Research on High-Precision Mountain Road Mapping Technology Based on UAV and LiDAR

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Abstract: Mountainous road topography is complex and the environment is harsh, posing challenges for traditional surveying technologies, which face significant operational difficulties and insufficient accuracy. This paper focuses on high-precision mountain road mapping technology based on Unmanned Aerial Vehicles (UAVs) and Light Detection and Ranging (LiDAR). It explores the technical principles, system composition, and data processing workflow. Experimental verification demonstrates that this technology can overcome topographic limitations, acquire high-precision road point cloud data, and provide precise support for the planning, construction, and maintenance of mountain roads.

1. Introduction

Roads are crucial conduits for economic development, resource exploitation, and personnel movement in mountainous areas. Their accurate mapping forms the foundation for road planning, design, construction, and subsequent maintenance. However, mountainous terrain is rugged, crisscrossed with ravines, and densely vegetated. Traditional surveying techniques, such as manual total station surveys, require personnel to be on-site, which is not only inefficient but also poses safety risks on steep slopes and in deep valleys. Satellite remote sensing is significantly affected by cloud cover and vegetation occlusion, making it difficult to guarantee accuracy. In recent years, the rapid development of UAV and LiDAR technology has introduced new possibilities for mountain road mapping. UAVs offer flexibility, mobility, and the ability to quickly cover large areas, overcoming the limitations terrain imposes on personnel. LiDAR actively emits laser pulses and receives echoes, calculating the time of flight to obtain 3D information about targets. It is unaffected by lighting conditions and possesses a certain ability to penetrate vegetation, enabling the precise acquisition of 3D data of the ground and features.

2. Technical Principles and System Composition of UAV and LiDAR

2.1 UAV Platform

The UAV, serving as the carrier platform for the LiDAR system, must possess good flight stability, endurance, and payload capacity. When operating in mountainous areas, the UAV must adapt to complex airflow environments, maintain stable flight attitudes, and ensure the accuracy of LiDAR data acquisition [1]. Simultaneously, longer endurance allows for expanding the mapping coverage per mission, reducing the number of take-offs and landings, and improving operational efficiency. The UAV's payload system needs to stably carry the LiDAR equipment and related data transmission and storage devices, ensuring the equipment is not disturbed by factors like vibration during flight.

2.2 LiDAR System

The LiDAR system primarily consists of a laser emitter, receiver, optical system, and control system. The laser emitter emits high-frequency laser pulses towards the target area. These pulses are reflected upon encountering the ground, roads, and vegetation, with some of the reflected light being received by the receiver. The optical system guides the light path for emission and reception,

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ensuring laser pulses accurately illuminate the target area and efficiently receive echoes. The control system regulates parameters such as laser emission frequency and power to adapt to different mapping scenarios and target types. By measuring the time difference between the emission and reception of a laser pulse and combining it with the speed of light, the distance to the target can be calculated. Utilizing the UAV's real-time positioning data, the laser point cloud data can be accurately georeferenced within a geographic coordinate system, thereby constructing a 3D point cloud model of the target area [2].

2.3 System Integration and Data Transmission

The UAV and LiDAR systems must be highly integrated to ensure collaborative operation during flight. The triggering and data acquisition of the LiDAR need to be synchronized with the UAV's flight control to guarantee the spatial continuity of the point cloud data [3]. Furthermore, the data transmission system must rapidly transmit the massive point cloud data acquired in real-time by the LiDAR to the ground control station. The ground station can monitor the data in real-time and perform preliminary processing, promptly adjusting the operational parameters of the UAV and LiDAR if data anomalies are detected.

3. Mountain Road Mapping Data Processing Workflow

3.1 Acquisition of Raw UAV Laser Point Cloud

First, personnel must plan the UAV's flight path based on the characteristics of the mountainous terrain and road distribution. Path planning must consider elevation changes in the mountains to ensure the UAV flies at an appropriate altitude, guaranteeing effective data acquisition by the LiDAR while avoiding collisions with obstacles like mountains and trees. A reasonable flight overlap should be set to ensure the completeness of the point cloud data and the accuracy of subsequent registration [4].

Next, the UAV flies according to the planned path, with the LiDAR continuously emitting laser pulses and receiving echoes, acquiring point cloud data of the mountain roads and surrounding terrain in real-time. This raw point cloud data contains 3D information of various features such as ground, roads, vegetation, and buildings. However, it is characterized by large volume and noise, requiring subsequent processing.

3.2 Separating Ground and Non-Ground Points Using Gradient Filtering

The raw UAV laser point cloud contains both ground and non-ground points. The core of mountain road mapping is to acquire information about the ground and roads, thus necessitating the separation of ground points from non-ground points. Gradient filtering is an effective method for achieving this separation [5]. The core idea of gradient filtering is to use terrain slope information to distinguish between ground and non-ground points. Ground points typically exhibit smaller slope changes, whereas non-ground points (e.g., vegetation) often have larger slopes due to their shape or relative position to the ground. Specifically, a local neighborhood for the point cloud is constructed, and the slope between each point and its neighboring points is calculated. A slope threshold is set; points with slopes below this threshold are classified as ground points, while those above are classified as non-ground points.

3.3 Extracting Initial Road Points Using Multi-Constraint Region Growing

After obtaining the set of ground points, road points need to be extracted from them. Region growing is a clustering method based on seed points, where adjacent points satisfying similarity criteria are iteratively merged into the region of the seed point, causing the region to grow. Given the characteristics of mountain roads, using a multi-constraint region growing method can improve the accuracy of road point extraction.

First, seed points are selected. These should be chosen within known road areas, either manually or automatically using prior knowledge. Multiple constraints are then set, including elevation difference, point cloud density, and texture features [6]. The elevation difference constraint ensures that the elevation variation within the growing region conforms to the gentle characteristics of roads. The point cloud density constraint ensures the growing region has the distribution density expected for roads. The texture feature constraint utilizes the differences in texture between the road surface and the surrounding ground (e.g., grassland, bare soil) to further filter road points.

Second, during the region growing process, starting from the seed point, adjacent points are evaluated sequentially to see if they meet all constraints. If they do, the point is incorporated into the current growing region and becomes a new seed point for continued growth until no more adjacent points meet the conditions [7]. Through multi-constraint region growing, initial road points are extracted from the ground points, preliminarily outlining the contours of the mountain roads.

3.4 Accuracy Evaluation and Final Road Point Determination

After extracting the initial road points, their accuracy is evaluated to determine if they meet the accuracy requirements for mountain road mapping. Accuracy assessment is mainly conducted in two ways: 1) Comparison with known reference data. If high-accuracy road control point data exists, the planar and elevation errors between the initial road points and the reference points are calculated. 2) Internal consistency check, analyzing the distribution continuity of the initial road points, the rationality of elevation changes, etc. If the accuracy of the initial road points meets the preset accuracy indicators, they are determined as the final road points. If the accuracy requirements are not met, it is necessary to return to the multi-constraint region growing stage, adjust the parameters of the constraints (e.g., elevation difference threshold, point cloud density threshold), reperform region growing to extract new initial road points, and then conduct accuracy evaluation again. This process iterates until final road points satisfying the accuracy requirements are obtained [8].

4. Experiment and Result Analysis

4.1 Experimental Area and Data Collection

A typical mountain road in East China was selected as the experimental area. This area has a large altitude span, ranging from 800 m to 2,000 m, and highly complex topography, including multiple steep slopes exceeding 40° and valleys up to hundreds of meters deep, making it highly representative for mountain road mapping experiments.

The experiment utilized a DJI Matrice 300 RTK multi-rotor UAV, which offers excellent wind resistance and long endurance, enabling it to adapt to the complex airflow conditions in the mountains. Before flight, technicians rigorously calibrated and debugged the UAV's flight control system, GNSS module, as well as the LiDAR's laser emitter, receiver, and clock synchronization system. Hovering tests were conducted over known control points to verify the UAV's positioning accuracy, ensuring horizontal positioning error was less than 2 cm and vertical positioning error less than 3 cm. For the LiDAR, a standard diffuse reflection panel was used to test its ranging accuracy at different distances, ensuring the system functioned correctly.

Following the pre-planned flight path, the UAV collected laser point cloud data over the experimental area. The flight altitude was set at 150 meters, ensuring the LiDAR could cover a wide mapping area while allowing laser pulses to effectively penetrate partial vegetation canopies to acquire ground information. The flight speed was set at 8 m/s, balancing data acquisition density with operational efficiency. The flight overlap was set at 80%, ensuring sufficient overlap between adjacent flight strips for subsequent point cloud registration and accuracy verification.

4.2 Data Processing and Results

4.2.1 Gradient Filtering Results

Using the Python-based open-source point cloud processing library PDAL, gradient filtering was applied to the raw laser point cloud. First, a K-neighborhood (K=16) was constructed for each point, and the slope within the neighborhood was calculated. The slope threshold was set to 15°; points with slopes less than this threshold were classified as ground points, others as non-ground points. The filtering results clearly showed that non-ground points, such as those from tall tree canopies and low shrubs, were effectively removed. The ground points retained the undulating characteristics of the mountainous terrain intact. Statistics showed that ground points accounted for 62% of the total raw point cloud.

4.2.2 Multi-Constraint Region Growing Results

Based on the ground points, the multi-constraint region growing method was used to extract initial road points. Ten seed points were manually selected on known road sections. Multiple constraints were set: the elevation difference constraint was set so that the elevation difference between adjacent points did not exceed 5 cm, considering that while mountain roads have slopes, elevation changes on local segments are relatively gentle; the point cloud density constraint required that the point cloud density within the growing region be no less than 30 points/m², as artificially constructed roads typically have higher point cloud density than the surrounding natural ground.

The extracted initial road points accurately reflected the alignment and morphology of the mountain roads. The boundaries between the road and the surrounding ground were clear. For instance, boundaries between the road and adjacent bare soil slopes, as well as boundaries where the road passed through valleys and met vegetation at the bottom, were clearly distinguishable. Preliminary statistics showed the number of initial road points was about 15% of the number of raw ground points, consistent with the actual ground proportion of roads in the experimental area (approximately 12%–18%).

4.2.3 Accuracy Evaluation Results

Twenty known high-accuracy road control points (planar accuracy ±1 cm, elevation accuracy ±2 cm) obtained via static GPS measurements within the experimental area were selected to evaluate the accuracy of the extracted final road points. Planar error statistics showed the maximum planar error between the final road points and the reference control points was 4.8 cm, the minimum was 1.2 cm, and the average planar error was 2.5 cm. Elevation error statistics showed the maximum elevation error was 3.6 cm, the minimum was 0.8 cm, and the average elevation error was 1.9 cm. All errors were below the thresholds, indicating this technology can meet the requirements for high-precision mapping of mountain roads.

4.3 Result Analysis

The high-precision mountain road mapping technology based on UAV and LiDAR demonstrated excellent performance. In the data acquisition phase, the UAV, leveraging its flexible flight capabilities, and the LiDAR, with its efficient data acquisition ability, quickly covered the complex experimental area and acquired massive yet precise raw point cloud data. Compared to traditional manual surveying, operational efficiency improved several times over, without requiring personnel to venture into dangerous terrain. During data processing, the gradient filtering algorithm, through reasonable slope threshold setting, efficiently and accurately separated ground points from non-ground points, successfully removing a significant amount of vegetation point cloud interference and clearing obstacles for subsequent road point extraction. The filtered ground points well preserved the detailed features of the mountainous terrain. The multi-constraint region growing method innovatively integrated various features such as elevation, density, and texture, aligning well with the actual characteristics of mountain roads. It effectively avoided misclassifying surrounding bare soil areas resembling roads or omitting parts of the road. The results of the accuracy evaluation quantitatively verified the reliability of the technology, with both planar and elevation errors at low levels, meeting the high requirements for mapping accuracy in mountain road planning and construction.

5. Conclusion

High-precision mountain road mapping technology based on UAV and LiDAR overcomes the limitations imposed by complex mountainous terrain and environment on traditional surveying.

Based on the experimental results, it demonstrates significant advantages in terms of data acquisition efficiency and point cloud processing accuracy, enabling the precise acquisition of 3D information for mountain roads. In the future, this technology will be further optimized and can play a more critical role in mountain road engineering, providing robust technical support for the development of mountain transportation.

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