International Transaction Journal of Engineering, Management, & Applied Sciences & Technologies

http://TuEngr.com

PAPER ID: 11A8M

3D DOCUMENTATION OF CULTURAL HERITAGE SITES USING DRONE AND PHOTOGRAMMETRY: A CASE STUDY OF PHILIPPINE UNESCO-RECOGNIZED BAROQUE CHURCHES

January D. Febro [1]

[1] *Department of Information Technology, MSU-Iligan Institute of Technology, PHILIPPINES.*

ARTICLEINFO

Article history:
Received 12 December 2019
Received in revised form 24 February 2020
Accepted 05 March 2020
Available online 19 March 2020

Keywords:
Drone photogrammetry; Cultural Heritage 3D Documentation; Photogrammetry workflow; Drone survey; Church 3D model; Digital cultural heritage site documentation.

ABSTRACT

Cultural heritage sites are legacies that must be preserved. However, anytime it can be ruined, no one can guarantee its continuance. For this reason, one should ensure that they are well-documented. In this study, a photogrammetry technique was used to generate 3D replicas of the Philippine Baroque churches that can be viewed online. A drone was used to acquire data images to test its feasibility as a practical and viable inexpensive tool for digital cultural heritage site documentation. The conclusion of this study greatly benefits the nation considering that digital documentation of cultural heritage sites like the Baroque churches was possible to accomplished by simply using a low-cost, non-intrusive technique, ideal for documenting cultural heritage sites with a high level of accuracy. Furthermore, key factors to be considered for outdoor, large-sites photogrammetry using drones were presented.

Disciplinary: Information Technology, Spatial/Geomatics Engineering.

1. INTRODUCTION

Cultural heritage sites are legacies from our past generations that must be preserved to sustain cultural identity and continuity for future generations. However, a substantial number of cultural heritage sites across many countries are ruined by several factors such as natural hazards, human conflicts, as well as aging and neglect that cannot be restored. Like the 2013 earthquake in the Philippines that struck and damaged the Loboc church and other historic churches in Bohol alone.

Cultural heritage documentation using photogrammetry is essential for cultural heritage preservation, restoration, and conservation. Photogrammetry is defined as "the art, science, and technology of obtaining reliable information about physical objects and the environment through processes of recording, measuring, and interpreting photographic images and patterns of recorded radiant electromagnetic energy and other phenomena" [1]. Studies in the literature review indicate that 3D modelling using photogrammetry technique is valuable in conservation and preservation as it can create a realistic digital copy [2][3]. In fact, the use of 3D models has gained attention lately for cultural heritage site conservation and management [3][4].

Back then, 3D digitization requires expensive and specialized equipment and software but today, the advent of low-cost technology and techniques like drones and photogrammetry offers us an alternative and affordable options. However, there is a dearth of studies involving 3D digitization for digital cultural heritage preservation in the Philippines.

The 3D model development of the Baroque churches in this study was rendered using data images obtained from the drone through the photogrammetry technique. The drone photogrammetric survey creates a 3D model from snapshots that is almost alike to the physical geometry, the reason it is considered to be representative of documentation technology [2][5]. Drones are ideal for capturing high subjects like the roof of a building and tall trees since it has a "higher planar data acquisition rate in upper zones" [6]. Such a method provides low-cost and easy technique of producing relatively accurate 3D models with high accuracy and with the visual completeness of the exterior façade of the Baroque churches. Moreover, 3D digital replication can be easily stored and uploaded on the web for preservation.

This study presents the practicality and usability of drone survey and photogrammetry technique for cultural heritage documentation in the Philippines by digitizing the four (4) Philippine Baroque Churches recognized by UNESCO as one of the World Heritage Structures – namely the Santa Maria Chuch, the Paoay Church, the Miag-ao and the San Augustin Church. In doing so, this also answers the "call for preservation and promotion of the Philippine Cultural Heritage Act 10066". More importantly, the general workflow of 3D photogrammetry is discussed. The support and realization of this study instigate digital documentation of cultural heritage sites to combat potential loss and for the sustainability of our cultural identity for future generations.

2. CONCEPTS AND RELATED WORK

Cultural heritage is not limited to monuments, buildings [24], or collection of things, but it also includes traditions, culture, events, or other non-physical things that are connected to it [7]. The focus of this study is the process of how to digitally preserved the tangible heritage, such as monuments, places, artifacts, and among others that are considered important and worthy where it should be digitally preserved to be passed down for the future generation.

Despite the different approaches in preserving cultural heritage in the world, there are unforeseen factors that will happen that can bring destruction to these treasures. Some of these factors are ongoing deterioration, natural disasters, and human conflict, and wars. Accordingly, the conflict in Central Asia and in parts of the Middle East and West Africa increases the destruction of historical sites. Some of the ruined cultural heritages are the Temple of Bel in Palmyra, destroyed by ISIS jihadist; the ancient city in the Syrian desert, destroyed by the ISL; the two world's largest Buddhas of Bamiyan, destroyed by the Taliban; the 3,000-year-old statues in Mosul museum, destroyed by ISL fighters; and lastly, the ancient city of Nimrud in Iraq.

So, the question then is, how can we preserve all of these cultural structures? Agosto and Bornaz [8] suggested that 3D digitization is the most applicable method to preserve cultural heritage. According to them, this method can be applied from the largest buildings to the smallest we can imagine. Remondino [9], also stated that 3D modelling of heritage and other archaeological objects are in demand since there are a lot of factors that will lead to the destruction of these things. He also mentioned the benefits of 3D documentation and modelling such as for digital preservation and conservation and historical documentation.

There have been ways to generate a virtual 3D replica model, in this case, the use of photogrammetry techniques. This approach may use different input data sources, from simple two-dimensional images.

2.1 PHOTOGRAMMETRY

Photogrammetry is taken from "Greek words *Photo*, *Gram* and *metry* which translated in English literally means, *light*, *drawing* and *measurement* respectively; defined as the science of obtaining reliable information about objects and of measuring and interpreting this information" [10].

A good discussion of this approach is delineated in the study of Aicardi, Chiabrando, Lingua, and Noardo [11]:

In photogrammetry, central projection is the widely accepted model. It is a spatial method that modifies a three-dimensional entity into a two-dimensional reality, and it arises when "there is an object, a projection center and a projection plane oriented in any way with respect to the projected object". This projection is generated over a projecting ray, adjoining the points of the object by means of "the projection center, and crossing the projection plane to create the image points which are the points projections". Acquiring a frame:" the object point P, the projection center O, and the image point P lie on the same straight line". The mathematical illustration that shows the collinearity conditions depicting the alignment connecting the points in the image and in the object system can be presented in Equation 1:

$$\frac{\xi-\xi_0}{c}=\frac{X'-X_0'}{Z_0'-Z'} \qquad \frac{\eta-\eta_0}{c}=\frac{Y'-Y_0'}{Z_0'-Z'} \tag{1}$$

where "ξ, η, ζ, (ζ = 0, for the image points and ζ = c for the projection center) shows the imaging system and X, Y, Z the object system".

The "coordinates X', Y', Z' of the point P and the coordinates X_0', Y_0', Z_0' of the projection center may be executed in the system X, Y, Z by the spatial rotation matrix R shown" in Equation 2:

$$\begin{pmatrix} X-X_0 \\ Y-Y_0 \\ Z-Z_0 \end{pmatrix}=\begin{pmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{pmatrix}\cdot\begin{pmatrix} X'-X_0' \\ Y'-Y_0' \\ Z'-Z_0' \end{pmatrix} \tag{2}$$

A collinearity equation can be obtained if the matrix Equation (2) is multiplied for the matrix RT= R−1, and substitute in the equations precisely to the image coordinates, as shown in Equation (3):

$$\xi=\xi_0-c\frac{r_{11}(X-X_0)+r_{21}(Y-Y_0)+r_{31}(Z-Z_0)}{r_{13}(X-X_0)+r_{23}(Y-Y_0)+r_{33}(Z-Z_0)} \qquad \eta=\eta_0-c\frac{r_{12}(X-X_0)+r_{22}(Y-Y_0)+r_{32}(Z-Z_0)}{r_{13}(X-X_0)+r_{23}(Y-Y_0)+r_{33}(Z-Z_0)} \tag{3}$$

The relations presented are closely correlated to the generated image in camera utilizing the central projection geometry concept.

2.1.1 DOCUMENTATION TECHNIQUES IN PHOTOGRAMMETRY

The primary goal of photogrammetry is "for mapping purposes; consequently, the technique was linked to the achievement of the best reachable metric accuracy" [12]. Consequently, it is used to measure the physical of a certain object using photography and is regarded as a great practical method for transforming 2D images into a 3D model and that images can be obtained from satellites, aerial or terrestrial sensors [13]. Accordingly, there are four (4) categories of photogrammetry techniques: Aerial, the Close Range, Terrestrial, and Space Photogrammetry.

- *Aerial Photogrammetry:* Photos are taken from a height of more than 300 meters. This method is one of the alternatives in technology which gives more detailed, real-time, fast and cheaper. The use of a drone is one of the deals in aerial photogrammetry [14].
- *Terrestrial Photogrammetry:* Photos are taken near the ground. Laser Scanning (LS) is widely used in terrestrial photogrammetry, and offers an accurate result but costly. It uses active sensors that transmit and receive light rays of range measurements and can be categorized in two classes: Triangulation and Time-of-flight (TOF).
- *Close Range Photogrammetry (CPR):* Photos are obtained from a height of fewer than 300 meters. According to Luhmann [15], the application of CPR gives an exceptionally high-precision output. Another common advanced technology used is the Unmanned Aerial Vehicle (UAV), wherein you can obtain data without needing a pilot but is remotely controlled.
- *Space Photogrammetry:* These are photos that are taken from space. 3D construction from satellite images is also possible and a precise 3D model calculated from same-date images [16].

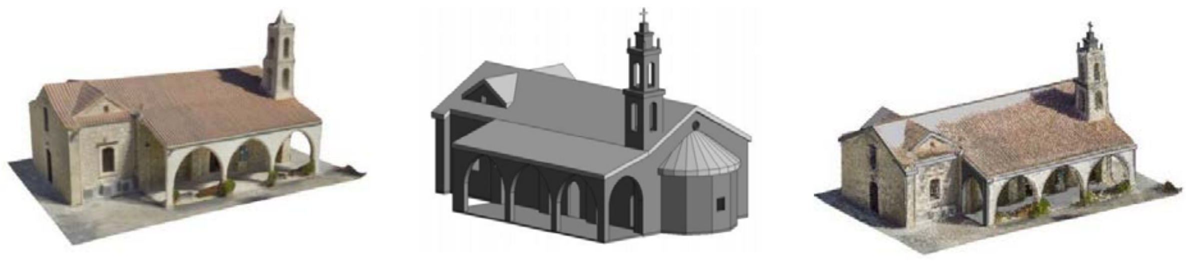
There are three categories of what photogrammetric products are according to Schenk [10], namely: photogrammetric products, computational results, and maps. He stated that the derivatives of single photographs or overlapping photographs are called photogrammetric products, while computational results are the one product in computational form like aerial triangulation that can be calculated on photographs. Lastly, maps are the dominant product given that they are developed with a high degree of accuracies at various scales. Examples are Planimetric maps and Topographic maps where the former includes only the horizontal position of ground features and the latter also includes elevation data.

2.2 RELATED WORK

Traditionally, digitization for storing images was in 2D form for the reason that it is cheaper and easy to do. Fabrizio et al. [13] presented an experiment with an objective to understand how different 2D and 3D provide the perception and understanding of the digital replica artifacts. The result points out that the 3D model of artifacts was more an effective way of digitally preserving tangible cultural heritage because it “augments the perception of physical characteristics of the artifacts allowing a more embodied experience with these objects or the sense of 3D multi-visualization”. In the Philippines, there is a dearth of study regarding preserving cultural heritage in 3D form.

There have been many studies conducted on ways how to digitize cultural heritage such as high definition laser, structured light scanners, and other techniques. Moreover, some studies are concentrated on a comparative assessment of the benefits of structured light, laser scanning, and photogrammetry. Arif & Essa [17] presented a case study on the conservation of Mughal heritage site tabulating the progress of documentation techniques in the Pakistani setting. They discovered the full potential used 3D-laser scanning technology used in heritage conservation. However, according to Steinicke and Feller [18] research, aerial images in photogrammetry is the most common way to make a model since it represents the geometry of the whole surface directly unlike data from laser scanner where according to them suffered a low density of measured points and costly.

Another case study presented by Themistocleous, Ioannides, Agapiou, and Hadjimitsis [19] to document and 3D print the Asinou Church (in fig. 1, a cultural heritage site in Cyprus. A different technique was used – UAV and photogrammetry. In their study, they used “Phantom 2 Quadcopter with GoPro Hero 3 camera” to capture around1000 images during the field survey of the church. A 3D model was rendered through Agi-Photoscan Professional software. Such simple methods gave a practical and low-cost-effective solution. In the study of Themistocleous, Agapiou, & Hadjimitsis [20], they used a ‘DJI F550 hex copter with attached 12-megapixel GoPro HERO^{+}’ for the aerial survey of the Foinikaria church. More than a thousand images were taken and post-processed through Agisoft Photoscan Professional software to render an accurate 3D model of the church. It was then exported to generate a BIM model of the church using CAD drawing software. The purpose of documenting the structure was for future potential restoration and/or expansion work. The output is shown in Figure 1.



(a) 3D model of the church (b) Point cloud with the BIM model (c) The BIM model of the church

Figure 1: 3D model of the Church.

In this study, photogrammetry will be used for the reason that this technique offers a simple, low-cost yet accurate-effective method of documenting the Philippine Baroque Churches in generating a digital 3D model. Furthermore, there is a dearth in the utilization of 3D digitization in preserving cultural heritage in the Philippines. Back then, 3D digitization required expensive, specialist equipment and software, but with the advent of low-cost technology and techniques like photogrammetry provides an affordable option.

3. STUDY AREA

The use of drone and photogrammetry techniques as an aid to digital 3D documentation efforts highlighted the practicability of this digital technology as an important tool in digital preservation and documentation of Philippine Cultural Heritage sites. A case study is presented through the four Baroque churches situated in Iloilo, Manila, Ilocos Sur, and Ilocos Norte in the Philippines. The details of the Baroque churches are shown in Table 1 and Figure 2. Accordingly, these four churches "have a unique architectural style, which is a reinterpretation of European Baroque by Chinese and Philippine craftsmen" [21].

Table 1: Baroque churches of the Philippines.

Name	Location	Coordinates (latitude, longitude)	Length x Width
The Church of Santo Tomas de Villanueva	Miag-ao, Iloilo	10376.00 122136.00	68.45 m x23.3 m
The Church of the Immaculate Conception of the San Agustin	Intramuros, Manila	14346.00, 120580.00	67.15 m x 24.93 m
Church of the San Agustin	Paoay, Ilocos Norte	18312.00, 1203150.00	110 m x 40 m
Church of Santo Tomas de Villanueva	N10 37 6.00 E122 13 6.00	Miag-ao, Iloilo	68.45 m (225ft) x 23.3 m (76 ft)

The San Agustin Church was built in 1571 and located within the historic-walled-city of Intramuros, Manila. It was named "a National Historic Landmark by the Philippine government in 1976" and the mother church of the Augustinian order (UNESCO). The Santa Maria Chuch ("Nuestra Señora de la Asunción") was built in 1765 and the archdiocese of the Santa Maria municipality in Ilocos Sur province. The Paoay Church is built in 1710 and located in the Municipality of Paoay, Ilocos Norte. It is renowned for its unique architecture, which is emphasized by its massive buttresses on both sides of the building. The Miag-ao Church ("Church of Santo Tomas de Villanueva") is built during 1787-1797 and located in the town of Miagao, Iloilo.

(a) San Agustin Church in Intramuros

(b) Santa Maria Church

(c) Church of San Agustin in Paoay

(d) Miag-ao Church

Figure 2: The Baroque Churches of the Philippines.
(Courtesy of Google Earth and Google Maps).

4. METHODS

To digitally preserve the cultural heritage sites in 3D form, requires data acquisition, data processing, and data representation. The workflow process for this study is shown in Figure 3.

The data acquisition should be done with careful planning. In this study, a low-cost drone is used to obtain data images that will be used for the 3D numerical data of the church facade. Surveying the area where the drone took off is essential during the data collection. Flight ranges and paths need to be established properly.

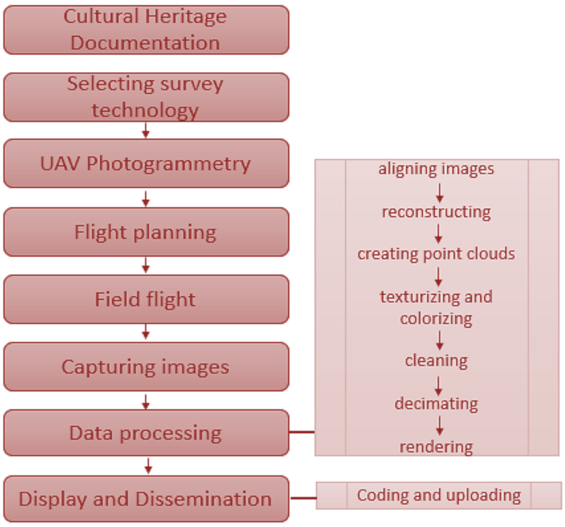


Figure 3: The Workflow process.

Normally, a single drone can achieve its objective using only a simple flight pattern depicted in Figure 4. The coverage mission for this study were simple geometric patterns, a combination of back-and-forth and the spiral illustrated in Figure 4a and 4b, organized into parallel and creeping line [22]. Square flight pattern follows an ellipse shape that will begin at the middle points then stretches towards its perimeters depicted in Figure 4c.

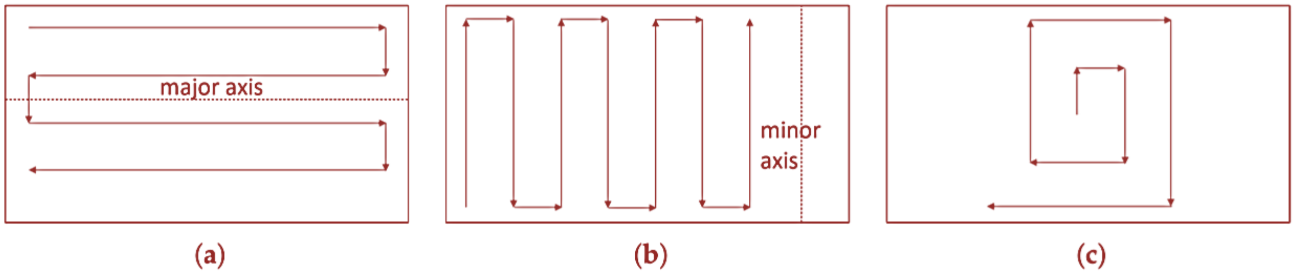


Figure 4: Simple flight patterns in rectangular areas with no decomposition: (a) Parallel; (b) Creeping Line; (c) Square. (after [22]).

The Boustrophedon Cellular Decomposition (BCD) [22] method was used in this study since the baroque churches are with obstacles and are depicted in Figure 5. This was already evaluated in real flights with 10% more efficient in performing the total coverage thus saving time.

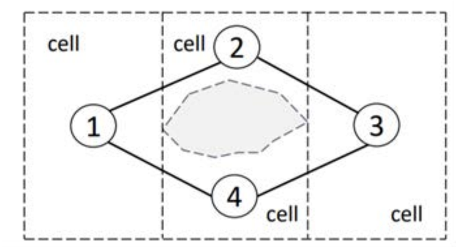


Figure 5: BCD area of interest.

In this study, a DJI Spark drone is used. This is a good choice since it is economical but with excellent specifications such as a flight autonomy system with vision positioning system assistance, a 3D sensing system that can sense obstacles up to 5 meters away, dual-band GPS, with a great-precision inertial measurement unit, and robust computing cores.

Precision and the right quantity of photos are key for generating a 3d realistic model. In acquiring data, multiple overlapped images of the Baroque churches are taken from various angles. It should be noted that the "overlapping degree of drone aerial imagery" is a critical factor in evaluating the quality of output [23]. Figure 10 shows the schematic diagram and equation in solving the overlapping degree of images. The formula to compute the result for the overlapping degree is defined in Equation 4. The image overlap area width and height are $\bar{P}_w, \bar{P}_h$, while the width and height of the image are P_w, P_h [23].

$$Degree\ of\ overlap = \frac{\bar{P}_w \times \bar{P}_h}{P_w \times P_h} \quad (4)$$

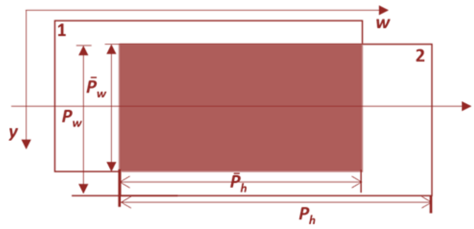


Figure 6: Overlap calculation schematic diagram.

The data processing is done after extracting images from the drone. It takes considerable time to render a 3D model and includes the following tasks:

1) arrangement of distinct local point clouds into a corresponding coordinate system,
2) photogrammetric clouds building, and
3) texture wrapping.

For photogrammetric processing and data cleaning, RealityCapture (RC) and MeshLab software are used. The data images are incorporated by a procedure into a unique coordinate system through RC software. Two different steps are followed, set alignment and set reconstruction. In alignment, ground-control points, and matching image-points are added, and the distance between two control points are defined. In reconstruction, defining the ground plane and setting the reconstruction region are needed to estimate the position and alignment of the integrated 2D images. Camera angles and calibrations are computed automatically during the alignment while the reconstruction region can be set automatically or manually. Elements depicted in the point cloud are automatically drawn, but to modify the existing model it should be manually inspected and removed before creating the mesh. Decimate the mesh if needed. Further, select what maximal texture resolution of the model to produce the UV map and compute a 3D triangular mesh in the desired quality. From this data, a point cloud is derived.

The model rendered in data processing has OBJ, JPG, and MPL files. It is estimated to have 5 hundred thousand to 1 million triangles for better simple scene quality, while 2 to 3 million for more complex scenes. It should be noted that rendering a lesser number of triangles means reduced file sizes and loads faster but reduced the quality. The final results involve a decision between 3D realistic model and web-friendly size model but taking into consideration the intended goal hereof, which is to upload the 3D replica models on the web for it to be accessible.

5. RESULTS AND DISCUSSION

This study created 3D replica models of the UNESCO-declared Philippine Baroque churches by using only a drone and photogrammetry as a way of digitally preserving cultural heritage sites. The workflow for the process of obtaining point cloud data with the 3D modelling method using photogrammetry tool can be summarized in Figure 7. We faced obstacles and setbacks like the weather, and environmental constraints, and field conditions during field experiments to acquire good data. Planning a flight is very important prior to actual field flight especially in the challenging environment with vast-size subjects. The quality of captured image data is important in photogrammetry, capturing images using right a drone needs to be considered properly. Once data images were acquired, you can now process your data to render the model. For wider dissemination upload your model on the web.

5.1 DATA ACQUISITION: THE SURVEY OF THE BAROQUE CHURCHES

The Baroque churches sites located in Ilocos Sur, Ilocos Norte, Manila and Iloilo were surveyed to capture data images for the use of cultural heritage documentation using the photogrammetry technique. The location and extreme conditions of the study area presented a challenge to field research in general. Figure 7 shows how the drone covered the church.

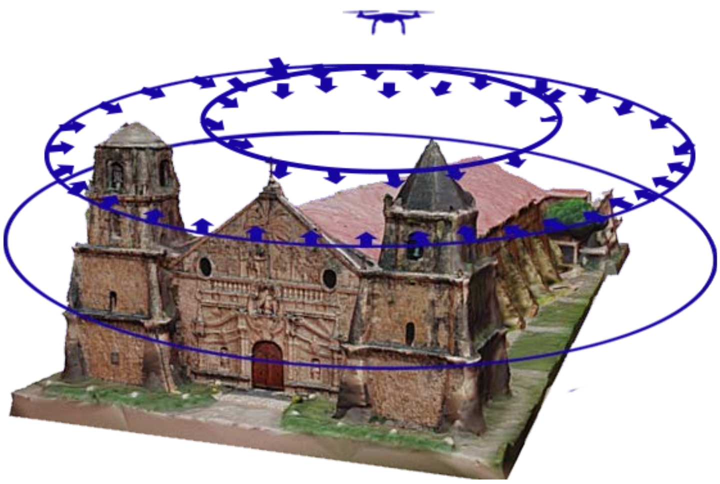


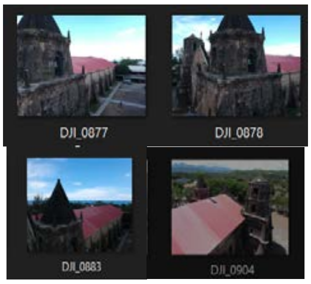
Figure 7: Drone coverage.

An easy-to-fly DJI drone with 1/2.3" CMOS sensor (12 MP) was used to obtain the 3D numerical data to capture the church facade. The image size is 3968×2976 pixels taken from 70 to 120 feet with an overlap of 75-90 degrees of the adjacent images. Figure 8 shows the thumbnail 90-degree overlap of the Miag-ao Church.

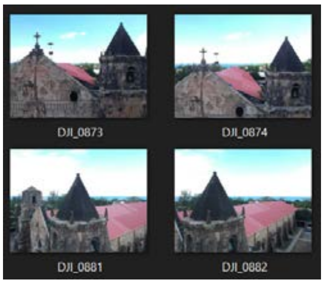
Figure 8: Image overlap.

Surveying the area and planning where the drones took off is essential during the data collection, and flight ranges and paths were established. The drone's flight is manually controlled due to trees or buildings around the area.

(a) harsh light



(b) with shadows



(c) ideal image

Figure 9: Shooting considerations.

Ideally, shooting conditions of the subject for good quality photogrammetry must be evenly lit, it can be achieved in an overcast or cloudy day. However, this is hard when shooting outdoor shots, wherein you cannot control the weather and you must pay attention to the changing clouds and sunlight conditions that might create harsh shadows. Dark shadows produced holes in the mesh which are visible during processing. This is what happens to the captured photos shown in some of the thumbnails in Figure 9. The technique of producing good quality 3D model lies in taking good photos wherein weather has a big factor. Facing with reality, the time spent in the field to document each church was limited with rain and the changing weather was an enemy aside from the environmental constraints like trees and tall buildings that surround the church. Really, efforts were made to ensure adequate survey coverage.

5.2 3D MODELLING

Image processing involved aligning images, building point-clouds as well as mapping the textures. These are all done prior to reconstructing the model. Firstly, the 2D images extracted from the drone are aligned based on image feature points and more importantly following shooting sequences. Figure 10 shows the point cloud of San Agustin after defining the ground plane and setting the reconstruction region of the aligned image.

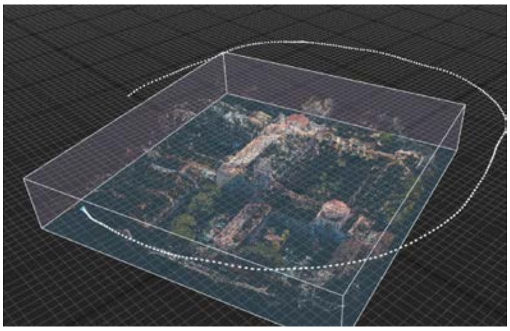


Figure 10: The point cloud visualization of the San Agustin Church.

About 1.9 million triangle count with 1 million vertices is generated to produce the San Agustin Church model, see Table 2.

Table 2: The Triangle and the Vertex count of the Church

Church	Vertex Count	Triangle Count
San Agustin Church	1004321	1999999
Sta. Maria Church	941214	1878381
San Martin Church	727222	1463163
Paoay Church	904266	1800000

The reconstruction region is manually set. Once it is set, the model is then recalculated in the defined space to colorize. Figure 11 shows the output of colorizing and texturizing and the 3D mesh sample of the San Agustin Church.

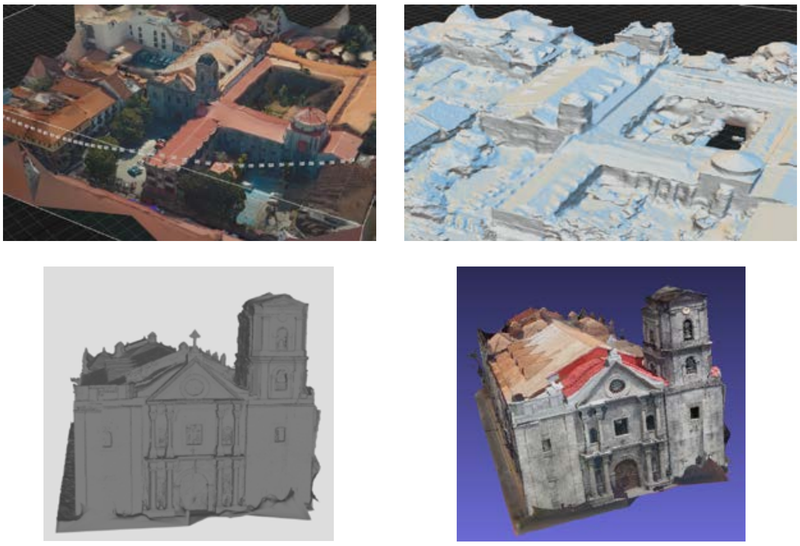


Figure 11: The 3D process of the San Agustin Church.

5.3 DISPLAY AND DISSEMINATION

There are considerations for the file size if 3D models are to be uploaded on the web that you may have to sacrifice the quality. Normally, it should be less than 20 MB in web-supported 3D format (like .OBJ, .BLEND, .FBX or .GLTF and .GLB). Taken for example, the Paoay object, it needs to be decimated thus reducing its vertex count from 8 billion to only 2 million. The output of this project is accessible in "philippinebaroquechurches.site" and shown in Figures 12 and 13.

Figure 12: Web interface accessible at http://philippinebaroquechurches.site

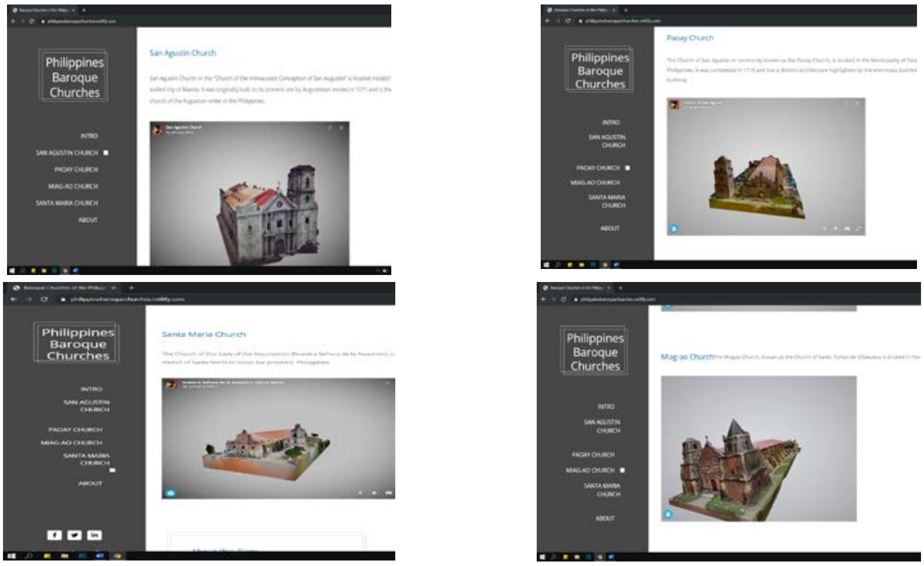


Figure 13: Web interface when the Baroque churches of the Philippines are navigated.

6. CONCLUSION

The study highlighted the use of affordable innovative technologies such as UAVs that will provide high resolution and accuracy images of a cultural site and photogrammetry technology that is an easy and low-cost method in producing 3D replica models from 2D images. Thereby, providing an effective and viable method to be used in digital cultural heritage preservation, and as a tool for cultural heritage experts in the Philippines. Unlike other studies that combined digital technologies, this study has achieved its goal by using only the UAV photogrammetry in constructing the 3D models of the Philippine Baroque churches viewable via a web browser.

This study presented workflow to digitally document cultural heritage sites. In photogrammetry, taking good quality digital images is of utmost importance in producing good output that it is necessary to have a clear idea of the area to be surveyed. These are key factors to be considered for outdoor, large-sites photogrammetry using drones

- Flight map or layout of the area to know the directions of flight – to reduce distance or flight time in order to lessen flight time hours of drones and to know the dimension of the subject and obstacles around the subject such as trees.
- Time schedule (date and time) to know the weather condition – minimize shadows 11 am to 1 pm is the ideal time.
- Cloud conditions – good cloud cover with adequate light.
- Flight alignment – flight lines should be parallel, this is important in 3D mapping.
- Types of drones used - make sure the drone is suitable for the project intended. usually, drones fly low with limited flight time, having an extra battery is necessary.
- Image overlaps - 75-degree image overlap is ideal for 3D photogrammetry.

Further, this study successfully demonstrated the suitability and practicability of the photogrammetry technique for digital cultural heritage documentation and preservation for which the country can make use of in preserving valuable cultural identity for future generations.

7. ACKNOWLEDGEMENT

This project was funded by the National Commission for Cultural and the Arts approved through Board Resolution No. 2019-225.

8. AVAILABILITY OF DATA AND MATERIAL

All relevant data are already included in this article.

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J. Febro is an Assistant Professor of Department of Information Technology at Mindanao State University – Iligan Institute of Technology, Philippines. J. Febro interests involve applications for Sustainable Development, ICT4D, Computing in Social Science, Health and Humanities.