and images about the original condition of the destroyed or damaged objects in order to re-create them as 3D models [10]. As well, such techniques for monitoring and documenting cultural heritage sites provide a long-

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term method to examine cultural heritage sites over time [11]. Close-range remote sensing, in conjunction with appropriate algorithms and data processing methodologies, allow data acquisition and interpretation in a fast, reliable and accurate way [11]. Several countries have already created databases for the management and preservation of cultural heritage, including Italy, Serbia and Bosnia-Herzegovina [12-14]. In its strategic initiative i2010 Digital Libraries, COM (2005) 465 final, Brussels, 30/09/2005, the European Commission proposed the European strategy for digitalisation, on-line access and digital preservation of the cultural heritage [15].

During the last years the use of UAVs for aerial surveys is becoming a consolidated application, commonly used for obtaining 3D models of the outer side of buildings [16]. UAVs can be used as a precise, automated and computer-controlled data acquisition and measurement platform, as a result of low-cost sensors such as off-the-shelf digital cameras, GPS/INS (Global Positioning System / Inertial Navigation System) based stabilization and navigation units [17]. In cultural heritage area UAV applications are mainly focused on documentation, observation, monitoring, mapping, 3D modelling and 3D reconstruction [18] as well as digital maps, digital orthophoto, digital elevation model (DEM) and digital surface models (DSM) [19]. UAV aerial imagery in combination with photogrammetry are emerging technologies providing an innovative approach to 3D documentation of cultural heritage [17].

Innovative digital applications in the field of protection and enhancement of cultural heritage, as well as the threats to archaeological and cultural remnants of the past, create important, innovative requirements and challenges of protecting cultural wealth of a country. The "Digital unblocking of holy islands" project uses traditional and photogrammetry methods and proposes digital service which requires the development of a digital infrastructure and its enrichment with culturally digital evidence and documentation data, in order to serve as an information hub for the management and promotion of ecclesiastical cultural heritage. It is an ongoing research project aiming to acquire 3D digital datasets of mass historic religious monuments and artefacts in the areas of the Archdiocese of Crete in Greece and the Holy Bishopric of Limassol in Cyprus [20]. The project's data will be also explored so as to create a geo-database linked with a Geographical Information System (GIS) platform, which will act as the digital atlas of the religious monuments [20].

The methodology for the mass digitization will be based on advance methods, aiming for fast but accurate processing. Therefore, the digital documentation record includes close range photographs, stereopairs, UAV images and point clouds, both internally and externally of facades and relics of selected monuments [20]. Following, the data will be exported into a Building Information Model (BIM), in order to gain knowledge from the existing structure regarding the structure and materials in order to interpret how the church was built. By using BIM, cultural heritage experts will be able to understand the geometry and the construction methods of the church in order to rebuild the model of the cultural heritage site as accurately as possible

2. METHODOLOGY

The project involves the documentation of several churches in the Limassol district, in the South coast of Cyprus. For each church, ground control points (GCPs) were first placed inside and outside of the church. The inside of the church was photographed using a hand-held camera, while the outside of the church was photographed using a camera mounted on a UAV. Following, Structure for Motion (SfM) photogrammetry software was used to generate a point cloud of the church. The completed point cloud was then exported into Building Information Modeling (BIM) software for documentation. The complete methodology is featured in figure 1.

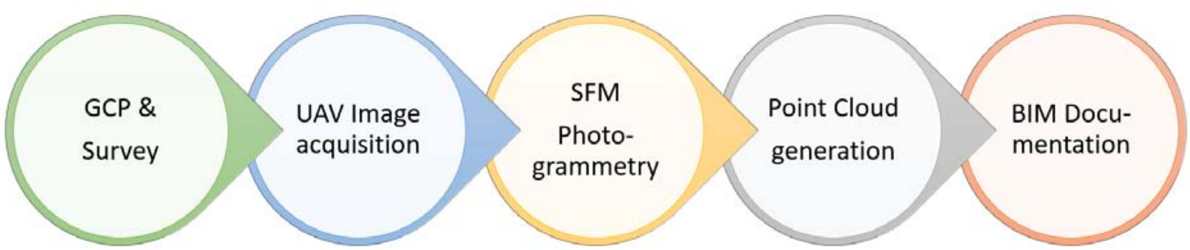

Figure 1. Methodology

2.1 UAVs

UAVs provide an affordable, reliable and straightforward method of documenting cultural heritage sites due to their affordability, reliability, ease of use, and the quality of the processed measurements [21-24]. Research indicates that aerial remote sensing and imaging can be conducted using large-scale low-altitude imaging and geospatial information [21, 25-27]. Research indicates that UAV data provide more detailed surveys of the archaeological site [28-33], which are used to document the site. UAVs are also useful to survey inaccessible and/or dangerous areas which cannot be accessed directly using other systems or piloted aerial systems [34, 35]. Also, researchers have used the combination of aerial imagery for 3D reconstruction of the cultural heritage site [35, 36].
Remote sensing technologies on a UAV platform are extremely useful for the detection and monitoring of cultural heritage features [37-40]. UAVs can be an efficient, non-invasive, and low-cost resource to document cultural heritage sites [37-40] and can be fitted with sensors which are able to produce an unprecedented volume of high-resolution, geo-tagged image sets of cultural heritage sites from above [37, 38, 41-43]. Researchers have used the combination of aerial imagery for 3D reconstruction of the cultural heritage site through the use of photogrammetry [35, 36].
Recent developments in photogrammetry technology provide a simple and cost-effective method of generating relatively accurate 3D models from 2D images [37, 44-48]. Aerial images taken from a UAV can be used to create ortho-photos, dense clouds, 3D model and Digital Elevation Models [44, 49]. It is necessary for the UAV to be equipped with a high resolution RGB camera to acquire images over the area of interest. The area should have fixed ground control points (GCPs) for geo-referencing in order to produce a photogrammetric ortho-image and point cloud 3D model of the area of interest and for comparison over temporal intervals. [(44, 50].

2.2 Photogrammetry

Photogrammetry is a precise 3D measurement technique based on the triangulation of several high-quality images that allow for the collection of semantic and spatial data of a building or object to be accelerated. Photogrammetry is able to generate full-color 3D and 2D models (in the various light spectrum) of the terrain [51]. The main outputs of photogrammetric surveys are raw images, ortho-photos, DEM and 3D points clouds created from stitching and processing hundreds or thousands of images. Several widely used commercial software are available in order to obtain 3D reconstructions of such buildings from images acquired by UAVs [52-55]. These tools, usually based on the Structure from Motion (SfM) approach, enables 3D reconstruction with camera self-calibration. The introduction of GNSS measurements in the photogrammetric reconstruction procedure, corresponding to the camera locations during image acquisitions, reduces the error level.

Agisoft Metashape Pro photogrammetry software was used to conduct the image processing. Agisoft Metashape is capable of interpolating digital images in order to create high resolution, scaled and georeferenced 3-D models from them [56]. All clear images with sufficient overlap were included in the processing in order to generate a dense point cloud of the church. Ground Control Points (GCP) were applied to correct the scale and geo-reference the model. To complete the georeferencing task, the program requires either Global Positioning System (GPS) coordinates associated with cameras, provided in an EXIF/ plain text file or GCP coordinates that can be used to achieve higher accuracy (up to 1 cm). Based on the latest multi-view 3D reconstruction technology, the software operates with arbitrary images and is efficient in both controlled and uncontrolled conditions. Photos can be taken from any position, providing that the object to be reconstructed is visible on at least two photos with sufficient overlay. Both image alignment and 3D model reconstruction are fully automated. Figure 2 indicate the location of the aerial images and the GCPs used for the photogrammetry [51].

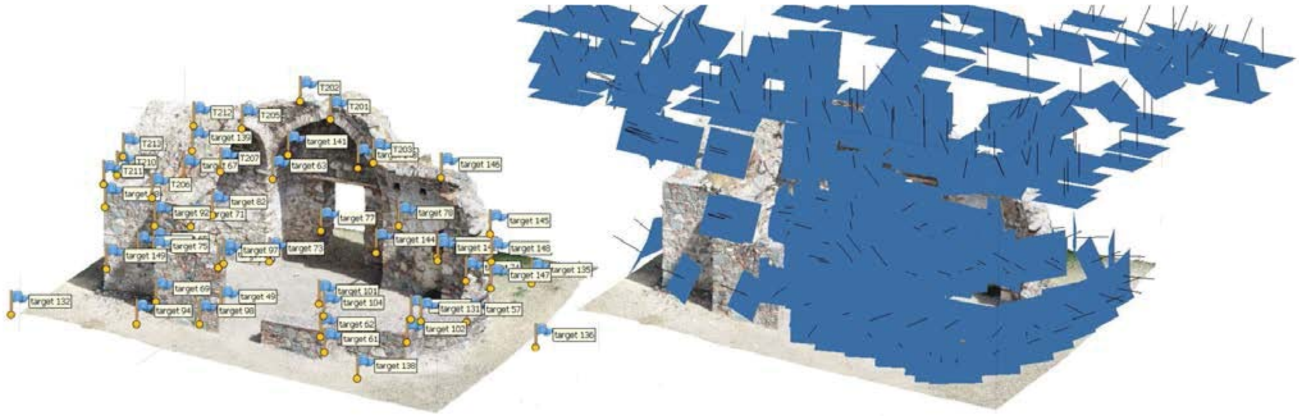

Figure 2: Left: Location of GCPs. Right: Image acquisition positions

The software implements image orientation and mesh generation through SfM and dense multi-view stereo-matching algorithms [57]. The first step in the program's procedure is SFM, which is a valuable tool for generating good quality meshes from images in a semi-automatic way [57]. At this stage the software analyses the dataset, detecting geometrical patterns in order to reconstruct the virtual positions of the cameras that were used [58]. SfM analyses the data-set, detecting geometrical patterns in order to reconstruct the virtual positions of the cameras that were used in order to align the images, including building a sparse point cloud (tie points) [58].

The second step involves the creation of a complete geometry of the scene using a dense multi-view stereo reconstruction. At this stage the dataset of images was employed to produce a high- resolution geometry of the surface [51]. This step successfully creates a 3D model, also known as a Digital Surface Model (DSM). The processing began with the ortho-mosaic production from multiple images. The completed alignment is then used to develop a dense point cloud which uses it to create a surface which allows draping of the imagery over the model by creating and building a texture from the original images and overlays the imagery onto the model mesh [37]. The obtained point cloud has been analyzed in order to extract information that can be useful to characterize the building geometric shape and structure, and to detect potential damages [59, 60]. The software then builds a polygon mesh and calculates a texture for the mesh. Figure 3 features the DSM and the point cloud of the church, which were generated using photogrammetry.

Figure 3: Left: Point cloud of church. Right: DSM of church

Following, surfacing algorithms employ the dense cloud's 3D point positions and the look angles from the photos to the matched points to build the geometrical mesh. The coordinates from the GCPs are then applied in order to scale the model to the correct dimensions. The software automatically aligns images based on pairing of features and creates a "sparse cloud" of elevations based on these points. The completed alignment is then used to develop a dense point cloud which is used to create a surface which allows draping of the imagery over the model by creating and building a texture from the original images and overlays the imagery onto the model mesh [39]. The photogrammetry software then builds a polygon mesh and calculates a texture for the mesh. The software generates the building of 3D models by reconstructing a dense point cloud and generating polygonal mesh model based on the dense cloud data. In addition, photogrammetry has an automatic tool of texture projection, which makes automatic projection from the color directly on the surfaces possible [61]. The completed ortho-photo and the Digital Elevation Model (DEM) of the church are featured in figure 4.

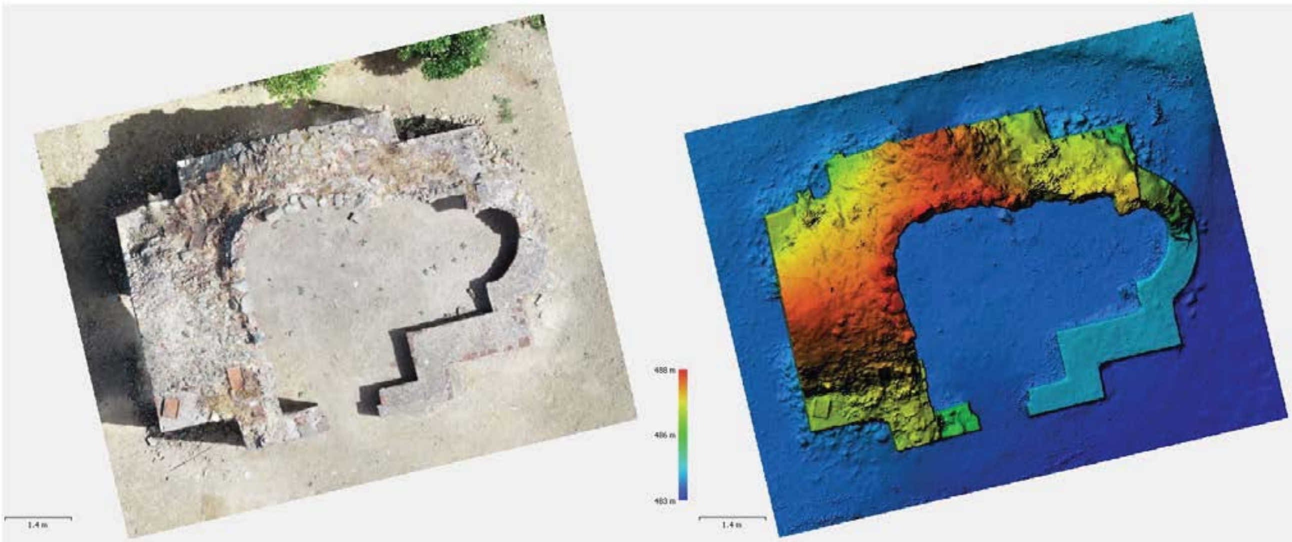

Figure 4: Left: Ortho-photo of the Church. Right: DEM of the Church

2.3 Building Information Modelling (BIM)

Following a phase of a detail data acquisition procedure, a Building Information Modelling (BIM) is used for design and management of projects in the built environment industry. BIM provides a multi layered, multi-dimensional, multi-disciplinary, parametric, smart and informative digital model of a project. Building Information Modelling (BIM) workflows provides the capability to document cultural heritage buildings in order to facilitate the existing building model structure with the information collected from the cultural heritage building in order to create an integrated Heritage Building Information Model [62]. The point cloud to BIM modelling utilizes state-of-the-art technology to convert the point cloud into accurate 3D BIM models. Point cloud to BIM modelling are considered to be more accurate than traditional surveys using measuring tools. The 3D BIM model created from UAV data was integrated with the building semantic data, providing information, such as construction materials, condition, color, texture, etc. [62].

Autodesk Revit software was used to generate a BIM 3D model of the church. The BIM model was overlaid with the point cloud [56]. After the 3D model generation, the point cloud model is converted to the .rcp indexed format and imported into Autodesk Revit software to generate a Building Information Model (BIM). BIM is an intelligent 3D model-based process that involves the generation and management of digital representations of physical and functional characteristics of places. It can also be defined as a BIM virtual information model. BIM design tools allow extraction of different views from a building model for drawing production and other uses. After the BIM model is constructed, drawings of the plans, elevations, and sections of the church can be generated directly from the BIM model for documentation purposes. Also, information such as material, color, height, thickness, etc. can be added to each component in the BIM database. A database was created to include information regarding the structure, including wall height, thickness, material, etc. This provided a valuable source of documentation of the church, for future restoration and maintenance works [56].

3. RESULTS

In this study, the Church of Timiou Prodromou in the village of Arakapas was used as a case study. Arakapas is a village in the Limassol District of Cyprus, located 5 km west of Eptagoneia. The ruined church of Timiou Stavrou (Holy Cross) is just outside Arakapas village, towards the village of Kalo Chorio village. The church is a small, cross-shaped, stone-

built church, which was most likely constructed during the Byzantine era. The stone-built walls on 2 sides, south and west, have been completely ruined, in addition to the roof; however, half of the dome above the altar is still intact.
The survey was conducted on 5/6/2019 using a high-resolution camera to document the inside and outside of the church. To document the outside of the church, 53 ground control points were used. Using the on-board 20MP high-resolution camera, 655 images were generated from a UAV at an altitude of 8 meters were used. The ground resolution was 1.36 mm/pixel. Figure 5 shows the elevations of the church from the North, South, East and West elevation. It is evident that the church lies in ruins and extensive restorations would need to be completed for the church to be functional.

Figure 5: Elevations of the original church from North, South, East and West

Following the photogrammetry process, a 3-D model of the Church was created. The model was also exported into BIM software, so that the missing walls and vaulted ceiling could be included in the image, thereby providing a draft of how the reconstructed church would appear (Figure 6).

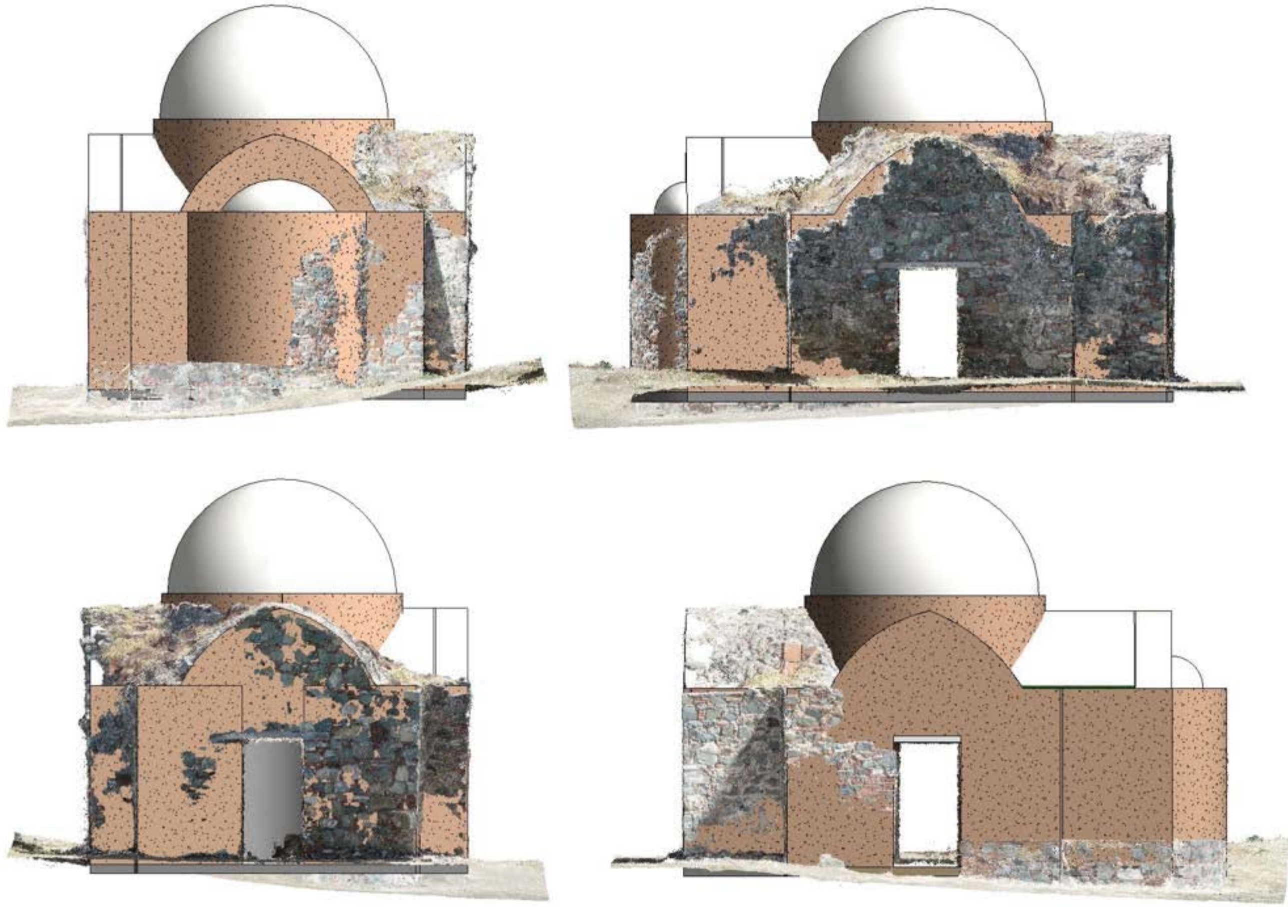

Figure 6: Elevations of reconstructed church from North, South, East and West with the original materials extracted from the digitized model

The floor plans, roof plan and sections of the church were created using the digitized model, in order to analyze and document the building structure (Figure 7).

Figure 7: Left: Floor plan of church; Right: Roof plan of reconstructed church from the digitized model

The end result of the photogrammetry was the creation of an ortho-photo of the church, as well as elevations, sections, 3d models and material texture integrated with the digitized model. The existing 3d model with the reconstructed 3d model are featured in Figure 8.

Figure 8: Left: 3D model of the existing Church right: 3D BIM model of the reconstructed church

Figure 9 features the existing 3D model which clearly documents the extensive damage of the church, as well as the combination of the 3D model with the interpreted digitized model, which shows the walls, roof and dome to the church.

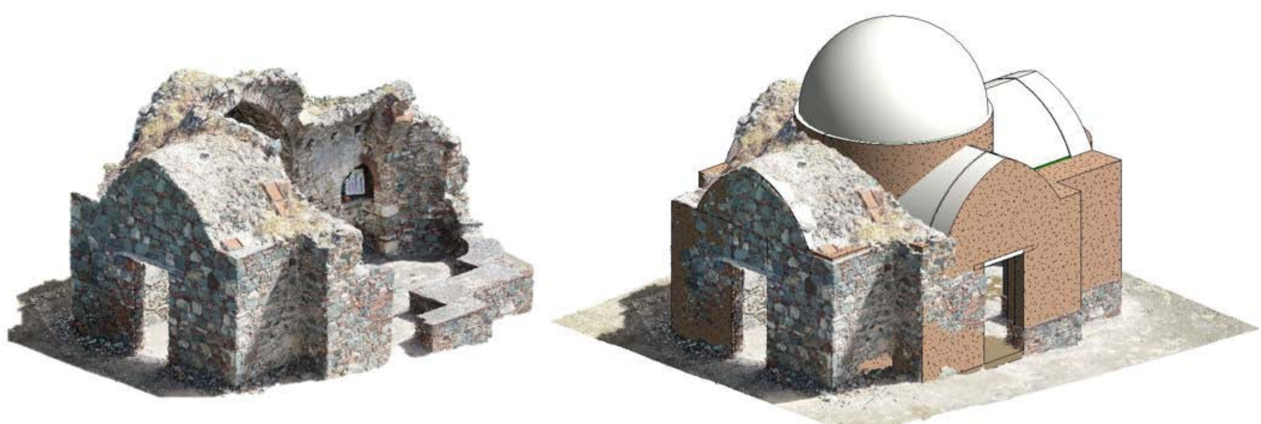

Figure 9: Left: 3D model of the existing Church; Right: 3D model of the reconstructed digitized model

4. CONCLUSIONS

The case study of the Church of Timiou Stavrou in Arakapas provides an excellent example where the high-resolution aerial imagery obtained from the UAVs was imported into Structure from Motion photogrammetry to create rapid and automated generation of a point cloud model and 3D mesh model. The high accuracy of the ortho-image and 3D model can be used to document and monitor changes to the church over time. The point cloud generated can be exported into BIM, in order to produce a BIM model and drawings of the structure. The high-accuracy documentation generated from the BIM model can be used to document the existing state of the structure and have it as a record for future renovation.

One of the most significant conclusions of the case study is the knowledge that is gained through the documentation of the existing church in regard to the geometry of the structure and the building materials, in order to interpret how the church was build. The use of BIM provides the necessary data to understand the geometry of the structure and the construction methods that were used to build the church, which will assist in restoring the church as accurately as possible. The methodology can be considered a valuable tool for documenting cultural heritage sites.

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