An Assessment of Errors Using Unconventional Photogrammetric Measurement Technology – with UAV Photographic Images as an Example

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Abstract

Unconventional photogrammetric measurement technology, which offers features that include no specific camera measurement requirements, few constraints and the ability to take images with different types of equipment, has been used in recent years for emergency natural disaster size assessment and planning disaster relief and mitigation. However, the measurement errors associated with unconventional photogrammetric measurement technology have thus far not been standardized as have those associated with traditional photogrammetric technology. Using the Typhoon Morakot disaster area as a study area, this study used unmanned aerial vehicles (UAV) to overcome the limits of ground photographic shooting angles to conduct low-elevation photography of sediment disaster areas. Using unconventional photogrammetric measurement technology in the field of computer vision, this study established post-disaster environmental three-dimensional terrain data. With the maturation of virtual-base-station real-time kinematic (VBS-RTK) technology in recent years, it was possible in this study to conduct real-time positing by reference to ground control targets to meet goals concerning rapid assessment of disaster situations and disaster relief horizontal accuracy. In addition to introducing relevant technological integration methods, this study explored the technology’s data accuracy and its applications. The empirical results suggest that the horizontal accuracy of the technology studied is within 50 cm and the elevation accuracy is within 1 meter in most cases. Hence, the unconventional photogrammetric measurement technology described in this paper is suitable for use in making quantitative calculations of topographic data from sediment disaster regions as well as rapid disaster relief judgments.

Key Words: Unmanned Aerial Vehicles (UAV), VBS-RTK, Computer Vision, Accuracy

1. Introduction

Sediment/debris disasters have been reported frequently in Taiwan in recent years and relevant assessment and response units often use unmanned aerial vehicles (UAV), which offer advantages including high mobility, high resolution and suitability for use with static cameras or dynamic video cameras to record images of disaster-hit areas. These tools make it possible to assess the range of the impact of a disaster in real time. However, it is difficult to obtain three-dimensional data on a disaster area in real time, which makes it difficult to quantify the scale of a disaster. In this study, unconventional photogrammetric measurement technology was
used with UAV. This technology makes it possible to take images and record videos without needing specific cameras for measurements, has few conditional rest- raints and can use different types of photographic equipment to construct three-dimensional images. It also uses virtual-base-station real-time kinematic (VBS-RTK) tech- nology to obtain location coordinates and elevation information for ground control targets rapidly and with a high degree of accuracy. This makes it possible to assess disaster situations quickly and effectively reduce the de- mand for labor when surveying sediment disaster areas, thereby providing relevant units with reference information regarding disaster mitigation and disaster relief in real time. This paper first briefly introduces three-di- mensional reconstruction technology and then describes the use of VBS-RTK measured control points and UAV im- ages in the rapid reconstruction of three-dimensional environments using photogrammetric technology in the field of computer vision. Second, this paper proposes a precision verification method for analyzing error sources and the error assessment process. Finally, it presents a case study and assessment of changes in earthwork before and after a disaster to verify the feasibility of the study results.

2. Three-Dimensional Reconstruction Technology

At present, common three-dimensional reconstruc- tion technologies include the technologies of traditional measurements, aerial measurements, ground and air- borne LiDAR and close-range photogrammetric and un- conventional photogrammetric measurement techniques from the computer vision field. The accuracy, costs, ad- vantages and disadvantages, as well as the commonly used applications of these technologies, are shown in Table 1. Computer vision technology is an emerging ap- plication and a current trend in research. Many studies have been conducted in various fields of application, in- cluding static image segmentation and integration, docu- ment analysis and identification, intelligent transportation and navigation systems, image comparison and vi- sion monitoring, as well as three-dimensional recon- struction [1–11].

Due to the time-sensitive urgency for relief of na- tural disasters or major accidents, the international aca- demic community has focused on the development of the "unconventional photogrammetry" approach and its pro- cesses for application in emergent disaster relief [12]. This approach has fewer constraints than traditional photogrammetry because it uses real-time disaster site images provided by residents or media, as well as un- calibrated photos. Chen et al. [13] successfully used a consumer-type digital video camera to replace a precise velocimeter and identify the various vibration state para- meters of a stayed cable. Sun [9] and Zhao et al. [14] used a consumer digital camera to obtain the topographic three-dimensional reconstruction results of engineering-measurement-level accuracy using multiple-view stereopsis (MVS) technology in the computer vision field. A research team from Wuhan University in China shared their experience with the complete process of using un- conventional photogrammetry to collect data on the Wenchuan earthquake on May 12, 2008, acquiring and process- ing data to achieve a display of the cross-strait forum from unconventional photogrammetric measure- ments obtained from the National Cheng Kung Univer- sity in 2010 [9,12,15]. Tsai [16] used 284 UAV photos in a small and smooth area (0.04 km²) for three-dimensional reconstruction by using SIFT and SfM technologies.

Unconventional photogrammetric measurement does not require the use of a specific camera for measure- ments and camera calibration. Moreover, unconventional photogrammetric measurement can process images ob- tained at different photographic angles, from different directions, at different brightness levels, and at different scales. Although unconventional photogrammetric mea- surement is more complex than traditional photogram- metric measurement for the calculation of internal and external parameters with lower accuracy levels, it can easily be used to quickly reconstruct three-dimensional topography from images taken at the site of a disaster. If these data are compared with topographic data obtained before a disaster, the topographic elevation gap and changes can be quantified and serve as a reference for follow-up disaster relief and disaster mitigation deci- sion-making. Figure 1 illustrates the three-dimensional reconstruction steps of unconventional photogrammetric measurements. Firstly, images of the target area are taken from multiple angles [11] and a scale-invariant feature transform (SIFT) is used to extract the features and con- duct image matching [6–8]. Then, structure-from-mo-
<table>
<thead>
<tr>
<th>Method</th>
<th>Optimal accuracy</th>
<th>Advantages</th>
<th>Disadvantages</th>
<th>Common applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traditional measurement</td>
<td>&lt; 5 mm</td>
<td>Universal instruments, high accuracy and high level of price acceptance</td>
<td>Low number of datapoints, highly affected by topography</td>
<td>Topographic measurements, earthwork estimation, river channel cross sections</td>
</tr>
<tr>
<td>Ground LiDAR measurement</td>
<td>&lt; 20 mm</td>
<td>Medium to high accuracy, low topographic impact, high number of data points</td>
<td>High price, few instruments</td>
<td>Structural modeling, earthwork estimation, topographic measurements, structural and environmental monitoring</td>
</tr>
<tr>
<td>Close-range photogrammetry</td>
<td>Approximately &lt; 10 mm, related to “ground sampling distance” and “geometric configuration”</td>
<td>Low to medium accuracy, low topographic impact</td>
<td>Low number of data points</td>
<td>Structural modeling</td>
</tr>
<tr>
<td>Airborne LiDAR</td>
<td>&lt; 100 mm</td>
<td>Low to medium accuracy, low topographic impact, high number of data points with multiple echoes</td>
<td>High price</td>
<td>Structural modeling, earthwork estimation, topographic measurements, structural and environmental monitoring</td>
</tr>
<tr>
<td>Aerial measurement</td>
<td>Approximately &lt; 250 mm, related to “ground sampling distance” and “geometric configuration”</td>
<td>Low to medium accuracy, low topographic impact</td>
<td>Low number of data points</td>
<td>Topographic measurements, earthwork estimation</td>
</tr>
<tr>
<td>Unconventional photogrammetric measurement</td>
<td>Variable, approximately 1/2 of GSD</td>
<td>Low to medium accuracy, low topographic impact, high number of data points</td>
<td>Difficulty in the standardization of accuracy assessment</td>
<td>Robot or vehicle automatic navigation, building comparison</td>
</tr>
</tbody>
</table>

Figure 1. DSM generation procedure using unconventional photogrammetry.
tion (SfM) technology is used to obtain camera parameters [11,17,18] and multiple-view stereopsis (MVS) is used for three-dimensional point cloud data with colors of objects [19]. SIFT, SfM and MVS are algorithms in the field of computer vision. This study used the default parameter values. The Bursa-Wolf seven-parameter method is used with reference points to transform the relative regional coordinates of the three-dimensional point cloud data into real-world coordinate system [11, 20]. Finally, the three-dimensional spatial drawing software Surfer is used to generate a digital surface model (DSM).

3. Three-Dimensional Reconstruction Error Analysis

3.1 Main Sources of Error

The accuracy of measurement data is vital to topographical differential estimation. Whether the greater issue related to accuracy is the actual differential amount or the measurement error range can only be clarified by assessing the accuracy of the topographical data. Using airborne LiDAR as an example, Hsiao et al. [11] argued that the use of a direction application for estimation and analysis is not recommended when the difference of the observed elevation in different periods is smaller than the instrument measurement accuracy. In this study, UAV is used for aerial photography and unconventional photogrammetric measurement technology from the computer vision field is used for three-dimensional reconstruction before coordinate transformation using control points. The major sources of error include the photographic equipment, the three-dimensional reconstruction algorithm, and the number, distribution, and accuracy of the coordinates of the reference control points, as illustrated below.

(a) Photographic equipment: images with higher ground resolution yield higher accuracy in three-dimensional reconstruction. However, image ground resolution is related to sensor size, image resolution and the lens focal distance of the photographic equipment. At present, the photogrammetric accuracy of many non-measurement cameras can satisfy the requirements of 1:100 to 1:200 topographic maps [20]. Non-metric cameras are constantly being developed. In addition to increasingly higher resolutions and higher levels of accuracy, the prices of these cameras are considerably lower than cameras for measurement levels. A 2008 market survey report by Microsoft Advertising suggested that the digital camera penetration rate in Taiwan is 74%, which is the third highest in Asia and far beyond the average rate of 65% in the region. This suggests that cameras that are not meant for measurements are popular in Taiwan.

(b) Three-dimensional reconstruction algorithm: Hemmert et al. [21] from MIT argued that the errors in image measurements are mainly due to three-dimensional reconstruction algorithms used with the best optical image capturing equipment. Snavely et al. [10] used a 300,000-pixel (640×480) video camera to take short-range images of a model inside a room and then used the most advanced MVS algorithm in the computer vision field for three-dimensional reconstruction, arguing that accuracy up to 1/200 can be achieved (which is to say that the accuracy of a 20-cm-wide object can be up to within 0.1 cm). These results indicate that the currently available three-dimensional reconstruction algorithms are feasible and practical. Therefore, such algorithms were used in this study.

(c) The number, distribution and accuracy of the coordinates of the reference control points: using reference points, in addition to coordinate transformation to convert the three-dimensional point cloud data of an object from its regional coordinates into real-world coordinates, we can check measurement accuracy. Wang [22] noted that it is preferable to have more than 6 reference control points distributed within the tested region. However, increasing the number of control points does not significantly improve accuracy. In this study, the UAV images are not in the same strip and the elevation of the area is in the range of 700 to 1,300 meters. Hence, more than 6 control points are needed for coordinate transformation. Moreover, VBS-RTK is the technology of the current global positioning system (GPS) satellite positioning benchmark network and VBS has a horizontal accuracy of approximately 2 cm and an elevation accuracy of approximately 5 cm [22]. The positioning time is the shortest, requiring only two seconds. As a result, VBS-RTK can be used to rapidly obtain high-accuracy coordinates and elevation information for reference control points.
3.2 Error Checking Approach

The coordinates of the three-dimensional reconstruction point data cloud are those of the relative coordinate system of the images, which are different from the real world coordinate system and cannot be compared with the topographic measurement data of other periods. Hence, using the real world coordinate system of reference control points, the three-dimensional point data cloud from the relative regional coordinate system were transformed in this study into the world WGS84 or the Taiwanese TWD97 coordinate system for error checking. The concept of error checking is to compare the three-dimensional point cloud achievements, after coordinate transformation, with the real world high-accuracy coordinates measured using VBS-RTK. In addition, because the three-dimensional point cloud data are of high density, there will be more than one three-dimensional point cloud in the central range of the aerial photographic target (as shown in Figure 2); hence, it is difficult to determine the location of the epicenter. For this reason, the points for checking in this study were selected in order, the checking point selection range was set and three-dimensional point cloud checking of representative points and error comparison was used as in the error checking process, as shown in Figure 3 and elaborated upon in the following section.

(a) Selection of points for checking: VBS-RTK was used to conduct high-accuracy coordinate measurements of the ground control target. Some points were used as reference control points for coordinate transformation, and the remaining points were used for error checking.

(b) Setting checking point selection range: in addition to the X, Y and Z-axis coordinates, the three-dimensional reconstruction point cloud also contains the red, green and blue color codes of the images for the reference of three-dimensional reconstruction (as shown in Figure 10); therefore, the location of the ground control target board can be determined in the three-dimensional point cloud (as shown in Figure 7). This study uses the center of the ground control target board as the center of a circle and half the width of the ground control target board as the radius of the circle (the ground control target board is 2 m in width; therefore, the radius of the circle is 1 m) that contains the maximum area within the range of the ground control target board and can contain all three-dimensional data clouds falling into the ground control target board.

(c) Proposing the representative points for point clouds checking: remove all three-dimensional point clouds falling into the above-described circle and determine the X, Y, Z averages of the point cloud to obtain the average values of the three axes (as shown in Eq. 1), as the representative check points of the three-dimensional point cloud.

\[
(X_{\text{avg}}, Y_{\text{avg}}, Z_{\text{avg}}) = \left( \frac{1}{n} \sum_{i=1}^{n} X_i, \frac{1}{n} \sum_{i=1}^{n} Y_i, \frac{1}{n} \sum_{i=1}^{n} Z_i \right)
\]  

(1)

(d) Error comparison: compare the representative check points of the three-dimensional point cloud \((X_1, Y_1, Z_1)\) with the high-accuracy coordinates measured using VBS-RTK \((X_2, Y_2, Z_2)\). The horizontal difference is as shown in Eq. 2 and the absolute value of the Z difference is the difference in elevation as shown in Eq. 3.

\[
\text{Horizontal difference} = \sqrt{(X_2 - X_1)^2 + (Y_2 - Y_1)^2}
\]

\[
|Z_2 - Z_1|
\]

Figure 2. Point data cloud (black spot) and ground control target inner radius (red circle).

Figure 3. Flowchart of the error checking approach.
4. Case Study

The abundant rainfall in the catchment region of the Tseng-Wen Reservoir and the long-duration, high-intensity rainfall that occurred during the landfall of Typhoon Morakot caused a large number of landslides and collapses, as well as damage and interruption to roads and bridges. The major collapse in Leye, which had a collapsed area of up to 90 hectares, ranks at the top among newly collapsed areas during Typhoon Morakot. Because it borders the Leye Tribe and affects major connecting roads, relevant units have invested large sums of money in its management. In view of this, the Leye collapse area and its surroundings in the Alishan region were selected as the experimental region for this study. The equipment used, three-dimensional reconstruction, error comparison and estimation of change in earthwork before and after the disaster are described below.

4.1 Equipment

The photographic equipment and reference control point measurement equipment used in this study are described and illustrated below.

1. Photographic equipment: UAV and a camera and lens, with their features and functions as shown in Table 2.

2. Reference control point measurement equipment: VBS-RTK, made by the German company Leica, was used in this study for reference control point measurements. The instrument specifications are as shown in Table 3 and the equipment and use are as shown in Figure 4.

4.2 Three-Dimensional Reconstruction

UAV photography is photogrammetry with a relatively small range and there are few ground control targets for measurement that can be covered in the testing area. Figure 5(a) illustrates a typical ground control target used in Taiwan. To obtain a sufficient number of control points for the UAV photographic data, more ground control targets are required. For easy identification in images, thick white thick boards 2 m in width and length were used in this study to create the ground control targets and black tape was used on the boards for marked contrast, as shown in Figure 5(b).

The experimental region is a collapsed area in the Alishan region of Taiwan. A total of 23 temporary ground control targets such as the one shown in Figure 5(b) were made for use in this area. The experimental area is shown in Figure 6. The 15 blue points are the control points for coordinate transformation of three-dimensional data and the eight red points are for checking upon coordinate transformation of the three-dimensional data. The take-off location is shown in Figure 7. The yellow circle is the takeoff location of the UAV and the red circle at the top of the image is the No. 12 temporary ground control target. In this study, the estimated relative flying height is

Table 2. Functions of equipment of the remote control UAV system

<table>
<thead>
<tr>
<th>Performance and Specifications</th>
<th>Appearance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Remote control helicopter</td>
<td><img src="image1" alt="Remote control helicopter" /></td>
</tr>
<tr>
<td>Methyl engine exhaust at 15 cc, Weight 4.8 kg, Maximum load 6 kg, Fuel tank 500 cc, Maximum cruise duration time 30 min, Flight radius 2–3 km, Maximum flying height 2–3 km</td>
<td><img src="image2" alt="Remote control helicopter" /></td>
</tr>
<tr>
<td>2. High-resolution digital camera</td>
<td><img src="image3" alt="High-resolution digital camera" /></td>
</tr>
<tr>
<td>Brand and type: Canon EOS 550D, Valid pixels: 18,000,000, Image size: 5184 × 3456 pixels, Shutter speed: 1/4000 second to 30 seconds</td>
<td><img src="image4" alt="High-resolution digital camera" /></td>
</tr>
<tr>
<td>3. Lens</td>
<td><img src="image5" alt="Lens" /></td>
</tr>
<tr>
<td>Brand and type: Canon EF 28 mm f/1.8 USM, Focal length: 28 mm, Maximum aperture: 1.8</td>
<td><img src="image6" alt="Lens" /></td>
</tr>
</tbody>
</table>
from 500 m to 1,800 m, approximate image scale is from 1/17800 to 1/64800 and approximate ground resolution is from 31 cm to 110 cm. As observed from the image, the temporary ground control target can be easily identified in the UAV images. For each ground control target, we used VBS-RTK to measure the coordinates of the center, as shown in Table 4. The standard deviation is in the range of 2–5 cm.

After 48 images of the experimental area were recorded from multiple angles (as shown in Figure 8), SIFT was used to extract features and conduct image matching. Figure 9 illustrates the panorama of the experimental area. Next, SfM was used repeatedly to obtain camera parameters and MVS was applied to obtain a three-dimensional

<table>
<thead>
<tr>
<th>Table 3. Leica ATX1230 GG Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of channels</td>
</tr>
<tr>
<td>L1 measurements</td>
</tr>
<tr>
<td>L2 measurements</td>
</tr>
<tr>
<td>12 L1 + 12 L2</td>
</tr>
<tr>
<td>Carrier-phase full wave length C/A narrow code</td>
</tr>
<tr>
<td>Carrier-phase full wave length with AS off or on P2 code/P-code-aided under AS Equal performance with AS off or on</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Code and Phase Measurement Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrier phase on L1</td>
</tr>
<tr>
<td>Carrier phase on L2</td>
</tr>
<tr>
<td>Code (pseudorange) on L1</td>
</tr>
<tr>
<td>Code (pseudorange) on L2</td>
</tr>
<tr>
<td>0.2 mm rms</td>
</tr>
<tr>
<td>0.2 mm rms</td>
</tr>
<tr>
<td>2 cm rms</td>
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<td>2 cm rms</td>
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<table>
<thead>
<tr>
<th>Accuracy (rms) with post processing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Static (phase), long lines, long observations, choke ring antenna</td>
</tr>
<tr>
<td>Horizontal: 3 mm + 0.5 ppm</td>
</tr>
<tr>
<td>Vertical: 6 mm + 0.5 ppm</td>
</tr>
<tr>
<td>Static and rapid static (phase) with standard antenna</td>
</tr>
<tr>
<td>Horizontal: 5 mm + 0.5 ppm</td>
</tr>
<tr>
<td>Vertical: 10 mm + 0.5 ppm</td>
</tr>
<tr>
<td>Kinematic (phase), in moving mode after initialization</td>
</tr>
<tr>
<td>Horizontal: 10 mm + 1 ppm</td>
</tr>
<tr>
<td>Vertical: 20 mm + 1 ppm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Accuracy (rms) with real-time/RTK</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kinematic (phase), moving mode after initialization</td>
</tr>
<tr>
<td>Horizontal: 10 mm + 1 ppm</td>
</tr>
<tr>
<td>Vertical: 20 mm + 1 ppm</td>
</tr>
</tbody>
</table>
The three-dimensional reconstruction results can be displayed using the Trimble Realworks Survey software version 4.22, as shown in Figure 10. A total of 3,965,453 point data clouds were produced with coordinates (TWD97_X, TWD97_Y, ellipsoid height) and three primary color codes (R, G, B). The average point cloud density is 1.6/m². The area for three-dimensional reconstruction is approximately 2.5 square kilometers and the elevation of the area is in the range of 700 to 1,300 meters. Fifteen points were used in this study to transform the relative regional coordinates of the three-dimensional point data clouds into the TWD97 coordinate system with ellipsoid heights.

Table 4. Coordinates of ground control target points and standard deviations

<table>
<thead>
<tr>
<th>No.</th>
<th>TWD97_X</th>
<th>TWD97_Y</th>
<th>h (m)</th>
<th>Standard deviation (m)</th>
<th>Purpose</th>
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<tbody>
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<td>1</td>
<td>218408.02</td>
<td>2595011.43</td>
<td>1161.24</td>
<td>0.022</td>
<td>Coordinate transformation</td>
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<tr>
<td>2</td>
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<tr>
<td>3</td>
<td>218978.26</td>
<td>2595508.39</td>
<td>1160.86</td>
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<tr>
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<tr>
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<td>8</td>
<td>219000.64</td>
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<tr>
<td>9</td>
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<td>10</td>
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<tr>
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<tr>
<td>12</td>
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<tr>
<td>13</td>
<td>219813.77</td>
<td>2594550.55</td>
<td>791.64</td>
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<tr>
<td>17</td>
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<tr>
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<tr>
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<tr>
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<td>2594906.54</td>
<td>961.58</td>
<td>0.027</td>
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<tr>
<td>23</td>
<td>219823.15</td>
<td>2594548.58</td>
<td>791.94</td>
<td>0.036</td>
<td>Error comparison</td>
</tr>
</tbody>
</table>
4.3 Three-Dimensional Reconstruction Error Comparison

After the coordinate transformation was conducted as described above, horizontal and elevation error comparisons of the three-dimensional reconstruction point data cloud were conducted using the eight points not used in the coordinate transformation. Based on the point number \( n \) and error reliability \( (Er) \) equation as proposed by Li [23] (as shown in Eq. 4), a reliability of more than 73.3% was obtained in this study (as shown in Eq. 5).

\[
Er = \frac{1}{\sqrt{2(n-1)}} \times 100\% \quad (4)
\]

\[
R = 1 - Er \quad (5)
\]

The error comparison method described in section 3.2 indicates that the horizontal error is in the range of 6 cm to 46 cm and the elevation error is in the range of 0.14 m to 1.09 m (details are given in Table 5). The residuals of 15 coordinate transformation points are as shown in Table 6.

4.4 Calculation of Change in Earthwork Using Three-Dimensional Reconstruction Point Data Cloud and Pre-Disaster DTM Data

Hsiao et al. [11] used high-resolution photos and unconventional photogrammetric measurement technology to estimate the earthwork of the collapse events of the No. 3 State Road. The research findings suggest that the technology can adequately estimate changes in earthwork quantities in areas of dramatic topographic change such as slope collapse.

DTM data of this area prior to the disaster is available, with a resolution of 5 m. Hence, we can use the UAV three-dimensional reconstruction results and the 5-m-resolution DTM data to calculate the earthwork.
The Trimble Realworks Survey software was used to overlay the data and select a 5-m resolution to calculate the earthwork results, as shown in Figure 11. The parts in colors ranging from orange to yellow indicate the loss debris and the parts in colors ranging from blue to purple are the deposit debris. The total accumulation of earthwork is 924,045.95 m³, the total earthwork loss volume is 4,144,489.78 m³ and the total earthwork deposit volume is 3,220,443.83 m³. If major sediment disasters occur in the future and measurement cannot be conducted by aerial photography, airborne ground LiDAR, or other standard measurement instruments, UAV can be used to collect two-dimensional images to judge the disaster situation and area, while simultaneously producing three-dimensional topographic characterizations of the area. UAV can be used to obtain a preliminary estimate the debris and sediment volumes of the collapsed slope and thus should be able to assist in real-time disaster prevention decision-making.

Table 5. Error comparison of point cloud and control points after three-dimensional reconstruction

<table>
<thead>
<tr>
<th>No.</th>
<th>GPS measurement value (a)</th>
<th>Value after coordinate transformation (b)</th>
<th>Horizontal difference (m)</th>
<th>Elevation/vertical difference (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>TWD97_X</td>
<td>TWD97_Y</td>
<td>h (m)</td>
<td>TWD97_X</td>
</tr>
<tr>
<td>16</td>
<td>219210.87</td>
<td>2595490.94</td>
<td>1151.67</td>
<td>219210.82</td>
</tr>
<tr>
<td>17</td>
<td>219217.21</td>
<td>2595494.94</td>
<td>1151.37</td>
<td>219216.93</td>
</tr>
<tr>
<td>18</td>
<td>219279.78</td>
<td>2595402.84</td>
<td>1137.07</td>
<td>219279.91</td>
</tr>
<tr>
<td>19</td>
<td>219442.13</td>
<td>2595357.57</td>
<td>1114.29</td>
<td>219442.24</td>
</tr>
<tr>
<td>20</td>
<td>218998.99</td>
<td>2595089.82</td>
<td>1053.61</td>
<td>218999.01</td>
</tr>
<tr>
<td>21</td>
<td>218680.58</td>
<td>2594817.43</td>
<td>1034.03</td>
<td>218680.34</td>
</tr>
<tr>
<td>22</td>
<td>219356.78</td>
<td>2594906.54</td>
<td>961.58</td>
<td>219356.71</td>
</tr>
<tr>
<td>23</td>
<td>219823.15</td>
<td>2594548.58</td>
<td>791.94</td>
<td>219823.11</td>
</tr>
</tbody>
</table>

Table 6. Residuals of 15 coordinate transformation points after three-dimensional reconstruction

<table>
<thead>
<tr>
<th>No.</th>
<th>GPS measurement value</th>
<th>Value after coordinate transformation</th>
<th>Residuals error (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>TWD97_X</td>
<td>TWD97_Y</td>
<td>h (m)</td>
</tr>
<tr>
<td>1</td>
<td>218408.02</td>
<td>2595011.43</td>
<td>1161.24</td>
</tr>
<tr>
<td>2</td>
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<td>2595106.05</td>
<td>1157.4</td>
</tr>
<tr>
<td>3</td>
<td>218978.26</td>
<td>2595508.39</td>
<td>1160.86</td>
</tr>
<tr>
<td>4</td>
<td>219420.24</td>
<td>2595392.96</td>
<td>1122.8</td>
</tr>
<tr>
<td>5</td>
<td>219180.25</td>
<td>2595332.11</td>
<td>1117.22</td>
</tr>
<tr>
<td>6</td>
<td>219191.1</td>
<td>2595297.91</td>
<td>1107.99</td>
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<td>2595288.62</td>
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<tr>
<td>8</td>
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<td>2595096.11</td>
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<td>10</td>
<td>219197.35</td>
<td>2594874.21</td>
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<td>11</td>
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<td>13</td>
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<td>219458.09</td>
<td>2594606.38</td>
<td>895.17</td>
</tr>
<tr>
<td>15</td>
<td>219507.34</td>
<td>2594598.33</td>
<td>901.42</td>
</tr>
</tbody>
</table>

Figure 11. Calculation of change in earthwork using the three-dimensional reconstruction results and pre-disaster DTM data.
5. Conclusion and Suggestions

5.1 Conclusions

1. Unconventional photogrammetric measurement technology is easy to use, does not require a professional measurement camera and has few restraints. It can be used to effectively, economically and rapidly conduct environmental three-dimensional reconstruction. Coupled with VBS-RTK for control points, it can satisfy the requirements of rapid and accurate disaster relief efforts. The proposed technology is suitable for post-disaster damage information collection and historical three-dimensional environment reconstruction based on historical photos.

2. UAV photography can overcome the topographic limitations of ground photography. The combination of unconventional photogrammetry and VBS-RTK can produce three-dimensional reconstruction point clouds with horizontal errors of less than 50 cm and elevation errors of less than 1 meter. This technology is suitable for calculation of quantified data for landslides and collapse degrees, and because it can effectively reflect topographic changes in real time, it can be used in disaster response decision-making to minimize disaster risks. The precision of unconventional photogrammetric measurement technology depends primarily on the ground resolution of the photos, the control point measurement precision and the three-dimensional reconstruction algorithms. Hsiao [11] used ground photos with resolutions similar to the ground for three-dimensional reconstruction and error verification, which is similar to the approach taken in this study. Tsai [16] used UAV photos for three-dimensional reconstruction using tools and methods similar to those used in this study, but the point clouds of results are few and scattered. A non-measurement camera with a resolution of 12 million pixels and Topcon GRS-1 were used in environmental three-dimensional reconstruction to take a total of 284 photos with 14 control points in a small (0.04 km²) and smooth area. Compared with conventional aerial measurement elevation results, the elevation error is approximately 50–60 cm. In this study, the disaster area size is about 2.5 km² and the elevation of the area is in the range of 700 to 1,300 meters. Only use 48 photos to reconstruction the three-dimensional terrain data rapidly and the accuracy of results is plentiful to calculate landslide depth and landslide volume.

5.2 Suggestions

The results of this study indicate that the elevation error is greater than the horizontal error without orientation. Hence, it is suggested that ground control targets should be located at points with elevation differences as large as possible to improve elevation accuracy. Using the GPS/IMU integrated on UAV is also useful for positioning and surface modeling. The method used for coordinate transformation of control points also affects the results of the coordinate system. Different coordinate transformation methods can be tested to assess differences in their accuracy. Unconventional photogrammetric measurement has great flexibility: it can process images taken from different photographic angles and directions, with different degrees of brightness and of different sizes. Hence, there is no one definitive error model estimation method. However, errors that result from the use of images for three-dimensional reconstruction have two main sources: image resolution and the length of the reference line. Hence, it is suggested that, in addition to the above-mentioned two sources and preparation of a model estimation error inquiry table, identification of the affected ground range and scale of natural disasters, a geological status survey, a river channel slope gradient and silt survey, a soil erosion survey, quantification of landslide and collapse procedural changes and validation of the three-dimensional digital simulation of slope should all be attempted.

References


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