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Space-constrained Mobile Laser-point Cloud Data Acquisition Method

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The mobile laser-point cloud measurement system has been widely used in urban high-precision mapping. In some urban spaces with many high-rise buildings and indoor spaces, high-precision point cloud data cannot be directly obtained due to weak or no global navigation satellite system (GNSS) signals. We propose a space-constrained mobile vehicle-mounted laser scanning data acquisition plan that can effectively utilize the advantages of ground 3D laser scanning and mobile vehicle-mounted laser scanning. In addition, the plan adopts multi-source point cloud data fusion technology to obtain high-precision complete point cloud data both indoors and outdoors. The validity and reliability of the plan are verified by data acquisition experiments, which provide a useful reference for future high-precision mapping.

1. Introduction

The rapid development of mobile measurement systems has the characteristics of fast data acquisition, low cost, and easy management and storage. Mobile measurement systems have achieved great success in quickly obtaining indoor and outdoor space information through combined sensors. Two main types of mobile 3D laser scanning systems are used: one is a simultaneous localization and mapping (SLAM)-based mobile 3D laser scanning system, and the other is a vehicle-mounted 3D laser scanning system based on high-precision inertial navigation.(1–3) The two types have different characteristics and advantages. The SLAM-based mobile 3D laser scanning system is suitable for indoor and outdoor areas with a small spatial range.(4–6) The vehicle-mounted 3D laser scanning system based on high-precision inertial navigation is a device that integrates multiple sensors to collect information and quickly obtain 3D surface information.(7–9) This system can be applied to the acquisition of indoor and outdoor 3D spatial information. The inertial navigation system (INS) is an autonomous navigation system that does not depend on the external environment. It has the advantages of high

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positioning precision in a short time and powerful anti-interference capability. It primarily relies on high-precision inertial navigation and odometer assistance for combined positioning, which can significantly improve GPS. The precision of the integrated navigation system in the unlocked state can be applied to indoor mapping.[10–13]

Combining the results of existing research and technological development, we proposed a data acquisition method using the combination of ground and vehicle-mounted laser scanning technology and applied it to the mapping of underground garages by summarizing and analyzing the existing methods. The vehicle-mounted laser scanning system based on high-precision inertial navigation quickly obtained a large range of indoor and outdoor data and directly obtained the point cloud in the geodetic coordinate system. In the area without a GNSS signal, the accuracy of the point cloud decreases with the time when the GNSS is out of lock. However, terrestrial 3D laser scanning has the advantages of convenient station setup and high relative precision. Therefore, we propose a data acquisition plan that integrates the mobile vehicle-mounted laser scanning system and the ground 3D laser scanning and combines the two methods to give full play to their respective advantages to quickly obtain a point cloud. In addition, we introduce the specific design process, data acquisition, and processing methods of the plan, and finally verify the precision of the data obtained, which meets the application requirements of indoor mapping.

2. Data Acquisition Plan

The plan was tested in a parking lot in a building of a business district. The vehicle-mounted laser scanning device was used to obtain data, and then the ground laser data were obtained according to the scanning results. The specific process is diagrammed in Fig. 1.

The field survey clarifies the ground traffic conditions, lighting conditions, and parking lot entrances and exits to ensure the smooth progress of data acquisition. Route planning is mainly based on the actual situation of the underground space and instrument parameters, and a reasonable route is designed to fully cover the survey area, avoiding long-term parking during the scanning process, and reducing the repeated scanning of sections.

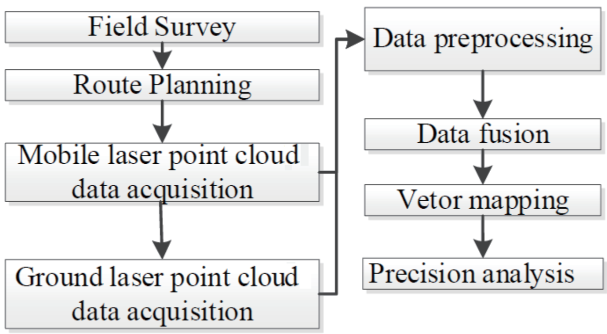


Fig. 1. Data acquisition plan.

2.1 Acquisition of vehicle-mounted laser scanning data

The vehicle-mounted laser system integrates multiple sensors to collect information and quickly obtain 3D information on the surface.(14,15) Through the combined calculation of GNSS, INS, and odometer data, the trajectory and attitude of the carrier are determined, and the distance and angle information obtained by the laser scanner are combined to obtain the 3D points of the measured object. When data acquisition is carried out in the outdoor part of a commercial area, the GNSS signal is weak due to the height and density of commercial buildings, and there is no GNSS signal during the data acquisition process in an underground parking lot. In contrast, the INS is an autonomous navigation system that does not depend on the external environment. The system has the advantages of high positioning precision in a short time and a strong anti-interference capability. Therefore, it mainly relies on high-precision inertial navigation and odometer assistance for combined positioning, which can significantly improve the precision of the integrated navigation system under conditions when the GPS loses lock. The laser scanner used in the vehicle-mounted laser system in this work was Riegl's VUX-1HA. Its main parameters are a range from 2 to 200 m, 360° omnidirectional scanning, 250 rps, and a scanning point frequency of up to 1017 KHz. To reach the millimeter-level of precision, we used an INS, which is a domestic high-precision system. Its main parameters are a drift of 0.01°/h, a combined attitude measurement precision heading better than 0.008°, a pitch better than 0.005°, and a roll better than 0.005°.

Usually, a vehicle-mounted laser system is installed above the vehicle. Owing to the height limit in the underground parking garage, the vehicle-mounted laser system should be integrated into a tricycle platform to pass the garage entrance. The system integration is shown in Fig. 2. Before the operation, the driving route must be designed, and a straight line route should be planned as much as possible to avoid vehicles parked in the garage. Data are acquired according to the design route. During the operation, it was necessary to use GPS and INS for initial alignment outdoors to obtain accurate initial position coordinates and attitude. During operation

Fig. 2. (Color online) Vehicle-mounted laser system.

in the basement, high-precision INS and odometer data are used to calculate the position and then to obtain the attitude and position information of the device at each moment. The 3D coordinates of the object being measured are calculated. After the data scanning is completed, the alignment is completed outdoors again, and the round-trip two-way solution and adjustment processing are realized.

2.2 Acquisition of ground laser scanning data

The ground laser scanner (Fig. 3) is in a fixed position, rotates 360° in the horizontal direction, and obtains the point cloud in the laser reachable region. Using the distance measured by the laser and the corresponding rotation angle, the 3D coordinates of the surface of the object are directly obtained after calculation to form a laser point cloud. The device used for data acquisition was Riegl's VZ-400, which scans 360° × 260° at a scan rate of 1000000 points/s and a measurement precision of 5 mm.

The ground laser scanner only needs to place a few stations to complement the vehicle laser data, but the point cloud obtained by the ground laser needs to use its high relative precision to correct the vehicle point cloud, so it is placed on the vehicle in the survey area during the measurement process. The data from the laser scanning system are easily occluded, and the scanning yields a wide range of data.

3. Data Processing

The data obtained by the ground laser scanner uses its own processing software for point cloud generation and splicing, and different stations are scanned and spliced together to generate a spliced point cloud.

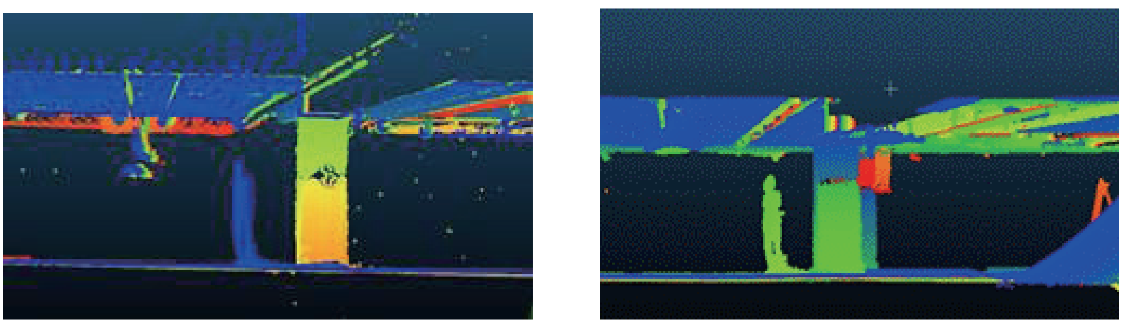
Fig. 3. (Color online) Ground laser scanner.

GPS data, inertial navigation data, odometer data, and laser data collected by the vehicle-mounted scanner need to be processed to generate high-density point clouds. The process includes point cloud preprocessing, integrated navigation data calculation, and fusion of integrated navigation results and laser data to generate point cloud data with 3D position and intensity information. The point cloud is then processed.

3.1 Point cloud data preprocessing

When the vehicle-mounted laser system acquires data, point clouds with uniform density can only be obtained by moving at a uniform speed. Therefore, point clouds in the driving and vertical directions with the point cloud density will appear uneven when the vehicle stops or the speed is uneven. The point cloud obtained by ground laser scanning is fan-shaped, and the closer the scanner is to the object being measured, the greater the point cloud density. Owing to multi-path reflection, dust, and other reasons, the acquired point cloud data inevitably contain noise. It is necessary to preprocess the point clouds obtained by vehicle-mounted and ground laser scanning to enable point cloud thinning and the removal of some noise points as well as points that are far away and do not need to be matched.

Point cloud thinning is based on the method of downsampling at an equal distance of 3 cm between points. The underground garage space was limited, so the scanner center distance threshold was set to 60 m. The removal of noise points was processed by statistical analysis and filtering of the neighborhood point cloud in the point cloud library (PCL). The point cloud was also processed by setting a threshold of the mean and standard deviation to remove point cloud nose in the results as a threshold. The points whose average neighborhood distance is outside the standard range can be defined as outliers and removed from the data. The main parameters were analyzed for each point, and the number of adjacent points and the standard deviation of multiple thresholds were set to 50 and 1, respectively. The effects before and after processing are shown in Fig. 4. The vehicle point cloud and ground laser-point cloud after point cloud generation, thinning, and denoising are shown in Fig. 5.



(a) (b)

Fig. 4. (Color online) Comparison before and after denoising and thinning. (a) Before denoising and thinning. (b) After denoising and thinning.

(a) (b)

Fig. 5. (Color online) Data map of point cloud. (a) Ground laser-point cloud. (b) Vehicle laser-point cloud.

3.2 Data fusion

According to the characteristics of the vehicle-mounted laser system, the precision of the point cloud will worsen with time, and the precision of the point cloud will also worsen as the distance from the laser center increases. In the process of data fusion, we take advantage of the relatively high precision of ground laser scanning data for processing. A diagram of the flow of the process is shown in Fig. 6, and the details of the process for data fusion for two different point clouds are described in the following subsections.

3.2.1 Data registration

First, the pretreated vehicle-mounted point cloud is segmented according to the driving distance. More than four corner points are selected as characteristic points (Fig. 7) in the point cloud, and the ground laser point cloud is transformed from relative coordinates to WGS84 coordinates. Second, the ground laser point cloud in the WGS84 coordinate system is used as the reference point cloud to correct the vehicle-mounted trajectory. The point cloud is recalculated for the modified trajectory, and a point cloud meeting the precision requirements is generated after many iterative calculations. Finally, all the data in the survey area are processed.

The principle of trajectory correction uses the high-precision inertial navigation device in the vehicle laser system with characteristics of high stability over a short period of time. In the local range, the control points and the points in the corresponding point cloud are linearly fitted, and then the trajectory points are linearly fitted according to time. Corrections are made to generate the correct trajectory. The point cloud data after coarse alignment are shown in Fig. 8.

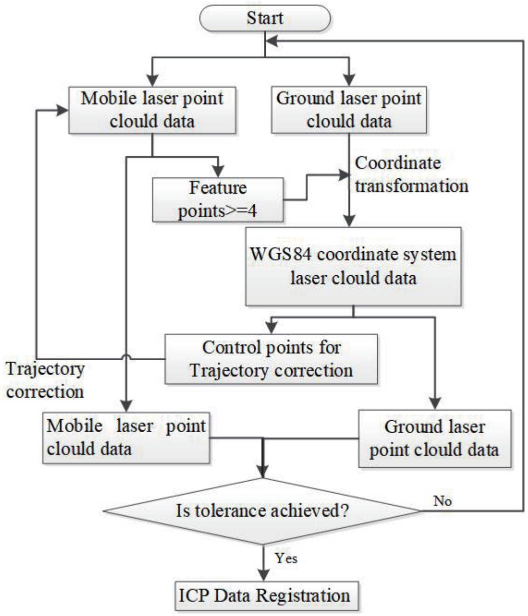
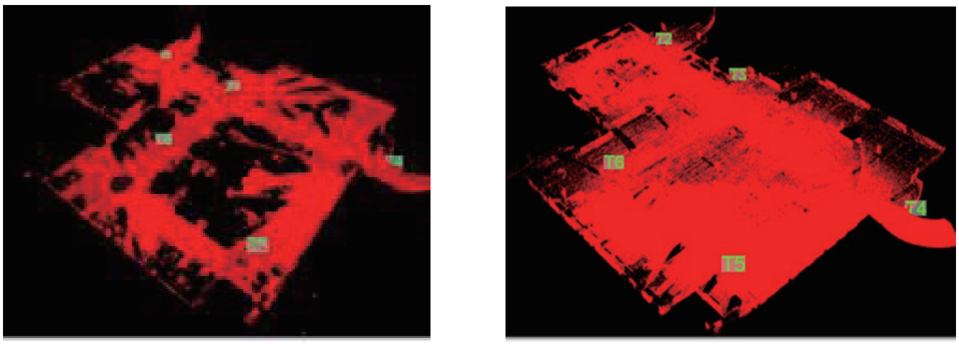


Fig. 6. Flow chart for data fusion.



(a) (b)

Fig. 7. (Color online) Diagram of point cloud data conversion. (a) Ground-based laser-point cloud feature points. (b) Vehicle-mounted laser-point cloud feature points.

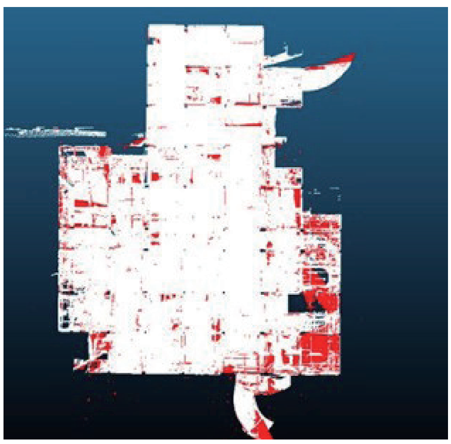


Fig. 8. (Color online) Point cloud after coarse alignment.

3.2.2 Registration algorithm of iterative closest point (ICP)

The ICP is the most popular registration algorithm for point cloud map registration and is an optimal registration based on least squares. Through repeated iterations, a set of rotation matrices R and translation vectors are found to prevent the convergence of matching errors, and the coordinates of the data point set P and the model point set X are set. The equations are

$$P = \left\{ P_i \in R, i = 1, 2, \ldots, N_P \right\} \tag{1}$$

and

$$X = \left\{ X_i \in R, i = 1, 2, \ldots, N_x \right\}. \tag{2}$$

The mean square matching error between P and X is

$$f\left(x, p\right) = \frac{1}{N} \sum_{i=1}^{N_P} \left\| X_i - P_i \right\|^2. \tag{3}$$

The point set p^{n+1} after $n + 1$ iterations can be expressed as

$$p^{n+1} = p^n + q_T. \tag{4}$$

Another expression of the mean square error can be obtained using Eq. (3) as

$$f\left(R, q_T\right) = \frac{1}{N_p} \sum_{i=1}^{N_P} \left\| X_i - P_i R - P_i \right\|^2. \tag{5}$$

If there is a set of rotation matrices R and translation vectors q_T that make Eq. (5) converge, then the rotation matrices R and translation vectors q_T are obtained. The ICP algorithm is used after the rough registration of the vehicle point cloud and the ground laser-point cloud. The initial position of the point cloud does not deviate significantly. Therefore, point cloud matching can be accurately realized for the point cloud with a large amount of data. The registration is realized by VS2010, C++ language configuration PCL under the WIN7 operating system environment. Registered point clouds of a quadrate pillar in Fig. 9 illustrate the effect of registration of two different point clouds. The green vehicle point cloud and the blue ground point cloud are basically at the same position at the corner of the pillar.

3.3 Vector map

The point cloud data can be used as basic data for a vector map of the underground garage. From the point cloud, the features of the underground garage can be clearly seen, such as the corner of the building, the outline of the pillar, the position of the ground parking space, and the

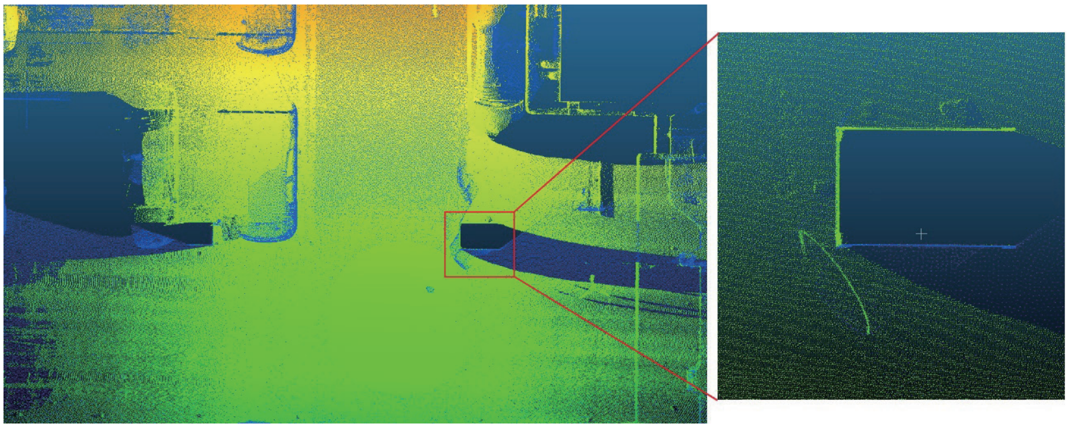


Fig. 9. (Color online) Point cloud after ICP matching.

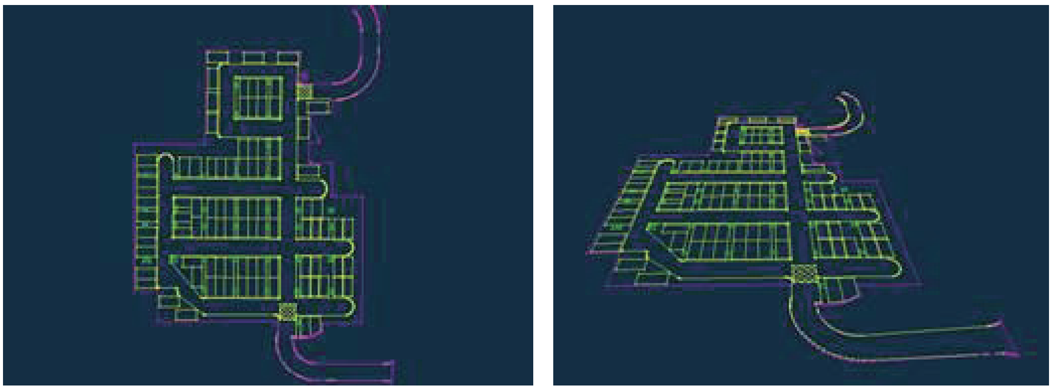


Fig. 10. (Color online) Vector map of underground garage.

arrow mark, as well as the pipeline above the underground garage. All the point cloud data have 3D coordinate information. The vector map (Fig. 10) obtained by the point cloud can provide a base map for later 3D modeling and can also provide more abundant geometric dimension information, such as height.

4. Precision Analysis

The precision is verified to obtain the root control points using a closed traverse survey and then to set up a full-station electronic tachymeter on the root control points to measure the coordinates of the characteristic points in the garage. Characteristic points include the corner points of the upright posts, the corner points of the indicating arrows, and the corner points of the room. The accuracy of the control point of the root of the graph meets the requirements of a fourth-class traverse survey.

Mapping is carried out in the point cloud, and the precision of the point cloud directly determines the precision of the mapping, so the precision of the point cloud must be verified

Table 1
Comparison table of point cloud and total station coordinates.

ID	Point cloud coordinate			Total station coordinate			Difference		
	x	*y*	*z*	*x*	*y*	*z*	*dx*	*dy*	*dz*
D11	9346.381	8045.571	37.566	9346.348	8045.547	37.567	0.033	0.024	−0.001
D12	9346.404	8048.352	37.608	9346.393	8048.341	37.611	0.011	0.011	−0.003
D18	9336.001	8055.927	37.693	9336.004	8055.931	37.675	−0.003	−0.004	0.018
D19	9327.862	8055.836	37.711	9327.960	8055.823	37.674	−0.098	0.013	0.037
D20	9319.901	8050.611	37.621	9319.886	8050.626	37.596	0.015	−0.015	0.025
D21	9327.953	8064.629	37.696	9328.041	8064.660	37.690	−0.088	−0.031	0.006
D22	9335.979	8064.595	37.622	9335.978	8064.600	37.627	0.001	−0.005	−0.005

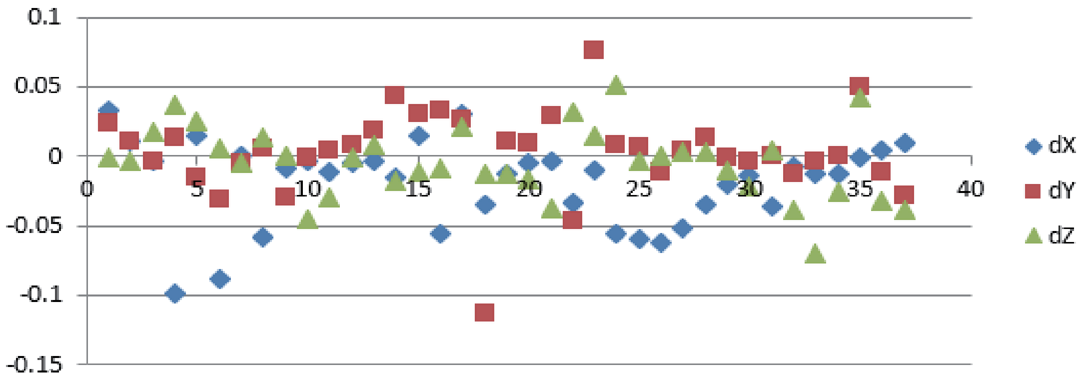


Fig. 11. (Color online) Diagram of error distribution.

before mapping to ensure the accuracy of the vector map. By loading the fused point cloud into the point cloud display software, the point cloud coordinates corresponding to the position of the feature points are collected, and the precision of the final point cloud data is obtained through statistical analysis. Table 1 is a list of some of the data used to evaluate precision and Fig. 11 shows the diagram of error distribution.

The comparison of the precision between the coordinates obtained by the feature point traverse and the coordinates in the point cloud shows that the point cloud obtained by this method meets the needs of underground garage mapping.

5. Conclusions

We analyzed the process of acquiring and fusing a vehicle-mounted laser scanning system and the ground laser-point cloud data, explained the purpose of the plan, and verified the feasibility of its use by statistics on the precision of the measurements. This plan had relatively high requirements for the precision of the INS system of the vehicle-mounted laser system, but the combined use of the vehicle-mounted laser system and the ground laser greatly improved the efficiency of indoor and outdoor mapping in a basement. The vehicle-mounted device directly obtained the point cloud of the geodetic coordinate system to realize the integrated acquisition of indoor and outdoor data. The proposed plan still requires additional work to be improved. First, other vehicle-mounted laser systems should be tested, such as a SLAM laser system, which is widely used in indoor mapping. Second, the plan should be applied to more places (e.g., shopping malls, streets, and parks) to verify its validity and applicability. Third, the research in this study focuses primarily on data collection and real-time computing, and research on the visualization strategy received less attention. Investigations on adaptive visualization strategies combined with multithreading architecture and the realization of rapid visualization under high concurrency conditions will be targets of future research work.

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