Research on Fast Pre-Processing Method of Tunnel Point Cloud Data in Complex Environment

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Abstract. In recent years, the application and research of three-dimensional laser scanning technology in tunnel engineering has continuously emerged, while the shortcomings still exists. This paper conducts research on quick preprocessing method of tunnel point cloud data based on three-dimensional laser scanning. For streamlining the tunnel point cloud model data, comparison analysis discusses are applied to both the downsampling algorithm and the point cloud denoising method respectively. Simulation experiments are introduced to compare the effects of different downsampling algorithms applied to the tunnel point cloud model, analyze the sampling efficiency and performance of each algorithm. Combining with statistical denoising and radius denoising algorithms, a distance denoising based on an iterative filtering model method is proposed. The result shows that this method is suitable for the tunnel point cloud model during the construction period with complex environment, and can effectively eliminate most of the point cloud noise.

1. Introduction
The application of 3D laser scanning technology in tunnel engineering is becoming more and more widespread, which can be used for over-under excavation analysis, leveling analysis, structural thickness analysis, volume calculation of tunnels and even monitoring and measurement of tunnels. 3D laser scanning point cloud data generally has a huge amount of data. There are many noises in tunnel application, which affects the analysis and utilization of point cloud data. At present, the automation and intelligence of data preprocessing methods such as denoising 3D tunnel point cloud are still Room for improvement.

Researchers at home and abroad have conducted certain research on point cloud data processing methods [1-6]. Xiao [7] proposed a surface reconstruction technology based on the multi-level partition of the unified algebraic set surface, which is used for the smooth denoising of anti-volume deformation and anti-feature distortion of the spatial unorganized relation point set. Mathieu [8] et al. improved and optimized the bilateral denoising algorithm in the field of image recognition, which is anisotropic and maintains the geometric features of the original mesh model, but the algorithm can mistakenly remove the overly sharp mesh vertices from the model. Shuang Cao et al [9] improved the bilateral filtering algorithm and combined it with neighborhood search to achieve bilateral filtering point cloud denoising
based on specific features, optimizing the defects of bilateral filtering algorithm that may make the point cloud model excessively smooth. Dongrong Ye [10] conducted a comparative analysis of the commonly used point cloud denoising methods and proposed a mean distance noise reduction technique using neighborhood search. Yuan Hua et al [11] improved the existing bilateral filtering algorithm based on curvature estimation to enhance the robustness of the bilateral filtering algorithm. Jinbo Qu et al [12] used density clustering to eliminate the outlier noises with low density in the point cloud model, and smoothed the model to preserve most of the local features.

In this paper, for the characteristics of the scanned point clouds during the tunnel construction period in complex environment, we propose the research on the pre-processing method of tunnel point cloud data based on 3D laser scanning, using the point cloud data collected in different periods in complex environment, and pre-processing the original point cloud data by point cloud downsampling analysis and distance denoising method based on iterative filtering model.

2. Tunnel point cloud downsampling study

2.1. Tunnel point cloud downsampling study
The tunnel point cloud data collected by the 3D laser scanner has a large spatial distribution density, long scanning mileage and large data volume. For the original tunnel point cloud data, firstly, the original point cloud data is segmented along the tunnel midline at a certain distance in the cross-sectional direction to form a number of "point cloud slices" containing tunnel mileage information (As shown in figure 1). The point cloud slices are used as the basic unit for pre-processing and noise reduction of the raw data, thereby streamlining the data volume and reducing the computational load on the computer.

2.2. Point cloud downsampling
Point cloud downsampling is one of the most commonly used methods to streamline point clouds. It can change the dense raw data into point cloud data with moderate spatial distribution density, which is easy for subsequent processing.

The choice of downsampling algorithm affects the efficiency and accuracy of the subsequent point cloud analysis processing. Therefore, downsampling analysis is performed to analyze the advantages and disadvantages of each algorithm based on the sampling results of different algorithms and to obtain a suitable downsampling algorithm for tunnel point cloud data.

In figure 2, a point cloud slice with a thickness of 2.0 m along the centerline of the tunnel. The total number of points in the original point cloud is 287,208. The original point cloud includes ventilation ducts, construction workers, and other scattered outliers in addition to the tunnel structure.

Figure 1. Tunnel point cloud slice.

Figure 2. Tunnel point cloud model for downsampling experiment.

The random method, uniform method and voxelization method are used to sample and test the point cloud slices. Among them, the voxelization method is divided into two types: based on the closest distance to the voxel center and based on the average distance from the voxel center. The test results are shown in figure 3 to figure 6, and the statistical results of downsampling data are shown in table 1.
The sampling results of different downsampling methods are as follows:

| Downsampling method                                      | Total number of source point cloud | Total points after downsampling | Sampling rate | Algorithm time-consuming(s) |
|-----------------------------------------------------------|------------------------------------|--------------------------------|---------------|-----------------------------|
| Random method                                             | 43081                              | 15%                            | 0.0126        |
| Uniform downsampling                                      | 41030                              | 14%                            | 0.0156        |
| Voxelized downsampling based on distance from the center of the voxel (Octree optimization) | 287208                              | 15%                            | 0.0377        |
| Voxelized downsampling based on average distance (Octree optimization) | 33448                              | 11%                            | 0.239         |

According to figure 2-figure 6 and table 1, under the similar sampling rate, the random method of downsampling consumes the shortest time and has the highest algorithm efficiency, but the point cloud density distribution of sampling results is not uniform, unstable; the uniform downsampling algorithm based on the farthest point method has similar sampling efficiency and time consumption as the random method, but ripple-like deformation occurs after sampling; The voxelized downsampling based on the distance from the center of the voxel and the voxelized downsampling based on the average distance, both of them have uniform point density distribution, and the time consumption of the algorithm is high after using Octree optimization, but it does not have a greater impact on the tunnel slice data with relatively small number of point clouds. In addition, the voxelized downsampling results based on the average distance of the point cloud distribution are prone to line streaks.
Combining the results of integrated sampling of geometric features with the efficiency of the algorithm, the voxelized downsampling based on the distance from the center of the voxel is selected as the point cloud refinement algorithm.

3. Distance denoising method based on iterative filtering model

The noise contained in the tunnel point cloud model can be divided into two categories: a class of cluttered outlier noise points, which is characterized by sparse spatial distribution and overall does not have obvious geometric features, accounting for a small percentage of all noise points; another class of structural noise points generated by scanning various facilities, equipment and personnel in the tunnel, which has certain geometric features and accounts for a relatively large percentage of all noise points (figure 7).

For the first type of noise points, better results can be obtained by statistical distance denoising and radius denoising, but the second type of noise points are difficult to be removed effectively by this method. When analyzing the tunnel deformation based on 3D laser point cloud data, for multiple periods of point cloud data at the same location in the tunnel, the outlier noise points in the point cloud are firstly removed by statistical distance denoising and radius denoising, and then the various types of noise in the tunnel are screened out by using the filtering model to achieve tunnel point cloud denoising.

Suppose the point cloud model obtained by the \(i^{th}\) laser scan is \(cl_i(i=1,2,3,\ldots,n)\), and the corresponding standard filter model is \(m_i\), then

1. Acquisition of the initial standard filter model \(m_1\)

For the point cloud model \(cl_1\) obtained from the initial scan, all structural noise points in the tunnel are removed by manual processing, and only the point cloud of the main structure of the tunnel is retained and used as the initial standard filter model \(m_1\).

2. Integrated denoising method based on standard filtering model

Step 1: Use statistical distance denoising and radius denoising to remove Outlier noise points
Step 2: In the same spatial coordinate system, for any point \(p_j\) in \(cl_i\), use the \(kd\) tree to search its’ nearest neighbor and obtain the nearest neighbor \(p'_j\), corresponding to \(p_j\) in \(m_{i-1}\), calculate the Euclidean distance \(d_j\) between the two. If \(d_j\) is greater than the distance threshold \(d_T\), the point \(p_j\) is removed as a noise point and the denoised point cloud model is obtained.

Step 3: The point cloud model that has been denoised in \(cl_i\) is used as the standard filter model \(m_i\) for the next scanning point cloud pre-processing.

Point cloud denoising processing flow is shown in figure 8.
4. Engineering example analysis
Taking the scanned point cloud data of a tunnel in Yunnan Province as an example, the raw data were pre-processed and the data were acquired using a FARO Focus3D X 130 laser scanner with a measurement accuracy of 2 mm and a scanning angle step of 0.09°.

4.1. Data Acquisition
Select the two-phase scan data of the tunnel to test the preprocessing method proposed in this study (figure 9).

![Flow chart of denoising method](image)

(a). Phase 1 Point Cloud  
(b). Phase 2 point cloud

4.2. Point cloud pre-processing
The original point cloud data contains a large amount of noise, and the point cloud density varies greatly. Take two tunnel point cloud slicing models as an example, and use the downsampling and denoising methods in this paper for pre-processing.

| Serial number | Name of point cloud | Number of source data points | Downsampling size | Points after pre-processing |
|---------------|---------------------|------------------------------|-------------------|-----------------------------|
| 1             | A1                  | 142300                       |                   | 54845                       |
| 2             | B1                  | 675228                       |                   | 267348                       |
| 3             | A2                  | 574164                       |                   | 247204                       |
| 4             | B2                  | 11888108                     | 0.01              | 516753                       |

In table 2, A1 and B1 are the two point cloud slices obtained by processing the point cloud of the
Phase 1, and A2 and B2 are the two point cloud slices obtained by processing the point cloud of the Phase 2 at the corresponding positions of A1 and B1. After downsampling by voxelization, statistical denoising and radius denoising are then performed to obtain the preprocessing.

Finally, using the method proposed in this study, we first remove the structural noise in the phase 1 point cloud model to obtain the point clouds shown in figure 10(a) and (c), and use this as the standard filtering model to perform denoising of the A2 and B2 point cloud slices to obtain the streamlined model shown in figure 10(b) and (d).

![Figure 10. Point cloud data pre-processing results.](image)

It can be seen from figure 10 that the preprocessing method proposed in this paper is able to realize the processing of tunnel point cloud slice data, and the preprocessing effect is good.

5. Conclusion and Discussion
This paper studies the method of processing tunnel deformation point cloud data based on 3D laser scanning technology and point cloud registration algorithm. The main conclusions are as follows:

1. The random method, uniform method and voxelization method are used to sample and test the point cloud slices. Among them, the voxelization method is divided into two types: based on the closest distance to the voxel center and based on the average distance from the voxel center. Tests have shown that voxelization downsampling based on the distance from the voxel center is better. The optimization of the algorithm through Octree spatial index takes a relatively long time, but it has less impact on the processing of tunnel point cloud slices.

2. For the multi-period point cloud data at the same location in the tunnel, a distance denoising method based on iterative filtering model is proposed, i.e., the outlier noise points in the point cloud are removed by statistical distance denoising and radius denoising, and the initial point cloud data of the tunnel is manually denoised, based on which the current point cloud data and the last processed point cloud data are compared, and a comprehensive denoising method based on the standard filtering model is used to realize the denoising of the current tunnel point cloud.

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