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;Traditional surveying technologies face great operational difficulties and insufficient accuracy. The purpose of this paper is to study high precision mountain road mapping technology based on UAVs, LiDAR. It discusses the technical principles, system composition and data processing workflow. The experimental verification proves that this technology can cross topographic obstacles and obtain the high-precision road point cloud data to provide accurate support for the planning, construction, and maintenance of mountain roads.

1. Introduction

Roads are the major conduits for economic development, resource exploitation and personnel movement in mountainous areas. Their precise mapping serves as the basis for road planning, design, construction and subsequent maintenance. But mountainous terrain is steep, cratered by ravines and thick with underbrush. Conventional surveying techniques, including manual total station surveys, necessitate the presence of personnel on-site — a process that is both inefficient and potentially dangerous in steep slopes and profound valleys. Cloud cover and vegetation occlusion are severely limiting the accuracy of satellite remote sensing. With the rapid development of UAV and LiDAR technology in recent years, a new perspective for mountain road mapping started to be opened. UAV's provide flexibility and mobility; it can easily cover long distances very quickly without the constraints that terrain places on personnel. LiDAR transmits laser pulses and captures echoes, measuring time-of-flights to gain three-dimensional target information. It is robust to light conditions and has some level of access through vegetation, allowing for accurate acquisition of 3D data on both the ground and features.

2. Technical Principles and System Composition of UAV and LiDAR

2.1 UAV Platform

Good flight stability, endurance, and payload capacity are required for the UAV since it is used as the carrier platform of the LiDAR system. In the process of operating in mountain areas, it is a new critical spiritual issue for UAV to adapt itself to complex airflow environments in ascending and descending processes of mountainous sites, keeping stable flight attitude and accuracy of LiDAR data acquisition [1]. At the same time, longer endurance permits increasing the mapping area per mission, less take-offs and landings and better operational yield. The payload system of the UAV should be able to carry the LiDAR equipment and related data transmission and storage devices steadily.

2.2 LiDAR System

The main components of a LiDAR system include the laser emitter, receiver, optical and control systems. The laser emitter fires high-frequency laser pulses at the aiming area. Those pulses reflect when they hit the ground, road and foliage, with some of that reflected light making it back to the receiver Light path of the emission and reception is guided by an optical system to make sure that laser pulses accurately illuminate a target area and echoes are received efficiently. Based on the

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specific mapping background and target types, the control system can accordingly adjust parameters including laser emission frequency and power. This calculation allows us to determine the distance to the target by factoring in the speed of light with time difference between when a laser pulse is emitted and received. And based on the real-time geolocation information of UAV, point cloud laser data can be positioned in a geographic coordinate system to establish a three-dimensional point cloud model of the environment [2].

2.3 System Integration and Data Transmission

These UAV and LiDAR systems need to be well integrated together for their flight collaborative operation. To ensure the spatial continuity of point cloud data, LiDAR triggering and data acquisition need to be synchronized with flight control of UAV [3]. In addition, the data transmission system needs to quickly transfer the enormous point cloud data, which is collected in real-time by the LiDAR, back to a ground control station. The ground station will let it monitor data in real-time and perform preliminary processing by promptly adjusting operational parameters on the UAV and LiDAR if anomalies are detected.

3. Mountain Road Mapping Data Processing Workflow

3.1 Acquisition of Raw UAV Laser Point Cloud

The first step is to plan the UAV's flight path based on the mountainous terrain and road distribution characteristics. Due to the change of elevation in mountains, UAVs will also need to adjust flying height based on terrain during path planning in order to make sure that LiDAR acquires data effectively. The flight overlap must be reasonable to guarantee the completion of point cloud data (PCD) and accurate registration in the further [4].

Then, the UAV follows the planned track, while the LiDAR continuously emits laser pulses and receives echoes, making real-time acquisition of point cloud data for mountain roads and surrounding terrain. The raw point cloud are 3D measures of features including, but certainly not limited to, ground and roads as well as vegetation and buildings. But it is huge and noisy so must be processed later.

3.2 Separating Ground and Non-Ground Points Using Gradient Filtering

The raw UAV laser point cloud consists with ground and non-ground points. The context of mountain road mapping is to obtain information about the ground and roads, so it is necessary to separate the ground point from the non-ground point. This separation can be accomplished well through gradient filtering [5]. The basic principle of gradient filtering is to compare slope information with the terrain height in terms of ground points and non-ground points. The transition of slope is generally small for ground points and large in the case of non-ground point (e.g., vegetation) because they tend to be broader, or due to their position relative to the ground. Indeed, such a point cloud local neighborhood is built, while thereupon the slope between each point and its surrounding is computed. A slope threshold is defined, and points below this slope are categorized as ground points while those above it are categorized as non-ground points.

3.3 Extracting Initial Road Points Using Multi-Constraint Region Growing

From the obtained set of grass points, it is necessary to extract the road points. Let us look back to a whole area segregation system referred as Region Growing. In region importing, the cluster is constructed from an initial seed point and one chance. Considering the area of mountain roads, multi-constraint region growing method can effectively improve the accuracy of road point extraction.

First, seed points are selected. This must occur on known road areas, either manually or automatically using prior knowledge. Then, several constraints are defined based on, e.g., the elevation difference between two points, the density of point clouds, and a set of texture features [6]. This constraint on elevation difference makes the elevation change in growing area obeys the gentle feature of roads. This guarantees that the growing region has point cloud density similar to what is expected for roads. Based on prior knowledge of the road surface and surrounding ground (for example, grassland or bare soil), this texture feature constraint is employed to further filter non-road points.

Second, when growing the region from the seed point, we sequentially check each neighbouring points at whether they satisfy all constraints. When they do, the point is included in this growing region and acts as a new seed point for further growth until no points neighboring it obey the conditions [7]. Then, initial road points from the ground points are extracted through multi-constraint region growing based on this; thereby, the preliminary contours of mountain roads are outlined.

3.4 Accuracy Evaluation and Final Road Point Determination

The accuracy of the extracted initial road points is assessed to confirm that they meet the accuracy standards for mountain road mapping. There are two primary methods to assess accuracy: 1) Comparison with Ground Truth. From the previous step, if there is high-precision road control point data, can calculate the planar and elevation errors between initial road points and reference points. 2) Internal consistency check : the continuity of initial road points distribution, a like: rationality of elevation changes. The initial road points are identified as the final road points if they satisfy the predefined precision indicators. If the accuracy is not up to standard, it is necessary to return to the multi-constraint region growing stage, adjust constraint parameters (elevational difference threshold, point cloud density threshold), repeat region growing extraction of a new initial road points, and then perform an accuracy evaluation again. This process continues until the intermediate road points meet the desired accuracy requirements [8].

4. Experiment and Result Analysis

4.1 Experimental Area and Data Collection

The experimental area was selected to be a typical mountain road in East China. The research area has a large altitude span of 800 m–2,000 m and of highly complex topography with multiple steep slopes with a slope degree exceeding 40° as well as valleys up to hundreds of meters deep; therefore, it is very representative for the mountain road experiment.

The UAV used in the experiment was a DJI Matrice 300 RTK, which has better wind resistance and longer endurance performance therefore can adapt to better complex airflow conditions in the mountain area. Prior to flight, technicians performed extensive calibration and debugging of the UAV's flight control system and GNSS module, along with the LiDAR's laser emitter, receiver and clock synchronization systems. Hovering tests were conducted at known control points to verify the positioning accuracy of UAV such that horizontal positioning error is less than 2 cm and vertical positioning error is less than 3 cm. A polymer-based diffuse reflection panel was used as a target beam and was reported to validate the ranging performance of the LiDAR at various distances (with fixed reflectivity values), thereby validating its functioning.

According to the planned flight path, UAV's laser point cloud data collection over the test area. Fire altitude was preset at 150 m, i.e. below this cruise height during flight to allow the LiDAR sufficient coverage of a wide mapping domain while permitting laser pulses to penetrate through partial canopy structure foliage and obtain ground information. The flight speed was controlled at 8 m/s, which provided a balance between the density of acquired data and efficiency in operation. Flight overlap was fixed at 80%, providing enough overlap between subsequent flight strips for point cloud registration and accuracy quantification.

4.2 Data Processing and Results

4.2.1 Gradient Filtering Results

Gradient filtering of the raw laser point cloud was performed using PDAL, an open-source software library for processing point clouds based on Python. Firstly, the K-neighborhood (K=16) of each point was constructed and the slope in the neighborhood calculated. The limit of the slope was assumed to be 15°; where if points with a slope value lower than it would be considered ground point otherwise non-ground. We could see that if we looked on the filtering results (nice looking) showed that they successfully removed non-ground points like tall tree canopy and small bushes/ shrubs. Retaining the undulating nature of the mountainous terrain, ground points were unchanged. Ground points made up 62% of the total raw point cloud statistics.

4.2.2 Multi-Constraint Region Growing Results

From the ground points, a multi-constraint region growing method was applied to derive initial road 30 points. Ten seed points were tentatively selected on known road segments. The constraints setting includes: the elevation difference constraint, to ensure that the height difference of adjacent points does not exceed 5cm (in consideration of mountain road slopes, local segments can be approximately considered a gentle slope); the point cloud density constraint, which requires point clouds within the growing region no less than 30points/m² (considering that artificially constructed roads typically have higher point cloud density compared with surrounding natural ground).

The characteristics of mountain roads were well captured by the extracted initial road points. Save for the fire, too bright and pure, the world was a black smear of buildings. What is mostly visible, for example, were boundaries between the road and bare soil slopes immediately adjacent to it, and along valley bottoms where road passed through valleys and met vegetation. More preliminary statistics indicated that the number of initial road points accounted for almost 15% of the amount of raw ground points, consistent with the actual ground proportion of roads in this experimental region (the relevant ratio is within a range from approximate value of 12% to approximately 18%).

4.2.3 Accuracy Evaluation Results

In order to assess the precision of the final road points, during extraction we selected twenty ground control points with high accuracy (planar ±1 cm, elevation ±2 cm) established at static GPS measurements drawn within the experimental area. The statistics of planar error showed that the maximum planar error between road points after optimization and reference control points was 4.8cm, the smallest planar error was 1.2cm, and average planar error is 2.5cm. The maximum, minimum, and average elevation errors were 3.6 cm, 0.8 cm, and 1.9 cm respectively according to the elevation error statistics. All errors were below the thresholds showing that this technology is capable of satisfying the requirements for high-precision mapping of mountain roads.

4.3 Result Analysis

High-precision mountain road mapping technology based on UAV + LiDAR, good effect. During the data acquisition process, thanks to its agile flight performance, UAV was able to cover the complex measurement range of experimental area quickly; with small size and high accuracy LiDAR, plenty of raw point cloud data has been obtained efficiently. Operational efficiency was improved several times over traditional manual surveying without having to place personnel in dangerous terrain. At the data-processing level, the filtering algorithm based on sloping ground proved highly effective in separating surface points from non-surface points through reasonable slope threshold settings, filtering vegetation point cloud interference and clearing subsequent road point extraction. The filtered ground points retained the structural characteristics of the mountainous topography. A new idea of multi-constraint, namely the combination of elevation, density and texture were introduced through region growing algorithm that fit well with the real characteristics of mountain road. It successfully did not misclassify surrounding naked soil areas that looked like road, nor omitted parts of the road. The accuracy assessment results quantitatively confirmed the reliability of the technology and yielded low errors in both planar and elevation aspects that meet the high demand for mapping accuracy for mountain roads planning and construction.

5. Conclusion

The high-precision mountain road mapping technology based on UAV and LiDAR overcomes the limitation of complex mountain terrain and environment on traditional surveying. The experimental results show that it has significant advantages in data acquisition efficiency and point cloud processing accuracy, and can accurately acquire 3D information of mountain roads. This technology will be further optimized in the future and can play an important role in mountain road engineering, providing strong technical support for the development of mountain transportation.

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