

Time-efficient filtering method for three-dimensional point clouds data of tunnel structures

Advances in Mechanical Engineering
2018, Vol. 10(5) 1–6
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DOI: 10.1177/1687814018773159
journals.sagepub.com/home/ade


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Abstract

With the development of subways and tunnels, health monitoring of these structures are more and more important. Terrestrial laser scanning is an essential highly accurate technology used to obtain the point clouds data. However, the enormous quantity of point cloud of a tunnel makes it difficult to monitor the long-distance tunnel effectively and efficiently. Therefore, a fast and accurate extraction method is critical for the health monitoring of tunnel structures. In this article, a “Circular Likelihood” method is investigated. The innovation of this study is the consideration of the symmetry and the circular shape of the tunnel structure, where most of the noise can be removed and lots of inefficient iterations are avoided; thus, the computing time is greatly shortened.

Keywords

Tunnel structures, point cloud, data extraction, circular filtering, terrestrial laser scanning

Date received: 15 September 2017; accepted: 3 April 2018

Handling Editor: Shan-Tung Tu

Introduction

The subway is everywhere nowadays, and the new constructions around subways are increasing with the rapid development of science and technology. This has had impacts on the tunnel structure, such as structural deformation, tilt, and settlement. It leads to transverse, longitudinal displacement and uneven deformation of the tunnel structures. The health monitoring of tunnel with different sensors is gaining attention.^{1–5}

The advantages of terrestrial laser scanning (TLS) technology are high accuracy, efficiency, and no contact. Therefore, it is widely utilized to monitor the deformation of tunnels and other structures.^{6–9} The three-dimensional point cloud data based on TLS measurement is surface-based which describes the panoramic scene of the tunnel. The deformation of the tunnel structure can, thus, be patronymically investigated and analyzed. Moreover, we can obtain information about other features, such as the central curve and settlement displacement.

However, the scanning, with millions of points per second, generates a large population of data points, which is especially the case for large-scale structures, such as long tunnels. The extremely high-resolution scanning of an instrument such as the Z + F Imager 5010X reaches several billions of points for every station. The assurance of data acquisition quality generally requires the scanning station to be set at every 20 m for the tunnel. Therefore, the measurement of long-distance tunnels generates enormous points data, which makes it difficult to extract and analyze the point cloud data. How to extract the necessary information efficiently and remove the noises from

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point clouds is one of the key issues for the TLS data processing.^{10–16} Several studies about tunnel filtering and analysis were carried out.^{17–19} Researchers used spatial statistics and scaling properties to deal with point cloud noises.²⁰ Some methods were proposed for tunnel point clouds filtering and extraction, such as mesh parameterization, Bayesian Sampling Consensus algorithm, and RANdom SAMple Consensus (RANSAC) method.^{21–25} Laser scanner and radiometric information were combined to construct an accurate discontinuum model of tunnels.²⁶ However, an accurate time-efficient method for the filtering and analysis of long-distance tunnel structure still needs to be explored.

Motivation

Disturbing points in the article refer to the point clouds of objects not attached to the tunnel, such as cables and observers. In order to filter the disturbing point, the article proposed a time-efficient geometry-based “Circular Likelihood” method, which mainly adopted circular function to approximate the section point clouds and filter the disturbing objects.

A measurement is carried out to monitor the deformation behavior of the tunnel structure using TLS technology. The processing of the tunnel central points includes five steps which are section extraction, plane projection, section filtering, central calculation, and curve approximation. First, the cross-sections are extracted vertical to the tunnel boundary. Second, projection is adopted to guarantee that all the points in every cross-section are on one plane and this improves the accuracy of the central point acquisition, because three-dimensional point cloud data are scattered. Third, circular approximation is used to filter the cross-section by separating disturbing points. Fourth, the central points are computed from the intersection of vertical and horizontal lines. Fifth, the central curve is acquired from the approximation of all the central points and the accuracy of the central curve is judged.

In this article, the third step for section filtering is focused on and the “Circular Likelihood” method is proposed to extract the point cloud of tunnel structures with high efficiency.

Methods

Circular Likelihood method, as the name indicates, takes the advantage of the circular-like shape of the tunnel in the filtering process in order to improve the efficiency. Precondition is that the shape of the tunnel is circular-like with congenial long axis and short axis. Investigation expanding to other tunnels like ellipsoidal or horseshoe-shaped ones will be made in the future work.

The article implements a circular function to approximate the section point clouds and filter the disturbing objects circularly; it can be described with coordinates of the center point (x_M, y_M) and radius R (equation (1)) and polynomial form (equation (2)). Parameters a_1, a_2, a_3 in equation (2) are already known from equation (1), while the unknown parameters a_4, a_5, a_6 are estimated with the input data of the X, Y, and Z coordinates of the point clouds by means of the Drixler algorithm based on the Gauß-Helmert model. The elements A1 and A2 shown in equation (3) are obtained. Then, a_4, a_5, a_6 are computed with A1, A2, and the stochastic model P_{ww} in equation (4)

$$(x - x_M)^2 + (y - y_M)^2 - R^2 = 0 \quad (1)$$

$$a_1x^2 + a_2y^2 + \sqrt{2}a_3xy + a_4x + a_5y + a_6 = 0 \quad (2)$$

with $a_1 = a_2 = 1, a_3 = 0$

$$A1 = - \begin{bmatrix} x_1^2 + y_1^2 \\ x_2^2 + y_2^2 \\ \dots \\ x_n^2 + y_n^2 \end{bmatrix}, A2 = - \begin{bmatrix} x_1y_1 \\ x_2y_2 \\ \dots \\ x_ny_n \end{bmatrix} \quad (3)$$

$$(\hat{a}_4, \hat{a}_5, \hat{a}_6)^T = - (A_2^T P_{ww} A_2)^{-1} A_2^T P_{ww} A_1 \quad (4)$$

This article adopts circular function to approximate the section point clouds and filter the disturbing objects, because the circular deviation of the disturbing objects is much larger than that of the tunnel shape. Using this principle, efforts are made to improve the time efficiency and accuracy of the filtering result. The procedure of the data process is illustrated in Figure 1.

When circle function is estimated for the given section point clouds, the residual of every point data is

```

while N(i)-N(i-1)> N(i-1) *1 %
    i=i+1;
    do circle fitting;
    for j=1:length(point data)
        if residual(j)> i*SDO then
            | delete the point p(j);
        else if residual(j)<= i*SDO then
            | keep the point;
        end
    end
    calculate N(i);
end

```

Figure 1. Procedure of data processing.

obtained and the standard deviation SD_0 is calculated. It is considered that the tunnel points have a continuous and progressive residual around SD_0 . If the residual threshold is increasing for the tunnel points, a larger population of correct points will be kept. And if the residual threshold keeps growing, the extreme situation is that the disturbing points will be contained in the tunnel point collection. Due to this reason, iteration method is proposed based on the standard deviation value, with an even incremental, which is the value of SD_0 in this article.

The iteration index i is from 1 to $imax$. SD_0 is the standard deviation of original data points to the original circle. During each iteration, the points are filtered by threshold $i*SD_0$. After iterative filtering, it is checked whether the point population in the $(i + 1)$ th iteration is homologous with that in the i th iteration. The homologous criterion is deviation under 1%, because the iteration threshold is not continuous and thus stricter criteria could not be reached. However, the criteria in this article fulfill the practical application, because result shows the disturbing points are absolutely segmented and the remained points described all the detailed shape of the tunnel. If the algorithm determines the homologous criteria as not, the iteration goes further, and if yes, the iteration terminates to output the i th iteration filtering result. The index $imax$ is where the standard deviation of i th iteration filtered points does not change from the $(i + 1)$ th iteration with a tolerance of 1%.

Data analysis

It is extremely critical to filter and analyze point cloud data, keeping the high accuracy and efficiency of TLS technology to be adopted for health monitoring of tunnel structures. In this article, we focus on the study of data filtering with the “Circular Likelihood” method.

Data of section projection

The section data are tested with the method to investigate the applicability of the circular approximation. The section profile of point cloud data is presented in Figure 2, where the point cloud is projected in a plane. The total number is 40,487 for the point cloud data. It is observed in Figures 2 and 3 that the data contain disturbing points in the upper and lower middle part and at the bottom. The goal is to discard these parts with effective filtering.

The standard deviation is 0.237 m between the point cloud and a fitted circular, and the circular is with a radius of 2.553 m by the method mentioned in the article. By filtering, the standard deviation will be decreased and influenced mostly by the tunnel shape but not the disturbing points.



Figure 2. Section profile of point cloud data.

Circular filtering

The disturbing points in the tunnel form a large population and occupy 10%–20% of the whole points population. The accuracy of the geometric model is significantly influenced by the disturbing points and, thus, they should be filtered. The influence of the disturbing points in the tunnel is illustrated in Figure 3. The outliers are marked in orange in Figure 3, and they pull the geometric curve away from the tunnel shape, obviously in the area A and B. The removal of the disturbing points results in the geometric curve approaching the main shape of the tunnel, which is the case shown in areas C and D.

“Circular Likelihood” method is applied for the tunnel section data. The ideal iteration is 9, where 35,896 points are kept. The radius of the corresponding best-fit circle is 2.6475 m, with a standard deviation of 0.1058 m. The deviation is caused by the projections and depressions of the tunnel shape.

Result

The “Circular Likelihood” method is adopted as in section “Circular filtering.” Iteration computation is carried out and the filtering results of iteration compared with the raw data are drawn. Iterations 5, 6, 9, and 11 are selected and presented in Figure 4.

It is observed in Figure 4 that as the iteration index increases, different filtering effects occur. The left and right bottom of the point cloud is over-filtered in iteration 5 as shown in Figure 4(a), and as the iteration increases, the over-filtering is improved as in Figure 4(b). This improvement continues until iteration 9, which is shown in Figure 4(c) with clear shape of the tunnel. Over this best point, the data points are under-filtered keeping a part of the disturbing points, shown in Figure 4(d).

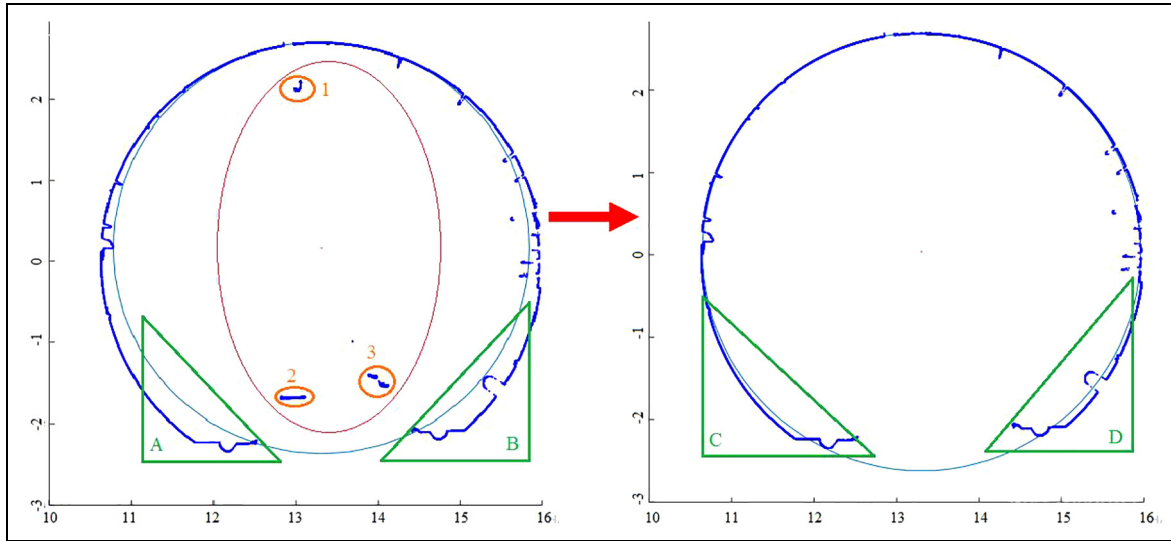


Figure 3. Influence of the disturbing points in the tunnel.

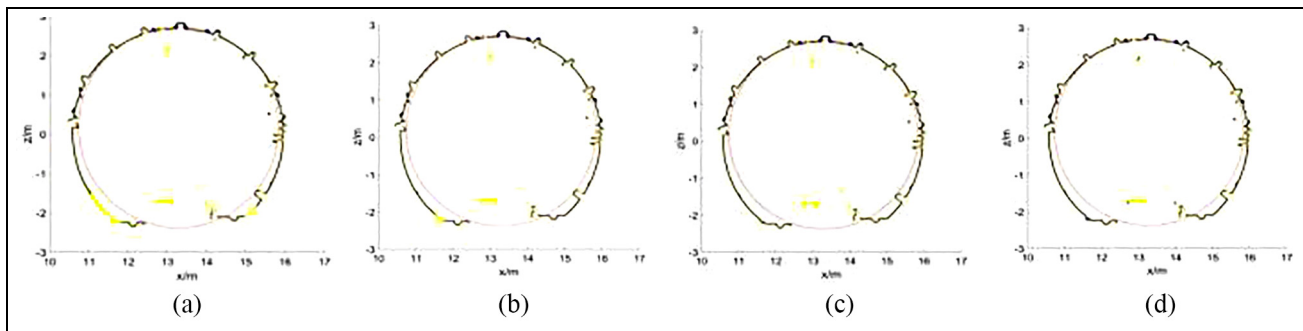


Figure 4. Circular filtering with different iterations: (a) Filtering in iteration 5; (b) Filtering in iteration 6; (c) Filtering in iteration 9; (d) Filtering in iteration 11.

Table 1. Iteration and parameters of filtered points.

Iteration times	Filtered points		
	Population	SD (m)	Radius (m)
1	14,241	0.0240	2.5562
2	20,176	0.0377	2.5712
3	23,444	0.0525	2.5833
4	25,928	0.0624	2.6067
5	29,845	0.0806	2.6227
6	32,304	0.0842	2.6397
7	35,242	0.1013	2.6465
8	35,812	0.1056	2.6468
9	35,896	0.1058	2.6475
10	36,180	0.1160	2.6422
11	36,263	0.1189	2.6408

Table 1 lists the detailed information of the iteration and filtered points: population of the filtered points, standard deviation (SD), and radius of fitted circle. From Table 1, it is observed that iteration 9 is the maximum

value of the iteration. The population and standard deviation of iteration 9 first reach incremental criteria. Radius of fitted circle of iteration 9 is the largest among the iterations which is marked with bold in Table 1. Before

iteration 9, the fitted circle is closer to the original circular contributed by the outliers; therefore, the radius is smaller than the real shape of the tunnel. After iteration 9, disturbing points are contained in the filtering result, influencing the circle fitting from centripetal direction of the tunnel, as a result, the radius becomes smaller.

According to Table 1, there is the best iteration when the filtered population and SD are not significantly changed, and the radius of fitted circle shows an extreme value. It is hinted that iterations less than 9 are corresponding to over-filtering phenomenon, and more than 9 are under-filtering phenomenon. Because the noises are inside the real tunnel profile, the maximum radius is the best filtering. The iteration times are much fewer compared with the other methods. For example, optimal solution for RANSAC algorithm usually requires more than 10 times of iteration, sometimes even several hundred times. For the large data set like long-distance tunnel, the circular Likelihood method saves much time cost. Furthermore, the proposed method is advantageous to filter disturbing points with large population, which is arduous for B-spline method to approximate. Last but not the least, this method manages to keep the important details of the tunnel shape such as projections and depressions.

Conclusion and outlook

In this study, a new method named “Circular Likelihood” is proposed and investigated. Taking advantage of the symmetry and the circular shape of the tunnel structure, most of the disturbing points could be removed and many inefficient iterations are avoided, so that the computing time is greatly shortened which provided a time-efficient model to solve one of the key issues for large amounts of TLS data processing. The method is effective and advantageous to filter disturbing points with large population and manage to keep important details of the tunnel shape.

Moreover, it could be automatic to optimize the circular filtering by the iteration and parameters of filtered points which could improve the accuracy for point cloud data. It is necessary and indispensable to ensure advantages of TLS measurement.

Declaration of conflicting interests


The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: The publication of this article was funded by the Open Access fund of Leibniz Universität Hannover. The authors

would like to acknowledge the support of Natural Science Foundation of Jiangsu Province (No: BK20160558). The authors also wish to acknowledge the support of all the colleagues in Geodetic Institute of Leibniz University Hanover for their valid information and help.

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