High-precision 3D real scene model construction method based on air-ground data combination

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Abstract. Due to low efficiency, low accuracy, and difficulty in intuitively realizing the real geological conditions for spatial data acquisition on mines and slopes, this study proposes the use of a 3D modeling method based on a combination of air and ground data. The method is based on Unmanned Air View (UAV) tilt photogrammetry data. In this article, 3D terrestrial laser scanning point cloud data is used as a supporting technique via control points to spatially fuse and improve the accuracy of the UAV tilt photogrammetry 3D model. This study uses the feature points to adjust the interior point coordinates of the UAV tilt photogrammetry 3D model. The application results show that the mining site model established by this method has high precision and processing efficiency. It can also display the overall characteristics of mines and provide a scientific basis for mining, exploration, measurement, and effective evaluation of slope stability.

Keywords. air-ground data; 3D modeling; UAV tilt photogrammetry; 3D terrestrial laser scanning

1. Introduction
With the construction of ecological civilization, the demand for information about mines and slopes is increasing. Supporting exploration and slope management requires complete, realistic, and high-precision spatial data. Similar to 3D spatial information data, 3D models
can completely restore the whole picture of an object, making spatial data intuitive and visible. Therefore, establishing 3D models has implications for mining, surveying, and other practical projects [1,2]. Therefore, detailed research on 3D modeling techniques is essential.

At present, new technologies, such as UAV tilt photogrammetry [3,4], close-range photography [5], 3D laser scanning technology [6], and aerial LiDAR [7] are powerful technologies for acquiring 3D geometric information. The original data sources used in 3D modeling mainly include images and 3D point clouds [8]. Many scientists across the world have studied 3D modeling. For instance, Mozhdeh et al. [9] conducted a detailed discussion of a UAV tilt photogrammetry system, which was used to model an open-pit gravel mine and evaluate the impact of imaging configuration and network stability on modeling accuracy. Angela et al. [10], Gerke et al. [11], and Nakada et al. [12] conducted relevant research on construction and accuracy to evaluate 3D models of tilt photogrammetry. Giammanco et al. [13] discussed the use of 3D laser scanning technology to create hail models and evaluate their complex shapes to provide accurate measurement results. Pesci et al. [14] performed a 3D digital scan of two leaning towers in Italy. These methods are based on a single data source for 3D modeling. Although the operation is simple, there are some drawbacks. For example, a 3D model based on UAV tilt photogrammetry technology has problems with loopholes, fuzziness, crazing, and low precision. Due to large amounts of data, it is problematic to process 3D models based on 3D laser scanning technology. In addition, due to the limited instrumental angle of view, information cannot be collected from the top of the object. Because of these limitations, some scientists have conducted detailed research on 3D modeling techniques. For example, Yan et al. [15] reconstructed a 3D scene using modeling software, utilizing orthophotos captured in UAV aerial photography, based on point cloud data scanned with a 3D laser scan. Lian et al. [16] used the Context Capture modeling system to conduct aerial triangulation for tilt photography data and ground close-range photography data. They fused the point clouds generated simultaneously and built the TIN and texture mapping to form a 3D model. Moon et al. [17] proposed a method for generating and merging hybrid point cloud data obtained from laser scanning and UAV-based image processing. They used it for earthwork analysis and verification. These research methods are 3D modeling of a combination of UAV image data and 3D point clouds or close-range images. These are also known as 3D modeling based on a combination of air and ground data, where various data sources have different effects on the models. Therefore, 3D modeling techniques based on a combination of air and ground data can compensate each other and maximize their benefits. However, combining them to improve accuracy and efficiency is an important research topic. Therefore, this study proposes a 3D modeling method based on the spatial fusion of control points and adjustment of feature points by model coordinates. This method is based on 3D model data of UAV tilt photogrammetry. The coordinates of the 3D model data for UAV tilt photogrammetry are adjusted to improve the accuracy of the model using point cloud data from the 3D terrestrial laser scan as feature points. The model established by this method can efficiently and realistically restore the original appearance of the target object. It can also form a foundation for engineering problems, such as mining, ecological restoration, and slope management.

2. Analysis of various open-air data in combination with 3D modeling techniques
2.1. 3D modeling combined with open-air images

The 3D modeling method uses UAV tilt photogrammetry and close-range photogrammetry to capture images and import the Context Capture Center scenic modeling system to realize the model construction. The software first uses the beam method of aerial triangulation [18–20]. This means that the beam consisting of each photo is used as the basic unit of adjustment. The collinear condition is used as the basic equation of adjustment to establish a unified error equation and solve the problem of the six external orientation elements in each photo of the area (Equation 1). Then, a stereo matching algorithm is used to obtain pixel disparity values to generate a disparity map. The disparity map and shooting posture model are used to fuse depth information and generate a dense point cloud. The two sets of point cloud data are fused to build a 3D TIN, and finally, a texture map is created to form a 3D real model. This method uses close-range photogrammetry data to correct missing data in UAV tilt photogrammetry. This greatly improves the side texture effect of the model. However, the workload of the ground collection is quite large and is only suitable for small areas or ancient buildings.

\[
v_i = a_i \Delta X + a_i \Delta Y + a_i \Delta Z + a_i \Delta \theta + a_i \Delta \psi + a_i \Delta \kappa - a_i \Delta X - a_i \Delta Y - a_i \Delta Z - l_i. \tag{1}
\]

where \(x\) and \(y\) are the coordinates of the visual point, \(f\) is the focal length, \(l_x\) and \(l_y\) are the constant terms of the equation in the \(x\) and \(y\) directions, respectively, \(X, Y,\) and \(Z\) are the correct number of coordinates of the desired point, \(sX, sY, sZ, a1, a2, a3,\) and \(a4\) are the external orientation elements, \(a1i = -f/H, a12 = 0, a13 = -x/H, a14 = -(f + x^2/f), a15 = -xy/f, a16 = y, a21 = 0, a22 = -f/H, a23 = -y/H, a24 = xy/H, a25 = -(f + y^2/f), a26 = -x.\)

2.2. 3D modeling of combined aerial images and 3D terrestrial laser scanning point clouds

Due to low accuracy and narrow application scope of the above methods, some researchers have proposed a 3D modeling method that combines aerial imagery with a 3D terrestrial laser scanning point cloud. This method mainly uses the ICP algorithm [21] to register point clouds and fuse them in space. However, the registration effect of this method is related to the initial position of the set point. Therefore, it is necessary to perform coarse registration initially by other means. The basic principle of the ICP algorithm is to calculate the closest corresponding points between the two sets of point clouds. Then, according to this sort of relationship, the motion parameters need to be found and finally used for data conversion.

\[
S^2 = \min \sum_{i=1}^{N} \|Q_i - (RP_i + t)\|^2. \tag{2}
\]

where \(N\) is the number of iterations, \(Q_i\) is the point in the reference point cloud, \(P_i\) is the corresponding point in the target point cloud, \(R\) and \(t\) are the rotation and translation matrices, respectively, that must be calculated.

From Equation 2, it can be seen that the ICP algorithm places the target function \(S^2\) through the corresponding point to register the data, fusing the UAV tilt photogrammetry data with the point cloud data space of the 3D terrestrial laser scanning. Point cloud data in different spatial coordinate systems are converted to the same coordinate system through registration. Finally, the data are fused to construct a TIN. Texture mapping is performed to obtain a new real scene 3D model. 3D modeling has numerous applications with high accuracy. However, when point cloud registration is completed, the minimum value is obtained by iteration, which causes deviations in the registration and errors in data fusion, affecting the accuracy of the 3D model building.
Therefore, this study improves spatial fusion in 3D modeling by combining aerial photography and point cloud data from 3D terrestrial laser scanning. A data fusion method is proposed based on control points and a method to adjust the internal coordinates of the UAV tilt photogrammetry 3D model. This method uses the point cloud data from the 3D terrestrial laser scanning as feature points to build a new 3D model and improve the accuracy of the UAV tilt photogrammetry 3D model.

3.3D model construction method based on air-ground data combination

3.1 Spatial fusion based on control points

Since the data collected by UAV tilt photogrammetry and 3D terrestrial laser scanning have their coordinate systems, they need to be integrated into the same spatial coordinate system, and the coordinates must match.

In this study, a self-made flexible square plate was used as a control point (as shown in Figure 1) for spatially merging UAV tilt photogrammetry 3D model data with 3D terrestrial laser scanning point cloud data. Before collecting data in the measurement area, the self-made control point must be placed in the measurement area. When collecting data using 3D ground laser scanning, one of them must be placed under the 3D terrestrial laser scanner. As a result, the center point of the control point matches the center point of the 3D laser scanner after leveling. Then, the data was collected. Data collection from UAV tilt photogrammetry was then performed, and control points in the measurement area, including the control point under the 3D terrestrial laser scanner, remained unchanged. After preprocessing the acquired data, they need to be fused in space. First, model data for UAV tilt photogrammetry and point cloud data for 3D terrestrial laser scanning are generated. Next, the center point of the control point under the 3D terrestrial laser scanner is used as the coordinate origin, and their X-, Y-, and Z-axis directions are matched with the establishment of the spatial coordinate system. This technique integrates UAV tilt photogrammetry model data with 3D terrestrial laser scanning point cloud data in the same spatial coordinate system. After this transformation, if the coordinates do not match exactly, one set of data needs to be spatially rotated.

The rotation axis is represented by a \((a_1, b_1, c_1)\) and b \((a_2, b_2, c_2)\), and \(\theta\) represents the rotation angle. First, \(ab\) is moved to the origin, as shown in Figure 2. Next, \(oc\) is rotated to the XOZ plane to create a projection point \(q\) of the point \(c\) on the plane YOZ and set the vertical axis of the Z-axis via \(q\). Then, \(op\) is obtained by \(oc\) rotating around the X-axis, whose rotation angle is \(\alpha\). As shown in Figure 3, \(op\) rotates around the Y-axis until it coincides with the Z-axis to obtain \(or\) whose rotation angle is \(\beta\) (clockwise). Finally, \(or\) rotates around the Z-axis, and an inverse operation is performed on these rotation operations to obtain the matrix \(M\) of spatial points that rotate around any axis, as shown in Equation 3. After spatial rotation, the UAV tilt photogrammetry model data coordinates are consistent with the 3D terrestrial laser scanning point cloud data. With these transformations, the UAV tilt photogrammetry 3D model and 3D terrestrial laser scanning point cloud data can achieve high-precision spatial fusion.
\[ M = \begin{bmatrix}
  a^2 + (1-a^2) \cos \theta & ab(1-\cos \theta) + c \sin \theta & ac(1-\cos \theta) - b \sin \theta & 0 \\
  ab(1-\cos \theta) - c \sin \theta & b^2 + (1-b^2) \cos \theta & bc(1-\cos \theta) + a \sin \theta & 0 \\
  ac(1-\cos \theta) + b \sin \theta & bc(1-\cos \theta) - a \sin \theta & c^2 + (1-c^2) \cos \theta & 0 \\
  0 & 0 & 0 & 1
\end{bmatrix}, \quad (3)
\]

Figure 1. Schematic diagram of the control point.

Figure 2. Rectilinear translation.

Figure 3. Linear rotation.
3.2 Adjusting coordinates of UAV tilt photogrammetry 3D model based on feature points

After UAV tilt photogrammetry, the 3D model data is spatially fused with the 3D terrestrial laser scanning point cloud data. The 3D terrestrial laser scanning point cloud data is then used as a feature point to improve the coordinates of the UAV tilt photogrammetry 3D model. The main processes for improving the accuracy of the model are:

1. The 3D terrestrial laser scanning point cloud data selected some characteristic points. As a result of mining operations, many locations steepen, and many joints appear, resulting in dense point cloud data in such places. The K-Medoids clustering algorithm can properly extract these feature points that represent these feature areas. The principle of the K-Medoids clustering algorithm is to divide the data into clusters closest to the cluster center according to the distance between the data object and the cluster center or the Euclidean distance between the two data objects, as shown in Equation 4:

$$\rho = \sqrt{(x_a - x_b)^2 + (y_a - y_b)^2 + (z_a - z_b)^2}^{1/2}.$$  (4)

2. The closest point algorithm that cluster the feature points (given a point set S and a target point \(q\) ∈ A of scale space A, the point of S closest to q is the point closest to point q) is used to identify the data for the corresponding points in the UAV tilt photogrammetry model data. The height difference between these feature points is calculated according to Equation 5:

$$\Delta z_i = z_i - z_{wi}, \text{ where } i \text{ is the number of feature points, } z_i \text{ is the } z \text{ coordinate of the 3D terrestrial laser scanning feature points, and } z_{wi} \text{ is the } z \text{ coordinate of the UAV tilt photogrammetry feature points.}$$  (5)

3. The point coordinates of all the data of the 3D model of UAV tilt photogrammetry are subtracted from the coordinates of the feature points of UAV tilt photogrammetry, and the relationship is shown in Equation 6:

$$d_j = \sqrt{(x_{wj} - x_{wi})^2 + (y_{wj} - y_{wi})^2 + (z_{wj} - z_{wi})^2}^{1/2}, \text{ where } j \text{ is the number of data points of the 3D model of UAV tilt photogrammetry.}$$  (6)

4. The distance influence factor is calculated by the distance influence from the feature point to each point, as shown in Equation 7:

$$k_i = 1 - d_i \left( \sum_{i=1}^{l} d_i \right)^{-1}.$$  (7)

5. The weighted average of the distances between feature points and data points in the UAV tilt photogrammetry model is used to adjust the point coordinates of the UAV tilt photogrammetry model. The new point coordinates are obtained, and the relationship is shown in Equation 8. Then, a TIN is built on the newly acquired point cloud to generate a texture mapping. Finally, a new 3D real scene model is obtained:

$$\tilde{z}_{wj} = z_{wj} + \frac{1}{j} \sum_{i=1}^{l} k_i \Delta z_i.$$  (8)
4. Application and analysis

4.1. Data acquisition and processing

In this study, a specific area of the Fang Quan Mine was selected for application and verification. First, 3D terrestrial laser scanning data was collected, and a self-made square plate was placed as a control point in the measurement area. One of them was placed under the Topcon GLS-2000 3D terrestrial laser scanner, whose center point coincided with the center point of the instrument after leveling (as shown in Figure 4). During the data acquisition, the station increased or decreased depending on the actual situation, but the scanning area had more than a 30% overlap. Considering the accuracy of the data, we covered the measurement area with fewer viewpoints and drew a position relationship diagram of the measurement station for data processing in the industry. The support software Topcon ScanMaster was used to preprocess the data collected by the 3D terrestrial laser scanner for splicing and denoising to obtain the 3D point cloud data of the mine (as shown in Figure 5).

Second, in order to collect UAV tilt photogrammetry data in the study area, only the 3D terrestrial laser scanning instrument was removed, and the positions of all control points were unchanged. A DJI PHANTOM 4 Pro UAV was used to collect the data (as shown in Figure 6). During the flight, the heading and lateral overlaps were 75% with the simultaneous shooting. The shooting height of the path was 25m above the ground. The UAV-captured photos were processed with uniform light and color, and the processed photos were imported into ContextCapture Center software to process and generate a 3D real scene model (as shown in Figure 7).

![Figure 4](image1.png)

**Figure 4.** The center of the instrument coincides with the center of the control point.
4.2. Reconstruction and precision analysis of the mine 3D model

The 3D model of the mine was reconstructed according to the method of study above. First, using the 3D model data of UAV tilt photogrammetry and the point cloud data of the 3D terrestrial laser scanning, the center point of the control point under the Topcon GLS-2000 3D terrestrial laser scanner was established as a spatial coordinate system. This point was considered the origin of the coordinates so that their data are integrated into the same spatial coordinate system (as shown in Figure 8). From the figure, it can be seen that the coordinates of the two data do not match exactly. Therefore, the above 3D points in space must be rotated around a straight line in any space. One of the 3D data was spatially rotated to match their coordinates (as shown in Figure 9). Second, according to the K-Medoids clustering algorithm, some points of the point cloud data of the 3D terrestrial laser scanning were selected as feature points. The feature points were then used to affect the distance of internal points in the UAV tilt photogrammetry 3D model and adjust the point coordinates of the UAV tilt photogrammetry 3D model. Finally, the new 3D point data of UAV tilt photogrammetry was acquired, and a 3D model was built (as shown in Figure 10). These processes are convenient and efficient because they are written in code using the Python language.

In this study, the data point position error was used for comparison before and after model adjustment. The error between the point cloud data of the 3D terrestrial laser scanning and the adjusted 3D model data of UAV tilt photogrammetry was calculated. The calculated error is...
displayed as a cloud image in Figure 11. The figure shows a maximum error of 1.0373 mm between the two sets of data with a narrow range. The error in most areas is about 0.0669 mm. After adjusting the feature points in UAV tilt photogrammetry, the 3D model of tilt photogrammetry was improved to approach the accuracy of 3D terrestrial laser scanning point clouds.

In summary, the method proposed in this paper has a broader application range and higher accuracy than the 3D modeling method combined with air-to-ground images. This method is also more convenient and error-free than the 3D modeling method that combines aerial photographs with a 3D laser scanning point cloud, which significantly improves the accuracy of the model.

Figure 8. Same space coordinate system.

Figure 9. Coordinates match.
5. Conclusion

In this article, we focused on the Fang Quan Mine as our research theme and studied the 3D modeling technique by combining UAV tilt photogrammetry with 3D terrestrial laser scanning technology. Based on the field survey, the following conclusions can be drawn:

(1) In this study, we propose a method to realize accurate data fusion by spatially fusing 3D model data of UAV tilt photogrammetry and point cloud data of 3D terrestrial laser scanning based on control points.

(2) This study uses point cloud data as feature points and calculates the weighted average of distances between the features and the internal point of the UAV tilt photogrammetry 3D model. The purpose is to adjust the coordinates of the internal point of the UAV tilt photogrammetry 3D model and obtain the final 3D model. This method significantly improves the accuracy of 3D models for UAV tilt photogrammetry. Such high-precision 3D models adequately support mining, ecological restoration, slope management, and other issues in real-world projects.

(3) The 3D modeling method optimizes the registration error problem of existing 3D modeling methods in combination with air-ground data. It provides new ideas for future research on 3D modeling techniques.

In summary, the method proposed in this paper can improve the accuracy of slope models containing joints or faults. In the future, we will further extract representative feature points
according to different areas of the 3D terrestrial laser model to improve the overall accuracy of the UAV tilt photogrammetry model.

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