Research on convergence analysis method of metro tunnel section--Based on mobile 3D laser scanning technology

ZHANG Hongfei\textsuperscript{1,a}, XIA Jinzhou\textsuperscript{1,b}

\textsuperscript{1}Shanghai Municipal Engineering Design Institute (Group) CO., LTD. Shanghai China
\textsuperscript{a}email: zhanghongfei@smedi.com, \textsuperscript{b}email: xiajinzhou@smedi.com

Abstract: The protection and monitoring of subway tunnels have always been an important guarantee for the safe operation of urban rail transit. The current monitoring of tunnel deformation and convergence relies on traditional technology methods such as convergence meters and electronic total stations. Although the 3D laser scanning method of stationary station setup and station-to-station splicing of monitoring station is gradually becoming mature, the error accumulation and slow operation efficiency brought by station-to-station splicing are still the bottleneck of subway tunnel protection and monitoring. Based on the analysis of the principles and advantages of mobile 3D laser scanning technology, this paper deeply studies the mobile 3D laser scanning technology for rapid collection of point cloud data in subway tunnels, proposes an improved RANSAC algorithm based on the tunnel ellipse parameter model, and extracts metro tunnel deformation information through denoising and fitting of the tunnel cross section point cloud data, achieving convergence analysis of metro tunnel section. The results show that this method can quickly and accurately obtain tunnel section data, which provides a new and efficient technical approach for subway tunnel protection monitoring.

1. Introduction

In recent years, during the construction and operation of urban subways, urban subway safety accidents such as pavement a, foundation pit collapse, and tunnel seepage often occur. The reason is that the subway tunnel structure is deformed. Therefore, the monitoring of the tunnel deformation of the subway has aroused the high attention of the competent authorities and industry experts at all levels\textsuperscript{[1,2]}. The commonly used method of subway tunnel protection monitoring is to use a convergence meter, a total station and other measuring instruments. This method has low operating efficiency and is easily affected by human error and the environment. With the cross-development of laser electronic technology and surveying and mapping technology, static station 3D laser scanning technology has gradually matured and been successfully applied to subway tunnel protection monitoring. However, this method requires the splicing of station data station by station, which inevitably causes error accumulation\textsuperscript{[3-5]}. In view of the need for high-precision deformation data support for the protection and monitoring of subway tunnels, the drawbacks of the static station 3D laser scanning technology have gradually emerged during the application process. Based on coordinating traditional methods and emerging technologies, we consider the mobile 3D laser scanning technology that combines the rail car and 3D laser scanner \textsuperscript{[6,7]}. This mobile scanning method can quickly and efficiently collect a large amount of point cloud data, and obtain the spatial information of the object, so as to make up for the shortcomings of traditional monitoring methods, and does not require the splicing of station data, thereby effectively avoiding the accumulation of splicing errors.
In this paper, a mobile 3D laser scanner is used to quickly collect point cloud data of subway tunnels, and the improved RANSAC algorithm based on the tunnel ellipse parameter model is used to denoise and fit the point cloud data of the tunnel section, so as to analyze the section of the subway tunnel. The measured results proved that this method is a fast and efficient method for obtaining convergent deformation data of subway tunnels.

2. Mobile 3D laser scanning technology

Mobile 3D laser scanning technology is similar to stationary 3D laser scanning technology, which is a combination technology that combines static station 3D laser scanning technology with track car, and carries multiple sensor devices such as laser odometer, high-precision inertial navigation and GNSS system, so as to realize the collaborative work of multiple systems[8].

2.1. Basic principles of 3D laser scanning

The main body of the 3D laser scanning technology is the 3D laser scanner, and the basic working principle is the principle of laser ranging[9]. In actual work, the high-speed rotating motor drives the scanning head and emits the laser. The laser is reflected by the surface of the object and received by the laser receiver. From the reflection process, the horizontal angle α, vertical angle β, laser propagation time t, signal intensity and other parameters data are obtained. The distance S relative to the target object can be obtained from the laser propagation time t, and combined with the position information of the scanner itself, we can obtain the 3D coordinate information and reflection intensity information of the target object surface through inversion. As shown in Figure 1.

![Figure 1 Principle of 3D laser scanning](image)

According to the working principle of the above-mentioned 3D laser scanner, the calculation formula of the target object coordinates (X, Y, Z) is as follows:

\[
X = S \cos \alpha \cos \beta Y = S \sin \alpha \cos \beta Z = S \sin \beta
\]

2.2. Principle of mobile 3D laser scanning data collection

Based on the principle of laser ranging, the mobile 3D laser scanning technology acquires point cloud data on the surface of the target object while recording data from various sensor systems. Particularly, in subway tunnels, the mobile 3D laser scanning data acquisition method is significantly different from the static station 3D laser scanning data acquisition method.

The mobile 3D laser scanning technology uses the track trolley to move on the rails, which can continuously obtain the point cloud data of the tunnel wall, while the stationary 3D laser scanning method uses fixed-point scanning, and the data of adjacent stations are spliced station by station through a common area. The former rotates and fixes the scanner in the horizontal direction, so that the laser transmitter rotates in the vertical plane, combined with the track car moving forward, the obtained point cloud data presents a spiral curve, as shown in Figure 2; the latter data is collected in the 360-degree panoramic scanning mode, that is, the horizontal rotation and the vertical rotation are...
turned on at the same time, the point cloud data obtained is centered on the measuring station. The farther away from the measuring station, the sparser the data. Therefore, the static station scanning of the latter can only obtain the complete data of a subway tunnel through station-to-station splicing, which inevitably leads to the accumulation of splicing errors.

Figure 2 Schematic diagram of mobile 3D laser scanning data acquisition

3. Research on convergence deformation monitoring method of metro tunnel section

Based on the above-mentioned mobile 3D laser scanning technology, the point cloud data of the subway tunnel wall can be obtained quickly, accurately and completely, combined with the point cloud data preprocessing and post-processing technology, the section of the tunnel section is generated, and the section convergence deformation information is further analyzed through statistical analysis. Based on the results of deformation analysis, corresponding protection and repair measures can be made immediately to realize the protection and monitoring of subway tunnels.

3.1. Data preprocessing

3.1.1. Point cloud data denoising

Point cloud data denoising, also known as point cloud filtering, is used to remove redundant, useless, and non-researched data. The commonly used method is to manually remove the data by manual selection. This method is not only incomplete, but also drops valid data by mistake. Based on the analysis of autonomous filtering methods such as distance filtering, statistical filtering, and mean filtering, this paper combines the general RANSAC algorithm to propose an improved RANSAC method based on the tunnel ellipse parameter model.

The algorithm theory is as follows:

(1) Model initialization. The collected tunnel point cloud data is named point set \( N \) (including \( n \) points). Point set \( N \) has both valid data and noise data. Randomly select \( m \) (\( m<n \)) point cloud data from point set \( N \) Form the subset \( M \) of the point set \( N \). Considering that the subway shield tunnel is mainly an elliptical section tunnel, suppose the equation of the subway tunnel section is \( Ax^2+Bxy+Cy^2+Dx+Ey+F=0 \). There are 6 unknown parameters in the equation, so when selecting the subset \( M \), in order to enable the initial model to describe the point set \( N \) appropriately and reduce the number of iterations of the algorithm, at least 6 points on the tunnel section are randomly selected to solve the ellipse equation to fit a tunnel section ellipse and obtain the initialization model \( Z \).

(2) The model is refined. Set the distance from the point to the ellipse equation as the threshold \( t \) to perform RANSAC algorithm filtering. The algorithm substitutes the data in the point set \( NM \) (remainder) into the initial model \( Z \) in turn, removes the data that does not meet the threshold \( t \), and adds other data to the point set \( M \) to form a new point set \( M^* \), and recalculates the ellipse parameter equation using the point set \( M^* \), and the refined model \( Z \) is \( Z^* \).
(3) Model confirmation. Repeat the above steps to traverse the point set \( N \) until it is impossible to add new data to make the error of the model \( Z^* \) smaller, then it is considered that a correct ellipse parameter model \( Z^* \) has been found, which can well describe all the valid data in the point set \( N \). In this case, the data in the point set \( M^* \) is the valid data, and the data in the complement \( N-M^* \) is the noise data. Through the above method, all point cloud data found on the tunnel section are finally extracted to eliminate noise.

3.1.2. Target fitting
The targets used in the 3D scanning of subway tunnels are mainly spherical targets. Target fitting means finding the center of the target, which is a key step in the preprocessing of 3D laser scanning point cloud data. In this paper, the difference between the distance from the edge of the spherical target to the center of the target and the radius of the spherical target is used as a variable. According to the principle of least squares, the square sum of the difference is calculated to fit the coordinates of the center of the target.

Assuming that the coordinates of the center point of the spherical target are \( P_0 (x_0, y_0, z_0) \), the sphere equation is:

\[
(x-x_0)^2 + (y-y_0)^2 + (z-z_0)^2 = R^2 \quad (2)
\]

Point \( P (x, y, z) \) is the edge point coordinates of the spherical target obtained by scanning, and the variables are replaced by:

\[
\begin{align*}
  x_0 &= \frac{a}{2} \\
  y_0 &= \frac{b}{2} \\
  z_0 &= \frac{c}{2} \\
  x_0^2 + y_0^2 + z_0^2 - R^2 &= d
\end{align*}
\]

After variable substitution, the spherical target sphere equation can be expressed as a matrix:

\[
[xyz]^T[abcd]^T = -\left[x^2 + y^2 + z^2\right]_{x+y+z=0} \quad (4)
\]

Through least squares adjustment, we can obtain:

\[
[abcd]^T = -[xyz]^T[xyz]^T = [xyz]^T[xyz]^T \left[x^2 + y^2 + z^2\right]_{x+y+z=0} \quad (5)
\]

The four parameters \( a, b, c, \) and \( d \) are calculated from formula (3-4), and then we can obtain the coordinates of the center point \( P_0 \) of the spherical target as:

\[
\begin{align*}
  x_0 &= \frac{a}{2} \\
  y_0 &= \frac{b}{2} \\
  z_0 &= \frac{c}{2}
\end{align*}
\]

3.2. Data post-processing
The post-processing of mobile 3D scanning point cloud data includes track trolley mileage correction, tunnel structure centerline extraction and tunnel section extraction.

3.2.1. Mileage correction
Since the odometer in the mobile 3D laser scanning system is connected to the wheels of the rail car,
the actual mileage measured by the odometer is the mileage of the rail car along the subway track (left or right rail), not the actual mileage of the car. The actual mileage should be the mileage of the trolley along the center line of the track, so the trolley mileage must be corrected. Specifically, it includes the mileage correction of the easement curve section and the circular curve section.

3.2.2. Tunnel structure centerline extraction

The centerline of the tunnel structure can be extracted by the quadratic curve fitting method based on the median \[10\]. The centerline of the tunnel structure extracted based on this method has a certain deviation from the centerline of the actual tunnel structure, but this does not affect the extraction of the tunnel section.

We can select a piece of scanned data arbitrarily and project it on the XOY plane and the YOZ plane, assuming that the Y-axis direction is consistent with the forward direction of the tunnel centerline, then calculate the median value of the X and Z directions corresponding to the point \(y_i\) (i=1, 2, ...,n) with a certain step length \(\Delta y\) according to formula (7).

\[
x_i = \frac{x_i(\text{max})+x_i(\text{min})}{2}
\]

\[
z_i = \frac{z_i(\text{max})+z_i(\text{min})}{2}
\]

In the interval of \(y_i\) (i=1,2,...n), \(x_i\) and \(z_i\) are respectively fitted with quadratic curves to obtain the centerline of the tunnel structure.

3.2.3. Tunnel section extraction

According to the extracted centerline of the tunnel structure, assuming that the point \(M (x, y, z)\) is any point on it, the point \(M\) and the points in its neighborhood constitute the curve \(S\), we can find the tangent vector of the point \(M\) on the curve \(S\), and use this tangent vector as the normal vector for extracting the cross section, which can extract the cross section of the tunnel point cloud.

3.3. Result output

According to the requirements of metro tunnel convergent deformation measurement, we intercept the 3D model section of the tunnel, compare it with the theoretical value of the designed section, calculate the deformation of one week between the intercepted section and the designed section, and then the deformations of characteristic points (such as the equiangular position [every 5°]) were obtained.

4. Case Study

4.1. Data collection

The test object is the K10+300-K11+575 section of the down line of Guangji South Road Station-Yangyu Lane Station of Suzhou Metro Line 1, with a length of about 1.2km. According to the length of the survey area and site conditions, we selected the position of the control point and deploy the target. The selection of the control point is based on the main principle of facilitating the deployment of the target and not affecting the operation of the rail car. We selected a control point every 50-60m and assessed it accurately to provide data for subsequent target fitting. Figure 3 is a schematic diagram of the control point selection and target placement scheme. After the control point selection, measurement, and target installation are completed, the rail car equipped with 3D laser scanning equipment and various sensor equipment are debugged to collect tunnel point cloud data.
4.2. Data processing
The point cloud data obtained by the scanning system is pre-processed and post-processed respectively using the SiSynchro software and the supporting LsTunnel software that comes with the system. This experiment chooses to start at K10+464m mileage and end at K10+860m mileage. A tunnel cross section is intercepted every 12m, with a point cloud thickness of 0.02m, and a total of 34 tunnel cross sections are intercepted, as shown in Figure 4.

4.3. Analysis of Convergence of Metro Tunnel Section
Convergence analysis of subway tunnel section is performed on the above processed tunnel point cloud data. Since only one period of tunnel point cloud data was collected in this actual measurement, it is impossible to conduct multi-phase data comparative analysis. Therefore, by importing the design centerline, design section and other files, and comparing with the point cloud data of this scan, the section convergence analysis is performed. The 34 tunnel cross-sections extracted above were compared and analyzed with the tunnel design cross-section imported into LsTunnel software, and 34 sets of tunnel cross-section deformation convergence analysis diagrams were obtained as shown in Figure 6.
Figure 5 Design section of subway tunnel

Figure 6 Comparison of actual and designed sections
Figure 5 shows the design section of the subway tunnel. Figure 6 shows the convergent deformation of the tunnel cross section and the design section at mileage K10+608m (the data on the circumference is the difference between the actual tunnel section and the design section in the radial direction). The data on the circumference of the section, the red part is a negative value, which means that the tunnel cross section is subjected to some external pressure, resulting in deformation into the tunnel; the green part is a positive value, indicating that the transverse section of the tunnel is subjected to external force here, which causes deformation outside the tunnel. From the deformation data on the circumference, the overall deformation value of the cross section is about 5mm, the local deformation exceeds 5mm, and the maximum deformation exceeds 2cm at the bottom of the circumference. According to the actual situation of the tunnel section, this is the place that the rails should be laid.

4.4 Accuracy evaluation
In this experiment, a total of 27 control points was selected to set up the targets. According to the actual measured control point coordinates, the additive constant was converted into the target center point coordinates and compared with the target center point coordinates obtained by fitting to evaluate the reliability of the data in this experiment.

| No. | △X/m | △Y/m | △H/m |
|-----|-------|-------|-------|
| 2   | 0.0003| 0.0006| -0.0011|
| 1   | -0.0002| 0.0003| -0.0014|
| L1  | -0.0002| 0.0005| -0.0012|
| L2  | -0.0003| -0.0004| -0.0015|
| L3  | -0.0007| -0.0002| 0.0023|
| L4  | -0.001| -0.0008| -0.0012|
| L6  | -0.0008| -0.0002| -0.0014|
| L7  | -0.0008| 0.0005| 0.0022|
| L8  | -0.0004| -0.0003| -0.0015|
| 3   | 0.0005| 0.0007| -0.0016|
| L10 | 0.001| 0.0004| -0.0015|
| L11 | 0.001| -0.0013| -0.0012|
| L12 | -0.0002| 0.0014| -0.0013|
| 4   | -0.0006| -0.0003| -0.0022|
| L13 | 0.0008| -0.0004| 0.0016|
| L14 | 0.0012| -0.0004| -0.0009|
| L15 | 0.0009| -0.0011| -0.0006|
| 5   | -0.0002| 0.001| -0.0016|
| L17 | 0.0013| -0.001| -0.0004|
| L18 | -0.002| -0.0019| -0.0016|
| L19 | -0.0005| 0.0014| -0.0023|
| 6   | 0.0006| -0.0019| -0.0011|
| L20 | 0.0014| -0.0013| -0.0017|
| L21 | -0.0017| -0.0008| -0.0012|
| L22 | -0.0013| -0.0022| -0.0007|
| L23 | -0.0018| -0.0013| -0.0019|
| L24 | 0.0013| 0.0025| -0.00013|

According to the calculation of the list, the error of the control point of the target ball is
\[ m = \pm \sqrt{m_x^2 + m_y^2 + m_z^2} = \pm 2.1 \text{ mm}. \]

Combined with the “Urban Rail Transit Engineering Monitoring Technical Specification”, the error of the control point is \( \pm 2.1 \text{ mm} \) and less than 6mm, so the data and results obtained in this experiment satisfy the accuracy requirements.

5. Conclusion
Urban subway rail transit has gradually developed into the most important mode of transportation in modern cities, and the operation and maintenance of subway tunnels has become increasingly important. Traditional monitoring methods can no longer complete the deformation monitoring of subway tunnels within a short skylight time. This article uses mobile 3D laser scanning technology with the improved RANSAC algorithm to obtain tunnel section data quickly, accurately, and fully, verifying that the data processing results are consistent with the tunnel. The general law of convergence deformation provides a new technical means for subway tunnel deformation monitoring.

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