Accuracy analysis and efficiency evaluation of 3D laser scanning technology based on SLAM in underground mine roadway measurement

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Abstract. There are problems of time-consuming and labor-intensive, low degree of automation and high safety risk in the traditional underground mine roadway engineering measurement. In this paper, a method based on SLAM 3D laser scanning technology is proposed to measure mine roadways. At the same time, an underground mine was selected to carry out a rapid scanning experimental study. In this study, the method of closed-loop control of measurement error is used to synchronously collect point cloud data and image data. The data are fused based on the error state iterative Kalman filter (ESIKF). In addition, the optimal transformation matrix was calculated by taking the downhole control point as the feature point to minimize the target error, and the accuracy of the point cloud was analyzed by coordinate comparison, and the measurement efficiency was evaluated. The results show that the in-plane error of the point cloud is ±0.041m. The error in elevation is ±0.088m. The error in the profile is 0.035m. These results meet the requirements for the accuracy of the measurement technology. Compared with the traditional measurement method of total stations, the work efficiency is improved by about 3 times. This method has a good application prospect in underground mine roadway measurement.

Keywords: 3D laser scanning technology; point cloud registration; fusion; accuracy analysis.

1. Introduction

Mineral resources are an important material basis for the existence and development of human society. The rational development and utilization of mineral resources is an important topic in the supervision of land resources [1]. Cross-border mining not only undermines the management order of mineral resources, but also may cause serious safety accidents. The safety of people's lives and property will also be threatened. Therefore, it is of great significance to grasp the current situation of mining in real time and accurately for effective supervision of mineral resources. At present, the regulatory means of cross-border mining in underground mines are relatively simple. Usually relies on total station wire measurement methods. However, this traditional single-point measurement method has many shortcomings. For example, the work efficiency is low, the labor intensity is high, the risk is high, the on-site measurement results are not intuitive enough, and the degree of automation is low [2]. Traditional methods have been difficult to meet the needs of intelligent and refined management of modern mining under the new situation.

3D laser scanning technology is also known as "reality reproduction technology". It is a new type of surveying and mapping technology developed in recent years. It has a wide range of applications in the fields of architectural planning, deformation monitoring, and urban underground space measurement [3-11]. It has the advantages of active, non-contact, and high accuracy. Overcoming the limitations of traditional measurement methods. It can go deep into the complex environment of narrow and irregular terrain to quickly obtain the three-dimensional dense point cloud information of the ground object. It can intuitively reflect the spatial location information and surface geometric characteristics of the ground object. Based on the unique advantages of 3D laser scanning technology. In order to improve the efficiency and safety of underground mine surveying. In this paper, an underground mine in Chongqing is taken as the research object to carry out the application test of 3D laser scanning technology. The point cloud and image data of the roadway are collected by closed-loop control and accumulation of measurement errors, and the extended Kalman filter is used. At the same time, the downhole control points were taken as feature points, and the iterative nearest point algorithm of the optimal matrix was calculated by the SVD decomposition method to fuse and register the data. A color 3D point cloud model is obtained. Combined with the traditional measurement method, the applicability of the new surveying and mapping technology in the field verification of underground mines is demonstrated from two aspects: data accuracy and collection efficiency. It provides reference ideas for innovating the supervision mode of mining and improving the supervision level of mineral resources.

2. 3D laser scanning system

The 3D laser scanning system is a multi-integrated sensor measurement system based on Simultaneous Localization and Mapping (SLAM) technology [12]. It is mainly composed of four main elements: laser scanner, inertial navigation IMU, high-resolution action camera, and SLAM algorithm. The main technical parameters are shown in Table 1. It consists of the FAST-LIO subsystem and the VIO subsystem. Ability to position oneself in unknown environments. At the same time, the surrounding scene map can be constructed according to its own posture and the environmental characteristics matched from the point cloud data, so as to quickly obtain high-precision 3D geographic information data [13-14]. The device does not rely on GNSS signals, so it is particularly suitable for data acquisition in underground confined environments. In the process of data acquisition, the surveyor only needs to walk around the target object with the equipment on his shoulders to collect the measurement information, and the system workflow is shown in Figure 1.

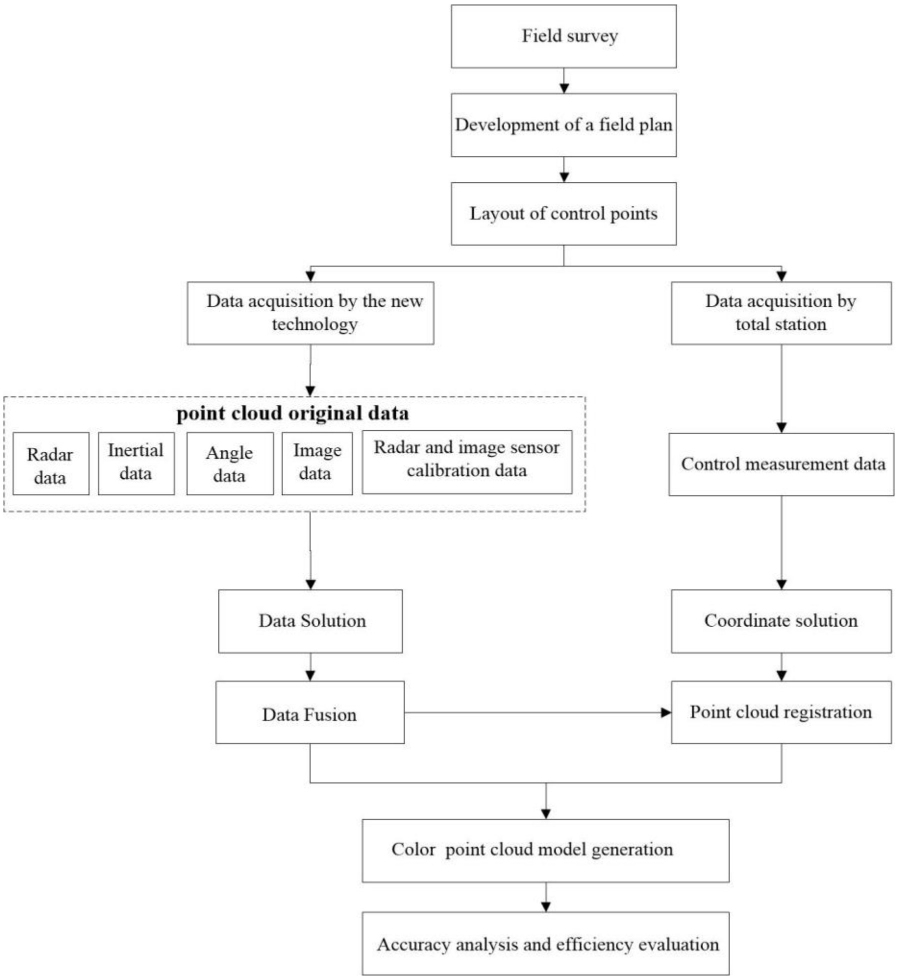

Figure 1. Workflow

Table 1. main technical parameters

Name	Main parameters
Frequency of data ingestion	300,000 points/sec
Measuring range	80m
Point cloud spacing	＜1mm
Scan the field of view	360°×270°
Delivery platform	Carry on both shoulders
Output point cloud format	Las、ply
IMU bias stability	8°/h
Action camera	The angle of view of the lens is 155°\ 23 million pixels\ 4.0 Super Stabilization
Device weight	1.6kg

3. Workspace overview

The working area is an underground mine located in Nanchuan District, Chongqing. The terrain is sloping from southeast to northwest. The landforms are mainly mountains, hills and dams. It is well represented in underground mines. The mine area is delineated by 7 inflection points. The north-south strike length is about 500 m. The average width of the inclination is about 1550 m. The area is about 0.64 km2. The mine mines cement limestone in the third member of the Jialingjiang Formation of the

Lower Triassic underground, and the mining depth is 590m-580m. The production capacity is 600,000 tons/year. The mine is mined by the inclined shaft and flat comprehensive development and room-and-pillar mining method, and the mined ore products are used as raw materials for cement processing.

4. Data collection and processing

4.1 Downhole control point data collection

There are nine 15" wire control points on the roof of the mine roadway (as shown in Table 2). Cement nails are used to drive into the base plate and the number is marked with paint in a conspicuous position. And evenly distributed in the roadway, stable and reliable, easy to identify and locate. The known GPS control point on the ground is used as the starting edge. Use a total station to perform traverse measurements in the mine underground by means of contact measurements in inclined shafts or flats. After internal calculation and adjustment processing, the control measurement data is formed. The average point error is 0.051m. The maximum plane-to-point error is 0.0891m. The error in the average elevation is 0.0374m. Meet the accuracy requirements of mine on-site verification and mapping. Table 2 shows the control points of the underground roadway wire.

Table 2. Underground roadway conductor control points

Numbering	X(m)	Y(m)	H(m)
KZ271	3228187.847	36418240.32	565.9258
KZ272	3228186.615	36418317.88	569.0386
KZ273	3228153.885	36418378.47	573.5067
KZ274	3228315.529	36418841.68	587.92
KZ275	3228395.032	36418865.41	588.9853
KZ276	3228431.94	36418969.46	588.8705
KZ277	3228184.897	36419079.63	587.3956
KZ278	3228096.494	36418925.45	587.866
KZ279	3228030.298	36418759.41	587.215

4.2 3D laser scanning data acquisition

A 3D laser scanning system was used to collect point cloud data and image data of the main shaft and roadway of the underground mine. Before scanning, scan control points should be reasonably arranged in the industrial square at the main wellhead. Planar targets made of highly reflective and wide-band reflective materials. Hang plumb lines at each control point at the top of the roadway so that it hangs vertically below the control point.

The closed-loop route control method was used to perform a segmented rapid scan of the industrial square and roadway. At the same time, RTK was used to measure the target image control point data. During the segmented scanning, the main roadway, stope, mining area, closed and other important areas of the mine are not missed, and the image control point information is collected. The position and angle of the scanner can be adjusted as needed to ensure that all contours of the object to be measured are fully scanned. The total length of this scan is 2.5 kilometers. A total of 4 segmented acquisitions were performed. It takes about 1 hour, 1 minute and 35 seconds.

4.3 Data processing

4.3.1. Data fusion

Due to the limited ability of laser point clouds and their intensity information to characterize targets. It is necessary to fuse the laser point cloud with the image, so that the point cloud not only has high-precision 3D geometric information, but also has richer texture information[15-16]. In addition to laser point cloud data and image data. The 3D laser scanning system also collects inertial measurement data, angle data, and various data of lidar and camera internal and external calibration parameters. In order to realize the effective fusion of laser point cloud and image data. In this paper, the error-state extended Kalman filter algorithm is adopted. Predict and estimate system states by means of first-order Taylor expansions and Jacobian matrices. The Kalman gain is calculated to minimize the error covariance and estimate the optimal state of the system. Finally, a three-dimensional color point cloud model with real geodetic coordinates is obtained.

The algorithm is expressed as:

The equations of motion are linear approximations of the first-order Taylor expansion of the observational equations:

$$\begin{cases} \mathrm{x}_{k+1} \approx f(\hat{\mathrm{x}}_k) + F_k \delta\hat{\mathrm{x}}_k + w_k, & w_k \sim \mathcal{N}(0, \mathrm{Q}_k) \\ \mathrm{z}_k \approx h(\check{\mathrm{x}}_k) + H_k \delta\check{\mathrm{x}}_k + v_k, & v_k \sim \mathcal{N}(0, \mathrm{R}_k) \end{cases}$$

Where F_k represents the Jacobian matrix of the state transition k function on the state variables, and H_k represents the Jacobian matrix of the observation model.

$$\delta\hat{\mathrm{x}}_k = \mathrm{x}_k - \hat{\mathrm{x}}_k, \quad \delta\check{\mathrm{x}}_k = \mathrm{x}_k - \check{\mathrm{x}}_k$$

$$F_k = \left.\frac{\partial \mathrm{f}}{\partial \mathrm{x}}\right|_{\hat{\mathrm{x}}_k}$$

$$H_k = \left.\frac{\partial \mathrm{h}}{\partial \mathrm{x}}\right|_{\check{\mathrm{x}}_k}$$

Update the covariance matrix $\hat{P}_k$:

$$\hat{P}_k = (\mathrm{I} - K_k H_k)\check{P}_k$$

Where K_k is the state gain matrix.

The specific integration process is as follows:

(1) Joint data calculation. The geodetic coordinate data of the point cloud in the WGS84 coordinate system was obtained by combining the laser point cloud with the inertial navigation data and the angle data.

(2) Fusion of laser point cloud and image data. Each point in the original point cloud corresponds to the pixels in the image one-to-one, and the laser point cloud and the image data recorded synchronously are mapped to the corresponding image pixel through the external parameter matrix calibration data of the camera, so as to obtain a color point cloud.

Figure 2 shows the point cloud effect of roadway before and after data fusion.

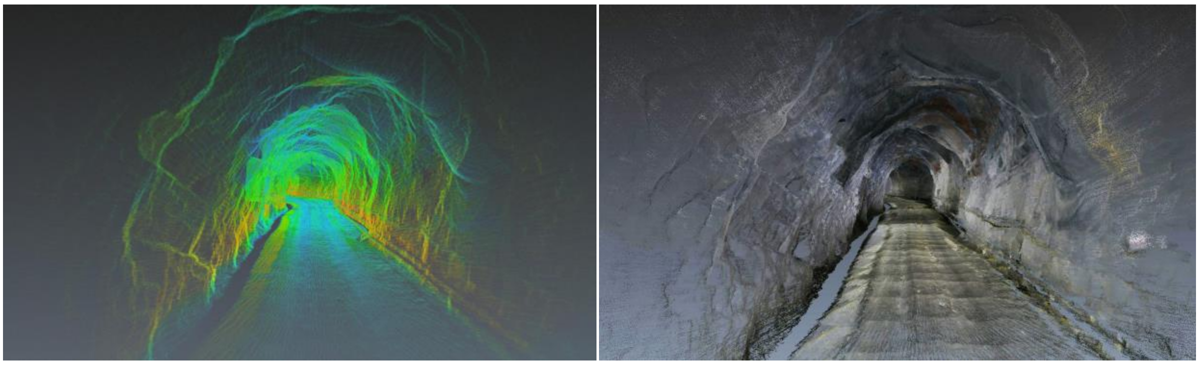

Figure 2. The effect of coloring and filtering fusion of roadway point cloud data

4.3.2 Point cloud registration

During continuous data acquisition. The problem of sensor position drift and coordinate error accumulation in the 3D laser scanning system reduces the data accuracy of the point cloud. In order to obtain high-precision three-dimensional spatial information of the roadway, the downhole control point was used as the feature point while closing the route control error. Specifies the initial position of the rotational translational transformation matrix. The SVD decomposition method was used to calculate the optimal solution, and then the nearest point iterative algorithm (Iterative Closest Point, ICP) was used to complete the point cloud registration[17].

The cloud compare software was used to use the ICP iterative algorithm for point cloud registration. The data is iteratively converged by continuously setting registration parameters such as the number of iterations, thresholds, and overlaps. The average RMS of the final registration is 5.5mm, which meets the requirements of registration accuracy. The point cloud after registration is in the same spatial coordinate system as the downhole control point. The matching effect of geometric space position is good, and the geometric attributes, spatial location and texture information of the mine roadway can be truly expressed. The superposition effect of point cloud registration and downhole control points is shown in Figure 3.

Figure 3. The superposition effect of point clouds and downhole control points after registration

5. Data analysis and efficiency evaluation

On the basis of the results of downhole control data. From the annual field inspection data of the mine, the points with uniform distribution and obvious characteristics were selected as the inspection points for this time. In the color 3D point cloud model, the coordinates of the feature points with the same name were measured for comparison and analysis, and the plane and elevation accuracy of the point cloud were analyzed. Ten detailed feature points of roadway features were selected for length measurement. Calculate and analyze the poor and medium errors of the profile. Finally, the efficiency of point cloud measurement was evaluated by combining field data collection and statistical items.

5.1 Accuracy analysis

Thirty-five checkpoints were selected to verify the plane accuracy and elevation accuracy of the point cloud. By comparing the XYZ coordinate values of each checkpoint. Calculate the corresponding coordinate difference, point error, and neutral error to evaluate its accuracy. The error in the measurement is calculated as follows:

$$M = \pm\sqrt{\frac{\sum_{i=n}^{n}\Delta_i^2}{n}}$$

Where M is the error in the points, n is the number of checkpoints, and Δ is the worst.

After calculation, the maximum plane error is 0.089m. The error in the plane point is ±0.041m. The maximum difference in elevation is 0.074m. The error in the elevation point is ±0.088m. The plane coordinates of the point cloud data are poor, and they fall in the range of 0.02-0.06m. The elevation difference of point cloud data falls in the range of -0.100~0.100m. This result satisfies the requirements for underground mine roadway measurements. The point error distribution of each checkpoint is shown in Figure 4.

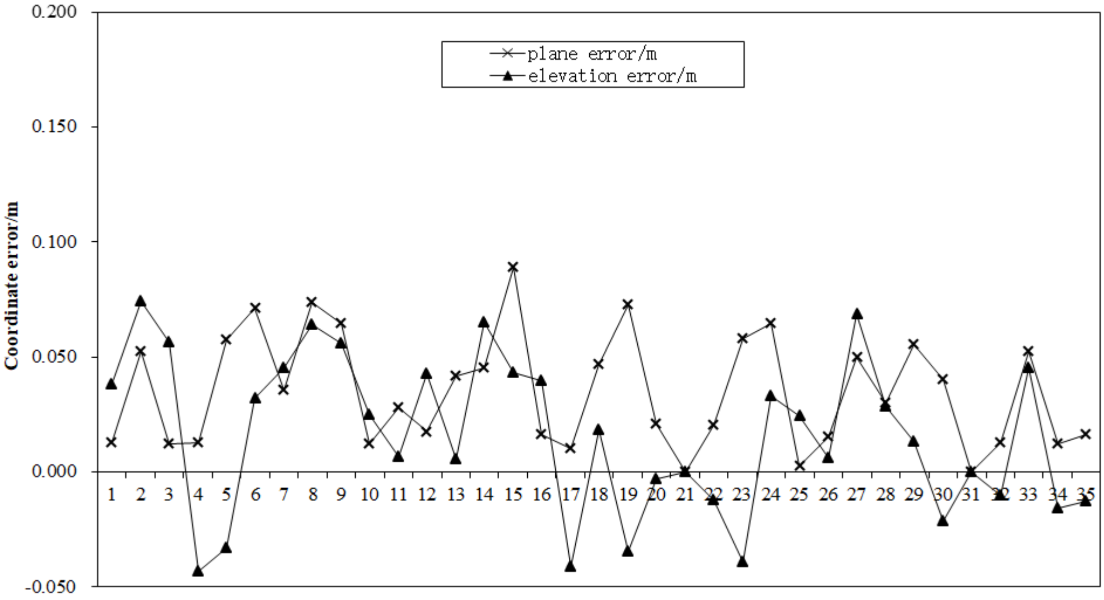

Figure 4. Error distribution of each checkpoint

5.2 Profile accuracy analysis

Ten detailed feature points of roadway ground objects were selected for length measurement and the profile accuracy was verified. According to the requirements of the "Quality Inspection and Acceptance of Surveying and Mapping Results", the number of checkpoints is less than 20, and the arithmetic mean of the error is used instead of the middle error. The maximum difference of the calculated profile is 0.06m, and the intermediate error is 0.035m. The poor distribution of the profiles of each feature is shown in Figure. 5.

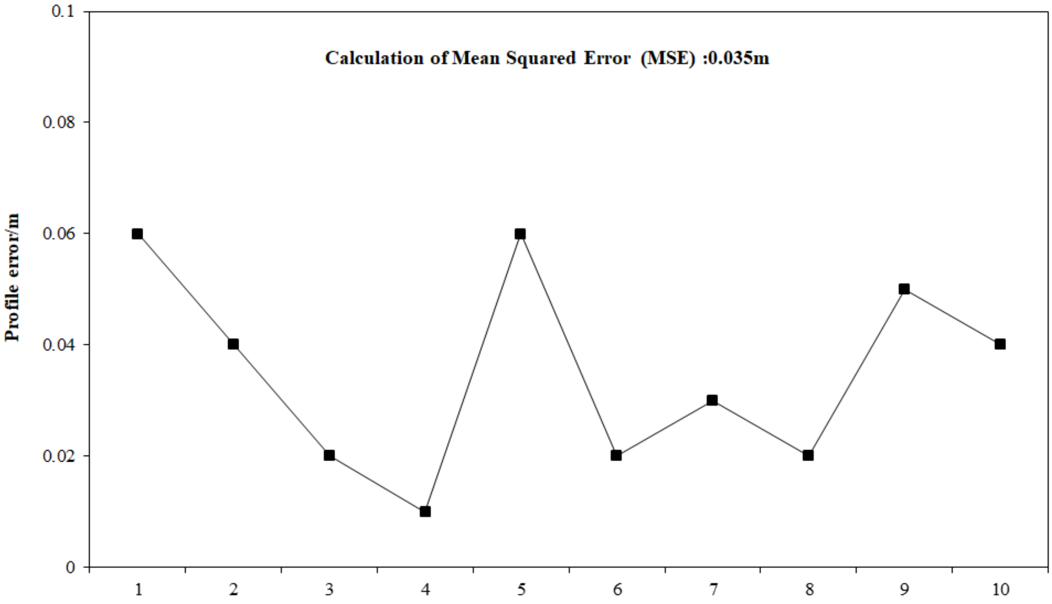

Figure 5. Poor distribution of feature profiles of each feature

5.3 Evaluation of work efficiency

According to the actual situation in the field, the work efficiency was statistically analyzed. In the annual on-site inspection work, the mine is generally measured by four surveying technicians using a total station. However, the 3D laser scanning survey was carried out by two technicians. The statistics are shown in Table 5. As can be seen from Table 5, the measurement efficiency of the 3D laser scanning device is about 3 times higher than that of the traditional total station measurement method. Among them, the processing efficiency of the internal office is similar, and the collection efficiency of the field is about 5 times higher. This method greatly reduces the labor and time costs of field surveys.

Table 5. Statistics on work efficiency

Job category	3D laser scanning equipment		Conventional total station measurement equipment	
	Statistical items	Unavailable/h	Statistical items	Unavailable/h
Field Collection	On-site survey	0.5	On-site survey	0.5
	Control points are selected on the ground	2	Control points are selected on the ground	2
	Buried stone to make a mark	4	Buried stone to make a mark	4
	Data acquisition	2	Topographic survey (1:2000 fragment survey)	36
	Feature point collection	1	Roadway traverse measurement (angle and ranging)	7.5
	Section length measurement	0.5	Data Logging	0.5
In-house processing	Data solving	3	Data solving	0.5
	Data fusion	4	Topographic mapping	10
	Point cloud registration	4	Measured roadway above	2
Total	-	21	-	63

6. Conclusion

In this paper, the application of SLAM 3D laser scanning technology in underground mine roadway measurement is studied. The accuracy of the point cloud was verified and the work efficiency was evaluated by the coordinate comparison method of the feature point with the same name. The test results show that the 3D laser point cloud data not only meets the measurement accuracy requirements of underground mines in terms of coordinate accuracy and profile accuracy. Moreover, the field collection of 3D point cloud data of the mine can be completed in a relatively short time, reducing labor and improving work efficiency. Compared with the traditional measurement methods, the 3D point cloud model obtained by data fusion and registration processing has rich spatial information, 3D expression and texture information. Import the 3D point cloud model into the Cyclone 3DR Viewer software, and use the 3D scene walkthrough display and data analysis functions. You can view the mining situation of the mine from all angles and angles. Combined with the data of the mining area, the mining location can be grasped in time and the cross-border mining can be warned. At the same time, the length of roadway excavation and mining volume in a certain period of time are calculated, so as to provide data support for the supervision of mineral resource exploration and development activities.

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References

[1] Pan Yongzhuo, Xie Hongbin, Yang Xue, et al. Research on the application of deep learning in the law enforcement of mineral resources[J]. Journal of Sichuan Geology, 2019, 39(4): 679-682.

[2] Cheng Xiaojun, Jia Dongfeng. Theory and technology of massive point cloud data processing[M]. Shanghai:Tongji University Press, 2014.

[3] Chen Xiaoli. Application of 3D laser scanning in architectural planning and as-built surveying and mapping[J]. Information Systems Engineering, 2023(3): 67-70.

[4] Tian Zehai,Yang Yousheng,Song Kangming. Application of 3D laser scanning technology in the verification and measurement of special-shaped building planning conditions[J]. Geospatial Information, 2021, 19(5): 81-84.

[5] Song Hening,Tang Chunxiao. Application of HERON backpack SLAM laser scanning system in architectural planning and surveying[J]. Beijing Surveying and Mapping, 2021, 35(4): 485-488.

[6] Lu Peiqing,Tang Chao. Application of mobile 3D laser scanning technology in deformation monitoring of subway tunnel[J]. Bulletin of Surveying and Mapping, 2020(5): 155-157.

[7] Chen Hongquan,Guo Wei. Application of 3D laser scanning technology in bridge deformation monitoring[J]. Modern Surveying and Mapping, 2016, 39(1): 36-39.

[8] Li Chao. Application of 3D laser scanning technology in mountain deformation monitoring[J]. Bulletin of Surveying and Mapping, 2012(11): 98-99.

[9] Zhang Yongming, Huang Yongsheng, Zhu Lei, et al. Application of 3D laser scanning technology in urban underground space measurement in Xining City[J]. Surveying, Mapping and Spatial Geographic Information, 2020, 43(3): 97-100.

[10] Meng Qingnian, Zhang Hongde, Wang Zhi, et al. Survey of urban underground space based on 3D laser scanner[J]. Bulletin of Surveying and Mapping, 2019(S2): 122-125.

[11] Chu Lixin, Tao Jun. Application of 3D laser scanning technology in urban underground space measurement[J]. Bulletin of Surveying and Mapping, 2018(5): 159-162.

[12] Xiong Chengli, Zhou Yousheng, Zheng Yongzhong. Application of air-ground integrated laser mobile measurement technology in large-scale topographic map update[J]. Bulletin of Surveying and Mapping, 2019(S1): 93-97.

[13] THOMSON C， APOSTOLOPOULOS G， BACKES D， et al. Mobile Laser Scanning for Indoor Modelling[J].ISPRS Annals of the Photogrammetry， Remote Sensing and Spatial Information Sciences， 2013， 11(II-5/W2)： 289-293.

[14] CUI Y， LI Q Q， YANG B S， et al.Automatic 3-D Reconstruction of Indoor Environment With Mobile Laser Scanning Point Clouds[J].IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing， 2019， 12(8)： 3117-3130.

[15] Chen Chi, Yang Bisheng, Peng Xiangyang. Automatic registration method for low-altitude UAV laser point cloud and sequence image[J]. Journal of Surveying and Mapping, 2015, 44(5): 518-525.

[16] Zhang Liang, Ma Hongchao, Gao Guang, et al. Automatic registration of urban aerial image and airborne lidar point cloud with similarity and invariance of point and line[J]. Journal of Surveying and Mapping, 2014, 43(4): 372-379.

[17] Shi Boxuan. Research on roadway point cloud processing method based on 3D laser scanning[D]. Xuzhou:China University of Mining and Technology, 2023.