UAS-based photogrammetry of cultural heritage sites: a case study addressing Chapel of Espírito Santo and photogrammetric software comparison

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ABSTRACT
The cost-effectiveness of unmanned aerial systems (UAS) makes them suitable platforms to survey cultural heritage sites. Developments in photogrammetry provide methods capable to generate accurate 3D models out of 2D aerial images. Considering the involved technologies, the purpose of this paper is to document the Chapel of Espirito Santo: a very relevant monument for Vila Real (Portugal) that is currently located at the campus of the University of Trás-os-Montes and Alto Douro. The UAS-based aerial imagery survey approach is presented along with photogrammetric process to build chapel's 3D model. Moreover, two photogrammetric software were compared – Pix4Dmapper Pro and Agisoft Photoscan – in terms of modelling accuracy and functionalities ease of use.

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CCS Concepts
•Information systems → Geographic information systems; Data analytics **•Computing methodologies** → Image processing

Keywords
UAV; Cultural heritage; Photogrammetry; 3D models

1. INTRODUCTION
Small-sized Unmanned Aerial Systems (UASs) consist of a versatile, simple and cost-effective technology to perform remote sensing-related tasks [1] in different areas [2]. Their reliability and ease-of-use makes them a good platform to survey cultural heritage sites. Usually, UASs are composed by a remotely piloted Unmanned Aerial Vehicle (UAV) with a set of sensors coupled to it. This allows to acquire georeferenced data with great centimeter per pixel resolution (Ground Sample Distance – GSD). In the

other hand, photogrammetry technology provides a simple and quick method to generate accurate 3D models out of 2D images [3] that can be based on aerial photographs previously collected using UAS.

Cultural heritage and archaeological site surveys are traditionally labor-intensive [4], since areas of interest can easily reach considerable areas. Besides, whist traditional imagery acquisition - by satellite or manned aircraft - is expensive and has a limited availability, terrestrial surveying (topographic or laser scanner) is prone to invasiveness. Alternatively, UASs can be applied to survey historically relevant sites [5] tackling the referred issues.

This study aims to document the historically relevant Chapel of Esp ŕito Santo (Vila Real, Portugal), as well as the driving process used to rapidly produce photorealistic 3D models - so far, working for small-scale cultural heritage sites -, relying on georeferenced imagery acquired with small-sized and low-cost UAS and photogrammetric software. The novelty lies in the documentation of the referred monument by the indicated process.

Photogrammetry was previously considered as a tedious and not appropriate to use and could only be used by expert users [6]. However, current robust and powerful frameworks with straight-forward pipeline turned photogrammetry accessible, even to non-expert' users. Thereby, digitalization of cultural heritage sites can be achieved in different ways, suppressing the need to make 3D modeling operation from the scratch, which is a time-consuming task that can also lead to inaccurate results.

In terms of organization this document is structured as follows: an overview of related work in UAVs applied to cultural heritage surveying is provided in section two; section three, describes the method to plan, acquire and process UAS-based imagery in cultural heritage sites; the fourth section presents the results obtained from an aerial survey performed over Chapel of Esp ŕito Santo and the results from its photogrammetric processing; and finally, section five presents some conclusions and provides next septs towards improving the obtained results.

2. BACKGROUND

3D models' production for cultural heritage and archaeological sites requires a strong methodology able to capture and digitize the models of such places. Due to damage susceptibility either by natural causes or human intervention, cultural heritage sites digital recording, documentation and preservation is required [6]. Digital documentation was simplified by the use of advanced technologies from the Geomatics and Geographic Information Systems (GIS) fields [7]. Data acquisition platforms used in these areas made this process easier, in which a large number of sensors are available for mapping purposes, such as: digital cameras, laser scanners or radars, both with the capability to provide 3D information [6]. Sensor's choice depends on desired accuracy, dimensions of the object or area, location constrains, portability, usability of the instrument, surface characteristics, survey goal, among others [6]. Different approaches where proposed to scan archeological objects based by fusing depth information with camera imagery [8], [9].

UASs platforms are rapidly becoming a valuable source for data acquisition for inspection, surveillance, mapping and 3D modelling issues [10]. Being UASs low-cost alternatives to the classical manned aerial photogrammetry, fixed-wing or rotary-wing UAVs are capable to perform photogrammetric data acquisition in manual, automatic or semi-automatic flights [10]. The UAS-based data can be used in a typical photogrammetric pipeline, where 3D results such as: Digital Surface Models (DSM) or Digital Terrain Models (DTM), contour lines, textured 3D models, among other types can be produced, in a reasonable automated way [10].

The use of UAS in cultural heritage site surveying was applied in several studies. Themistocleous et al. [11] conducted a survey over the cultural heritage site Asinou Church in Cyprus using a rotary-wing UAV equipped with a camera to build the 3D model of the church . Lo Brutto et al. [5] evaluated the usage of both, rotary-wing and fixed-wing UAVs, in two different places of Italy. The Temple of Isis in Agrigento was surveyed with the rotary-wing UAV and a landscape artwork. The Crack of Gibellina was surveyed with the fixed-wing UAV. The authors stated that the generated final products (3D models and orthorectified mosaics) showed a high level of detail, allowing to perform accurate studies and analysis. Themistocleous et al. [4], used a rotary-wing UAV to survey the Panagia Chryseleousa church in Foinikaria, Cyprus. The images were processed to generate an accurate digital 3D model by using Structure from Motion (SfM) techniques. The generated point cloud was used to create a Building Information Model (BIM) that was then used to generate floor plans of the church. Xu et al. [12] used a combination of terrestrial laser scanner to scan building facades and an UAV to scan the building roofs in a temple in China. Achille et al. [13] used rotary-wing UAVs to vertically survey post-seismic environment to extract information identifying the need for potential building interventions. This approach allowed to effectively survey tall buildings in old town centers or congested areas. Stal et al. [10] used a combination of ground and aerial imagery taken by a rotary-wing UAV to produce high detailed 3D models from a Mayan cultural heritage site in Edzná, Mexico. The produced models were published online in a dedicated website and made available through an interactive 3D viewer.

3. DATA ACQUISITION AND PHOTOGRAMMETRIC PROCESSING

This section describes the methodology used in this study. It is composed by three different stages, namely, flight planning, data acquisition and photogrammetric processing as presented in Fig. 1.

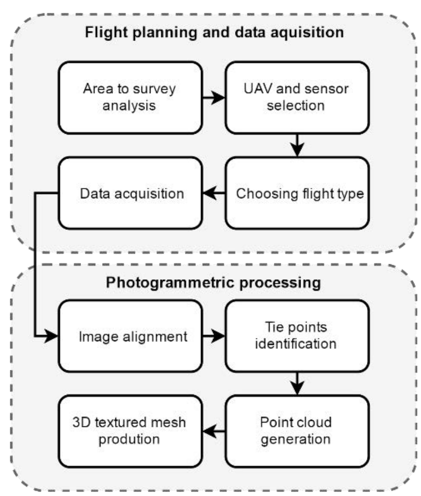

Figure 1 Workflow of the method used to plan, acquire and produce 3D models of cultural heritage sites.

3.1 Flight planning and data acquisition

Flight planning stage relies on the selection of the UAS type and sensor depending on the goal to achieve. Different factors must be evaluated before carrying-out the survey: the size of the area to survey, the spatial resolution and the presence of potential aerial obstacles, along with the weather conditions that can restrict UAS operability. This evaluation leads to a correct choice of the small-sized UAV type to be used.

Since UAS are the main physical structure to be used, two types of small-sized UAVs can be considered: fixed-wing and rotating-wing both have their advantages and disadvantages. Generally, fixed-wing UAVs benefits from longer flight times and longer cover range, allowing to cover larger areas in a single flight. Rotary-wing UAVs, on the other hand, benefits from the ability to stand in a certain position while flying, allowing to acquire data with greater detail in specific regions of interest. Both platforms have the ability to carry imagery sensors to perform data acquisition, however, payload capacity must also be evaluated, usually, depending on the number of rotors, rotary-wing UAVs can support higher payloads. The area to cover is also a characteristic to evaluate because it has direct implication in the autonomy of the UAS.

The aerial platform must be equipped with an imagery acquisition sensor to collect images to digitally reconstruct the site, a GNSS receiver for flight operations and to provide geographical information for each acquired image. The GNSS receiver along with an autopilot module enables to flight autonomously following a predefined set of waypoints, while acquiring images from the area to survey. This UAV-based technique can be used to replace or complement the traditional methods providing an easier and reliable documentation of cultural heritage sites.

Depending on the surrounding area of the cultural heritage site, the suitability to use an UAV to fly close to the scene may vary, in some cases, it may even become dangerous. In areas with no obstacles the UAV can be used in an autonomous flight, *i.e.* full automatic operation mode, by a predefined flight plan. A single-grid flight with the camera set in the nadir position (pointing straight to the ground) is enough to map the whole scene for the generation of an orthophoto mosaic. To obtain more details and for generating a more accurate 3D model, a double grid flight with oblique images (camera set in an oblique angle) or a free flight (manual) mission are more suitable. That way, the vertical parts of the cultural heritage sites can be captured with greater detail. Obstacles that can interfere with UAV risk of operability are: tall buildings, or trees, those obstacles might prevent the use of the UAV in automatic operation mode in lower altitudes. Higher altitude flight might not acquire all the details of the scene. In that case, depending on the obstacle dimensions and coverage, a manual flight in close proximity can be realized, capturing the missing data.

3.2 Photogrammetric processing

After each flight, the acquired data needs to be processed in a photogrammetric processing software. These types of software can generate point clouds, 3D textured meshes, orthophoto mosaics, digital elevation models. These data types will allow users to inspect the site as if they were still present *in-situ*. The generated orthophoto mosaic can be imported to a Geographic Information System (GIS) software to make measurements and further analysis, the same applies for the 3D textured mesh that can be imported to a Computer Aided Design (CAD) software where measurements and annotations can be made, to a 3D rendering software to include in virtual environments to provide virtual visitations. To correct potential inaccuracies the 3D textured mesh can be imported to a 3D modeling software

The process to generate such outputs is composed by different steps, initially, the input imagery passes through an alignment that takes into account internal and external camera parameters along with image coordinates and the overlapping between the images. This step enables to obtain a correct position and orientation of each image obtaining a 3D projection of common identifiable points present in multiple images, also known as tie points. After this step it is possible to add Ground Control Points (GCPs) for geolocation improvements, to delimit the boundaries of a certain area of interest and to mask pixels in the image that are not intended to be present in the final outputs (e.g. pixels representing the sky, certain undesired objects and incorrect estimations). In this way, the identified tie points are considered to generate dense point clouds, according to a set of matching parameters. The generated point cloud is used in the computation of the remaining outputs: 3D models, orthorectified mosaics and digital elevation models.

4. CASE STUDY OF CHAPEL OF ESPÍRITO SANTO

This section describes and presents the results from the application of the data acquisition and photogrammetric processing, previously described in section 3. An UAS constituted by a remotely controlled rotary-wing UAV was used to perform two flights in the cultural heritage site of Espírito Santo Chapel (Vila Real, Portugal). The generated 3D models from both flights are evaluated and compared with an already existing 3D model - manually produced and available in online sources - of the surveyed Chapel.

4.1 Site description

As mentioned, the data used to attest the methodology was acquired from the Chapel of Espírito Santo (also known as Chapel of Bom Jesus do Hospital), presented in Fig. 2, which located in the campus of the University of Trás-os-Montes e Alto Douro in the city of Vila Real, Portugal (41°22'42.7"N; 7°35'01.6"W). This Chapel is original from the fourteenth century and among the years it had been subject to constant site changes in the city of Vila Real, until in the twentieth century it was established in the nowadays location [14].

Figure 2 Chapel of Espírito Santo in its current location.

4.2 Data acquisition description

The data acquisition missions were conducted with DJI Phantom 4 (DJI, Shenzhen, China). This relatively low-cost platform is composed by a rotary-wing light-weight UAV (1380 g) with a maximum flight time of approximately 28 minutes per battery. It comes equipped out-of-the-box with a controller, GPS/GLONASS receiver, camera, and frontal collision avoidance system. The camera has a 12.4-megapixel sensor that allows capturing images with the maximum resolution of 4000×3000 pixels. It is attached on a 3-axis gimbal that allows a good camera stabilization and allows the camera to be pointed horizontally (0°) or vertically (90°).

The imagery acquisition was performed in a cloudy day. Thereby, there was no need to edit images to reduce the shadowing effects. Two different flights were performed. In this study Pix4Dcapture app (Pix4D SA, Lausanne, Switzerland) was used to plan and carry out the flights. Firstly, an autonomous double grid flight was carried out with an overlap of 80% and the camera angle at 80°, in which 82 images were taken at 50m above ground level. This altitude was chosen to avoid trees interference. In the second flight, the UAV was manually piloted to perform two circles around the Chapel, in which a total of 101 images were obtained. This way, the acquired data allows to have a context from the surroundings of the cultural heritage site (nadir flight) and more information related with the site itself (manual flight).

After the flights execution, the images were imported for a photogrammetric processing software Pix4Dmapper Pro (Pix4D SA, Lausanne, Switzerland) and to Agisoft Photoscan (Agisoft LLC, St. Petersburg, Russia), both have the capacity to support the steps described in section 3. Parameters on both photogrammetric processing tools where chosen to be the most similar as possible, after image alignment and sparse point cloud generation, a dense point cloud was created which had some incorrect point estimations, as points belonging to vegetation and clouds estimated in the chapel's roof. However, these inaccuracies were easily corrected by deleting points from the dense point clouds and in the case of Pix4Dmapper Pro also by labelling some images. Next, a 3D textured mesh was generated, in both, with high settings and a texture size of 16384 x 16384 pixels.

4.3 Results

With photogrammetric processing completed, several outputs could be extracted. In the case of this study only the generated 3D models were evaluated. Moreover, from imagery acquired during the nadiral flight an orthophoto mosaic and digital surface model were generated with a GSD of 2 cm, as presented in Fig. 3.

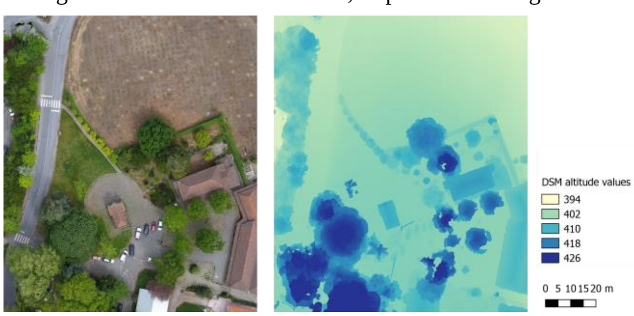

Figure 3 Orthophoto mosaic and DSM of the surveyed area.

Measurements on both generated models from the manual flight were carried out in comparison with measurements taken in the field and both achieved reliable results with a RMSE deviation of 1.8 cm for the model generated from Agisoft Photoscan and 1.6 cm for the model generated from Pix4Dmapper Pro. The usage of GCPs and scale bares could improve this error. A 3D model of the Chapel already existed and was available online [15], this model was constructed using a dedicated 3D modelling software SketchUp (Trimble Inc., California, USA). Fig. 4 presents the front and right facades of the Chapel UAS-based generated models and the manual model available in online sources.

(a)

(b)

(c)

(d)

Figure 4 Front and right facades of the 3D models: (a) facades belonging to the model generated from the nadir flight; (b) facades belonging to the model generated from the manual flight in Pix4Dmapper Pro; (c) facades belonging to the model generated from the manual flight in Agisoft Photoscan; and (d) facades belonging to the model created using SketchUp

By analyzing the generated model from the nadiral flight a notorious lack of detail from the vertical parts is observed, which is directly related with the flight plan. The flight height at 50 meters also has implications in the generated results, which can be noticed in the top of the Chapel's model - more specifically, in the crucifix- and in the windows belonging to the lateral facades. The models generated from the manual flight images is the one with more similarities to the reality, in both cases. Although, when closely analyzed, some inconsistencies that could be easily repaired in a 3D modeling software are observable. Comparing both photogrammetric models with the manually modelled model, it is possible to notice that the later is geometrically inconsistent, mainly in what regards to Chapel's roof. Besides, the quality of the used textures could have been improved. Considering the comparison of the four models, it turns out that the Chapel's generated model relying on manual flight's imagery presented the best results in both, Pix4Dmapper Pro and Agisoft Photoscan.

5. CONCLUSIONS AND FUTURE WORK

This paper addresses UAVs application to survey cultural heritage sites in an efficient and non-invasive way. A DJI Phantom 4 was used to survey the Chapel of Espir ťo Santo with two different flights that aimed to evaluate the photorealism of the models generated by the acquired data. The obtained aerial imagery was imported into the Pix4D mapper and Agisoft Photoscan to generate a high-resolution 3D model. Models generated from the manual flight data in both processing software programs had a high photorealistic level and an error lower than 2 cm. Despite both models having some imprecisions, this can be solved by providing a better dataset of images capturing finer details or by using a 3D modelling software. The acquired UAS-based imagery provided valuable outcomes that can support cultural heritage site digital documentation, Furthermore, the generated 3D models can be used for visual inspection. The computed orthophotomosaic and DSM provided an general overview the area where the Chapel of Espir ťo Santo is located.

As future work, the combination of UAS-based imagery and ground-based imagery will be addressed, to assess if better results can be obtained, usage of fixed-wing UAVs will also be addressed. It is also intended to explore the generated cultural heritage 3D models in virtual or augmented reality contexts.

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