Research on high-precision mapping of complex terrain based on UAV remote sensing and 3D laser scanning

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Abstract: Accurate mapping of complex terrain is very important in the fields of geological disaster monitoring and smart city construction. However, traditional surveying and mapping methods are inefficient, costly and have incomplete data coverage in complex scenes. In this paper, a high-precision mapping method of complex terrain is proposed, which combines Unmanned Aerial Vehicle (UAV) remote sensing and 3D laser scanning. Through the collaborative observation scheme of "wide area coverage in the air+ground detail enhancement", combined with deep learning assisted point cloud registration and noise filtering technology, the measurement of plane accuracy ± 5cm and elevation accuracy ± 3cm has been achieved. In addition, the terrain adaptive filtering algorithm developed by the research has improved the completeness rate of extracting surface information from vegetation covered areas to over 90%. The effectiveness and universality of the method have been verified in typical scenarios, providing a new technical solution for high-precision mapping of complex terrains.

1. Introduction

Accurate mapping of complex terrain is the core requirement in the fields of geological disaster monitoring, smart city construction and natural resource management. Traditional surveying and mapping methods face obvious limitations in complex scenes: constrained by factors such as topographic fluctuation, poor visibility conditions and high demand for manual intervention, resulting in low efficiency, high cost and incomplete data coverage [1]. In landslide monitoring, it is difficult for traditional methods to obtain high-resolution surface deformation information quickly [2]; In urban 3D modeling, the occlusion of building facades and ground objects often leads to data holes, which affects the accuracy of the model.

In recent years, unmanned aerial vehicle remote sensing (UAV-RS) and 3D laser scanning (terrestrial/airborne laser scanning, TLS/ALS) technologies have become important means for complex terrain mapping due to their non-contact, high efficiency, and high precision characteristics [3-4]. UAVs equipped with LiDAR or optical cameras can quickly acquire large-scale surface information, while ground-based 3D laser scanners (TLS) can capture detailed features of vertical structures such as building facades and rock walls. However, single technologies still have obvious shortcomings [5]. Affected by flight height and payload limitations, the point cloud density is relatively low, and data gaps are easily produced in vegetated areas [6]; TLS is limited by the range of station setup, while ALS suffers from higher point cloud noise due to the stability of the flight platform.

This study proposes a high-precision mapping method for complex terrain that integrates UAV remote sensing and 3D laser scanning. By designing a collaborative observation scheme of "wide area coverage in the air+ground detail enhancement", combined with deep learning assisted point cloud registration and noise filtering technology, the method achieves measurement accuracy within ± 5cm in the plane and ± 3cm in the elevation. A terrain adaptive filtering algorithm is developed to improve the completeness of surface information extraction in vegetation coverage areas to over 90%. Finally, the effectiveness and universality of the method are verified in typical scenarios.

2. Research methods and technical routes

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2.1 System architecture design

A collaborative technology system integrating UAV remote sensing and 3D laser scanning (LiDAR) is designed. The system follows the technical route of "data collection-data fusion-information extraction-achievement application", and its core lies in giving full play to the advantages of the two technologies, and overcoming the bottleneck faced by a single technology through collaborative observation of the sky and the earth and intelligent data processing. The cooperative observation system architecture of "wide coverage in the air+detail enhancement on the ground" is adopted. The architecture is a multi-level and closed-loop organic whole, and its workflow is shown in Figure 1 below.

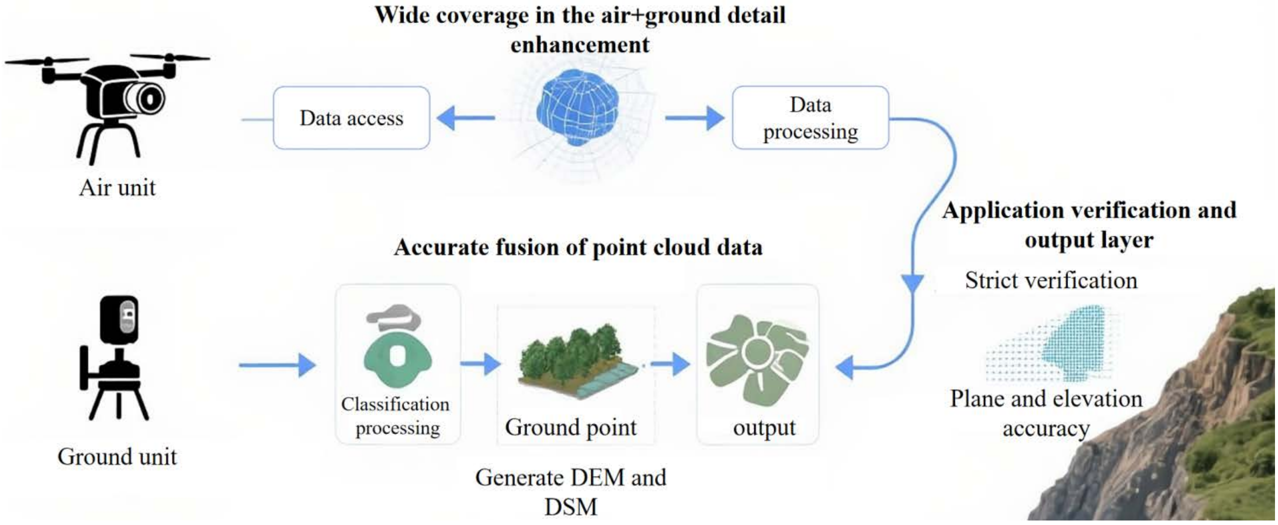

Figure 1 Collaborative observation system architecture

The data acquisition layer adopts the hierarchical observation architecture of "air-ground" cooperation. The aerial unit is composed of UAV platform equipped with tilt camera and laser radar, which is responsible for scanning the survey area in a wide range and with high efficiency, quickly obtaining 3D information of topography, surface and upper part of vegetation canopy, and realizing wide-area coverage [7]; The ground unit adopts TLS, which is arranged in key areas and blind areas of UAV observation. Through multi-station scanning, high-precision fine point clouds of elevation and shaded areas are obtained, which effectively makes up for the lack of details and blind areas of aerial data.

In the data preprocessing and fusion layer, firstly, the original point cloud and image data obtained by UAV and ground equipment are solved, denoised and roughly registered; Then, through the high-precision multi-source point cloud registration algorithm assisted by deep learning proposed in this study, the precise alignment and deep fusion of sky-place cloud data with different perspectives, densities and scales are realized, and finally a unified, complete and seamless "true 3D" scene point cloud model is generated [8].

In the intelligent data processing and extraction layer, the unified "true 3D" point cloud model generated by fusion is refined. The core link is to apply the self-developed terrain adaptive filtering algorithm to realize the automatic classification of point clouds, accurately distinguish ground points, vegetation points and building points, and focus on solving the problem of extracting ground points in vegetation-covered areas, effectively separating the real terrain information under vegetation cover [9]. Based on the classification results, diversified surveying and mapping products such as high-precision digital elevation model (DEM), digital surface model (DSM) and 3D real-life model are further generated, providing reliable data support for subsequent applications.

In the application verification and output layer, the generated high-precision DEM, 3D model and other results are applied to practical scenarios such as landslide deformation monitoring, earthwork calculation and urban 3D modeling to verify the practicality of the method. At the same time, the final results are evaluated for accuracy through inspection and verification points set up in the field, and their plane and elevation accuracy are strictly verified to ensure that the design goals of ± 5cm in plane and ± 3cm in elevation are achieved.

2.2 Ky technology

2.2.1 Optimization technology of multi-platform cooperative observation scheme between heaven and earth

The collaborative planning method of UAV altitude, heading, overlap and ground scanner station location based on mission requirements is studied. Establish standard operating procedures (SOP) to ensure the complementarity and consistency of the two kinds of data in space, time and accuracy, and maximize the efficiency and data integrity.

2.2.2 High-precision automatic registration technology of multi-source point clouds assisted by deep learning

Aiming at the registration problem of sky-place clouds caused by large difference in visual angles and uneven density, a point cloud registration method based on depth feature learning is studied. Using neural network to automatically extract the macro and local structural features of point clouds, instead of the traditional method of relying on manual design of feature points, the fast, robust and high-precision automatic registration is realized, which lays the foundation for data fusion.

2.2.3 Adaptive filtering and classification technology of point cloud for complex terrain

One of the core innovations of this study. Aiming at the poor performance of existing filtering algorithms in steep slopes, gullies and vegetation areas, a terrain adaptive filtering algorithm was developed [10]. The algorithm will dynamically adjust the filtering parameters and judgment threshold by combining the multi-dimensional characteristics such as slope, elevation variance and point cloud density, which will significantly improve the accuracy and completeness of point cloud classification (especially ground point extraction) in complex environment, and the goal is to improve the completeness of surface information extraction in vegetation-covered areas to over 90%.

2.2.4 Accuracy verification and uncertainty analysis technology of multi-source data fusion

Establish a systematic accuracy evaluation system, and strictly test the absolute accuracy and relative accuracy of the final product through the measured data in the field. This paper analyzes the mechanism of error generation and transmission in the process of fusion, quantitatively evaluates the reliability of the results and analyzes the uncertainty to ensure the scientificity and credibility of the research results.

3. Experimental design and result analysis

In order to verify the validity and universality of the proposed method, two typical complex terrain areas are selected for experiments: experimental area A is a mountainous landslide with severe terrain fluctuation and dense vegetation coverage, and there are obvious landslide cracks and scarps, so it is difficult for traditional surveying and mapping to obtain complete and high-precision data; Experimental area B is an urban canyon area with dense high-rise buildings and narrow streets. The GNSS signal is limited and the ground objects are seriously blocked.

In each experimental area, three data acquisition and processing schemes are carried out simultaneously:

(1) Scheme 1 (single UAV remote sensing): Only UAV with LiDAR is used for aerial survey.

(2) Scheme 2 (single ground scanning): only the ground 3D laser scanner is used for multi-station scanning.

(3) Scheme 3 (this research method): cooperative observation of UAV and ground scanning is adopted, and the fusion and processing algorithm proposed in this paper is applied.

By comparing the accuracy, completeness and efficiency of the three schemes, the research method is comprehensively evaluated. A total of 200 high-precision checkpoints were laid out in the field as true values for precision verification.

The accuracy of DEM generated by the three schemes is verified by field checkpoints, and the statistical results are shown in Table 1. In the mountain scene, the single UAV scheme is affected by vegetation occlusion, and the elevation accuracy is poor; Although the single ground plan has the highest accuracy, the data coverage is limited, and it is difficult to obtain the complete data of the whole landslide. The fusion scheme in this study achieves high-precision coverage of the whole region on the premise of ensuring accuracy (plane < 5cm, elevation < 3cm). In urban scenes, a single UAV scheme produces a large number of data holes due to occlusion, and its accuracy is seriously reduced; The single ground plan has high accuracy in streets but lacks roof data. In this study, the fusion scheme effectively makes up for their respective defects, and achieves the best comprehensive accuracy. The root mean square error (RMSE) of plane and elevation is stable within 5cm and 3cm, reaching the predetermined index.

Table 1 Statistical table of DEM accuracy of different schemes (unit: m)

Experimental area	Plan	Average plane error	RMSE	Average elevation error	Elevation RMSE
Mountain landslide (A)	Option One (UAV)	0.068	0.082	0.061	0.075
	Option 2 (Ground)	0.025	0.031	0.018	0.024
	Option Three (Integration)	0.032	0.041	0.026	0.029
Urban canyon area (B)	Option One (UAV)	0.152	0.183	0.135	0.162
	Option 2 (Ground)	0.041	0.049	0.022	0.028
	Option Three (Integration)	0.038	0.046	0.025	0.031

In the dense vegetation area of experimental area A, the number of real ground points extracted by different schemes is compared with the number of real ground points measured manually, and the extraction integrity rate is calculated. As can be seen from Figure 2, the single UAV scheme (Scheme 1) has the lowest extraction integrity rate (about 65%) because the laser cannot penetrate the dense canopy. Although the single ground plan (plan 2) can obtain the undergrowth terrain near the station site, the overall integrity rate is still not ideal (about 75%) due to the limitation of visibility conditions. The fusion scheme and adaptive filtering algorithm adopted in this study effectively integrate a small number of effective undergrowth points and ground scanning details obtained by UAV, and significantly improve the integrity rate to 92%, far exceeding the target of 90%.

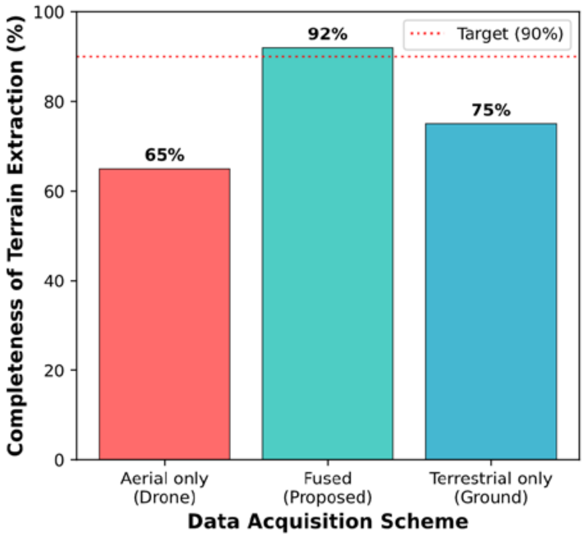

Figure 2 Comparison of integrity rate of terrain extraction in vegetation areas of different schemes

4. Conclusion

A high-precision mapping method for complex terrain that integrates UAV-RS and TLS/ALS technologies has been proposed. By designing a collaborative observation scheme of "wide area coverage in the air+ground detail enhancement" and combining deep learning assisted point cloud registration and noise filtering techniques, measurement targets with a planar accuracy of ± 5cm and an elevation accuracy of ± 3cm have been successfully achieved. In the experimental verification of typical complex terrain areas, this method significantly improves the integrity and accuracy of data acquisition. In the mountain landslide scene with dense vegetation, the fusion scheme improves the integrity rate of surface information extraction in vegetation-covered areas to 92%, far exceeding the single UAV or ground scanning scheme; In the urban canyon area with dense high-rise buildings, the fusion scheme effectively makes up for the data blind area of single technology, and obtains the best comprehensive accuracy, with the RMSE of plane and elevation stable within 5cm and 3cm respectively. In addition, the terrain adaptive filtering algorithm and multi-source data fusion technology developed in this study provide reliable technical support for high-precision surveying and mapping in complex environment. This research method shows good universality and effectiveness in practical application, and provides important technical support for geological disaster monitoring, smart city construction and natural resource management.

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