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Application of UAV-Based Photogrammetry for Generating High-Resolution Terrain DEM in the Sapa Mountainous Area, Vietnam

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***Abstract* - Unmanned Aerial Vehicle (UAV) photogrammetry has emerged as an effective and low-cost solution for high-resolution topographic mapping, especially in areas characterized by complex terrain and limited accessibility. This study investigates the applicability and accuracy of UAV-based photogrammetry for detailed terrain mapping in the mountainous region of Sapa, Lao Cai Province, Vietnam. A rotary-wing UAV equipped with a consumer-grade RGB camera was deployed to survey an area of approximately 3.46 km², capturing 1,235 aerial images with a ground sampling distance of 6.49 cm/pixel. The acquired imagery was processed using Structure-from-Motion (SfM) and Multi-View Stereo (MVS) techniques to generate a dense point cloud, digital surface model (DSM), and orthophoto. Ground Control Points (GCPs) measured using GNSS/RTK were employed for geo-referencing and accuracy assessment. The results indicate that the UAV-derived products achieved centimeter-level accuracy, with a total positional RMSE of approximately 2.47 cm at calibration points. Despite higher errors observed at independent check points due to steep slopes and terrain variability, the study demonstrates that UAV photogrammetry is a reliable and efficient approach for high-resolution mapping in mountainous environments. The findings confirm the potential of low-cost UAV systems as a practical alternative to conventional surveying methods for terrain analysis, infrastructure planning, and environmental monitoring.**

Keywords – UAV, DEM, Mapping, Sapa, Vietnam

I. INTRODUCTION

In recent years, advances in geospatial technologies have substantially improved practices in mining surveying. Conventional surveying methods, such as Electronic Distance Measurement (EDM), Total Station (TS), and Real-Time Kinematic Global Navigation Satellite System (RTK GNSS), are capable of achieving millimeter-level accuracy; however, they typically involve high operational costs, intensive labor requirements, and prolonged fieldwork durations. To overcome these limitations, alternative topographic surveying technologies including Terrestrial Laser Scanning (TLS) and airborne Light Detection and Ranging (LiDAR), also known as airborne laser scanning (ALS) have been increasingly adopted (Tien Bui et al., 2018). Despite their technical advantages, the application of TLS and LiDAR in open-pit mining environments remains constrained by significant costs and logistical challenges. In particular, the limited observation range of TLS requires a large number of scanning stations in complex open-pit terrains, while LiDAR data may suffer from notable vertical uncertainties when applied in highly heterogeneous open-cast mining areas (Jonathan L. Carrivick, Mark W. Smith, & Quincey, 2016).

Parallel to these developments, recent advances in robotics and GNSS technologies have driven the rapid evolution of Unmanned Aerial Vehicles (UAVs). UAV photogrammetry has consequently emerged as a promising technology capable of complementing or, in some cases, replacing conventional surveying instruments (Siebert & Teizer, 2014). In particular, small and low-cost UAV platforms equipped with non-metric digital cameras have proven to be practical and cost-effective alternatives for topographic reconnaissance and volumetric measurements (Clapuyt, Vanacker, & Van Oost, 2016; Cryderman, Mah, & Shufletoski, 2014; Siebert & Teizer, 2014). UAV-based surveying techniques have been successfully applied across a broad spectrum of disciplines, including civil engineering (Park, Kim, & Choi, 2013), disaster prevention and hazard monitoring (Birk, Wiggerich, Bülow, Pfingsthorn, & Schwertfeger; Niethammer, James, Rothmund, Travelletti, & Joswig, 2012), and agricultural studies (Zarco-Tejada, Diaz-Varela, Angileri, & Loudjani, 2014). Moreover, due to their capability to rapidly acquire high-resolution data over large areas, UAV technologies present an effective observational solution for small- and medium-scale open-pit mining sites in Vietnam.

More broadly, Unmanned Aerial Vehicles (UAVs) have transformed modern geospatial data acquisition for surveying and mapping applications. Compared with traditional aerial photogrammetry and ground-based surveying methods, UAV platforms offer greater operational flexibility, lower deployment costs, and the ability to capture imagery with very high spatial resolution (Colomina & Molina, 2014; Nex & Remondino, 2014). Advances in photogrammetric processing methodologies, particularly Structure-from-Motion (SfM) and Multi-View Stereo (MVS), enable automated three-dimensional reconstruction from overlapping UAV images (Westoby et al., 2012). These techniques facilitate the generation of dense point clouds, digital elevation models (DEM), and orthomosaic images with a high degree of geometric accuracy.

As a result of these capabilities, UAV photogrammetry has been widely employed in applications such as geomorphological analysis, infrastructure monitoring, environmental mapping, and transportation corridor surveys (Turner et al., 2012; Cryderman et al., 2014). The production of high-resolution DEMs makes UAV-based systems particularly

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well suited for mapping terrain with high relief and complex morphology. Nevertheless, the positional accuracy of UAV-derived products is strongly influenced by the quality and spatial distribution of Ground Control Points (GCPs). Previous studies have demonstrated that an appropriate GCP configuration significantly enhances photogrammetric accuracy and reduces systematic errors during bundle block adjustment (James & Robson, 2014; Mancini et al., 2013).

In mountainous regions such as Sapa in northern Vietnam, accurate and high-resolution terrain information is crucial for infrastructure development, environmental monitoring, and disaster risk assessment. UAV photogrammetry offers a time-efficient and cost-effective means of generating detailed terrain models in such challenging environments. Therefore, the objective of this study is to evaluate the performance of UAV photogrammetry for high-resolution terrain mapping in the mountainous area of Sapa. The research focuses on UAV data acquisition, photogrammetric processing, and accuracy assessment based on ground control points.

II. STUDY AREA

The study area is located in the mountainous region of Sapa, Lao Cai Province, Vietnam, which is characterized by steep slopes, highly variable elevations, and complex terrain conditions (Figure 1). Such geomorphological features pose significant challenges for conventional surveying methods and require high resolution spatial data for reliable terrain representation. A UAV based photogrammetric survey was conducted over an area of approximately 3.46 km² to acquire detailed surface information. The survey collected a total of 1,235 aerial images from 1,232 camera stations, ensuring sufficient forward and side overlap for accurate three dimensional reconstruction. Flights were performed at an average altitude of 245 m above ground level using a camera with a resolution of 5472 × 3648 pixels and a focal length of 8.8 mm. Under these conditions, a ground sampling distance (GSD) of approximately 6.49 cm/pixel was achieved, providing high spatial resolution suitable for precise topographic mapping and terrain analysis in mountainous environments.

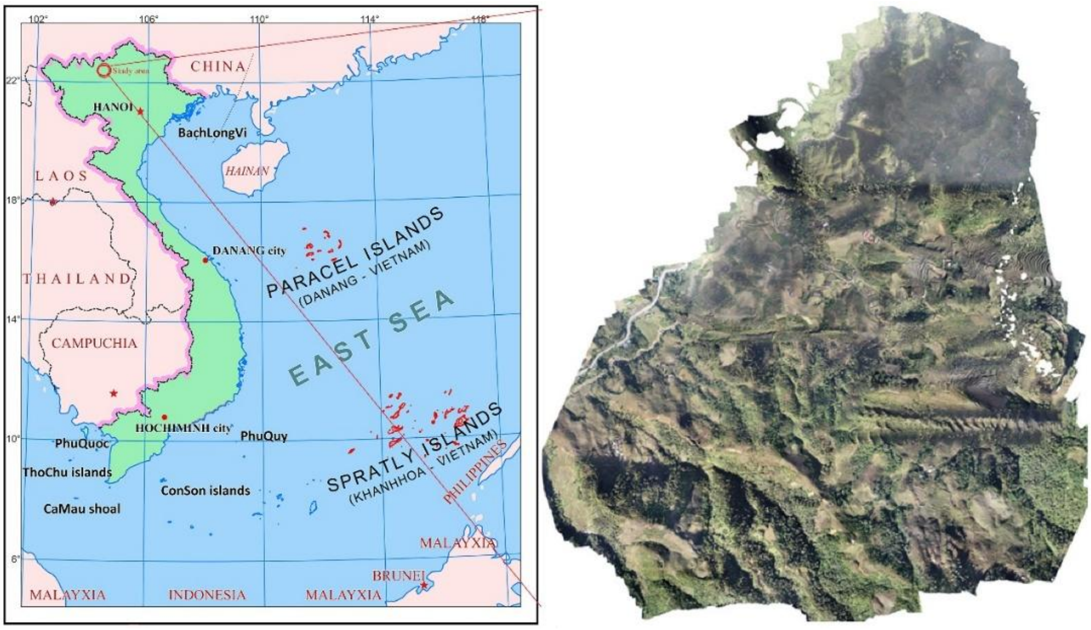

Figure 1. Location of Study are

III. MATERIALS AND METHODS

Principle of UAV based mapping technology

Unmanned aerial vehicles (UAVs) refer to a broad class of aircraft systems designed to operate without an onboard human pilot (ICAO, 2011). These systems are also commonly described using alternative terms such as remotely piloted aircraft or unmanned aerial systems. According to ICAO (2015), however, a distinction exists between these terminologies: unmanned aerial systems typically denote platforms that operate autonomously without pilot intervention and are predominantly associated with military applications, whereas remotely piloted aircraft refer to unmanned platforms that are actively controlled by a remote pilot during flight (Stöcker, Bennett, Nex, Gerke, & Zevenbergen, 2017). UAVs can be classified based on a wide variety of platform types, which differ in physical size, structural configuration, and power systems. These characteristics directly influence operational capabilities such as payload capacity, flight speed, maximum altitude, and operational range, thereby defining the range of applications for each UAV type.

Within the domain of surveying and mapping, UAVs are commonly categorized according to their airframe structure and take-off and landing mechanisms. Two principal categories are generally recognized: fixed-wing and rotary-wing UAVs. Fixed-wing UAVs rely on aerodynamic lift, offering higher energy efficiency and longer flight endurance, which enables the acquisition of imagery over large areas in a single mission. In contrast, rotary-wing UAVs are comparatively less energy-efficient and have shorter flight durations; however, their capability for vertical take-off and landing makes them particularly suitable for operations in mountainous terrains or confined locations where conventional runways or landing zones are not available.

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UAV and Camera

In mountainous surveying applications, rotary-wing UAV platforms such as the DJI Phantom 4 Professional are widely utilized due to their operational flexibility. In this study, given the relatively small extent of the survey areas, a Phantom 4 Professional was selected for image acquisition. This UAV is a quadcopter equipped with four high-performance rotors (Figure 2), providing stable flight characteristics. The onboard GPS/IMU system enables precise attitude control, hover stabilization, and automated take-off and landing functions with high reliability (Ajayi, Salubi, Angbas, & Odigure, 2017).

The platform supports both manual flight operation via a remote controller and automated flight missions through Android or iOS-based mobile applications. In automatic flight mode, key mission parameters including flight trajectory, flight speed, altitude, image acquisition area, and forward and side overlap can be predefined, allowing efficient and systematic collection of aerial imagery. The UAV is equipped with a 20-megapixel RGB camera featuring a focal length of 8.8 mm and a sensor size of 13.2 × 8.8 mm, which facilitates the acquisition of high-resolution aerial photographs suitable for photogrammetric processing (DJI, 2017).

Figure 2. DJI Phantom 4 Professional

Establishment of ground control points

Ground control points (GCPs) are essential for both geo-referencing UAV-derived products and assessing the positional accuracy of the resulting Digital Surface Model (DSM). Accordingly, GCPs were established on the ground prior to UAV image acquisition. As all quarry sites were actively operating during the survey period, preliminary field reconnaissance was conducted to identify safe and suitable locations for GCP placement using a handheld GPS device (Mapping v3.8 installed on a smartphone). The GCPs were distributed as uniformly as possible throughout each study area and positioned at locations that were easily accessible for ground measurements. The number of GCPs varied among study sites, depending on the required mapping accuracy and the spatial extent of each area.

To ensure clear visibility and reliable identification of GCPs in aerial images, the targets were marked using highly reflective materials to enhance image contrast. Each GCP marker had a printed size of 60 × 60 cm. Subsequently, the three-dimensional coordinates (X, Y, Z) of the GCPs were measured in the VN2000 / UTM Zone 48N coordinate system using GNSS/RTK methods, integrated with the existing horizontal and vertical surveying control networks available at the mining sites. Distribution of calibrated and checked points and estimated error are presented in figure 3.

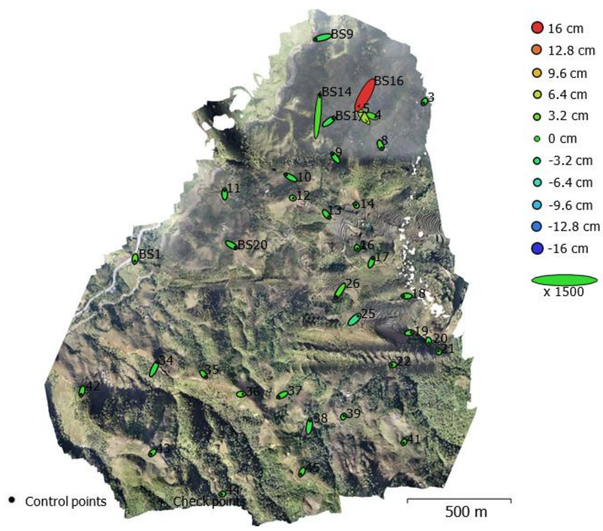

Figure 3. Distribution of calibrated and checked points and estimated error

UAV image acquisition

Aerial image acquisition for the study area was conducted using an automated flight planning mode of the Phantom 4 Pro UAV, implemented through the Pix4D Capture application installed on an iOS smartphone. In automatic flight mode, several key mission parameters were uploaded to the UAV, including the extent of the mapping area, flight altitude, and both forward and side image overlaps. Due to limitations in

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battery endurance, multiple flight missions were required for each study area to ensure sufficient image coverage for photogrammetric processing. The flight missions conducted for the different study areas are summarized in Table 1. In all cases, forward and side overlap values were set to 80%; however, flight altitudes varied among sites to accommodate differences in terrain characteristics (Table 1). Based on these predefined parameters, automated flight plans were executed to acquire the aerial imagery used in this study.

Table 1. Flying missions

Flight Altitude (m)	Ground sampling distance (cm/pixel)	No of images	Area (km²)	Camera resolution	Focal length (mm)
245	6.49	1235	3.46	5472 × 3648	8.8

Processing and accuracy assessment

In this study, UAV imagery collected in the field was processed using Agisoft PhotoScan Professional (version 1.9). The photogrammetric processing workflow implemented in Agisoft PhotoScan comprises five main stages: (i) photo alignment, (ii) bundle block adjustment, (iii) model optimization, (iv) three-dimensional surface reconstruction, and (v) generation of the Digital Surface Model (DSM). In the initial stage, distinctive key points are automatically detected on each input image. These features are then matched across multiple overlapping images through mutual comparison, a process referred to as photo alignment. After the geometric relationships among images are established and refined, corresponding key points representing identical objects in different images are accurately matched. Based on these matched features, a three-dimensional point cloud is reconstructed, from which the DSM is generated. Additionally, high-resolution orthophotos can be produced by mosaicking the UAV images using the estimated camera geometry.

Accuracy assessment of the Digital Surface Model (DSM) is a critical component of the photogrammetric workflow, as the validity of the derived products depends on their positional reliability. In this study, both horizontal and vertical accuracies were evaluated by comparing DSM-derived coordinates with ground control points measured using a Leica total station, and the discrepancies were quantified using the Root Mean Square Error (RMSE). Specifically, accuracy metrics were calculated for the, following the methodology recommended by Agüera-Vega (Agüera-Vega, Carvajal-Ramírez, & Martínez-Carricondo, 2016). The corresponding equations employed for these calculations are presented below.

$$\Delta X = \mathrm{X_{DSM}} - \mathrm{X_{GCP}} \quad (1)$$

$$\Delta Y = \mathrm{Y_{DSM}} - \mathrm{Y_{GCP}} \quad (2)$$

$$\Delta Z = \mathrm{Z_{DSM}} - \mathrm{Z_{GCP}} \quad (3)$$

$$\Delta XYZ = \mathrm{XYZ_{DSM}} - \mathrm{XYZ_{GCP}} \quad (4)$$

$$RMSE_X = SQRT\left[(1/n)\sum_{i=1}^{n}(\Delta X)^2\right] \quad (4)$$

$$RMSE_Y = SQRT\left[(1/n)\sum_{i=1}^{n}(\Delta Y)^2\right] \quad (5)$$

$$RMSE_Z = SQRT\left[(1/n)\sum_{i=1}^{n}(\Delta Z)^2\right] \quad (6)$$

$$RMSE_{XYZ} = SQRT\left[(1/n)\sum_{i=1}^{n}((\Delta X)^2 + (\Delta Y)^2 + (\Delta Z)^2)\right] \quad (7)$$

where X_{GCPi} and X_{DSM} are the X-coordinate component of GCP and corresponding coordinate in DSM, respectively; Y_{GCPi} and Y_{DSM} are the Y-coordinate component of GCP and corresponding coordinate in DSM, respectively; Z_{GCPi} and Z_{DSM} are the Z-coordinate component of GCP and corresponding coordinate in DSM, respectively.

IV. RESULTS AND DISCUSSIONS

In term of processing time, an average of 10 hours was spent to process orthographic images and DSMs on a computer with Windows 10 64-bit operating system, 2.93 GHz × 4 CPU, and 32G RAM. The point cloud of the quarry with around 50 million 3D points, was extracted according to the data processing method described above, and an orthographic image and a DSM were generated with resolutions of 5 and 35 cm, respectively. The results are shown in Table 2 and 3 and Figure 4. The root mean square error (RMSE) of the position coordinates was analyzed to be about 5 cm in total direction.

The results of this study highlight the strong capability of UAV-based photogrammetry to generate high-resolution and geometrically reliable terrain products in mountainous areas. The dense point cloud derived from more than 1,200 UAV images successfully captured fine-scale topographic features, including steep slopes and elevation discontinuities, which are typically challenging for conventional ground-based surveying methods. The achieved ground sampling distance of 6.49 cm/pixel enabled the reconstruction of detailed surface morphology suitable for terrain analysis and mapping tasks.

The accuracy assessment demonstrates that the application of an adequate number and spatial distribution of Ground Control Points plays a critical role in improving model reliability. The calibration points yielded a total RMSE of approximately 2.47 cm, indicating a high level of consistency between the UAV-derived DSM and ground measurements. These results are comparable with those reported in previous UAV photogrammetry studies conducted in complex terrain, confirming that consumer-grade UAV platforms can achieve survey-grade accuracy when supported by robust photogrammetric workflows and well-distributed GCPs.

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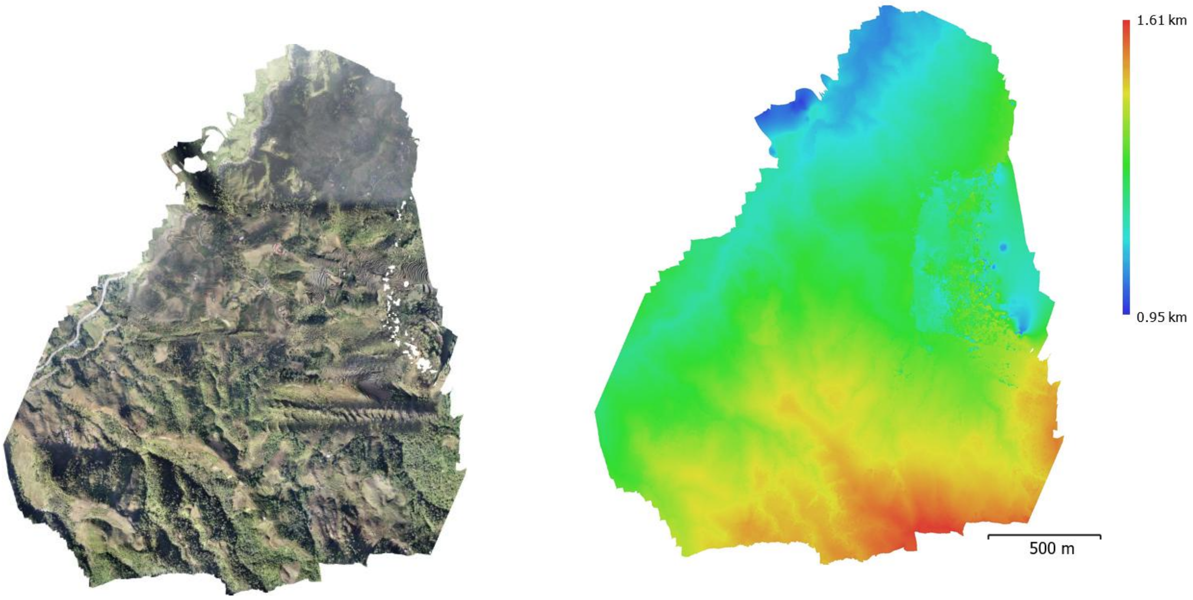
Table 2. Error and RMSE in X, Y, Z and XYZ of GCPs used for the model calibration

Calibration points	X error (cm)	Y error (cm)	Z error (cm)	Total error (cm)
10	-2.55844	1.54916	-0.768838	3.08815
11	-0.0334994	2.05517	-0.646842	2.15482
12	0.355657	-0.107738	2.02962	2.06336
13	1.28081	-1.31937	-0.736238	1.98073
14	-0.250035	0.232628	0.271316	0.436172
16	0.225567	-0.543763	-0.206008	0.623698
17	0.815879	2.0377	-0.290872	2.21415
18	-1.8528	0.0102422	-0.393446	1.89414
19	1.1918	0.311753	0.802352	1.47015
20	0.0389913	-0.979216	-0.803654	1.26738
21	-0.243056	0.424594	0.22313	0.53772
22	-0.754274	-0.109073	0.234678	0.797434
25	2.2263	2.10663	-3.95492	5.00357
26	-2.2591	-3.39318	1.29016	4.27572
3	-0.500029	-0.802625	0.192084	0.964952
36	1.16724	0.0570482	1.89014	2.22223
37	-2.06465	-1.06655	0.0353842	2.32412
38	0.577151	3.36591	-1.71381	3.82094
39	0.290243	0.518694	0.295462	0.663764
4	2.10317	-0.868652	1.51423	2.73327
41	-0.265283	-0.428539	0.210873	0.546341
42	-0.525267	-1.89526	0.798421	2.12259
43	-0.874611	-0.8345	-0.26723	1.23804
44	-0.517594	-0.13206	0.0571415	0.537223
45	-0.763384	-1.31062	0.75265	1.69321
8	0.575424	-1.65642	0.940395	1.98977
9	-1.52936	1.97261	-0.151308	2.5006
BS1	-0.18586	-1.38189	2.01773	2.45263
BS17	2.60742	1.85641	-1.50328	3.5362

BS20	2.30052	-1.36466	-0.387735	2.70278
BS9	-4.04086	-1.05136	-1.998	4.62881
34	1.80536	3.67622	-1.00107	4.21617
35	1.12415	-1.30179	0.129331	1.72485
RMSE	**1.48692**	**1.56274**	**1.1982**	**2.46754**

Table 3. Error and RMSE in X, Y, Z, and XYZ of GCPs used for the checking DSM

Checked points	X error (m)	Y error (m)	Z error (m)	Total error (m)
5	2.29747	-3.19523	5.13689	6.47113
BS14	1.2223	13.4127	1.41658	13.5425
BS16	-4.10562	-7.45573	15.9781	18.1037
RMSE	**2.80645**	**9.04981**	**9.72441**	**13.5772**



(a) (b)

Figure 4. Processing results for Sapa site (a) Orthophoto (b) DSM

From an operational perspective, UAV photogrammetry offers substantial advantages over traditional surveying techniques, including rapid data acquisition, reduced fieldwork requirements, and increased safety by minimizing exposure to hazardous terrain. In the context of mountainous regions in northern Vietnam, where access constraints and environmental conditions often limit the efficiency of conventional methods, UAV-based surveying represents a highly practical solution. Nevertheless, careful consideration must be given to flight design, overlap ratios, and ground control configuration to mitigate systematic errors and ensure data reliability.

V. CONCLUSION

This study confirms the effectiveness of UAV-based photogrammetry as a reliable and efficient method for high-resolution terrain mapping in mountainous environments. The UAV survey conducted over a 3.46 km² area in Sapa achieved a ground sampling distance of 6.49 cm/pixel and produced a dense point cloud comprising tens of millions of points, enabling detailed representation of complex terrain features. Accuracy evaluation using GNSS/RTK-measured ground control points demonstrated centimeter-level positional accuracy, with an overall RMSE of approximately 2.47 cm at calibration points.

Although higher errors were observed at independent check points due to rugged topography and steep slopes, the results remain within acceptable limits for most topographic mapping and environmental applications. Compared with conventional ground-based surveying methods, UAV photogrammetry provides significant advantages in terms of

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efficiency, cost-effectiveness, spatial resolution, and operational safety.

Overall, the findings of this study demonstrate that low-cost UAV systems, when combined with appropriate photogrammetric processing and ground control strategies, can serve as a powerful alternative for terrain mapping in mountainous regions. Future research should focus on optimizing GCP configurations, integrating RTK/PPK-enabled UAV platforms, and evaluating multi-temporal surveys to further improve accuracy and applicability in complex landscapes.

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