Research on Deformation Monitoring of Roadway Surrounding Rock Based on Mobile 3D Laser Scanning Technology

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Abstract: Aiming at the problems of low data acquisition efficiency, unintuitive data form, low relative accuracy, and inability to continuously monitor the whole cross-section in traditional roadway rock deformation monitoring methods, a roadway rock deformation monitoring method based on mobile 3D laser scanning technology is proposed. Firstly, the mobile 3D laser scanning technology is used to obtain the real 3D point cloud data of the roadway surrounding rock; secondly, the multi-scale dimensional features are used to classify the 3D point cloud data, filter the invalid point cloud data, and form the accurate point cloud data of the roadway surrounding rock surface; then the 3D laser scanning is carried out on a regular basis for the deformation-prone areas of the roadway, and the Iterative Closest Point Algorithm (ICP algorithm) is used to align the overlapping part of the point cloud to achieve the point cloud splicing and point cloud stitching of the two scans. The point cloud splicing and point cloud overlapping of the two scans are achieved; finally, the multi-scale model-to-model point cloud comparison algorithm (M3C2 algorithm) is used to compare the point cloud data of the two periods of the roadway, and the appropriate parameters are selected to indicate the displacement change of the surface of the roadway rock with the size of the color value, so as to realize the monitoring of the deformation of the roadway rock in the three-dimensional full cross-section of the roadway. The method is applied to the deformation monitoring of the surrounding rock in the return roadway of 21407 working face in a coal mine, and the results show that: the mobile laser scanning technology can be used to obtain the complete point cloud data of the roadway, and the deformation area of the surrounding rock is successfully identified after the classification of the scanned point clouds in different time periods, the alignment of the point clouds, and the comparison of the point clouds, and the deformation condition of the surrounding rock of the roadway is visually reflected in the three-dimensional full-section deformation condition of the surrounding rock of the roadway. This method is suitable for monitoring the overall de-formation of the surrounding rock of the roadway under complex environmental conditions, and the de-formation of the surrounding rock is identified by different color areas.

Keywords: Surrounding rock deformation monitoring; mobile 3D laser scanning; point cloud registration; Point cloud comparison.

1. Introduction

Coal is the main energy source in China, and the total amount of coal resources buried at a depth of 2000m is 5.9 trillion tonnes, so the development of deep-earth resources is an important direction for the future development of science and technology in China. Deep-earth coal resources are mainly distributed in the east-central region of China, and the coal mines in this region have entered deep mining. After entering deep mining, the roadway is easily affected by high geostress, high geothermal temperature, high osmotic pressure, and strong mining disturbance, which leads to large deformation, long duration, and serious damage of the roadway peripheral rock. In order to ensure the stability of the roadway perimeter rock during the safe and efficient mining of deep-earth resources, it is necessary to carry out regular deformation monitoring of the supported roadway perimeter rock, and to carry out timely pressure relief and supplementary support for the deformed areas, so as to avoid the serious deformation of the roadway perimeter rock.

The deformation of roadway perimeter rock is the most intuitive external reflection of the change of its internal mechanical behaviour. He Qiaoying proposed a two-dimensional planar imaging method based on which the distance information and size information of the roadway can be obtained and the point information of the surrounding rock can be monitored. Li Yanhe and others independently developed a large-range strain sensor optical cable using weak fibre grating sensing technology to measure the internal deformation of the surrounding rock. However, the data obtained by these measurement methods are obtained in a two-dimensional plane and the acquired data are limited. Therefore, a reasonable method is needed to improve the working efficiency, and then quickly and accurately complete the monitoring work of the roadway surrounding rock.

Three-dimensional laser scanning technology is a new type of measurement technology, with the advantages of convenient operation, high accuracy, etc., which is widely used in the field of measurement, and makes up for the shortcomings of the monitoring technology of the roadway surrounding rock. Firstly, the measurement points are arranged in the roadway, and the 3D laser scanning equipment is used to obtain the 3D point cloud data, and after the processing and splicing of the point cloud data, the internal enclosing rock structure and characteristics of the roadway can be presented, and the deformation condition of the enclosing rock is obtained through the comparison of the two phases of the roadway point cloud data. Chen Xiaowei proposed a roadway point cloud central axis extraction method based on the least squares method to determine the centre point of the whole roadway, and then superimposed the multi-phase point cloud data through the position of the centre point to obtain the change of the point cloud within the roadway section; Chen used 3D laser scanning to obtain the point cloud of the roadway, and streamlined the point cloud data of the roadway based on the secondary feature extraction, which retained the characteristics of the enclosing rock of the roadway and Improved the accuracy of the roadway point cloud; Dai Wenxiang used 3D laser scanning technology to obtain the real 3D point cloud data of the coal mine roadway, fitted the extracted discrete points of the roadway section through the alphashape algorithm, and used the method based on the difference to calculate the multi-dimensional difference of the data in order to get the specific data of the roadway deformation and to achieve the full coverage of the monitoring of the deformation of the roadway in the mining area. With the gradual development of 3D laser scanning technology, SLAM technology has also been widely used in underground space measurement. The core of mobile laser scanning technology is the multi-sensor fusion SLAM technology, through the observation of the surrounding environment characteristics when moving, and then combined with its own position, to build a three-dimensional point cloud model, compared with the traditional monitoring means, in the roadway perimeter rock deformation monitoring with significant advantages, for the safe production of the mine to bring great convenience. Geng Zhijiang used laser SLAM technology to sense the internal information of the shaft, used K-means algorithm to extract the boundary point cloud of the shaft, established Markov mathematical model to get the centre of the point cloud slices, and then established the centre baseline of the shaft, and then analysed the tilt deformation of the shaft according to the method of whole and segmentation. Ye Fei proposed the observation method of mobile backpack 3D laser scanning system, and took the typical river section of Baihetan hydropower station reservoir area as an example to carry out the experimental research on the application of mobile backpack 3D laser scanning system. Song Kai proposed a 3D laser positioning and mapping method based on a backpack mobile surveying system, which can quickly realise positioning and 3D point cloud data construction, and be applied to data acquisition in indoor or underground environments.

In this study, the 3D point cloud data of the roadway will be rapidly acquired based on the multi-sensor fusion SLAM technology, and the deformation of the roadway perimeter rock will be acquired through the point cloud data processing and the comparison of the two-phase point cloud scanned at different time periods. On this basis, relying on the return airway of 21407 working face in a coal mine, a field test is carried out to obtain the deformation data of the roadway perimeter rock by comparing the point cloud data scanned in different time periods, which will provide data support for the analysis of the stability of the roadway perimeter rock and the safe and efficient production of the mine.

2. Principles of Mobile 3D Laser Scanning

Mobile 3D laser scanning technology is essentially a multi-sensor fusion simultaneous localisation and map building (SLAM) technology, which has been widely used in a variety of automatic measurement fields.SLAM technology was firstly applied in the field of robotics, which can start moving from an unknown environment, and carry out its own localisation according to its own positional attitude and characteristics of its surroundings in the process of moving, and meanwhile, construct an incremental map based on its own localisation, to achieve autonomous positioning and map building for the robot, as shown in Fig. 1. type map to achieve autonomous robot localisation and map construction, as shown in Fig. 1. Multi-sensor fusion SLAM technology is to fuse the data from LIDAR with the data from inertial sensors to solve the problems of missing data and data distortion when LIDAR is moving, and to effectively improve the performance of LIDAR front-end and back-end algorithms to generate a high-precision three-dimensional point cloud model.

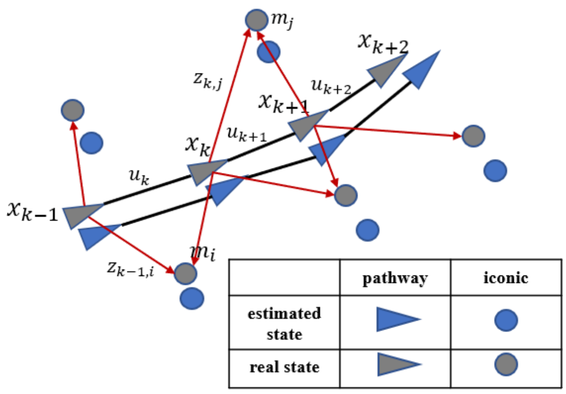

Figure1. Schematic diagram of SLAM technology

3. Point Cloud Roadway Deformation Monitoring Method

3.1. Classification of point cloud lane data

There are many equipments and pipelines in the roadway, so the classification of 3D point cloud roadway data is an important preprocessing step for effective application of deformation monitoring in coal mine roadways. The roadway point cloud acquired by mobile 3D laser scanning technology, but the geometric dimensional characteristics of each point are different at different scales. For example, at small scales, the roadway enclosure rock and the pipe are two-dimensional planes; at large scales, the roadway enclosure rock still belongs to two-dimensional planes, while the pipe presents three-dimensional features. Combining the information from different scales, the features of certain categories in the roadway scene are established to achieve accurate classification of the point cloud data.

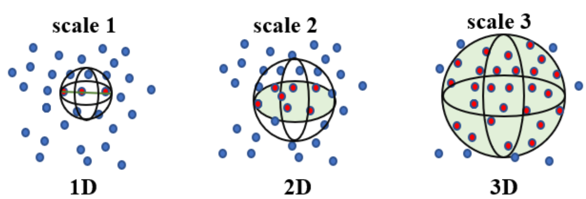

Figure 2. Dimensional characteristics of point clouds at multi-ple scales

Firstly, the local dimensional features of point cloud data at different scales are calculated. Assuming that it is a 3D point cloud, take any point in point cloud $C = \{p_i = (x_i, y_i, z_i)\}_{i=1...N}$ as the centre of the circle, and scale D as the diameter to construct the neighbourhood sphere. Fig. 2 shows the dimensional features of the point cloud data at multiple scales.

Principal Component Analysis (PCA) is performed on the domain sphere constructed from each point in the point cloud to find the eigenvalues λ_i (i = 1,2,3) and sort them in decreasing order of magnitude, and $\lambda_1 \geq \lambda_2 \geq \lambda_3$. The proportion of variance of each eigenvalue is $P_i = \lambda_i / (\lambda_1 + \lambda_2 + \lambda_3)$. Setting the constraint $P_1 + P_2 + P_3 = 1$, the magnitude of the variance proportion of the eigenvalues determines the point cloud dimensionality characteristics at scale D. When the neighbourhood sphere principal component analysis has only one eigenvalue $P_1 = 1$, the point cloud presents a one-dimensional distribution; when the neighbourhood sphere principal component analysis has two eigenvalues λ_1 and λ_2, $P_1 + P_2 = 1$, the point cloud presents a two-dimensional distribution; and when when the neighbourhood sphere principal component analysis has three eigenvalues λ_1, λ_2, λ_3, $P_1 + P_2 + P_3 = 1$, the point cloud presents a three-dimensional distribution. Setting the constraints, with two eigenvalue parameters can define any point cloud presenting one-dimensional, two-dimensional, and three-dimensional distributions under the scale D. △ABD in Fig. 3 is represented as the scale domain of the eigenvalue variance of the principal component analysis of the 3D point cloud. The dimensional features under different scales can determine whether different kinds of point clouds can be separated, and the stronger its three-dimensionality, the easier the point cloud data can be classified.

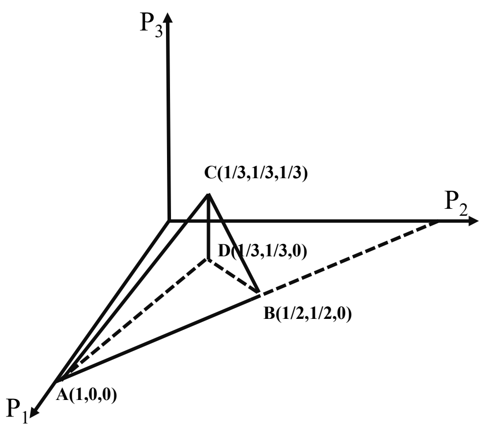

Figure 3. The variance scale coordinate system of the eigen-values

3.2. Point cloud lane data alignment

The point cloud lane coordinate system acquired by mobile 3D laser scanning technology is different, and it is necessary to find the conversion relationship between the two coordinate systems so that the two point clouds can be in the same coordinate system, i.e. point cloud alignment. Point cloud alignment is used for point cloud splicing and overlapping of two-phase point clouds, and the alignment process is divided into two steps. In the first step for coarse alignment, the four-point consistent set alignment algorithm is used, i.e., more than four points corresponding to each other are selected in the overlapping part of the two point clouds, and the two point cloud data are transformed to the same coordinate system, so that the two point clouds are roughly aligned to provide a good initial value for the fine alignment; in the second step for the fine alignment, the Iterative Closest Point algorithm (ICP) is used to The second step of fine alignment is to use Iterative Closest Point (ICP) algorithm to align the overlapping parts of two point clouds, so as to realise point cloud splicing and overlapping point clouds in two phases.The ICP algorithm is used to align the overlapping parts of point clouds $P = \{p_1, p_2, p_3, ..., p_n\}$ and $Q = \{q_1, q_2, q_3, ..., q_n\}$ by solving the rotation matrix R and translation matrix t between the target point cloud and the source cloud. Currently, the ICP algorithm is widely used in point cloud alignment, this method has high accuracy and does not need to extract feature points, its principle is: according to certain constraints, search for the closest point in the two point clouds, and then calculate the optimal matching parameters *R* and *t,* so as to minimize the error function. The error function is:

$$E(R,t) = \frac{1}{n}\sum_{i=1}^{n}(\|q_i - (Rp_i + t)\|)^2 \qquad (1)$$

Where *n* is the number of the nearest points of the two point clouds, *n* is an arbitrary point in the target point cloud P, *n* is a neighbouring point corresponding to the source point cloud Q, *R* is the rotation matrix, and *t* is the translation matrix.

When the calculation result of ICP algorithm meets the set alignment error or the maximum number of iterations, the calculation is finished, the point cloud data have been aligned.

3.3. Comparison of two phases of point cloud alleyways

In order to compare and analyse the point cloud roadway point cloud data acquired by scanning in different time periods, the Multiscale Model-to-Model Cloud Comparison algorithm (M3C2) was used to directly compare and analyse the point cloud data of the two phases of the roadway and to monitor the changes of the surrounding rock. It is set that the point cloud acquired in the first phase is the original point cloud P, and the point cloud acquired in the second phase is the comparison point cloud Q.

Firstly, the normal vector of the original point cloud P needs to be calculated. The original point cloud P is downsampled to get the core point cloud which is uniformly distributed and retains the characteristics of the surrounding rock inside the roadway. Take the core point i as the centre and D as the diameter, fit a plane with its surrounding point cloud data, and calculate the normal vector *N* and roughness of the fitted plane, as shown in Fig. 4(a). The roughness is calculated as:

$$\sigma(D) = \sqrt{\frac{\sum_{m=1}^{M}(a_m - a)^2}{M}} \qquad (2)$$

where is the spacing from the mth point in the point cloud to the fitted plane, *a* is the average spacing from all the point clouds within the diameter D to the fitted plane, and M is the total number of point clouds within the diameter D. The point cloud is then projected onto a cylinder with the core point *i* in the original point cloud as the axis and the normal vector *N* as the median axis.

Then a cylinder with core point i in the original point cloud as the axis, *d* as the projected diameter, normal vector *N* as the central axis and height H. This cylinder intersects the comparison point cloud. The number of points in the cylinder containing the original point cloud and the comparison point cloud are n_1 and n_2, respectively, along the core point normal vector in the original point cloud to calculate the average position of the two phases of the point cloud in the column, the average position is i_1 and i_2, respectively, and the spacing of the two average positions is the distance of the core point i change. Calculation of the core point of the whole original point cloud can lead to the whole original point cloud change, as shown in Fig. 4(b). In the calculation process, whether the appropriate normal vector diameter D, projection diameter d and maximum calculation depth H can be set will directly affect the subsequent calculation effect.

For the point cloud with high roughness, the normal vector measurement distance is one of the important parameters, and when the normal vector measurement distance is smaller than the point cloud roughness, the direction of the normal vector will change, which in turn overestimates the distance between the two phases of the point cloud, as shown in Fig. 4(c). In order to improve the local distance measurement accuracy and avoid large errors in channel deformation monitoring, further spatially variable confidence intervals need to be determined. Due to the uncertainty of the spatial variation of the positioning and alignment errors, the alignment error REG and the local roughness of the two-phase point cloud measured along the normal direction and and will be used to construct the confidence intervals with a confidence level of 0.95 or higher. The and are in are calculated based on the two-phase local point cloud contained within the cylinder, and the average positions of the two-phase point cloud in this region are i_1, i_2.

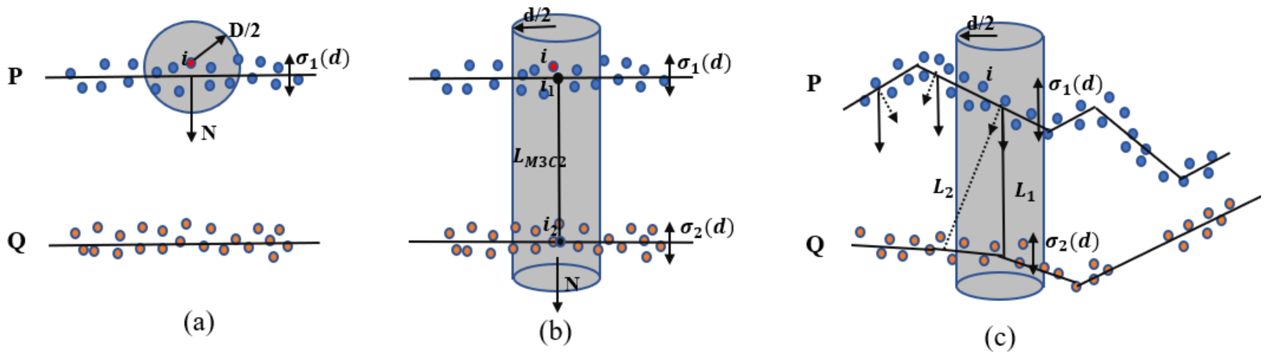

Figure 4. Principles of M3C2 algorithm

4. Field Applications

4.1. Point cloud lane data acquisition

The equipment selected for the experiment is GOSLAM RS100S 3D laser scanner, which is a mobile 3D laser scanner with medium and long range, and its portable data solver constitutes a 3D laser scanning system, which realises the generation of high-quality 3D point cloud data in complex environments. The data can also be displayed in real time on mobile phones and other mobile terminals, so that it can be viewed instantly and a complete 3D point cloud model can be exported at the end of the scanning process. The system hardware is designed to be lightweight and convenient, and the data can be collected easily by handheld, cycling, vehicle and other means. In the process of data acquisition, it can be used to acquire data wherever it passes through, which is highly applicable. As the maximum scanning distance of the device is 150m, the point cloud coordinates will be deviated after exceeding 150m, and the monitoring area needs to be scanned twice. After scanning each section of the roadway, it is necessary to back up 10m, and then scan the next section of the roadway, and the overlapping area of the two sections of the point cloud using the ICP algorithm for point cloud splicing, so as to present the three-dimensional point cloud model of the entire roadway, as shown in Figure 5. The deformation of the roadway surrounding rock is a slow-change dynamic process, which needs to be monitored regularly to ensure the stability of the roadway surrounding rock.

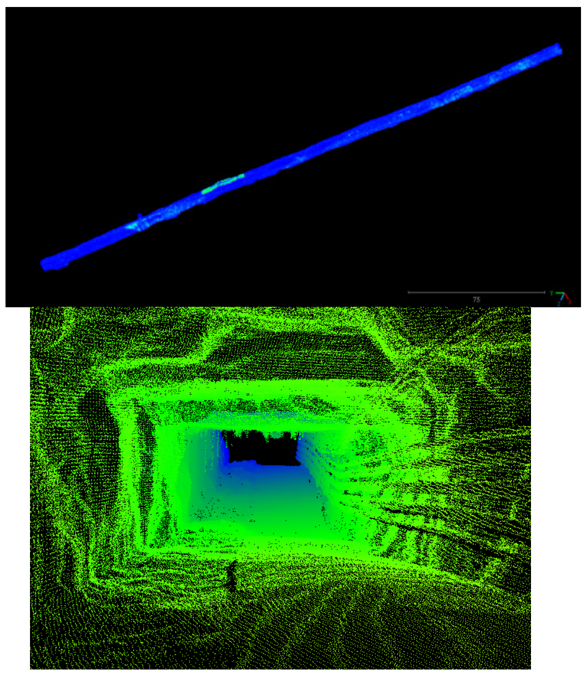

Figure 5. 3D point cloud data of roadways

4.2. Point cloud roadway deformation monitoring

4.2.1. Point cloud classification

Using mobile 3D laser scanning equipment, the complete data of the top and bottom plates of the roadway and the two side walls of the coal pillar side and the return mining side are collected. However, there are more noise points inside the roadway (e.g., pipelines and moving vehicles and equipment on the back-mining side), which affect the monitoring of the deformation of the roadway perimeter rock, and need to be separated from the noise points. The point cloud classification process is divided into five steps: ①manually select a small range of point cloud data, and split the point cloud data into two categories (roadway rock and pipeline); ②set the scale range and scale interval, the minimum scale should be larger than the minimum density of the point cloud, and the maximum scale can be defined according to the size of the pipeline;③5perform the principal component analysis of the point cloud of the peripheral rock and pipeline point cloud, calculate the dimensional characteristics at different scales, as the basis of classification; ④Construct a binary classifier to find the best combination of point cloud classification; ⑤ 5Apply the binary classifier to the whole roadway point cloud classification to achieve the classification of roadway point cloud data. The scale range of 0.1~1m and the scale interval of 0.1m are selected to calculate the feature vectors of the point cloud, and the classification effect is shown in Fig.6, in which the red colour is the internal pipeline point cloud data of the roadway, and the blue colour is the point cloud data of the roadway peripheral rock. Finally, through filtering, the pipeline point cloud data is removed, leaving the roadway surrounding rock point cloud data, as shown in Fig.7.

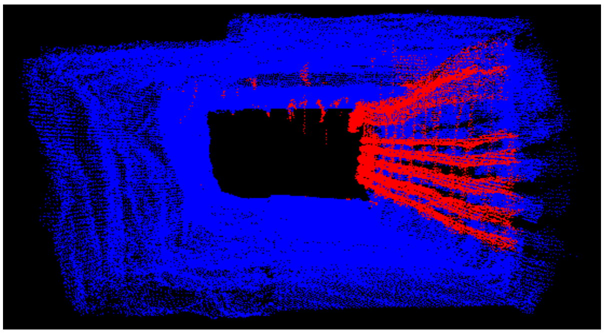

Figure 6. Point cloud data classification results

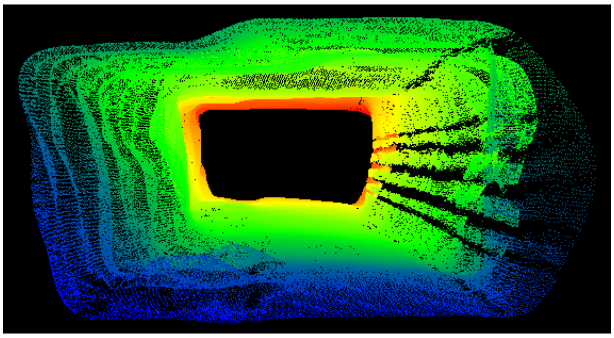

Figure 7. Point cloud data of roadway surrounding rock

4.2.2. Point cloud alignment

Due to the limited measuring distance of the mobile 3D laser scanner, when the scanning distance is too long, it will affect the construction of the point cloud model of the roadway, and it is necessary to scan the roadway in sections, and then realise the point cloud splicing by aligning the overlapping parts of the two point clouds. Fig.8 shows the flow chart of point cloud splicing. Coarse alignment is carried out first, and in the case that the initial positions of both source and target point clouds are unknown, more than four point pairs corresponding to each other are selected from the overlapping parts of the two point clouds to complete the initial alignment of the overlapping regions of the two point clouds, as shown in Fig.8(b). Fine alignment is a more accurate alignment on the basis of coarse alignment, using the corresponding point distances of the source and target point clouds, calculating the rotation matrix R and translation matrix t, calculating the alignment error after the transformation, and if the alignment error is less than the constraints, then the point cloud alignment is finished. The alignment error is set to be less than 1 cm, and the alignment process of the overlapping region of the two point clouds is shown in Fig.8(c), the stitching of the two point clouds is completed. Before the deformation analysis of two-phase point cloud, it is necessary to overlap two-phase point cloud completely, the process is the same as the above operation.

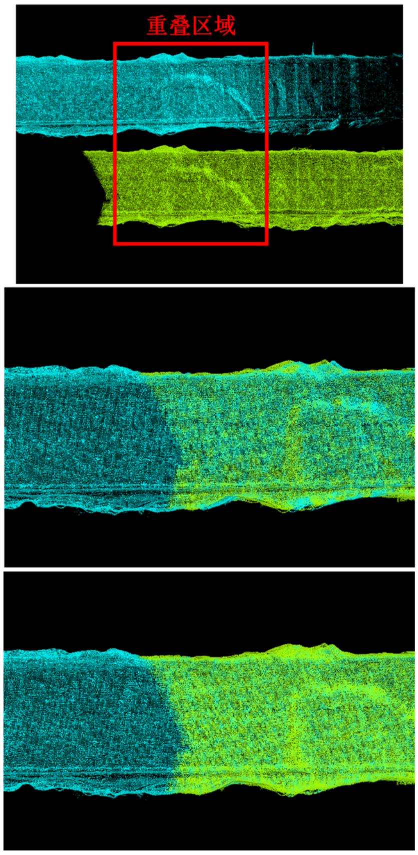

Figure 8. Point cloud stitching

4.2.3. Deformation Analysis

The M3C2 algorithm is used to compare the point clouds of the aligned two-phase point clouds to derive the overall deformation and display the difference in the form of a chromatogram, where different colour distributions indicate the distribution of the deviation of the two-phase point cloud model in different regions, and the depth of the colours indicates the magnitude of the deviation in that region. The first period point cloud is taken as the original point cloud and the second period point cloud is taken as the comparison point cloud, and the colour spectrum representing the difference is presented on the comparison point cloud. The chromatogram generated at the end of the point cloud comparison calculation has three colours: blue, white and red. The blue colour represents the shedding of coal lumps on the surface of the roadway surrounding rock, which is negative; the white colour represents no displacement change of the roadway surrounding rock; the red colour represents the deformation condition of the roadway surrounding rock, which is positive, and the darker the colour means the greater the deformation of the surrounding rock.

The two-phase point cloud data are downsampled with a relative accuracy of 0.02 m. Due to the irregular shape and complex structure of the roadway surrounding rock, it is necessary to set the appropriate normal vector diameter *D*, projection diameter *d* and maximum computational depth *H* to improve the accuracy and efficiency of the calculation. A section of the two-phase point cloud with good alignment is selected, and four sets of parameters are set to check its calculation accuracy and efficiency: (a)D_1=0.2m， d_1=0.3m， H_1=0.5m；(b)D_2=0.4m，d_2=0.3m，H_2=0.5m；(c)D_3=0.4m， d_3=0.6m， H_3=0.5m， (d)D_4=0.4m， d_4=0.3m， H_4=1m. The calculation results are shown in Fig.9. Fig.9(a) and Fig.9(b) indicate the influence of selecting different normal vector diameters on the calculation results, and their calculated maximum deformation are both 0.35 m. Due to the uneven distribution of data in some regions in the point cloud, if the normal vector diameter is selected too small and the data in this region in the comparison point cloud is sparse, the calculation bias occurs, which leads to a larger negative value of the comparison results; the projection diameters set in group (b) and group (c) are Different, the projection diameter is set too large, which can reduce the influence of surface roughness on the calculation results, but it will also affect the calculation accuracy, such as the maximum deformation calculated in group (b) is 0.35m, while the deformation calculated in group (c) is 0.33m; the maximum calculation depth H has an influence on the calculation accuracy and efficiency, as shown in Fig.9(b) and Fig.9(d), when the calculation depth is too large, its deformation monitoring effect is not When the calculated depth is too large, the deformation monitoring effect is not ideal, and a suitable warning value can be set. When the calculated maximum depth is equal to the warning value, the area will be red, which indicates that the deformation here is large, and it is necessary to unload the pressure and reinforce the support in time.

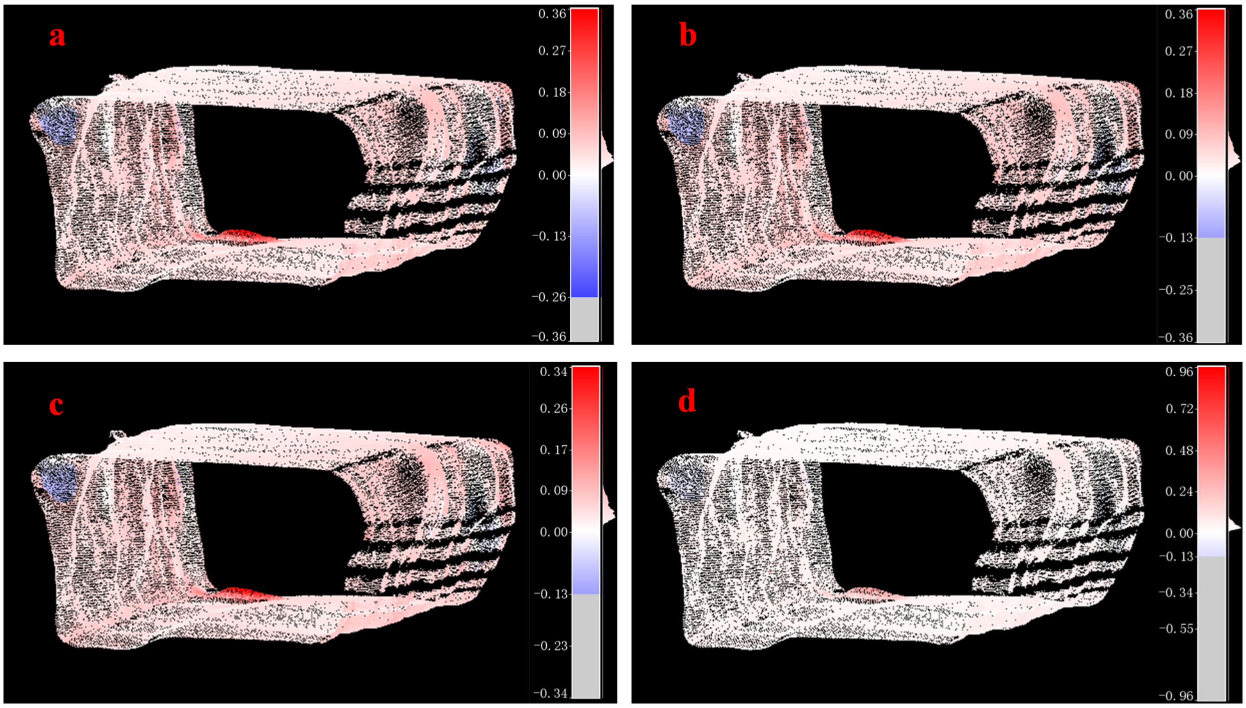

Figure 9. Calculation accuracy of different parameters

According to the above analysis, group (b) parameters are selected to monitor the deformation of the point cloud of the whole section of the roadway, and the point cloud comparison results are shown in Fig.10 and Fig.11. Observing Figure 11, we can observe that the top plate of the roadway tends to have no change, the deformation interval of the two gangs is about 0.13m, the deformation of the surrounding rock at the bottom corner of the coal pillar side is larger, and the bottom drum phenomenon occurs in some areas of the bottom plate. The reason for the small deformation of the roadway roof is that: during the excavation of 21407 return-airway, the roof adopts strengthened support method, and the anchor cable support is adopted uniformly. The deformation area can be determined by measuring the distance between the point of the deformation area and the starting scanning position, or a certain position section can be selected to obtain the surrounding rock deformation, as shown in Fig.12. Fig.12 intercepts the point cloud roadway comparison cross-section from the scanning starting position of 10m, 32m, 50m, 80m, the cross-section width of 0.15m, the deeper the red represents the greater the deformation of the position.

Figure 10. Comparison results of point clouds in two periods

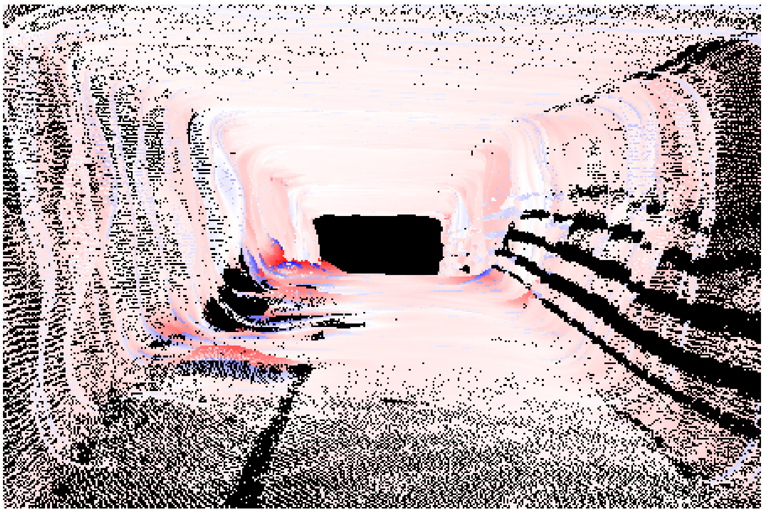

Figure 11. Internal view of the point cloud comparison results

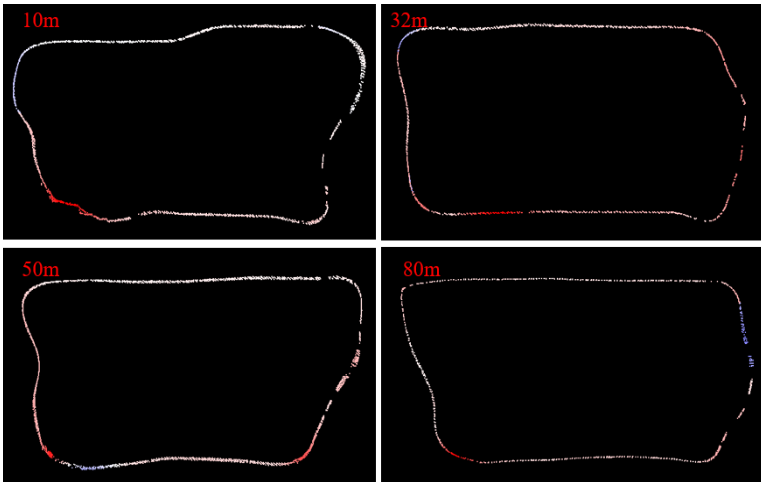

Figure 12. Comparison diagram of roadway deformation section

5. Summary

A roadway perimeter rock deformation monitoring method based on mobile 3D laser scanning technology is proposed, and field experiments are carried out to verify the feasibility and recognition accuracy of the method and effectively apply it to roadway perimeter rock deformation monitoring and early warning.

(1) Multi-sensor fusion SLAM technology based on 3D laser scanning is adopted to improve the accuracy of the 3D point cloud model of the roadway, and to solve the problems of high error and low efficiency of the existing roadway perimeter rock monitoring methods in monitoring.

(2) Based on the actual scanning data of the mine roadway, multi-scale dimensional features were adopted to classify the 3D point cloud of the roadway, which achieved the point cloud retention on the surface of the roadway peripheral rock; based on the ICP algorithm, the overlapping part of the two point clouds was aligned, which realised the splicing of the two point clouds; and by using the M3C2 point cloud comparison algorithm, the deformation status of the roadway peripheral rock was indicated by the difference of the

chromatograms, and the deformed area and deformation trend of the roadway were identified.

(3) The three-dimensional point cloud model of the roadway in different periods was established, which realised an overall mastery of the displacement change process of the roadway surrounding rock, and at the same time was able to make a timely warning of the deformation area, which provided a scientific basis for the automated monitoring and early warning identification of the roadway surrounding rock under complex conditions.

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