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A Method for Detecting the Spacing of Steel Arch Frames in Construction Tunnels Based on Three-Dimensional Laser Technology

Chuanyi Ma[1], Hongzheng Luo[2], Chuan Wang[1], Gaohang Lv[2, *]

[1]Shandong HI-Speed Group, Jinan, China

[2]School of Oilu Transportation, Shandong University, Jinan, China

Email address:

962787295@qq.com (Chuanyi Ma), 729148748@qq.com (Hongzheng Luo), 1157909517@qq.com (Chuan Wang), lvgh1125@163.com (Gaohang Lv)

[*]Corresponding author

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Abstract: The present invention provides a point cloud spacing extraction algorithm for tunnel steel arch frames. This method first calculates the angle between the point cloud of the tunnel steel arch construction section and the adjacent coordinate axis and rotates it so that its axial direction is parallel to the adjacent coordinate axis. Then, the point cloud axial normal vector is calculated, and a threshold is set based on the calculated normal vector to extract the steel arch point cloud. Then, a clustering algorithm is used to extract the single steel arch point cloud, Use the C2C-Distance method based on the kd tree to calculate the closest distance from each point in a single steel arch point cloud to another single steel arch. Take the average value to obtain the distance between the tunnel steel arches, fit the single arch point cloud, fit a spatial circular point cloud, calculate the difference between the single point cloud and the spatial circular point cloud, and extract the excessively distorted part in the single point cloud. This method has good robustness and is suitable for various working conditions of tunnels. It can effectively extract point clouds of steel arch frames and obtain point cloud spacing with millimeter level errors, making it suitable for monitoring tunnel construction quality.

Keywords: Point Cloud, Normal Vector, Euclidean Clustering, Steel Arch Frames, Tunnel

1. Introduction

At present, in the process of tunnel construction in our country, there is insufficient attention paid to the quality monitoring of tunnel steel arch support construction [1-3]. During the construction process, it is very easy to encounter unqualified spacing between steel arch supports, which affects the overall safety and quality of the construction. Therefore, monitoring the construction quality of the steel arch spacing and deformation during the construction period of the tunnel is an indispensable part of modern tunnel engineering.

Noise removal is an indispensable part of point cloud preprocessing, among which common denoising algorithms include voxel filtering [4], statistical filtering [5], radius filtering [6], etc., which can effectively remove outliers and excess noise in point clouds. The processed point cloud usually requires feature calculation, and the normal is the most basic and important feature of the point cloud. Currently, the main methods for calculating the normal are RANSAC [7] and the least squares method [8], which essentially fit the plane parameters within a certain neighborhood. The point cloud extracted through feature extraction can be clustered for instance segmentation, commonly used clustering algorithms include Euclidean clustering [9], region growth [10], normal differentiation [11], etc.

This article proposes a point cloud spacing calculation method for steel arch frames based on 3D laser technology to achieve monitoring of steel arch frame spacing in construction tunnels.

2. Algorithm Principle

2.1. Kd Tree

As shown in Figure 1, it is a two-dimensional data search diagram with k=2. Each layer of the kd-tree [12, 13] is a dimension of the data, and the data interval of that dimension is split by a child node. Data within this dimension that is less than the value of that node is placed in the left child number, while data that is greater than the value of the node is placed in the right child tree. Each layer of kd-tee is separated in the next dimension of the data. When the dimensions of the data are used up, it returns to the first dimension and continues to iterate until the searched data is determined. This method can reduce time complexity. Create a kd-tree to use the median of each dimension of the data value as the segmentation hyperplane.

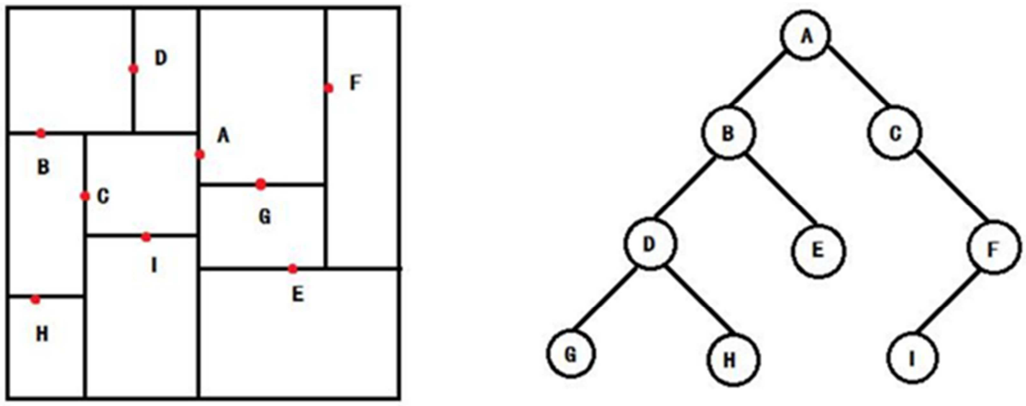


Figure 1. *Schematic diagram of kd-tree with k=2 (a) Spatial partition diagram; (b) Tree structure diagram.*

2.2. Normal Vector Estimation

The point cloud normal vector calculation method based on the least squares fitting method [14, 15] uses the least squares method to fit local points to obtain plane parameters, and uses the plane normal as the point cloud normal vector. Take any point p_i from the point cloud data, query the k neighboring points of point p_i, and find the best fitting plane based on the minimum sum of squares of the distance from the sampling point to the fitting plane. Use the normalized plane normal vector as the unit normal vector of point p_i. The formula derivation process is as follows:

Let the equation expression for the fitting plane be:

$$ax + by + cz + d=0 \tag{1}$$

For the whole point cloud, build a Covariance matrix:

$$M_{3\times3}=\frac{1}{m}\sum_{i=1}^{m}(p_i-\bar{p})(p_i-\bar{p})^T \tag{2}$$

$$\bar{p}=\frac{1}{m}\sum_{i=1}^{m}p_i \tag{3}$$

Where, $p_i \in P$; $\bar{p}$ is the center point of all points in point set P.

Calculate the Eigenvalues and eigenvectors of covariance M according to formula $\lambda V=MV$, where $\lambda=(\lambda_0,\lambda_1,\lambda_2)$ is the eigenvalue of M and $V=(V_0,V_1,V_2)$ is λ Corresponding feature vectors. Calculate the four parameters a, b, c, and d by obtaining the minimum value of each feature value to obtain the best fitting plane, and calculate the distance from the point to the plane as the rough value in this paper. Unitize the normal vector of the least squares fitting plane to $\vec{n}=(a', b', c')$.

2.3. Euclidean Clustering

For a certain point P in space, the KD Tree nearest neighbor search algorithm is used to find K points closest to point P. Among these points, those with a distance less than the set threshold are clustered into the set Q. If the number of elements in Q does not increase, the entire clustering process will end; Otherwise, points outside of point p must be selected in the set Q and the above process repeated until the number of elements in Q does not increase. The specific process is:

(1) Find a point p10 in space, use kdTree to find the nearest n points, determine the distance from these n points to p10, and place points p12, p13, p14, etc. with a distance less than the threshold r in class Q; (2) Find a point p12 in Q (p10) and repeat (1); (3) Find a point in Q (p10, p12), repeat (1), find p22, p23, p24, and put them all into Q; (4) Complete the search when Q can no longer add new points.

3. Method for Detecting the Spacing of Steel Arch Frames in Construction Tunnels

This method first calculates the angle between the point cloud of the tunnel steel arch construction section and the adjacent coordinate axis and rotates it so that its axial direction is parallel to the adjacent coordinate axis. Then, the point cloud axial normal vector is calculated, and a threshold is set based on the calculated normal vector to extract the steel arch point cloud. Then, a clustering algorithm is used to extract the single steel arch point cloud, Use the C2C-Distance method based on kd-tree to calculate the closest distance from each point in the point cloud of a single steel arch to another single steel arch, and take the average value to obtain the distance between tunnel steel arches.

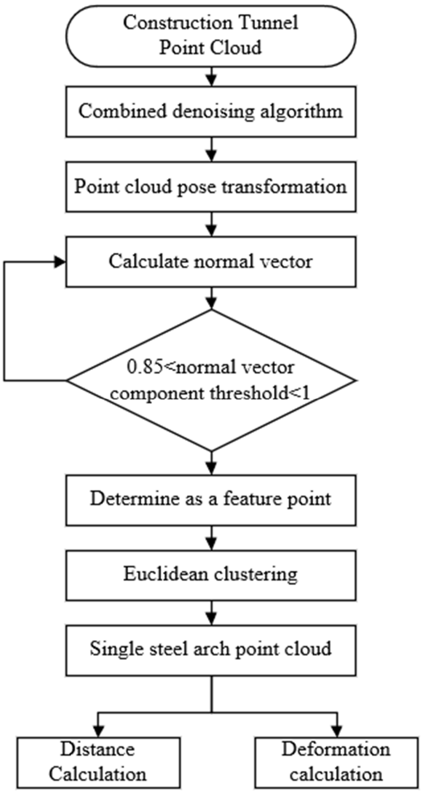
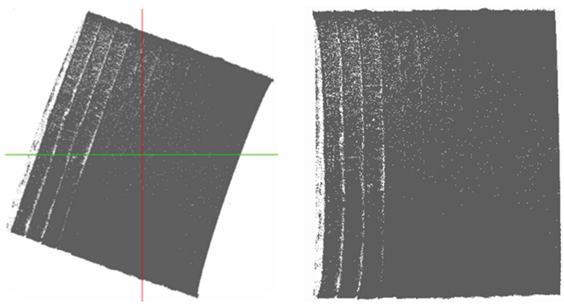


Figure 2. *Implementation process for detecting the spacing of steel arch frames in construction tunnels.*

4. Engineering Applications

This article takes a construction highway tunnel in Shandong Province as the research object, and uses laser three-dimensional scanning technology to collect point cloud data. By using CloudCompare software to denoise and crop point clouds, point cloud data near the palm face is obtained. The preprocessed point cloud is projected, sliced, and other operations are performed to obtain the tunnel axis. Point cloud pose transformation is performed based on the angle between the axis and the coordinate axis. The adjusted point cloud pose is shown in Figure 3 (b).



(a) (b)

Figure 3. *(a): Point cloud before pose transformation (b): Point cloud after pose transformation.*

Perform normal vector estimation on the point cloud after pose transformation to obtain the normal vector components in the X, Y, and Z directions. Based on the orientation of the tunnel along the coordinate axis after pose adjustment, extract the point cloud with a normal vector component size between 0.85 and 1.0 in the corresponding direction, as shown in Figure 4. Perform denoising on the extracted point cloud, as shown in Figure 5. Perform Euclidean clustering on the extracted point cloud to obtain a single steel arch point cloud, as shown in Figure 6, and calculate the spacing, as shown in Figure 7.

The specific distance calculation method is to traverse a single arch point cloud, perform a K-nearest neighbor search on each point in the point cloud, with K=1, and search for another arch point cloud, that is, search for the nearest distance from each point in the first point cloud to the second point cloud, establish a new index V, and return the nearest distance calculated each time to the index V.

Figure 4. *Undenoised.*

Figure 5. *Denoised.*

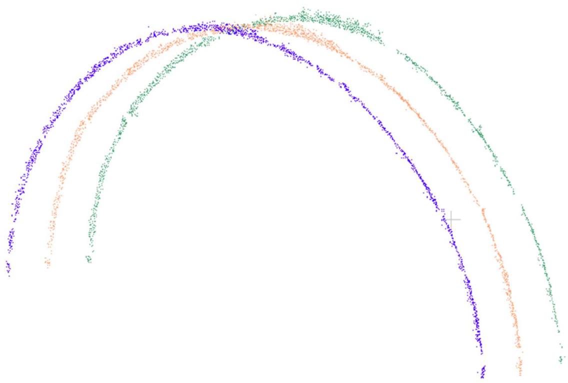


Figure 6. *Clustered Point Cloud.*

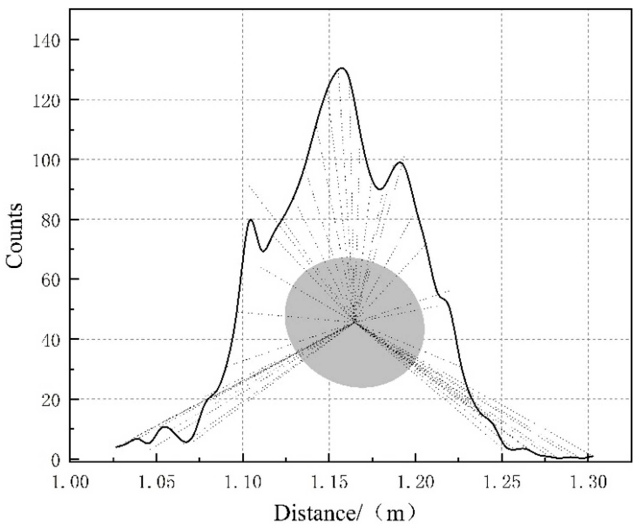


Figure 7. *Distribution of Distance between Two Steel Arch Frame Point Clouds.*

5. Conclusion

This article first preprocesses the point cloud and extracts the steel arch point cloud using normals. The obtained steel arch point cloud is segmented using Euclidean clustering, and the distance calculation is performed on the segmentation results. The actual results show that this method can effectively extract the steel arch point cloud from the construction tunnel point cloud, and has the advantages of high computational efficiency and high segmentation accuracy. However, the noise resistance effect of this method is poor, Therefore, the next step will be to consider how to reduce the impact of noise on the extraction.

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