Accuracy analysis of 3D model of open-pit mine based on tilt photogrammetry

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Abstract. Mineral resources account for a large proportion in the development of national economy in China. The topography conditions around the mine site are complex, and accurate measurement of the mine topography can ensure that the mineral resources are mined safely and reasonably. The traditional mine survey has certain danger. With the advantages of flexibility and no site constraints, the UAV is equipped with a high-resolution lens and combined with tilt photogrammetry technology to obtain high-resolution images of multiple angles of the mine area and fine texture information of the feature surface in a short period of time. A total of 918 optical images were collected as raw data using a consumer-grade UAV equipped with a common optical lens. They were pre-processed and modeled to generate a high-precision, clear-textured 3D model of the study area. The root mean square of the pixel is 0.53 after aerial triangulation and adjustment. Compared with the actual measured value, the mean square error of plane coordinates is ±0.1 cm, and the maximum error is 0.2 cm, the mean square error of height is ±0.1 cm, and the maximum error is 0.2 cm. The mean square error of model plane coordinates is ±2.9 cm, and the maximum error is 10.2 cm. The mean square error of height is ±6.4 cm, and the maximum error is 8.6 cm. The results show that the production model meets the requirements of relevant specifications and the use of tilt photogrammetry in hazardous areas can improve the safety of surveyors.

1. Preface

Mineral resources provide a great help to the development of our national economy. High accuracy surveying of the terrain around the mine can provide guidance for the scientific programming of the mining area so that the mineral resources can be rationally exploited. Traditional mine surveying takes a long time, the workload is large, and the work of surveyors is at great risk [1]. The new technology of 3D laser scanning also causes little practical application due to its high cost [2]. UAV has the advantages of high mobility, low cost and no site constraints. Combining tilt photogrammetry 3D modeling with mine surveying can effectively solve the tricky problems in mine mapping, and can also provide effective information and data for the environment around the mine [3]. The development
of tilt photogrammetry in foreign countries began in the 1990s. Pictometry, a US company, was the first to investigate tilt photogrammetry and designed the EFS/POL system [4]. In recent years, tilt photogrammetry has made great progress both at home and abroad. Harwin and Lucieer [5] proposed multi-view stereo vision technology in 2012, and produced digital products with point error of 1-3cm to monitor sub decimeter coastal erosion. Grun et al. [6] used high-resolution satellite imagery (GeoEye-1) combined with UAV imagery to generate high-resolution 3D models to restore and reproduce historical buildings in Bhutan. China is a late starter in UAV tilt photogrammetry. In 2014, Wu et al. [7] used close-field photogrammetry to obtain three-dimensional information of the open-pit mine area, but it was difficult to obtain good results due to the complex topographic conditions of the mine area. Xie et al. [8] used fixed-wing UAVs for dynamic monitoring of mine reserves, and the relative error of the calculated mine reserves did not exceed 5%, which proved the reliability of UAV monitoring. Ma et al. [9] compared the UAV photogrammetry technology with GPS-RTK measurement data and concluded that the measurement results of UAV aerial survey technology can meet the demand. Yu [10] showed that the accuracy of the real 3D model made by using the tilt image collected by UAV is reliable, and it can be applied in practical engineering.

2. Tilt photogrammetry and 3D modeling

2.1. Principle of tilt photogrammetry technology

Tilt photogrammetry technology means that on the basis of traditional photogrammetry, it can acquire more complete, specific and complete terrain information by adding sensors and increasing angle of view. Conventional single camera aerial survey systems can only obtain orthophotos at vertical angles, while UAV tilt photogrammetry technology can acquire one set of orthophotos and four sets of tilt images by carrying multiple (up to five) lenses of tilt cameras (Figure 1). Five groups of images with different angles are collected and processed to extract information such as plane and elevation texture, color and shelter relationship of the terrain, thus creating a high-precision 3D model [11].

![Figure 1. Multi-shot image data acquisition.](image)

The geometry of tilt photogrammetry is shown in Figure 2. The direction of aerial flight is indicated by an arrow, the tilt of the camera is \(a\), the symbol \(b\) indicates the viewing angle of the camera, the flight height of the UAV is \(h\), and the maximum and minimum values of the horizontal distance between the UAV and the corresponding feature in the multi-view tilt image are indicated by the symbols \(D\) and \(d\) respectively.

![Figure 2. Geometric principles of tilt photography.](image)

2.2. Relevant techniques for tilt photogrammetry modeling

2.2.1. UAV tilt photogrammetry system. Tilt photogrammetry system consists of GNSS navigation system, inertial navigation system and tilt camera system. GNSS navigation system can obtain geographic coordinates, inertial navigation system can obtain the attitude angle at the moment of lens
exposure, and tilt photogrammetry system can obtain images of ground objects in five different directions.

2.2.2. Image matching. Image matching is a process of establishing a connection between points of the same name within an image through eigenvalue extraction. The main two algorithms are SIFT and ASIF. The basic steps of image matching in the process of UAV tilt photogrammetry are roughly divided into three steps: firstly, screening the image pairs to be matched and extracting the feature values of the images; secondly, coarse matching of the image pairs to obtain the initial homonymous point pairs; and thirdly, exact matching on the basis of the second step, while deleting the mis-matched points in the second step. This process becomes known in many literatures as pyramid image matching.

2.2.3. Tilted multi-view image block combined adjustment. Geometric correction and correct recognition of the dislocation relationship between images are difficult in the data processing of oblique photogrammetry, In order to ensure the matching accuracy and positioning accuracy of the same name points in the image, the exterior orientation elements of the inclined image are selected from the POS data information, and the least square matching method, the matching file method of the same name and the bundle block combined adjustment method are used to solve the problem.

2.2.4. Texture mapping. The fineness of model texture is one of the key indexes to evaluate the quality of a 3D model. The traditional 3D modeling mostly uses the field photos to map the surface of the model after the model is built, which increases the additional workload. The raw data collected by tilt photogrammetry has texture information, Therefore, it is only necessary to correspond the texture in the image to the model, that is, to establish the corresponding relationship between the two-dimensional space and the 3D space in the image. This process is called texture mapping.

3. Example of 3D modeling by tilt photogrammetry in mining area

3.1. Data source
The selected experimental area is an open pit mine near TanTan Village, Dongxing City, Guangxi Zhuang Autonomous Region (as shown in Figure 3). The selected modeling area is 500 meters long and 400 meters wide with an elevation difference of about 160 meters. The terrain undulating greatly can intuitively verify the quality of modeling. 918 tilt photography photos taken with DJI Phantom 4 Pro (It is divided into two groups, each group is 459). The camera model is SONY ILCE-6000, the lens is E 20mm, F 2.8, the image size is 6000*4000, the sensor size is 23.5mm, and the spatial reference system is WGS-84.

![Figure 3. Satellite images of open pit mines.](image-url)
3.2. Data processed
Firstly, the image control points are laid manually in the study area and the coordinates of the image control points are measured (to ensure accuracy); the flight altitude, side overlap and forward overlap parameters are set correctly after the air route is planned. Check and correct the image, and delete the unqualified image. Next, aerial triangulation was performed to obtain pre-production data, aerial triangulation is performed to obtain pre-production data, and then the image matching correction and image association (called stabbing points) were carried out with the image control point data. Finally, the 3D model with coordinates was obtained. After obtaining the preliminary model, the parts of the production results that are inconsistent with the actual need to be repaired with the help of software, and then return to map to obtain the color 3D model data.

3.3. 3D modeling results
Using high resolution optical image to generate point cloud data and establish a 3D model of the study area (as shown in Figure 4 and Figure 5), the established model can fully obtain the real scene of the surrounding environment of the mining area, and obtain the accurate spatial position, geometric shape and geological characteristics of the mining area, which can provide important parameters for the reasonable mining of the mining area.

4. Precision analysis
In this paper, the accuracy analysis of the 3D model of the open-pit mine established by tilt photogrammetry technology was carried out from three aspects: 3D model results, aerial triangulation accuracy and model accuracy.

4.1. Mine modeling results
The overall appearance of the mountain model shape undulating, the number of significant errors is very small, and the real 3D world mountain structure consistent. The model as a whole has no cavities, no excess debris, and no suspended pieces, consistent with natural phenomena.

In local detail, the curvature of the road is exactly the same, and the stones on the ground in a real 3D world can be highlighted rather than treated as a plane. From this it can be seen that the 3D model is consistent with the real world in spatial shape (as shown in Figure 6 and Figure 7). From the perspective of texture color, the model color is slightly thicker and the whole picture is sharper, but it is basically the same as the real world, and there is no big change. Mine details are not overlooked and can be fully expressed whether the rock layers at the side of the hill or the scratches on the ground in the pits at the bottom. It shows that the 3D model of open pit can clearly and completely express the true structure of the area with high accuracy.
4.2. Accuracy evaluation of aerial triangulation

4.2.1. Pixel accuracy evaluation. The mean square root of the image element can be used to evaluate the results of combined adjustment of aerial triangulation. The root mean square of the image control points of the region studied in this experiment is 0.53 pixel after adjustment, which does not exceed the specified 0.6 pixel, so it meets the requirements.

4.2.2. Accuracy evaluation of image control points. The coordinate values of image control points are changed after the combined adjustment of aerial triangulation, and according to the original external measurement plane and elevation error values to calculate the error table (such as Table 1). Finally, compare with the national maximum limit difference table (such as Table 2) to check the accuracy. The mean square error of plane coordinates is ±0.3mm, and the maximum error is 1.1mm; the mean square error of height is ±1.0mm, and the maximum error is 1.1mm. The maximum difference between the two must not exceed the stipulation.

Table 1. Error table of encrypted coordinate values of image control points and original data.

| Name  | Number of stabbing point photos | Horizontal error /mm | Elevation error /mm |
|-------|---------------------------------|----------------------|--------------------|
| dx1-1 | 4                               | 1.1                  | -1.3               |
| dx1-2 | 6                               | 0.4                  | 0.3                |
| dx1-3 | 5                               | 0.5                  | 1.0                |
| dx1-4 | 3                               | 0.6                  | -0.5               |
| dx1-5 | 5                               | 0.1                  | -1.1               |
| RMSE  |                                 | ±0.3                 | ±1.0               |

Table 2. Check point error maximum difference table.

| Mapping scale | plane /m | Altitude /m |
|---------------|----------|-------------|
|               | flat     | hilly       | mountains   | plateau   | flat     | hilly   | mountain | plateau |
| 1:500         | 0.5      | 0.5         | 0.7         | 0.7       | 0.4      | 0.4     | 0.6      | 1.2     |
| 1:1000        | 1.0      | 1.0         | 1.4         | 1.4       | 0.4      | 0.4     | 1.0      | 1.5     |
| 1:2000        | 1.8      | 1.75        | 2.5         | 2.5       | 1.0      | 1.0     | 2.0      | 2.5     |
4.3. Model Accuracy Evaluation

4.3.1. Plane Accuracy Evaluation. The check point data in the model is extracted and then compared with the measured data. The residuals in X, Y and Z directions are calculated to evaluate the accuracy of the model. As can be seen from Table 3, the maximum error in the X-direction among the statistical check points in the area is 5.6 cm, with a mean square error of ± 5.0 cm; the maximum error in the Y-direction is 8.6 cm, with a mean square error of ± 5.0 cm. The plane accuracy of the points on the 3D model produced in this experiment meets the accuracy requirements of the relevant specifications.

Table 3. 3D model control point coordinate residual statistics table.

| Name  | △X/cm | △Y/cm | △Z/cm | Plane /cm |
|-------|--------|--------|--------|-----------|
| dx1-1 | -0.9   | 4.0    | -4.0   | 4.1       |
| dx1-2 | 1.4    | -2.3   | -3.6   | 2.7       |
| dx1-3 | -6.6   | -3.5   | -5.0   | 7.5       |
| dx1-4 | 5.5    | -8.6   | -8.4   | 10.2      |
| dx1-5 | -5.6   | 2.7    | 8.6    | 6.2       |
| RMSE  | 5.0    | 5.0    | 6.4    | 2.9       |

4.3.2. Model elevation accuracy. In the industry, the mean square error is an important measure when conducting elevation accuracy evaluation. The requirements for elevation error in different scales and in different terrains (flat, hilly, mountainous, plateau) are also different. The maximum error in the Z-direction of the check point for this experiment is 8.6 cm, and the mean square error is ± 6.4 cm. From Table 4, we can see that the elevation accuracy meets the requirements.

Table 4. Topographic accuracy table.

| Accuracy level                  | Grade I | Grade II | Grade III |
|---------------------------------|---------|----------|-----------|
| Mapping scale                   | 1:500   | 1:1000   | 1:2000    |
| Flat land mean square error of height /m | 0.37    | 0.37     | 0.75      |
| Hilly mean square error of height /m | 0.75    | 1.05     | 1.05      |
| Mountains mean square error of height /m | 1.05    | 1.50     | 2.25      |
| Plateau mean square error of height /m | 1.50    | 3.00     | 3.00      |

In summary, the root mean square of the image element is 0.53 image elements after aerial triangulation and survey adjustment. Compared with the real measurement value, the mean square error of plane coordinates is ± 0.1cm, and the maximum error is 0.2cm. The mean square error of height is ± 0.1cm, and the maximum error is 0.2cm. The mean square error of model plane coordinates is ± 2.9cm, and the maximum error is 10.2cm. The mean square error of height is ± 6.4cm, and the maximum error is 8.6cm. It is obvious that the 3D modeling using tilt photogrammetry has high accuracy and uniform accuracy distribution. Its accuracy is fully compliant with industry reference specifications.

5. Conclusion

In this paper, a 3D model of a mine with accuracy up to centimeter level is obtained through the study of tilt photogrammetry and 3D modeling. The feasibility of combining tilt photogrammetry 3D modeling with mine mapping was verified, and the following conclusions were obtained:

1) 3D modeling of UAV tilt photogrammetry meets the mapping needs of the mine surface, and the accuracy of the model meets the requirements of relevant specifications.
(2) UAV remote sensing technology can solve the geological disaster investigation restricted by complex terrain conditions. By establishing a high-resolution 3D model of the survey area, it can improve efficiency, reduce the intensity and risk of field work.

(3) Modeling has high requirements for source data. The image needs to have a good texture in order to be better recognized, the same tone, mirror and smooth surface processing are poor, must be post-processing and repair. When modeling, due to occlusion at the bottom or side of the building, feature points are not extracted enough, and the model will be distorted or even empty. These issues are to be discussed by all colleagues in the industry to make progress together.

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