3D Modeling of Bajang Ratu Temple using UAV Photogrammetry with Oblique Images

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Abstract. The Bajang Ratu Temple is located in Dukuh Kraton, Temon Village, Trowulan District, Mojokerto Regency, Indonesia, one of the heritage buildings of the Majapahit Kingdom. 3D modeling is one of the efforts that can be used to carry out reconstruction of the Bajang Ratu Temple. In this study, 3D modeling of Bajang Ratu Temple uses a close-range photogrammetry method with low and high oblique images taken using a non-metric camera on the Unmanned Aerial Vehicle. The results of this study were obtained geometric accuracy, that is RMSEx = 0.043 m, RMSEy = 0.049 m, and RMSEz = 0.092 m for high oblique images. While, for low oblique images, the geometric accuracy are RMSEx = 0.054 m, RMSEy = 0.062 m, and RMSEz = 0.120 m. The visual analysis results show that the exterior structure of the 3D model formed has resembled the true Bajang Ratu Temple in reality. Based on the shape's analysis, the 3D model object has an RMSE value of less than 0.5 m, so that it can appropriate the criteria for Level of Detail of order three that is RMSE < 0.5 m.

Keywords: close-range photogrammetry, low/high oblique images, UAV

1. Introduction

Bajang Ratu Temple is one of the Majapahit Kingdom's historical heritage buildings located in Dukuh Kraton, Temon Village, Trowulan District, Mojokerto Regency. This temple is a gate-type "Paduraksa" building, which is a gate that has a roof. 3D modeling is a useful way to convey information visually and spatially from objects of cultural heritage. Along with the development of technology in the field of computer vision, photogrammetry is increasingly used because of its ability to produce particular 3D products [1]. This research aims to do 3D modeling of the Bajang Ratu Temple, utilizing a method that is Close Range Photogrammetry by using low and high oblique images. Low oblique photos are done in a position between the aircraft carrying the camera and the earth's surface with a certain tilt [2]. Meanwhile, a high oblique image depicting the horizon seen in the photo [3]. Aerial photographs can be said to oblique if the slope is more than 3˚. If the horizon is not visible, it is called low oblique. Meanwhile, when the horizon appears, it is called high oblique [4]. The use of close-range photogrammetry allows for the reconstruction of geometry and textures on parts of buildings such as roofs that cannot be achieved using Terrestrial Laser Scanning & Terrestrial Photos [5]. In addition to the top, close-range photogrammetry using oblique images can also take pictures at the same time as the facade of the building [6]. Then, from this method, an analysis of the LOD Order 3 will show the architectural model in more detail, such as the structure of the roof, doors, and windows and has an RMSE < 0.5 m [7]. The 3D modeling of the historical
heritage objects can help and facilitate the community in adding insight into the historical heritage of the Majapahit Kingdom in Trowulan District, Mojokerto Regency, East Java, Indonesia.

2. Data and Method

The location of this research is located at Bajang Ratu Temple in Dukuh Kraton, Temon Village, Trowulan District, Mojokerto Regency, with coordinates 112° 23’ 55.5” BT 07 ° 34’03.9” LS [8].

![Bajang Ratu Temple](image)

Figure 1. Bajang Ratu Temple (OpenStreetMap)

2.1. Data and Equipment

The data used in this study are Bajang Ratu Temple with low & high oblique images and control point coordinates of GPS Geodetic and Total Station. The hardware used in this study is Dell Inspiron Laptop 3459 Intel Core i5, Drone DJI Phantom 4 Pro, Geodetic GPS Topcon Hiper Pro, Total Station Reflectorsless Hi-Target ZTS-320, and pre-mark. The software used in this study is DJI GO 4, GPS data processing software, Total Station data processing software, and Structure from Motion software.
2.2. Data Processing

This research's data processing begins with the photo selection stage, which is useful for getting good photo quality. Then, the modeling stage of Bajang Ratu Temple's 3D reconstruction uses the Structure from Motion (SfM) principle. The first step to do is “align photos” in order to obtain the orientation parameters inside and outside the camera through a bundle adjustment that uses the basic principle of close-range photogrammetry, that is, when a photo is taken, the beam of light from the object will spread like a straight line to the center of the camera lens until it reaches film field. The condition where an item's point in the plane of an image is located in a line in space is called the state of collinearity [10]. The collinearity equation is used as follows,

\[
\begin{align*}
    x_a - x_0 &= -c \left[ \frac{m_{11}(X_A - X_L) + m_{12}(Z_A - Z_L) + m_{13}(Y_A - Y_L)}{m_{31} X_A - X_L + m_{32} Z_A - Z_L + m_{33} Y_A - Y_L} \right] \\
    y_a - y_0 &= -c \left[ \frac{m_{21}(X_A - X_L) + m_{22}(Z_A - Z_L) + m_{23}(Y_A - Y_L)}{m_{31} X_A - X_L + m_{32} Z_A - Z_L + m_{33} Y_A - Y_L} \right]
\end{align*}
\]

(1)

(2)

\[
R = R_w \cdot R_p \cdot R_k
\]

(3)

\[
\begin{bmatrix}
    c \omega \cos \kappa & -\sin \omega \cdot \sin \kappa \cos \kappa + \cos \omega \cdot \sin \kappa & -c \omega \sin \kappa \\
    -\sin \omega \cdot \sin \kappa \cos \kappa + c \omega \cdot \cos \kappa & c \omega \cos \kappa & -c \omega \sin \kappa \\
    \sin \omega & -\sin \omega \cos \kappa & \cos \omega \cos \kappa
\end{bmatrix}
\]

XO, YO, ZO are the center point of the camera, xa, ya, -c are the coordinates of point A in the coordinate file system, and XA, YA, ZA are the coordinates of point A on the ground coordinate system where c is the focal length of the camera, and R is the element of the rotation matrix. Initially, the object is defined in the coordinate system file then coordinate transformation is carried out to get the object's coordinates in the ground coordinate system. The transformation uses the process of resection and intersection, which requires control points to obtain orientation parameters inside & outside the camera. Bundle Adjustment Self Calibration calculates these parameters. Through the process of resection and intersection, the condition of collinearity is used to determine the position of the camera when shooting as well as 3D coordinates of allied points on at least two overlapping and well-oriented photos [3].

Figure 2. UAV take-off position
The second step is the process of extracting the points on the photo using the SIFT algorithm to become a point cloud [9]. Then, the point cloud will be carried out at the masking stage, which is to eliminate points that are not used (outside the building area). The next step is georeferenced to tie the processed products to the earth's coordinate system and equalize the coordinate system between the photos with the ICP that has been taken in the field. At the georeferencing stage, an RMSE test was also conducted to meet the LoD requirement of order 3, that is, RMSE < 0.5 m [7]. Next, the results of the point cloud will be reproduced into a dense cloud. After the dense cloud is formed, a meshing stage is carried out to create the Triangulated Irregular Networks (TIN) as a framework 3D model of Bajang Ratu Temple. The last step, a texturing step, is used to give a texture to the 3D object so that it has the appearance of the original object in the field.

3. Results and Discussion

3.1. Results and Analysis of 3D Models

Below are the results of the 3D model RMSE, using the close-range photogrammetry method.

![Figure 3. High Oblique CRP 3D Model Error Diagram](image)

Based on the table before, the RMSe of ICP High Oblique CRP method on the X-axis is 0.043 m, the Y-axis is 0.049 m, and the Z-axis is 0.092 m with the total RMSe of the 3D error of 0.111 m.

![Table 4. Low Oblique CRP 3D Model Error Diagram](image)

Based on the table above, the RMSe of ICP Oblique CRP method on the X-axis is 0.054 m, the Y-axis is 0.062 m, and the Z-axis is 0.120 m with the total RMSe of the 3D error of 0.145 m. From tables 1 and 2, there are differences in the results of the ICP RMSE X, Y, and Z-axis. These differences can be influenced by differences in flight height during data acquisition, image matching process during image processing, and the effect of vehicle rotation [11].
In addition, the shift of shadows on photos that are not in a straight line will cause errors in the position and orientation of the camera when determining the coordinates of the 3D when the Bundle Adjustment process. The resolution of images can also affect geometric accuracy [12]. RMSE shows the suitability of the model for the observed point data. The lower RMSE value indicates that the model has better accuracy; conversely, if the RMSE value is higher, the model has less accuracy [13]. Here below are pictures of a 3D model result from high oblique close-range photogrammetry processing.

![3D model display](image)

**Figure 5.** High Oblique CRP 3D Model Display
(a). Front look; (b). Right-side view; (c). Back view; (d). Left side

Here below are pictures of a 3D model result from oblique close range photogrammetry

![3D model display](image)

**Figure 6.** Oblique CRP 3D Model Display
(a). Front look; (b). Right-side view; (c). Back view; (d). Left side

Based on the 3D model reconstruction of the Bajang Ratu Temple structure's close-range photogrammetry method, the High Oblique & Oblique CRP method uses the SfM (Structure from Motion) principle, and the following results are obtained.

**Table 3. Geometry results**

| Result            | Close-Range Photogrammetry |                |
|-------------------|-----------------------------|----------------|
|                   | High Oblique               | Low oblique    |
| Point Cloud       | 343.852 points              | 280.759 points |
| Dense Point Cloud | 14.163.175 points           | 7.776.276 points |
| Wireframe         | 942.074 faces dan 472.855 vertices | 518.417 faces dan 260.128 vertices |
Based on the above table, some of the differences in the results of reconstruction from the 3D model can be caused by the photo's quality and the photo's distance taken to the object. SfM requires many images that overlap in the image matching stage to extract photos to get tie points and critical points. If the images have low quality & the distance of taking photos of objects is too close, causing the SIFT algorithm is less than the maximum in performing feature point matching of overlapping images, resulting in fewer point clouds at the align photos stage [14] [15]. The identified point cloud is then docked to produce a dense point cloud; this is influenced by computing power & hardware configuration in processing data. Furthermore, from the dense point cloud results, Triangulated Irregular Networks (TIN) is formed as the object's surface framework [15]. The more number of point clouds that are identified, then the formation of the net becomes more so that it can reconstruct the 3D model of Bajang Ratu Temple that looks more detailed like the real object in the field.

(a) (b)

Figure 7. Noise Inside the Temple
(a). at High Oblique CRP; (b). at Oblique CRP

The 3D model results that have been formed in figure number 4 show significant differences compared to the original object in the field in figure number 1. The difference is that at the entrance to the temple's body, there is noise resulting in the display in the door, not according to the real Bajang Ratu Temple in the field. The camera's position causes the noise with the earth's surface having a certain tilt that causes the camera not to take more precise images on the temple's inner ceiling. Therefore, the internal roof can't be extracted from the photo's points to form a point cloud. Meanwhile, image number 3 has a similar appearance to the Bajang Ratu Temple in the field because the camera's position is facing straight to the object so that the camera can take pictures on the inside ceiling of the entrance temple. Figure 4 shows the differences in the low and high oblique close range photogrammetry method.

4. Conclusions

Based on the results of research that has been done, the following conclusions are obtained:

1. 3D reconstruction of Bajang Ratu Temple structure using CRP High & Low Oblique methods obtained 343,852 points and 180,759 points. Dense cloud of 14,163,175 and 7,776,276 points. Wireframe of 942,074 & 518,417 faces and 472,855 & 260,128 vertices.
2. Geometric accuracy of high oblique close range photogrammetry is obtained, that RMSE_x = 0.043 m, RMSE_y = 0.049 m, and RMSE_z = 0.092 m. While, for low oblique close range photogrammetry that RMSE_x = 0.054 m, RMSE_y = 0.062 m, and RMSE_z = 0.120 m.
3. From the results of the RMSE, the 3D model of Bajang Ratu Temple appropriate the LoD 3 criteria, that is RMSE <0.5 m and the 3D model can display the roof, door and relief structures in the Temple.
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