Research Article

Slope Topography Monitoring Based on UAV Tilt Photography Technology and Sensor Technology

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In order to solve the problems of high risk and low efficiency of the traditional rock mass structure logging method of open-pit mine slope, this paper proposes a method to improve the geological logging of traditional open-pit mine slope by using UAV tilt photography technology. Taking the slope of an open-pit quarry as an example, this method expounds the application method and work flow of UAV photography technology in geological logging. The experimental results show that the maximum and minimum absolute errors in the X direction of UAV test are 5.1 cm and 1.1 cm, respectively; MAE value is 2.90 cm; and RMSE value is 3.17 cm. The maximum and minimum absolute errors in Y direction are 3.3 cm and 0.9 cm, respectively; MAE value is 2.36 cm; and RMSE value is 2.498 cm. Vertical error refers to the error in elevation. The maximum and minimum absolute errors in Z direction are 9.6 cm and 5.7 cm, respectively; MAE value is 7.44 cm; and RMSE value is 7.54 cm.

Conclusion. The reliability of this technology is verified by comparing the occurrence measured by compass and that calculated by point cloud. On this basis, the dominant occurrence of structural plane is divided, which provides basic data support for the analysis of mine slope stability.

1. Introduction

The occurrence of geological disasters is the inevitable product of the evolution of geological bodies to a certain stage. In essence, the prevention and control of geological disasters are to restore the geological body in an unbalanced or critical equilibrium state to a new equilibrium state through artificial means. Due to the rapid development of economy, the tourism development of complex landforms such as Qifeng and Junling, as well as large-scale engineering construction and resource development, and the collapse disasters of high and steep slopes occur frequently. However, for high and steep slopes and high-level dangerous rocks, due to the lack of close contact, it is difficult to accurately obtain the physical characteristics such as the size of dangerous rocks and the distribution and development of rock mass structural planes, so it is impossible to accurately grasp the evolution state of geological bodies, which is extremely harmful and greatly increases the difficulty of treatment [1]. In order to effectively control the collapse disaster of high and steep slope, geological survey and rock mass stability evaluation are very necessary, but the survey of high and steep slope and the acquisition of geological and topographic information have always been engineering problems [2]. The stability evaluation from the perspective of geology mechanics also needs to establish corresponding physical and mechanical models supplemented by simulation calculation and analysis. For high and steep slopes, effective and accurate terrain data is more difficult to obtain.

2. Literature Review

Due to the advantages of multisensor data fusion, all countries attach great importance to the research on the theory and application of multisensor data fusion system and have obtained rich research results. Azizi, M. A. use Ku band GB-INSAR to detect the complex earth rock landslide in an urban area and monitor the landslide area in near real...
time [3]. It is pointed out that GB-INSAR is not applicable to all types of landslides, mainly for landslides with slow change and medium speed range, but GB-INSAR cannot effectively observe the phenomena of debris flow and rock falling from slope, indicating that the single monitoring of GB-INSAR has limitations. Kocharyan, G. G. placed a metal disc equipped with a worm gear engine at the monitoring station to produce a controllable displacement (0.01 mm) of 120 meters [4]. They tried to estimate GB-INSAR measurements, but they were limited by DEM matching accuracy. The metal disk is not clear on the topographic point cloud, which is the difference in the scale of remote sensing data, resulting in the limited evaluation of deformation mapping results. Nizametdinov, N. F. set up a station at the same position by using slope radar and total station at the same time to monitor the deformation of the slope of an open-pit mine in China. Several radar monitoring targets are set in the scene, and the reflection prism of total station is installed next to the target. The total station uses the automatic looking prism mode to collect deformation, which is consistent with the time interval of deformation obtained by slope radar. At the same time, it realizes the matching between slope data and total station data in its own coordinate system [5]. However, there was no significant displacement in the selected scene. Since the target shape variables were less than 1 mm, the fusion result was also the trend comparison of the two sensor data. Abramov, A. V. according to the relationship model between slope radar system and SAR image and the relationship model between slope radar system and terrain data, this paper analyzes the geometric mapping three-dimensional matching method based on range and azimuth conditions, which has achieved good results [6]. Ding, W. and others analyzed the geometric mapping 3D matching method based on range and azimuth conditions according to the relationship model between slope radar system and SAR image and the relationship model between slope radar system and terrain data. This method achieved good results [7]. In a landslide monitoring operation, Zhang, D. and others fused high-precision laser scanning point cloud and slope radar results for data fusion. Although there is no detailed description of how to obtain higher interference phase quality, the most critical area is localization relative to work activities, and the displacement detected by GB in SAR is visualized in three dimensions by merging with the three-dimensional model [8].

Jiangling, L. I. and others use the data obtained by laser scanning technology as the main support of external elevation information. According to the geometric projection principle of radar imaging, they realize the registration between point cloud data and radar pixels on the projection plane, so as to promote the conversion from the coordinates of ground radar image to local three-dimensional coordinates. The research results are used to explain and analyze the three-dimensional deformation in the monitoring application of practical slope radar system [9]. Foo, Y. L. and others believe that in general, all types of slope radar systems have not significantly improved the accuracy of deformation measurement. The adjustment of mechanical structure and the difference of radar system have introduced new (unconventional) processing links, resulting in inconsistency within the system, which will increase the cumulative error and affect the accuracy of deformation calculation.

From the research results of many scholars at home and abroad, it can be seen that photogrammetry technology can realize rapid and accurate three-dimensional reconstruction of geological bodies [10]. However, at present, UAV photogrammetry is mainly used in the monitoring and investigation of geological disasters, and there is less research on rock mass structure interpretation and logging. Studying the application of UAV in this field will help to analyze the stability of slope. Based on the analysis and summary of the application status of this technology at home and abroad, this paper forms a set of UAV tilt photography workflow suitable for geological logging of open-pit mines. Taking a rock slope in an open-pit quarry in province as an example, the point cloud model is used to extract the occurrence information of structural plane, and the reliability of this method is verified by comparing the manual measurement results.

3. Research Methods

3.1. UAV Photographic Observation System and Work Flow. The UAV photography and observation system is mainly composed of two parts: air flight part and ground control part. The air flight part includes unmanned aerial vehicle, PTZ and photographic equipment, and the ground control part includes ground controller, digital image display, and flight control system. The flight control system is the core of the whole observation system, so that the UAV can fly autonomously in varying degrees between manual control and automatic control.

The research of this paper adopts a certain type of UAV, which is divided into light UAV. This type of UAV has the advantages of light weight, low cost, flexibility, portability, and speed [11] (see Table 1 for specific parameters).

According to the technical code for slope engineering of noncoal open-pit mines (Ministry of Housing and Urban Rural Development, 2014) and the code for investigation of landslide, collapse, and debris flow disasters (1:50000) (Ministry of Land and Resources, 2014), on the basis of making full use of the advantages of UAV photography and observation system, the geological investigation of open-pit mines that can be carried out includes the following: (1) investigating the distribution range of adverse geological processes such as landslide and collapse in the site; (2) finding out the type, occurrence, and distribution of structural plane; and (3) establishing three-dimensional point cloud model, orthophoto map (DOM), and digital surface model (DSM) of geological hazard body as permanent records of slope at a certain time.

The geological survey of open-pit slope based on UAV photographic observation system is mainly composed of three parts: mining area data preparation, field aerial photography data acquisition and indoor aerial photography data processing and analysis [12]. The task of data preparation of the mining area is to collect satellite photos and topographic data of the working mining area, preliminarily plan
the route, and check the UAV equipment in advance. Field aerial photography data acquisition mainly includes site survey, route design, ground control point layout, and UAV aerial photography [13]. Indoor aerial photography data processing and analysis is to use the photos obtained by UAV aerial photography to reconstruct the rock mass in three dimensions; generate three-dimensional point cloud, DOM, and DSM; and digitally interpret the rock mass to obtain the occurrence information of rock mass and establish the spatial data file of rock mass. According to the above contents, the working process of geological logging and investigation of open-pit slope based on UAV photography is shown in Figure 1.

3.2. 3D Reconstruction and Occurrence Extraction of Rock Mass. Due to the limitation of the picture frame of the UAV equipped with photography equipment, a large number of photos need to be collected according to a certain sequence and interval to realize the three-dimensional reconstruction of rock mass. Based on the principle of stereo vision, each feature point should correspond to at least three pictures. In order to better reconstruct the sparse geometry of the target scene from the two-dimensional image, the navigation overlap rate and side overlap rate should be more than 70%. As a three-dimensional reconstruction method of monocular vision, structure from motion (SFM) has the characteristics of strong robustness, wide applicability, and large reconstruction scene. For rock mass, which does not have regular texture, regular contour, large reconstruction scene, and uneven natural illumination intensity, the reconstruction effect of SFM method can better meet the needs of all aspects. The research shows that the accuracy of terrain data using SFM method can reach centimeter level.

3.2.1. 3D Reconstruction of Rock Mass Based on SFM Method. SFM method is a method to estimate the camera parameters of the motion state through the homonymous feature points between different pictures and recover the 3D scene by using the epipolar geometric relationship between the camera parameters and the homonymous feature points. Like the human eye perceives the three-dimensional state of the object through movement or perspective change, SFM method observes the points in real space from different perspectives to obtain the depth information of the scene, so as to realize the matching of feature points with the same name and restore the sparse three-dimensional structure of the scene. In this paper, the open source library VisualSFM developed by Wu (2013) of the University of Washington is used to realize the three-dimensional reconstruction of rock mass. The specific process includes feature point extraction and matching, sparse reconstruction, and dense reconstruction.

Feature point extraction and matching. Because the scale and rotation angle of the picture will inevitably change when shooting with UAV, the ambient light intensity will not change much in one shooting process, and the ambiguity can also be controlled manually. Therefore, the scale invariant feature transform (SIFT) algorithm is used to extract the features of the pictures taken by the UAV. When extracting the feature points, the SIFT algorithm has the invariance of image rotation, translation, scaling, and affine and has certain anti illumination interference and viewing angle change ability. The specific operation steps of SIFT algorithm ① use Gaussian convolution function to transform the scale of UAV aerial photos, so as to obtain the expression sequence of the image in different scale spaces. ② The equation form of difference of Gaussian (DoG) in scale space is used to convolute with the image to obtain the extreme values. The extreme points corresponding to these extreme values are the feature points of the image. After the feature points are extracted, the topological structure between the images is established by combining the GPS coordinate information and the pose angle information of inertial measurement unit (IMU) when the UAV collects the image, and the corresponding relationship between the feature points between the image and the image is calculated by using the nearest neighbor NN algorithm to complete the matching work.

Sparse reconstruction. Sparse reconstruction is to use the matched feature point set of the same name to incrementally reconstruct the scene and obtain a “rough” three-dimensional point cloud model. The basic idea is (1) to reconstruct the three-dimensional coordinate information of a point from two-dimensional images, at least know the position of the point in the two images and the internal and external parameters of the corresponding image. Since the whole process is taken with the same camera, the internal parameters of the image have been determined when the camera leaves the factory. Only the external parameters of the image, i.e., the rotation matrix and translation vector between the images, need to be taken. (2) After knowing all the internal and external parameters of the two pictures, the three-dimensional coordinates of the spatial points can be calculated according to triangulation; that is, the three-dimensional spatial coordinates corresponding to the matching points can be restored by using the projection relationship. (3) Because the feature point matching is not absolutely accurate, the calculated three-dimensional point coordinates also have errors. In order to obtain more accurate results, it is necessary to use the bundle adjustment (BA) step by step iteration to continuously minimize the re-projection error between the projection points and the observed image points and calculate the best camera pose and the three-dimensional point cloud coordinates of the
scene. However, according to the research, when the picture quality is high and the GPS coordinate information is accurate, the ability of Ba method as an optimization algorithm to reduce the error is very limited.

Intensive refactoring. For irregular objects such as rock mass, the “rough” point cloud model restored by sparse reconstruction is not enough to describe it finely. Therefore, it is necessary to increase the density of point cloud and improve the fineness of the model. According to the previous research results, CMVS-PMVS (cluster multiview stereo patch-based multiview stereo) method is used to cluster and classify the images, remove the redundant images in the original image, and then generate a series of sparse patches and corresponding image regions from the sparse matching points with high reliability, and repeatedly diffuse and filter these regions, so as to obtain a relatively fine rock mass point cloud model.

3.2.2. Extraction of Rock Mass Structure Occurrence. The 3D point cloud model obtained by 3D reconstruction can be understood as describing a rock mass with tens of millions of 3D coordinate points, and all structural information of the rock mass is contained in these “points.” Since the topological structure of the whole point cloud model is based on the GPS sensor and IMU sensor machine carried on the UAV, the point cloud coordinates generated by three-dimensional reconstruction are the coordinates under WGS84 geodetic coordinate system, and their coordinate position relationship is the same as the objective world. The relatively stable occurrence of rock mass structural plane can be calculated directly by extracting the coordinates of points on the exposed surface of rock mass structure. Referring to the research results [14], the geometric relationship of structural plane occurrence is shown in Figure 2. Assuming that there is a structural plane \( J \) in the space, and the occurrence is expressed by inclination \((0'\sim360')\) - inclination \((0'\sim90')\), the occurrence of the structural plane is \(\alpha,\beta\). Pick the coordinates \(J_1(x_1, y_1, z_1), J_2(x_2, y_2, z_2), \) and \(J_3(x_3, y_3, z_3)\) of three points that are not collinear on the structural plane, and then, the unit normal vector \(n(\text{n}_x, \text{n}_y, \text{n}_z)\) of structural plane \(J\) can be expressed as follows [15]:

\[
\begin{align*}
\text{n}_x &= \frac{A}{\sqrt{A^2 + B^2 + C^2}} \quad \\
\text{n}_y &= \frac{B}{\sqrt{A^2 + B^2 + C^2}} \quad \\
\text{n}_z &= \frac{C}{\sqrt{A^2 + B^2 + C^2}}
\end{align*}
\]

where

\[
\begin{align*}
A &= (y_2 - y_1)(z_3 - z_1) - (z_2 - z_1)(y_3 - y_1) \\
B &= (x_3 - x_1)(z_2 - z_1) - (z_3 - z_1)(x_2 - x_1) \\
C &= (x_2 - x_1)(y_3 - y_1) - (x_3 - x_1)(y_2 - y_1)
\end{align*}
\]

According to the geometric relationship between \(n\) and \(\beta\) in Figure 2 [16], the included angle of the unit vector \((0, 0, 1)\) in the direction of \(n\) and \(z\) is the inclination \(\beta\) of the structural plane.

\[
\beta = \arccos \left| \frac{\text{n}_z}{\sqrt{\text{n}_x^2 + \text{n}_y^2 + \text{n}_z^2}} \right|.
\]

And because \(\text{n}_x^2 + \text{n}_y^2 + \text{n}_z^2 = 1\), then

\[
\beta = \arccos |\text{n}_z|.
\]

To calculate the tendency of the structural plane, it is necessary to determine the quadrant of the projection \(n'\) of the unit normal vector \(n\) of the structural plane in the X - Y plane [17]; then,
when \( n_x^2 > 0 \),

\[
\alpha = \left\{ \begin{array}{ll}
\arccos \frac{n_y}{n_x^2 + n_y^2} & \left( n_x^2 > 0, n_y > 0 \right) \\
2\pi - \arccos \frac{n_y}{n_x^2 + n_y^2} & \left( n_x^2 > 0, n_y < 0 \right)
\end{array} \right.
\]

When \( n_x^2 < 0 \),

\[
\alpha = \left\{ \begin{array}{ll}
\arccos \frac{-n_y}{n_x^2 + n_y^2} & \left( n_x^2 < 0, n_y > 0 \right) \\
2\pi - \arccos \frac{-n_y}{n_x^2 + n_y^2} & \left( n_x^2 < 0, n_y < 0 \right)
\end{array} \right.
\]

(1) When \( n_z = 0 \), it means that the structural plane is upright and the tendency does not exist. Its occurrence is generally described by strike

According to the above principles, CloudCompare plugin can be used to extract the stable occurrence of rock mass structural plane based on three-dimensional point cloud data [18, 19].

4. Result Analysis

4.1. Field Data Acquisition. Taking an open-pit quarry as an example, the total area of the mining area is about 101,510 m², the maximum elevation of the top of the slope on the slope surface is about +85.0 m, and the elevation of the bottom varies from +5.0 m to +20.0 m. After the field survey, it is found that the natural slope of the mountain in the mining area is about 15°~25°, the overall field of vision is wide, and the GPS satellite signal is stable, which is suitable for UAV flight. Therefore, the shooting process adopts the airborne computer automatic control mode. According to the size of the mining area, plan the route, set the navigation height of 140 m, and the overlap rate of heading and side direction is 80%. At the same time, 8 ground control points are arranged within the mining area and the three-dimensional coordinates are measured with RTK (Table 2). A total of 217 photos were taken during this flight, which took 13 minutes, and the orthophoto map and digital surface model with ground resolution of 3.9 cm/PX were generated.

4.2. Horizontal and Vertical Errors. The accuracy of point cloud model reconstruction is evaluated by using the coordinates of 8 ground control points measured by RTK. Pick up the center of the ground control point target in the point cloud model, read the coordinates, and compare with the data in Table 2. The results are shown in Figure 3.

The accuracy is evaluated by mean absolute error (MAE) and relative root mean square error (RMSE). Horizontal error refers to the deviation between the measured value and the true value of UAV on the X-Y plane [20], which is divided into x and Y directions. The maximum and minimum absolute errors in the X direction of this test are 5.1 cm and 1.1 cm, respectively; MAE value is 2.90 cm; and RMSE value is 3.17 cm. The maximum and minimum absolute errors in Y direction are 3.3 cm and 0.9 cm, respectively; MAE value is 2.36 cm; and RMSE value is 2.498 cm. Vertical error refers to the error in elevation. The maximum and minimum absolute errors in Z direction are 9.6 cm and 5.7 cm, respectively; MAE value is 7.44 cm; and RMSE value is 7.54 cm [21, 22].

From the above calculation results, it can be seen that the vertical accuracy of UAV measurement data is significantly lower than the horizontal measurement accuracy by about three times. The reason may be that the vertical accuracy of GPS itself is lower than the horizontal accuracy. In general, the maximum value, minimum value, MAE, and RMSE are kept within the accuracy of centimeter level [23], which is basically sufficient for the occurrence logging of rock mass structural plane and ensures the reliability of occurrence extraction to a certain extent.

4.3. Extraction and Accuracy Verification of Rock Mass Occurrence. As the rock mass of nantao slope is well exposed, the structural plane is obviously developed, and the slope toe is gently inclined, which is suitable for manual measurement, and this section of slope is selected to extract and verify the occurrence information of rock mass

| Number | Ground control point coordinates/M | X [m] | Y [m] | Z [m] |
|--------|-----------------------------------|-------|-------|-------|
| G1     | G2                                | 305835.837 | 3127230.082 | 15.014 |
| G2     | G3                                | 305830.566 | 3227096.412 | 11.332 |
| G3     | G4                                | 303848.825 | 3028034.090 | 11.078 |
| G4     | G5                                | 301004.015 | 3327157.308 | 13.315 |
| G5     | G6                                | 301050.258 | 3326985.668 | 13.245 |
| G6     | G7                                | 301205.034 | 3326984.380 | 20.428 |
| G7     | G8                                | 300875.022 | 3326967.954 | 21.324 |
| G8     |                                   | 301233.966 | 3327165.605 | 15.239 |

Table 2: Coordinates of ground control points.
structural plane. Use geological compass to measure the structural plane with stable occurrence, and record the position of the structural plane. Cut out the Nandang part from the dense reconstructed point cloud model, circle three non-collinear points with the mouse according to the manually measured and marked structural plane position, record their coordinate information, and calculate the occurrence of the structural plane according to the method described in the previous section. The results are shown in Table 3.

Through the comparison between the attitude measured by 20 compasses and the attitude calculated according to the point cloud coordinates [24, 25], it can be found that the average absolute error of inclination is 4.00°, and the average absolute error of inclination is 2.29°. The attitude results obtained by the two measurement methods are basically the same, so the attitude calculated by reconstructing the point cloud by UAV photography is reliable. All 106 occurrence stereograms are projected onto the isodensity network.
to draw the occurrence isocratic map and pole map, analyze the isocratic map and pole map, and divide the dominant occurrence of nantao slope rock mass into 5 groups. The ranges of dominant occurrence are: ① 139°~177°, ② 203°~221°, ③ 220°~247°, ④ 228°~247°, ⑤ 326°~352°. Among them, group ① is relatively slow, and the other four groups are relatively steep.

5. Conclusion

This paper expounds the technical principle and work flow of UAV photography technology in mine slope geological logging and applies this technology to the structural plane logging of a mine slope in. The following conclusions are drawn:

(1) Compared with the traditional structural plane occurrence logging method of compass + tape, UAV photography technology overcomes the limitations of rock mass structural plane statistics, avoids the danger of high and steep slope survey, improves the work efficiency of geological logging, and makes it easier to obtain the basic data of geological survey

(2) Combined with the motion recovery structure (SFM) algorithm, the two-dimensional photos obtained by UAV photography can recover the three-dimensional point cloud data with rock mass structure under complex terrain conditions, and the occurrence of rock mass structural plane can be interpreted by extracting the point cloud coordinates. In addition, the point cloud model also records all rock mass structures of the slope in a certain period, which can provide data support for the study of the impact of mining on slope stability in the future

(3) Compared with the RTK measurement results, the horizonal and vertical errors of the UAV tilt photogrammetry in this test are within the centimeter accuracy, which ensures the reliability of occurrence extraction to a certain extent

(4) Comparing the attitude measured by compass with that calculated by point cloud coordinates, it is found that the absolute average error of inclination is 4.00°, and the absolute average error of inclination is 2.29°, which proves the reliability of reconstructing point cloud attitude by UAV photography. All the acquired occurrences are drawn in the stereographic projection of chipping, and the dominant occurrences of five groups of structural planes are obtained, which are, respectively: ① 139°~177°, ② 203°~221°, ③ 220°~247°, ④ 228°~247°, ⑤ 326°~352°. These can reflect the spatial position relationship of rock mass structural plane in the measured area.

At present, the interpretation of rock mass structure using UAV tilt photography technology is only aimed at the interpretation of the occurrence of structural plane. In the future, the research in this field will be further extended to the acquisition of trace length, spacing, gap width, and other information of rock mass structural plane. On this basis, the automatic recording of all parameters of structural plane can be realized.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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