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3D MODELING USING UAV-PHOTOGRAMMETRY TECHNIQUE FOR DIGITAL DOCUMENTATION OF CULTURAL HERITAGE BUILDINGS

*I GD Yudha Partama[1], Putu Edi Yastika[2] and I Made Wahyu Wijaya[3]

[1,2,3]Universitas Mahasaraswati Denpasar, Indonesia

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ABSTRACT: Over the last decade, imaging techniques using Unmanned Aerial Vehicles (UAVs) and photogrammetry-based computer vision technique have developed rapidly, enabling advances in three-dimensional (3D) modeling for the preservation, documentation, and management of cultural heritage buildings. This study aims to evaluates the accuracy of UAV photogrammetry for Stupa exploration at Pegulingan Temple. The data obtained is expected to become a documentation that can be used in maintenance as well as in future reconstruction. In this study, 3D model was generated by aerial photographs taken by small UAV (drone) and photogrammetry based SfM-MVS algorithms technique. To test the accuracy of the SfM-MVS method in generating the 3D model, the accuracy assessment was calculated based on the total error (RMSE) of the 3D model coordinates (XYZ) estimated by the SfM-MVS against the measured coordinates from RTK-GNSS and TLS. Based on these results, the overall accuracy in the horizontal and vertical sections is 11.3 mm and 14.1 mm, respectively, this demonstrates that the model achieves high accuracy at the mm scale. The mean cloud to cloud (C2C) distance between the TLS and the UAV point cloud were very small (0.03 mm), it means the accuracy between the two technique is almost the same. The findings indicated that the 3D stupa model generated by UAV-photogrammetry technique was sufficiently accurate to support cultural heritage buildings conservation management.

Keywords: Cultural heritage, Digital documentation, SfM-MVS, UAV-Photogrammetry

1. INTRODUCTION

Protection and preservation of cultural heritage building assets need to be carried out considering the importance of these buildings for historical restoration, educational facilities, tourism continuity, and the identity of the nation which always upholds the value of cultural heritage [1]. One way to protect the building is to document its physical aspects, including the model and structure. This is useful in case of damage in the future, whether due to age, climate, or natural disasters [2]. It is especially helpful during reconstruction and renovation. Currently, the documentation of cultural heritage buildings is limited to analog design drawings (sketch design drawings on paper) [3]. These conditions make it difficult to manage in the event of structural damage or changes. For this reason, one way that can be used to document the heritage of cultural heritage buildings is to record these objects in a digital format based on three-dimensional (3D) objects [4].

Traditional non-image-based techniques, such as traditional terrestrial surveying, can be utilized to produce detailed drawings of buildings when modern technologies are inaccessible or prohibitively expensive. However, these methods require skilled operators, are time-intensive, and are limited in surveying inaccessible features. Additionally, they are inefficient when dealing with complex structures requiring a large number of data points. On the other hand, traditional image-based methods, like panoramic imaging, provide a wide field of view but are generally confined to ground-based perspectives. Close-range photogrammetry captures high-detail imagery of smaller areas, making it suitable for intricate details like carvings or ornamentation but less effective for documenting larger sites comprehensively [4].

Over the last decade, Modern Terrestrial surveys using a terrestrial laser scanner (TLS) can produce high-quality images of cultural heritage building objects, while robotic total stations allow researchers to more easily collect large amounts of object data. However, using such a geomatics-based approach requires considerable expertise and a large survey budget [5]. As an alternative, imaging techniques using unmanned aerial vehicles (UAVs) have developed rapidly, enabling advances in three-dimensional (3D) modeling for the preservation, documentation, and management of cultural heritage buildings [6].

UAV can be used to obtain 3D models easily, reliably for large-scale mapping and capturing areas that are inaccessible and dangerous to access (high facades, roofs, or damaged buildings). In addition, UAV imaging is real-time capability, fast image acquisition, cost-effective, and offers an ideal way to survey complex cultural heritage sites [7]. The combination of UAV and photogrammetry techniques has the following advantages: (1) Remote control system, allowing the UAV to be perfectly positioned to collect images at various heights and angles; (2) different sensors, ensuring that different types of images can be used, including infrared, visible spectrum, and thermal images taken from calibrated and non-calibrated cameras, and (3) high-quality results, allowing researchers to control for reliability and accuracy results [8].

In several studies, UAV-photogrammetry has been demonstrated to achieve a Level of Detail up to Level 3 (LOD3). Achieving LOD3 in documenting cultural heritage buildings offers significant benefits for conservation and reconstruction, including the creation of detailed 3D models that accurately capture architectural elements such as windows, doors, relief, and decorative features. These models facilitate precise analysis, support restoration efforts, and enable the preservation of intricate historical details for future generations. They also support interdisciplinary research and education by providing detailed data for analysis and facilitating public engagement through modern applications like AR/VR [9].

Research suggests that UAVs are highly adaptable to a variety of heritage documentation needs, from archaeological sites to complex architectural monuments [10]. For instance, UAV systems have been successfully employed to document large-scale sites like historical caravanserais and intricate architectural remains, using advanced photogrammetric techniques to overcome visibility and inaccessibility issues [11].

The purpose of this study was to document cultural heritage buildings in 3D using a combination of UAV and Photogrammetry technology, to obtain a 3D model with a high level of accuracy and detail. In addition, this study also aims to update data on cultural heritage buildings at the Pegulingan Temple site. The data obtained is expected to become a documentation that can be used in maintenance as well as in future reconstruction.

2. RESEARCH SIGNIFICANCE

This approach is highly significant in advancing the preservation and documentation of cultural heritage. UAV-photogrammetry offers a cost-effective and time-efficient method to capture inaccessible or hazardous areas, such as high rooftops, intricate facades, or expansive archaeological landscapes, which are challenging for traditional techniques. This method provides accurate, high-resolution 3D models that are crucial for conservation, restoration, and public education efforts, ensuring the long-term safeguarding of cultural heritage against threats like natural disasters, urbanization, and degradation [12]. By integrating cutting-edge technology into heritage conservation, this research addresses global challenges and offers scalable solutions for digital heritage documentation, bridging traditional practices with modern technological innovations to preserve cultural assets for future generations.

3. METHODOLOGY

3.1 Acquisition of Aerial Photographs

Aerial photography of the object was performed using a small format camera (4K; FOV 77; 20 MP) mounted on a small quadcopter UAV (DJI Mavic 2 Pro Drone) (Fig. 1a). To improve the accuracy and level of detail of the model, aerial photography was taken in two sets of flight missions (vertical and oblique photography).

In the first mission, the drone camera was set to the nadir point to capture the horizontal objects of the temple. The flying altitude was set to 27 m above ground level, it enables the UAV to capture fine details, such as intricate architectural features, while maintaining enough coverage of the area being surveyed [13], and the coverage area was 0.4 ha, with a total of 177 photos. In addition, the overlapping rate of photos (forward lap and side lap overlap) is set at a minimum of 80% for forward lap and 70% for side lap, as recommended by photogrammetric software for a multi-image matching approach. This configuration is ideal for ensuring reliable image alignment and minimizing gaps in the data, thereby reducing the need for unnecessary post-processing and improving the accuracy and efficiency of the 3D reconstruction process [14]. For efficiency and to maintain consistency of image capture, the flight mission was set to an auto pilot programme to take aerial photographs automatically according to the planned flight path (Fig. 1b).

In the second mission, the UAV camera was used to capture vertical objects of the temple using an oblique view, employing a Point of Interest (POI) flight strategy to ensure comprehensive coverage of the stupa and produce a detailed 3D model [15]. The POI strategy, illustrated in Fig. 2, involves the drone circling the object of interest in a circular motion. This flight strategy can be pre-programmed by specifying the radius and height from the object of interest. The UAV's camera was programmed to maintain a fixed viewing angle on the stupa, and images were captured every 3 seconds as the UAV circled the stupa at three different heights: high, mid, and ground levels. Finally, we checked all of the images and removed a few images with low quality and blurry effects in order to minimize the error of feature matching.

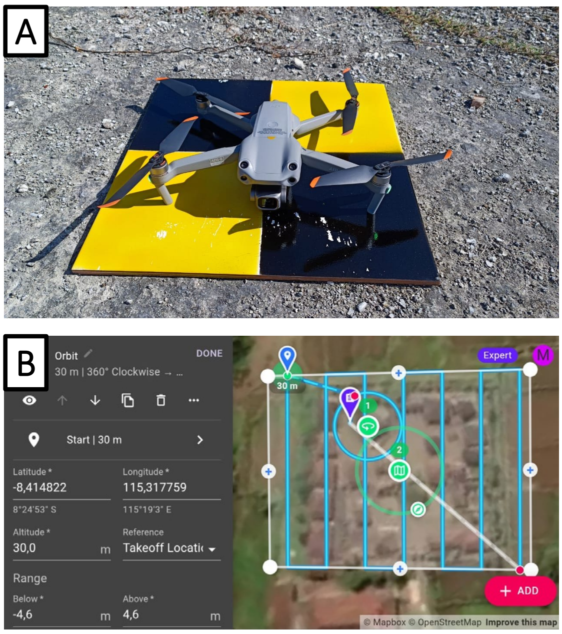

Fig.1 Drone DJI Mavic 2 Pro (a), and planned flight path

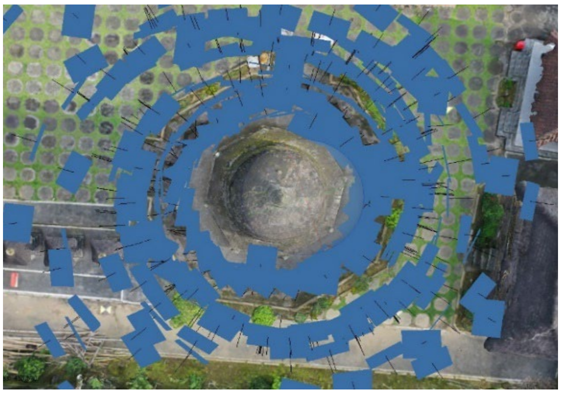

Fig.2 The Point of Interest (POI) flight mission

3.2 Measurement of Ground Control Point (GCP) and Independent Control Point (ICP)

The GCPs were black-yellow target squares with dimensions of 0.5 x 0.5 m and were placed on ground. ICPs were placed on natural features, such as temple corners, the facade features of the temple and some on the inside of the area, the number and distribution of GCPs and ICPs used in this study were 8 and 40, respectively. The distribution of GCPs and ICPs were shown in Fig.3.

In this study, GCPs were used for georeferencing and optimisation in the SfM photogrammetry process [16]. The ICPs were used to assess the accuracy of the UAV-Photogrammetry method and the 3D model. Measurements of the GCP and ICP coordinates were carried out using the Real-Time Kinematic Global Navigation Sattelite System (RTK-GNSS) and Electronic Total Station (ETS).

Fig. 3 Distribution of GCP and ICP (a), and measurement of GCP and ICP using RTK-GNSS and ETS (b)

3.3 SfM-MVS Photogrammetry Processing

To generate the three-dimensional dense point cloud (DPC) model, a set of aerial photographs with a high degree of overlap was processed using the photogrammetric method based on the SfM and MVS algorithms. In the initial stage, a series of aerial images are employed as the input for the alignment photo process of the Structure from Motion (SfM) algorithm. In this stage, the SfM algorithm is used to determine the relative camera position, the intrinsic and extrinsic parameters, and the sparse point cloud. Furthermore, GCPs are used for georeferencing coordinates and optimising the position of the point cloud. MVS is used to reconstruct the actual geometric shape by projecting the pixels in each overlapping photo into 3D space, thus generating DPCs, orthophotos and digital surface models (DSM).

3.4 3D Comparison and Accuracy Assesement

To test the accuracy of the SfM-MVS method in generating the 3D model, the accuracy assessment was calculated based on the total error (RMSE) of the 3D model coordinates (XYZ) estimated by the SfM-MVS against the measured coordinates from RTK-GNSS and ETS at 40 ICP points, using the following equations (Equations (1) to (3)).

$$RMSE_x = \sqrt{\frac{\sum_{i=1}^{n}(x_{RTK,i} - x_{computed,i})^2}{n}} \quad (1)$$

$$RMSE_y = \sqrt{\frac{\sum_{i=1}^{n}(y_{RTK,i} - y_{computed,i})^2}{n}} \quad (2)$$

$$RMSE_z = \sqrt{\frac{\sum_{i=1}^{n}(z_{RTK,i} - z_{computed,i})^2}{n}} \quad (3)$$

Where:
RMSE is the root–mean–square error
x, y, z computed, i is the point coordinates in the UAV images.
x, y, z RTK, i is the point coordinate measured from RTK.
n is the number of GCPs

On the other hand, for a more detailed accuracy assessment and to determine the level of detail of the model, a comparison of two 3D models generated from SfM-MVS and Terrestrial Laser Scanner (TLS) was also conducted. To facilitate a comparison of the three-dimensional models, the DPC is employed to generate the models in question using the CloudCompare software. This software utilizes a specific octree structure to recursively partition a cubical volume of space in order to determine the nearest neighbor distance between the reference and compared point clouds. It works by searching for the nearest point in the reference cloud to the compared cloud and then calculates the Euclidean distance. To assess the reliability of the proposed technique, the DPC surface density, and some statistical error (mean error and standard deviation error) of each technique were also evaluated.

4. RESULTS AND DISCUSSION

To evaluate the effectiveness of the SfM-MVS method in generating 3D models, accuracy assessments were conducted at the global levels, specifically focusing on the temple and stupa regions. The findings, summarized in Table 1, indicate overall accuracy levels of 11.3 mm for horizontal and 14.1 mm for vertical measurements. These residual errors, as reflected by the horizontal and vertical RMSE values, can be attributed to several factors, including lighting conditions, image overlap, and camera settings [17]. For example, inconsistent lighting can introduce variations in image textures, complicating the image matching process during photogrammetric reconstruction. Moreover, insufficient image overlap, particularly in areas with low visual texture or repetitive patterns, can compromise the robustness of the 3D reconstruction. Despite these challenges, the model demonstrates a high level of accuracy, achieving precision at the millimeter scale, which is suitable for detailed cultural heritage documentation and analysis [18].

Based on Table 1, the RMSE on the vertical axis is larger than that on the horizontal axis. This discrepancy may result from the aerial photography distance being excessively high, which increases the likelihood of radial distortion in the photographs. Despite lens calibration, radial distortions, such as barrel or pincushion effects, can still alter the perceived geometry of straight lines, especially under uneven lighting conditions. Furthermore, in low-contrast images caused by diffuse or flat lighting, lens distortions may be less noticeable visually but can distort the shape and position of key points. This distortion complicates image matching and alignment for photogrammetry software, potentially reducing the overall accuracy of the reconstructed models [19, 20].

For instance, variations in lighting can create inconsistent textures in captured images, leading to errors during image matching in photogrammetric processing. Additionally, insufficient image overlap can reduce the robustness of the 3D reconstruction, particularly in areas with low visual texture or repetitive patterns. To provide a comprehensive analysis, additional studies or specific research would be required, including: 1) comparing RMSE values under various lighting conditions and overlaps during multiple flights, 2) assessing the impact of lens calibration quality on residual errors, and 3) evaluating the georeferencing process, particularly the density and distribution of GCPs used.

However, of the three values, the resulting 3D model of Pegulingan Temple has met the accuracy standard based on the Level of Detail 3 (LOD3) classification with an error value of less than 0.5 meters [21]. This also shows the success of the SfM-MVS method in the digital documentation of cultural heritage. Theoretically, the smaller the Ground Surface Distance (GSD), the lower the RMSE generated in the model. Furthermore, Figure 4 shows the visualization of orthophoto and DSM in the temple complex and stupa region, based on the figure shows that the highest and lowest parts are at the peak and base of the stupa region. The height of the stupa based on the SfM-MVS model is 14 m.

Table 1. Accuracy assessment of 3D models from UAV-photogrammetry techniques

Output	Spatial resolution (mm/pixel)	RMSE X axis (mm)	RMSE Y axis (mm)	RMSE Z axis (mm)
Orthophoto	5.94	11.0168	11.5191	14.0712
DSM	2.13			

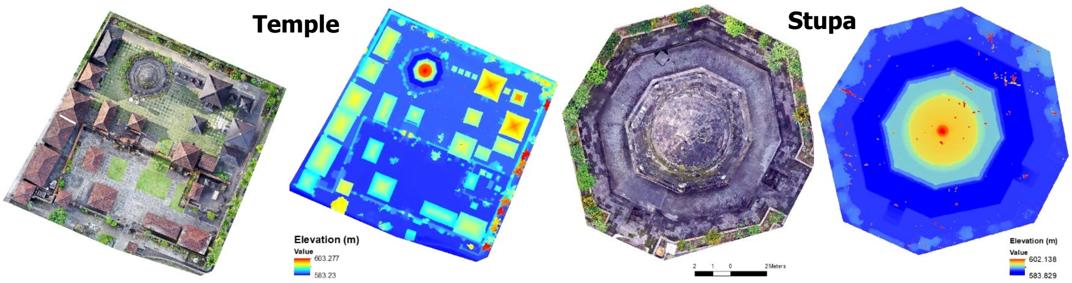

Fig. 4 Orthophoto and DSM of a) Temple region, and b) Stupa region

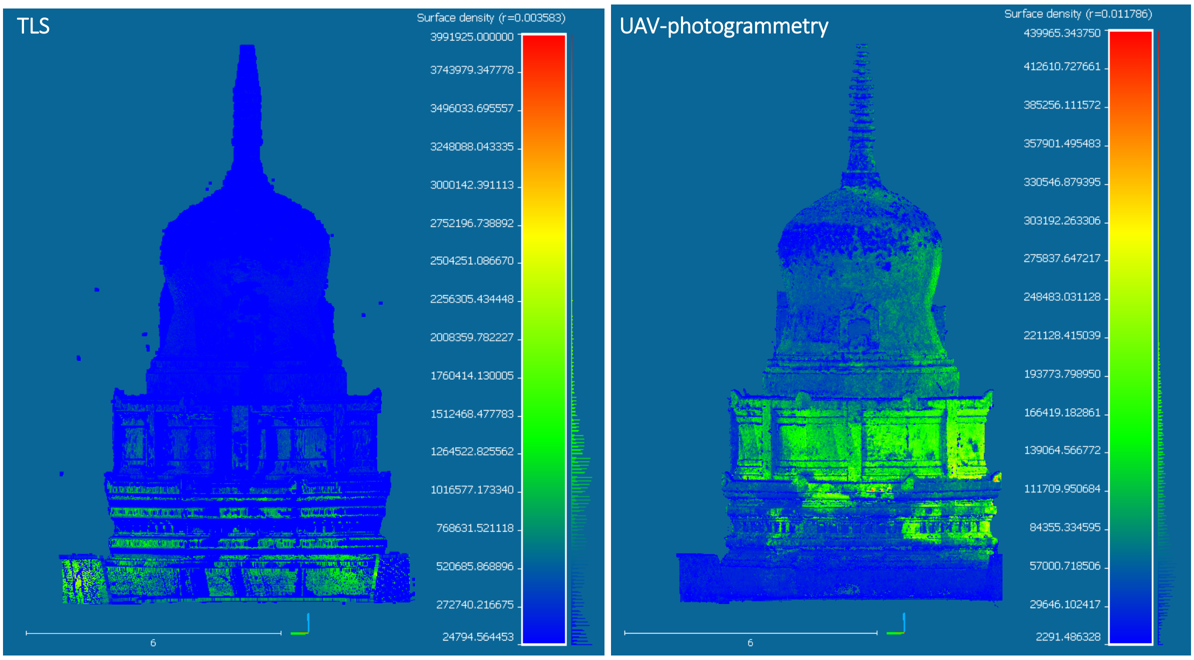

Fig. 5 Surface density of DPC from TLS and UAV-photogrammetry

Figure 5 shows the surface density of DPC from TLS and UAV-photogrammetry, where the number of DPC is measured in square metres. Based on the figure, the maximum and minimum number of DPCs generated by TLS are 3.99 million and 24.79 thousand, respectively. While the total DPC from UAV-photogrammetry is 439.96 thousand and 2.29 thousand. It can be concluded that the number of DPCs produced by TLS is 10 times greater than UAV-photogrammetry.

For effective reconstruction of cultural heritage buildings, a minimum point density of 10 to 20 points per square centimeter is often recommended to ensure the models are suitable for detailed conservation and analysis [22]. This density allows for accurate representation of surfaces and features, capturing small yet significant details effectively. In this study, the point density produced by UAV-photogrammetry falls within this recommended range. To further enhance the density of the Dense Point Cloud (DPC), the settings in photogrammetric software, such as Agisoft Metashape, can be adjusted to the Ultra High mode. This adjustment can yield a DPC with 2–3 times greater density compared to the High setting, ensuring even finer details for applications that demand high precision [14].

In addition, the distribution of point clouds on the model is more evenly distributed on TLS. Meanwhile, in UAV-photogrammetry, only certain points are seen to have many DPCs, such as the bottom segment of the stupa that stands out when the UAV captures images with oblique view. In addition, in this section the texture relief of the stupa also looks clearer and heterogeneous, which is dominated by stupa carvings. Therefore, the sparse point cloud resulting from feature matching is obtained more in that area. The success of this process is dependent on two key factors: image quality and image overlap level. In contrast, TLS generates DPC through an ultrafast pulse method utilising a scanner (capable of collecting up to 1 million points per second) [23]. However, this approach is limited by the presence of noise, including high-reflective surfaces (e.g., headlights, water), transparent surfaces (e.g., glazing), and elements in motion (e.g., people, vehicles) [24, 25].

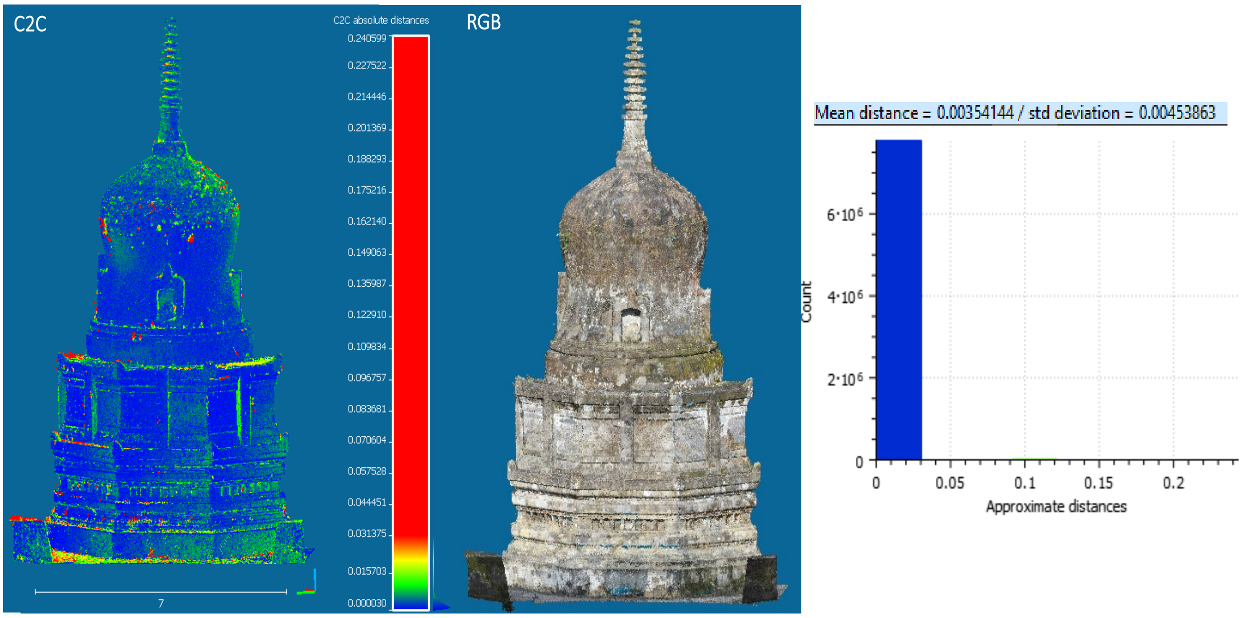

Fig. 6 Cloud-to-cloud (C2C) distance between TLS and UAV point cloud

Figure 6 shows the cloud-to-cloud (C2C) distance between TLS and UAV point cloud. The blue represents minimum distances, which was 0.003 cm and the red indicates maximum distances, which was 24.06 cm. Overall, based on the visualization of C2C model, almost surface dominated with blue colour, which demonstrated the small distance between point cloud generated with UAV and TLS, its mean that UAV-photogrammetry technique has the high accuracy of 3D model. This is also illustrated by both the mean and standard deviation of C2C which is very small, 0.354 cm and 0.454 cm, recpectively. The output of UAV on the temple compared with the TLS point clouds found that the calculated error value of TLS and UAV point clouds were almost the same.

Only the small set of DPC were get the red colour (low accuracy) due to the outlier and noise, especially in the corner of the stupa. This noise can appear from DPC generation both from SfM-MVS method and TLS. For structural analysis or dimensional measurements, outliers might not influence the results significantly if their occurrence is limited. In such cases, the point cloud filtering or outlier removal techniques can help mitigate any potential errors without negatively impacting the model's overall usability [26].

As mentioned in [27], the point cloud may contain many unnecessary elements and noise, another problem with laser scanning is the occurrence of blind spots due to obstructions or undesirable measurement conditions. Therefore, it is not always possible to scan the entire object. On the other hand, in image matching proceesses of SfM-MVS method, image exposure, in this study we choose the automatic setting, so the quality especially brightness value will change with time depend on lighting, at the time the wheather was cloudy, so the exposure time affected the image quality. The different quality of aerial photos causes matching errors in the feature matching process in SfM-MVS, which affects the accuracy of the model [28].

More analysis was performed on some details of the façade. Figure 7 shows the profile of a Pegulingan Temple on the vertical and horizontal cross-section. The analysis revealed that the mean distance in the two cross-sections is not significantly different, with a value of approximately 5 mm. However, the standard deviation in the vertical plane is larger, at 6.78 mm, while in the horizontal plane it is 4.60 mm. Here the limitations of terrestrial techniques are seen as the laser scanner was unable to scan several difficult angles, which the photogrammetric results managed quite well thanks to UAV images [29, 30]. However, it is interesting to note that SfM-MVS generated a smooth circular profile of the column. This suggests a form of interpolation and/or smoothing performed after the matching process to conform to certain geometric constraints.

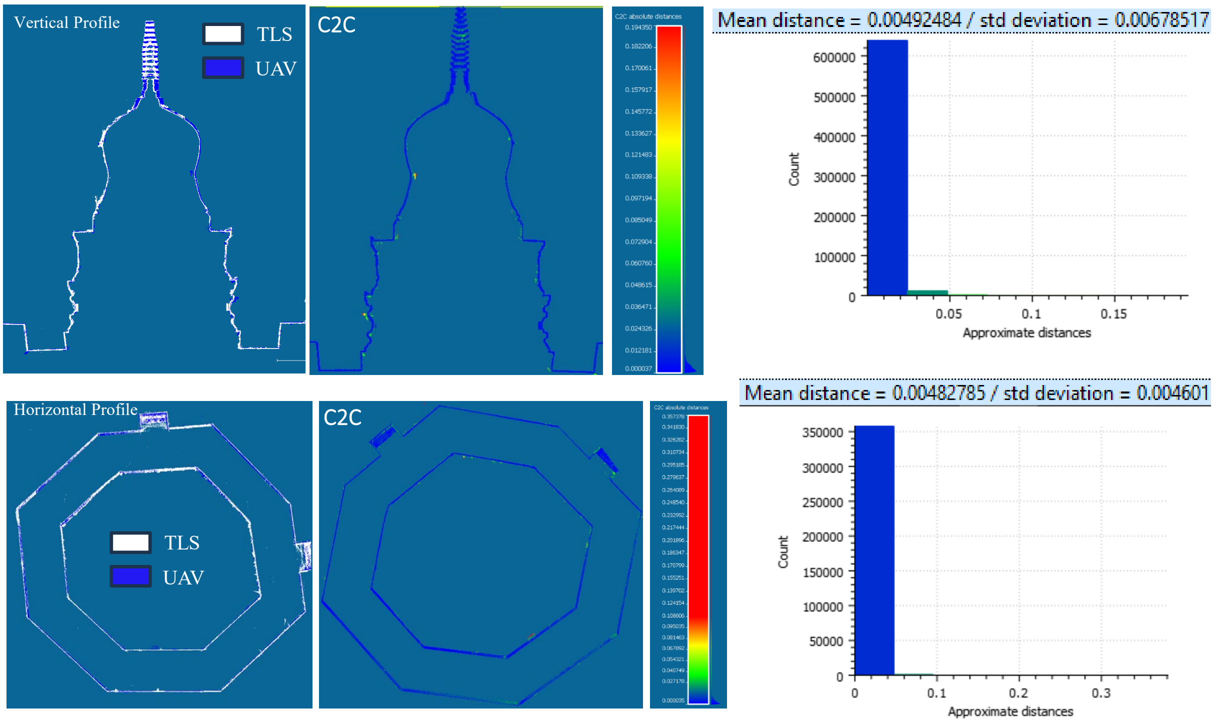

Fig. 7 C2C distance between ETS and UAV in vertical and horizontal cross-section

According to Figure 8, the mean and standard deviation of C2C between UAV and TLS in the uppermost region of the stupa are higher than the mean and standard deviation of the overall model (mean and STD are 1.70 cm and 1.76 cm, respectively). This is because the uppermost portion of the stupa represents the most challenging area for both UAV and ETS data collection. In data collection using TLS, the location of the TLS is considerably lower than the top of the stupa, resulting in the generation of DPC only on the sides and bottom of the stupa disc. In contrast, when a UAV is used for data collection, the maximum distance will be recorded on the sides and top of the stupa disc. This is because the camera on a UAV is only capable of taking aerial photos in the nadir and oblique view. Additionally, the position of the UAV is above the stupa, which limits its ability to capture all details of the region. Figure 8 shows that the DPC with the highest distance difference is in the centre (between the top and bottom discs).

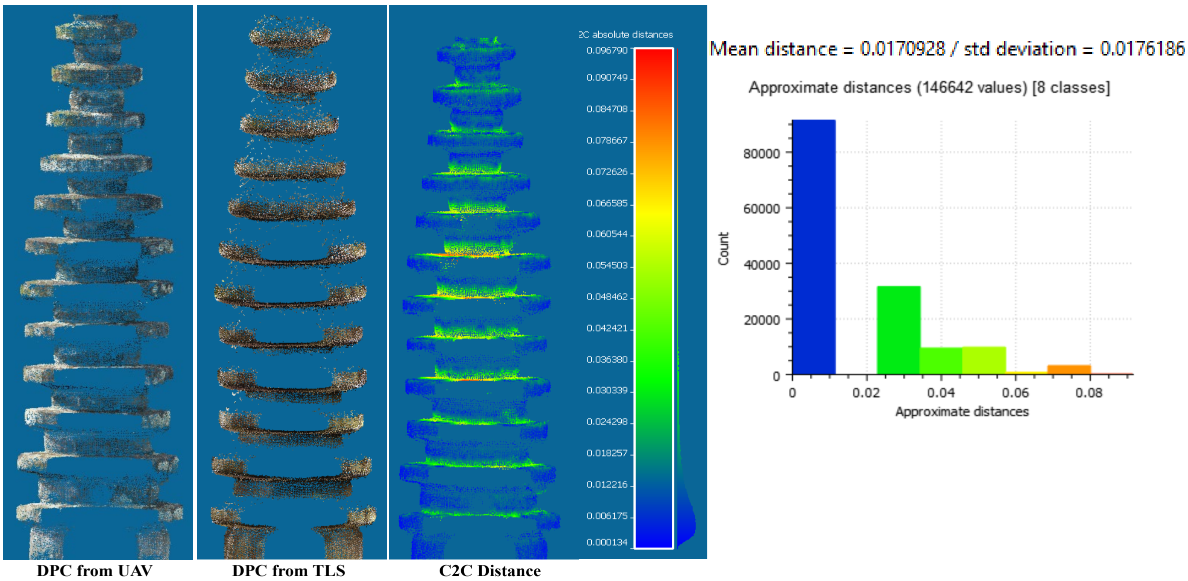

Fig. 8 C2C distance between TLS and UAV-photogrammetry at top of the stupa

Table 2. Comparison between UAV-photogrammetry and TLS in generating 3D model of cultural heritage

Item	UAV-photogrammetry	TLS
Price	25 million (DJI Mavic 2 Pro)	150 million (FARO S70)
Total labours	2 persons /ha	5 persons/ha
Data acquisition time	2 hours	8 hours
User expertise	Beginner	Advance-Professional
Data processing time	2 hours	12 hours
Level of accuracy	mm scale	mm scale

Table 2 shows how well the UAV-photogrammetry and TLS methods work in making 3D models of cultural heritage buildings. The table demonstrates that, in terms of cost, small UAVs is significantly more affordable than TLS, and only require the basic skills for operation. In terms of data acquisition, UAV is more effective than TLS due to their ability to fly autonomously. In contrast, TLS is a considerably more complex and sophisticated process, particularly in the scanning phase. To produce a comprehensive 3D model from all potential viewpoints, the retrieval position must be adjusted. Additionally, the range of TLS is constrained to objects that are directly facing the scanner. In some cases, reaching higher objects may require the assistance of a crane, which further increases the time and labour requirements of TLS.

In the data processing, TLS is more time-consuming, which is 6 times longer than photogrammetry in producing 3D models. This is due to the fact that TLS produces a significantly higher number of DPCs (10 times more than UAV-photogrammetry). In terms of accuracy, both methods demonstrate high levels of accuracy (up to the millimetre scale).

5. CONCLUSION

This study evaluates the accuracy of UAV photogrammetry based SfM-MVS algorithm for Stupa exploration at Pegulingan Temple. The RMSE value was determined to be 11.3 and 14.1 mm in horizontal and vertical directions, respectively. Thus, small value demonstrates the success of the SfM-MVS method in the digital documentation of cultural heritage building. The number of DPCs produced by TLS is 10 times greater than UAV-photogrammetry. Based on cloud-to-cloud (C2C) distance between TLS and UAV photogrammetry, almost surface dominated with blue colour, which demonstrated the small distance between these DPC (mean distance = 0.003 cm).

At the top of the stupa, both methods have low accuracy, this is because each method has weaknesses, especially in the data collection stage, TLS is more perfect in the collection of vertical objects and UAVs on horizontal objects, so the two methods are complementary. However, in terms of effectiveness, the UAV photogrammetry method outperformed TLS in terms of price, total labor, data acquisition and processing time, and level of expertise. In addition, the results could potentially be used for further analysis and for the management of the cultural heritage buildings.

This study implemented the automatic aerial triangulation method to process the UAV images. This method requires less human involvement but needs the use of high-end computers to process the UAV images. This method is faster than the conventional close-range method which requires image matching to be done manually for every stereo model. This study is very useful for related agencies, for example those in the building maintenance, heritage conservation, architecture, archaeology, and construction fields. Further studies should examine how UAV-photogrammetry can maintain consistent accuracy under different environmental conditions and develop mitigation strategies such as controlled flight paths, image post-processing techniques, or hybrid systems combining UAV and TLS data.

6. ACKNOWLEDGMENTS

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