Application Research on Tunnel Convergence Deformation Monitoring Based on Mobile 3D Scanning Technology

Zhi WANG and Yabo ZHAO, China

Key words: 3D Laser Scanning, metro tunnel, convergent deformation, deformation monitoring

SUMMARY

Convergent deformation is one of the main diseases of subway tunnel, which is usually caused by the change of stress load around the tunnel, such as the influence of surrounding foundation pit construction, and the occurrence of convergent deformation will also cause tunnel cracks, seepage and other diseases. The traditional method of convergent deformation measurement is mainly to measure the change of the distance between the two reflectors by sticking the reflector on both sides of the tunnel and measuring the change of the distance between the two reflectors by total station. Because of the short window period at night, the efficiency of the method is low, and the results are difficult to express automatically. In this paper, a tunnel mobile scanning system based on track forward is designed. The hardware is mainly composed of rail mobile car and carrying 3D laser scanner. It detects the tunnel convergence deformation, generates the positive projective image by quickly obtaining the tunnel 3D point cloud, and matches the segment, and calculates the convergence deformation according to the 3D point cloud information of each ring. Taking Qingdao metro as an example, this paper introduces the application of mobile scanning technology in the convergence deformation detection of subway tunnel, which provides some reference significance for the popularization and application of this technology in tunnel monitoring.

SUMMARY

收敛变形是地铁隧道的主要病害之一，通常是由于隧道周边应力荷载发生变化导致，如周边基坑施工等影响，收敛变形的发生也会引起隧道裂缝、渗水等其它病害。传统收敛变形测量的手段主要是通过在隧道两侧粘贴反射片，通过全站仪测量两个反射片间距的变化，由于受夜间窗口期短的影响，该方法效率低，成果难以自动化表现。本文设计一种基于轨道前进的隧道移动扫描系统，硬件主要由轨道移动小车和搭载的三维激光扫描仪组成，研究该隧道移动扫描系统对隧道收敛变形进行检测，通过快速获取隧道三维点云生成正射影像，并基于正射影像进行管片的划分及里程的匹配，进而根据每一环的三维点云信息计算收敛变形情况。以青岛市地铁为例，介绍了移动扫描技术在地铁隧道收敛变形检测的应用情况，为该技术在隧道监测的推广应用提供了一定的借鉴意义。

1.FOREWORD

Tunnel convergent deformation refers to the deformation of the tunnel under the action of uneven external force, which causes the deviation of the tunnel spatial morphology contour from the design[1]. The reason for the change of the load around the tunnel is usually caused by the construction works in the protection area near the subway line[2], such as the foundation pit excavation, or the long-term uneven spatial change of the stratum load exceeds the expected value[3]. Tunnel convergence deformation harm is great, will lead to the emergence of some other diseases, such as cracks, water seepage, etc.[4], for shield segment tunnel, will also cause segment dislocation[5]. All of these will have hidden safety risks to the structure of the subway tunnel, thus affecting the safe operation of the subway.

Convergent deformation measurement is mainly made by measuring the size of two specified positions in the tunnel space and reflecting the convergent deformation by the change of the size of the same position in different periods[6].The traditional detection method is to place two reflective sheets on both sides of the tunnel wall at the specified mileage along the direction of the tunnel. After the subway is out of service at night, a total station is used to use the tunnel control points to perform rear intersection and set up stations, and then the two reflective sheets are actually measured[7].Due to the short window period of night operation, the detection efficiency of this method is low, and the results are difficult to automatically display[8].The emergence of mobile 3D laser scanning technology has greatly changed many disadvantages of traditional methods.The mobile 3D scanning system can collect 3D point cloud information of the tunnel space while traveling rapidly in the tunnel with the help of rails.By processing and analyzing the acquired point cloud, a comprehensive and accurate spatial deformation of the tunnel can be obtained[9].This article analyzes and introduces the application of mobile three-dimensional scanning in the convergence deformation of shield tunnels, and provides certain reference significance for the promotion and application of this technology in other tunnels.

2.MOBILE SCANNING VEHICLE DESIGN

The tunnel mobile scanning system mainly consists of a rail car, a 3D laser scanner, a software control system, and related accessories. The rail car integrates various sensors such as odometer and track gauge measuring instrument. Its main function is to use the track to allow the car to move along the direction of the tunnel. The scanner is connected to the rail car through a bracket. After the connection, the instrument is braked in the horizontal direction. When working, the scanner lens can only rotate on the plumb plane perpendicular to the center line of the tunnel. The scanner performs three-dimensional scanning while the rail car is traveling, and collects three-dimensional point cloud data in the tunnel space. The specific module composition is shown in Figure 1.

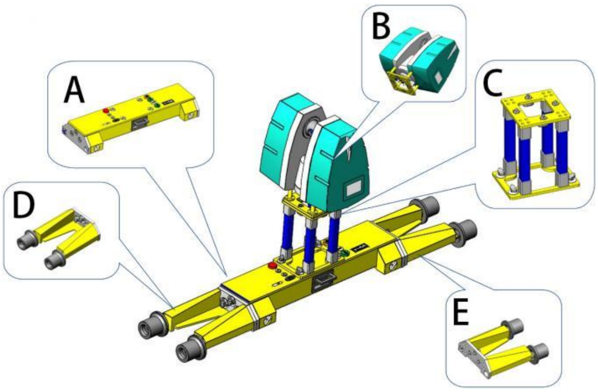

Fig.1 Schematic diagram of rail car hardware composition

A in Figure 1 is the console module, which is used to control the start, travel, parking, light switch, etc. of the car, as well as forced stop in emergency situations. B in the picture is the scanner module, which can currently be equipped with scanners from Leica, Faro, Z+F and other brands. C in the picture is the connection module, used to connect the scanner and the rail car together. D and E in the picture are wheel modules. The overall design of the rail car hardware adopts a detachable modular design, which makes it easier for operators to transport the rail car to the subway tunnel.

The tunnel mobile scanning system is uniformly controlled by control software installed in an industrial laptop. The scanner is controlled by the computer by connecting to the Wifi network that comes with the scanner. The connection between the computer and the rail car is achieved through Bluetooth. The forward or backward movement of the track car on the track is automatically driven by the motor in the car, without the need for manual pushing. The car's automatic driving speed is designed into 5 gears, with the lowest speed being 0.9km/s and the highest speed being 4.5km/h. Different driving speeds can obtain tunnel point cloud data of different qualities to meet different engineering needs.

After the hardware system is integrated, the system time synchronization is required. The system unifies the time of multiple sensors through computer system time, that is, interpolates odometry and displacement sensors based on the number of point cloud sections received by the computer per unit time, thereby achieving time synchronization of the scanned point cloud, mileage, and track gauge.

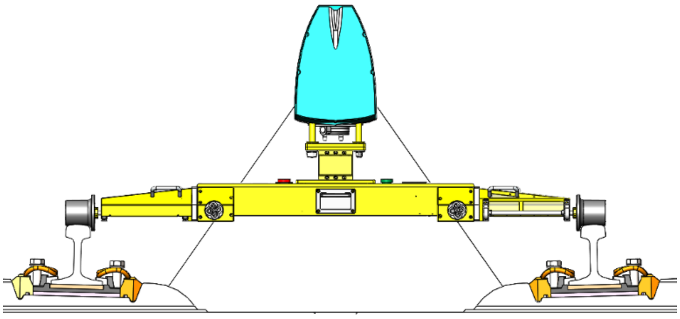

Fig.2 Front view of the rail car in operation

The laser scanner uses the center of its scanning lens as its origin, with the x-axis to the right, the y-axis forward, and the z-axis upward to define the coordinate system. When working, the scanner uses a two-dimensional spiral mode to scan to obtain the original data of the scanner in the x- and z-axis directions. The correction values of the left and right incremental photoelectric axis angle encoder data provide the y-axis data, thereby rendering raw scanner data as a point cloud in 3D space. The front view of the rail car when it is running is shown in Figure 2.

3. POINT CLOUD COLLECTION AND PREPROCESSING

3.1 Point Cloud Collection

When the subway is shut down at night, the mobile tunnel scanning car is transported to the designated tunnel section, assembled as required and the equipment status is checked. The inspection mainly includes whether the connection between the various modules of the rail car is correct, the wireless connection between the computer and the scanner, and whether the Bluetooth connection between the computer and the rail car is normal. After the inspection is completed, the parameters for the car's operation need to be set, such as the car's driving speed, the point cloud collection frequency of the scanner, etc. Figure 3 is an on-site photo taken during connection inspection after the rail car is assembled.

Fig.3 Status inspection and parameter setting of rail car after assembly

After parameter setting is completed, perform system initialization settings. First, use the control software on the computer to let the scanner rotate and start scanning. After the rotation speed stabilizes, start the car and drive forward. The operation flow chart of the tunnel mobile scanning car is shown in Figure 4.

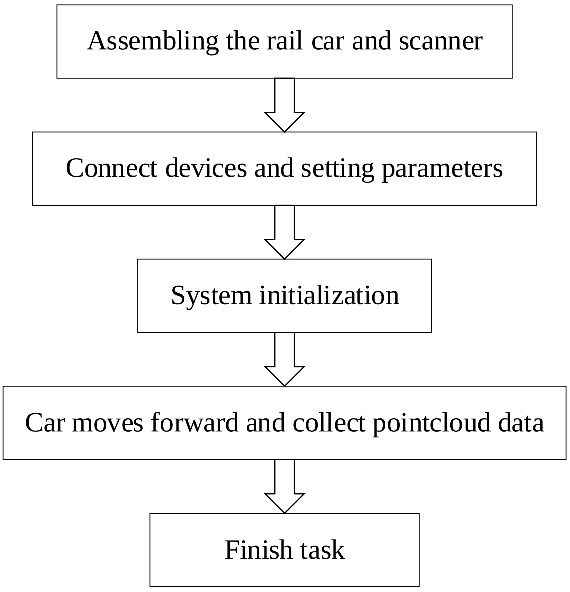

Fig.4 Tunnel mobile scanning system operation flow chart

Convergence is the relative change in the spatial distance between two designated positions in the tunnel. For shield segment tunnels, it is mainly the change in diameter, so the convergence results do not involve absolute coordinates[10].There is no need to jointly test known control points during on-site operations, which greatly saves field operation time.Compared with the stationary 3D laser scanner, the tunnel mobile 3D laser scanner does not need to set up a target in the tunnel for subsequent point cloud splicing. It is more efficient and the tunnel 3D point cloud information acquired is more uniform and complete[11].

In a given environment, the quality of the point cloud obtained by the mobile scanning system is related to the traveling speed of the car and the scanning frequency of the scanner. The slower the car travels and the higher the collection frequency, the denser the point cloud obtained, and the higher the quality of the subsequent processing results. The distance between two adjacent rotations of the scanning lens is:

$$d = \frac{v}{f} \qquad (1)$$

In the above formula, v is the traveling speed of the car, in m/s, and f is the collection frequency of the scanner, in Hz. Taking the Leica P40 3D laser scanner as an example, its default acquisition frequency is 50Hz. If the car travels at a speed of 0.5 meters per second, the tunnel space point cloud of 0.5 meters in the tunnel mileage direction is composed of a spiral space curve formed by the scanner lens rotating 50 times.

3.2 Data Preprocessing

Data preprocessing mainly includes inspection of original collected data, denoising of point cloud data and hole filling processing. The inspection of original collected data is mainly to check and judge the integrity and quality of the obtained three-dimensional point cloud. As shown in Figure 5, it is a 3D point cloud model obtained by moving 3D scanning in a certain subway section. Browse the point cloud model to check whether it covers the on-site collection area and whether the segment boundaries are clearly visible.

Point cloud denoising refers to the process of removing obstacles in the working environment during on-site scanning and spatial objects that are not required for subsequent processing and analysis, such as moving people, work equipment, etc.

There are generally two methods of traditional denoising methods. One is overall denoising, which uses the tunnel spatial contour as a benchmark and sets a threshold value, such as 15cm, to remove all spatial objects that are more than 15cm away from the tunnel wall. This method is simple and efficient. Another method is to select the noise data one by one by establishing a spatial selection box and delete the point cloud data in the selection box. This method requires careful inspection of the point cloud and is more time-consuming[12]. However, both methods cannot remove discrete noise points close to the tunnel wall.

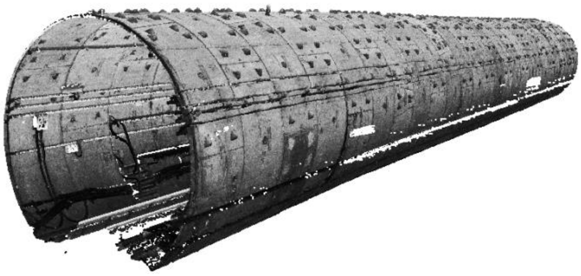

Fig.5 Tunnel mobile scanning 3D point cloud model

This paper proposes an iterative circular fitting denoising method to remove noise near the tunnel wall. First, an initial circular fitting is performed on the tunnel section containing noise, and the initial parameters of the circle are calculated, including the coefficients of the circular equation, circle center coordinates, radius and other parameters.Then calculate the shortest distance d_i from the cross-section point to the circle on a certain mileage, and then form a distance point set $d\left\{d_1, d_2, \cdots, d_n\right\}$, and calculate the mean value d_{mean} and standard deviation σ of the point set d according to equations (2) and (3).

$$d_{mean} = \frac{\sum d}{n} \qquad (2)$$

$$\sigma = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(d_i - d_{mean})^2} \qquad (3)$$

It is stipulated that the section points are noise at $\left|d_i - d_{mean}\right| > 2\sigma$. After continuous iteration, the noise points around the tunnel wall can finally be removed.

Point cloud hole patching mainly refers to the process of patching point cloud data that has not been scanned due to obstruction by obstacles on site through fitting in post-processing software. If the missing area of the point cloud is small, the fitted data is more consistent with the actual situation and has no impact on subsequent analysis and calculation results. If the missing area of the point cloud is large, there is no guarantee that the fitted data is consistent with the actual situation.

4. CONVERGENCE DEFORMATION ANALYSIS

4.1 Segment segmentation and mileage matching

The tunnel studied in this article is a shield staggered joint tunnel. The blocks that constitute the segment ring include three types: standard block (B), adjacent block (L) and capping block

(KP). Ring segmentation and mileage matching of segments are prerequisites for subsequent calculation of segment convergence, which is usually done in orthophotos. The orthoimage is generated based on the point cloud using the inverse distance weighted method. First, construct a k-d tree (short for k-dimensional tree) on the point cloud data, which can speed up the calculation. The difference range of the point cloud is the circumscribed rectangle parallel to the x and y axes of the point cloud coordinate system, and the difference radius is set to 0.02m to fill the hole pixels. If the difference radius is too small, the image will produce black hole pixels. If the difference radius is too large, the amount of calculation will increase. Generally, this value is set to the interval size of the points[13].

According to the above method, the generated image is subjected to edge detection based on the canny operator and straight line detection based on the Hough transform, and the detected straight line is extended to identify the capping block, thereby facilitating subsequent mileage marking. Expand the generated image along the center line of the bottom track, and the expansion effect is shown in Figure 6. The image from left to right shows the tunnel's direction of travel toward the long mileage. The middle part of the image is the top of the tunnel, the upper part is the right side of the tunnel along the long mileage direction, and the lower part is the left side of the tunnel along the long mileage direction. The clarity of the image depends on the traveling speed of the car during field collection and the collection frequency of the scanner.

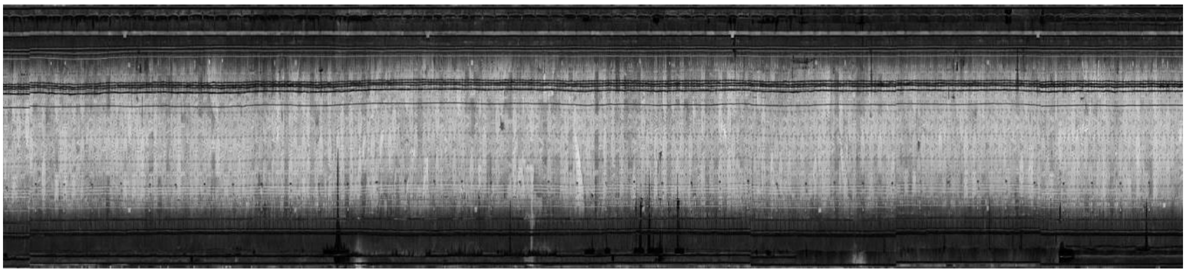

Fig.6 Orthophoto of a certain subway section

On the generated orthophoto, segmentation and mileage markings are made on each segment starting from the first segment. The marking content includes the position, ring number and mileage of each ring segment. Only one segment needs to be marked uniformly on each ring. In order to facilitate program calculation, the lower left corner of the KP block of each ring is marked to distinguish the starting mileage position of each segment. The schematic diagram of segment image marking is shown in Figure 7.

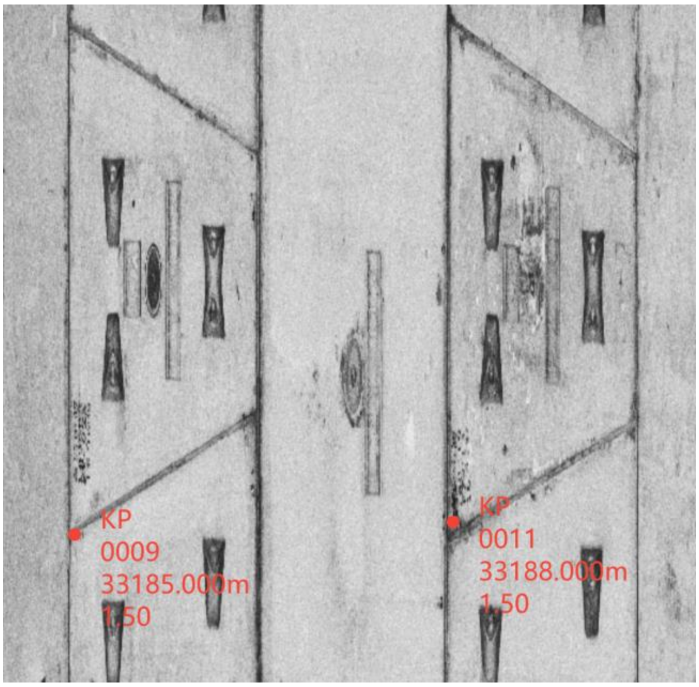

Fig.7 Tube image labeling map

In Figure 7, the dot marked with KP block is located at the lower left corner of the wedge-shaped segment. 0009 and so on are the ring numbers of the segment, 33185 is the corresponding mileage of the segment, and 1.5 is the ring width.

4.2 Convergence calculation

According to the segment ring information and mileage matching information, the three-dimensional point cloud is segmented to generate independent orthophotos and three-dimensional model images of each ring segment. The rendering is shown in Figure 8.

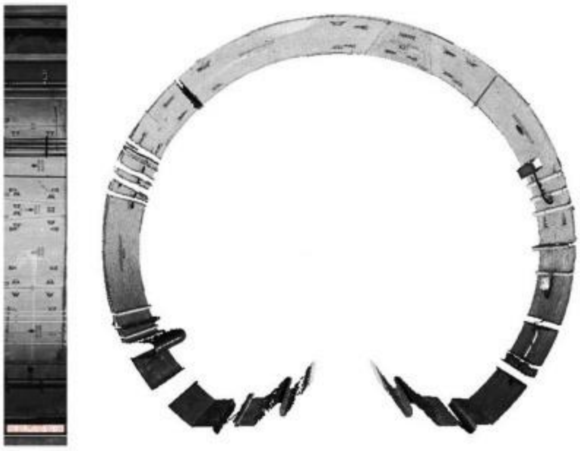

Fig.8 Orthophoto and 3D model of the segment after segmentation

After the segment is divided into rings, an independent plane coordinate system is first constructed based on the point cloud transformation. Fit and calculate the center coordinates of the circular point clouds on both sides of the split ring position, and then find the radius of the circular point clouds on both sides. The difference between the fitted radius and the design value is the convergence deformation amount. By calculating the radius value at each position of the same ring, the spatial deformation of the segment can be fully reflected.

Use (xi, yi) to represent the measured point cloud coordinates in the converted XOY plane. The normal vector of the XOY plane is consistent with the direction of the tunnel line.The equation of a circle is：

$$(x-x_0)^2+(y-y_0)^2=R^2 \qquad (4)$$

In the formula, (Xo, Yo) are the coordinates of the center of the circle, and R is the radius of the circle. For the measuring point (xi, yi), list its error equation[14]：

$$v_i=\sqrt{(x_i-x_o)^2+(y_i-y_o)^2}-R \qquad (5)$$

In the formula, vi is equivalent to the distance between point i and the circle.

$$v_i=\left(-\frac{x_i-x_o}{\rho_i} \quad -\frac{y_i-y_o}{\rho_i}\right)\begin{pmatrix}\delta x_o\\ \delta y_o\\ \delta R\end{pmatrix}-l_i \qquad (6)$$

In the formula：

$$\rho_i=\sqrt{(x_i-x_0)^2+(y_i-y_0)^2} \qquad (7)$$

$$l_i=R-\sqrt{(x_i-x_0)^2+(y_i-y_0)^2} \qquad (8)$$

The initial value of the iteration of the circle center coordinates can be taken as the mean coordinate of all measured points, and the initial value of the radius can be taken as the design value. After calculating the coordinates of the circle center according to the above process, starting from the zenith direction and clockwise along the tunnel's long mileage direction, calculate the distance D between the center of the circle and the actual measured points on the circumference. Comparing it with the design value is the convergence deformation value.

Tab.1 Segment convergence deformation analysis table

Content	Value
Mileage	ZK33+174
Ring Number	185
Segment design radius	2.7m
Actual measured maximum radius	2.7077m

Actual measured minimun radius	2.6930m
Measured average radius	2.7054m
Maximun deformation	7.7mm
Maximun deformation position	95.6^{o}

As shown in Table 1, the convergence deformation of a segment in a certain subway section is calculated based on the above algorithm. The maximum deformation position is along the long mileage direction, with the tunnel center as the origin, and the angle from the zenith direction clockwise to the maximum deformation position. Based on the mobile three-dimensional laser scanning analysis results, the deformation amount of the diameter or radius of each ring and the corresponding deformation position can be obtained, providing a basis for subsequent tunnel maintenance.

5.SUMMARY AND OUTLOOK

3D laser scanning technology broke through the traditional whole station can only measure limited space method, can quickly obtain the space of massive high precision 3d cloud and reflection information. This technology provides a new detection method for the quality detection of subway tunnel, which not only greatly improves the detection efficiency, but also has a wider data coverage, more complete information and higher authenticity. According to the measured 3D point cloud, the 3D model of the tunnel holographic space can be built. Based on this model, it is more convenient to identify the tunnel safety situation.According to its projective image and reflectivity information, the tunnel convergence, water seepage, crack, platform and other diseases can be effectively detected.

Convergence is a common disease of subway tunnel. With the long-term change of subway tunnel operation and the change of geological structure, timely, accurate and effective detection of convergence and deformation and taking prevention and control measures are crucial to the safe operation of tunnel. The traditional measurement means such as full station measurement and reflection sheet can no longer meet the requirements of fine and intelligent subway management. Based on the emergence of mobile 3D laser scanning technology, the traditional detection method has been greatly changed. It not only quickly obtains the detailed information of the tunnel convergence deformation, but also constructs the three-dimensional space model of the tunnel, which provides a reference for the further development and change of other diseases such as misplatform and water seepage.

REFERENCES

[1]STIROS S, KONTOGIANNI V. Mean deformation tensor and mean deformation ellipse of an excavated tunnel section[J]. International Journal of Rock Mechanics and Mining Sciences, 2009, 46(8): 1306 - 1314

[2]BASSETT R, KIMMANCE J, RASMUSSEN C. An automated electrolevel deformation monitoring system for tunnels[J].Proceedings of the Institution of Civil Engineers-Geotechnical Engineering, 1999, 137(3):

117 - 125.
[3]王智,薛慧艳.三维激光扫描技术在异形建筑竣工测量中的应用[J].测绘通报,2018(7):149-152. (Zhi WANG,Huiyan XUE.Application of 3D Laser Scanning Technology in the Survey of the Completion of the Special Shape Building[J]. Bulletin of Surveying and Mapping,2018(7):149-152.)
[4]卢颖.基于三维激光扫描的桥梁检测技术应用研究[D].吉林:吉林大学,2011.(Yin LU.Application Research on the Bridge Detection Technology Based on the Three-dimensional Laser Scanning[D].Jilin:Jilin University,2011.)
[5]郑德华,沈云中,刘春.三维激光扫描仪及其测量误差影响因素分析[J].测绘工程,2005,14(2):32-35. (Dehua ZHENG，Yunzhong SHEN, Chun LIU.3D laser scanner and its effect factor analysis of surveying error[J].Engineering of Surveying and Mapping，2005,14(2):32-35.)
[6]FEKETE S，DIEDERICHS M，LATO M. Geotechnical and operational applications for three-dimensional laser scanning in drill and blast tunnels[J]. Tunnelling and Underground Space Technology，2010，25(5)：614 - 628.
[7]VAN GOSLIGA R，LINDENBERGH R，PFEIFER N. Deformation analysis of a bored tunnel by means of terrestrial laser scanning[C]// Proceedings of the ISPRS Commission V Symposium Image Engineering and Vision Metrology. Dresden：[s.n.]，2006:167 - 172
[8]YOON J S，SAGONG M，LEE J S，et al. Feature extraction of a concrete tunnel liner from 3D laser scanning data[J]. NDT and E International，2009，42(2)：97 - 105.
[9]GORDON S J，LICHTI D D. Modeling terrestrial laser scanner data for precise structural deformation measurement[J]. Journal of Surveying Engineering，2007，133(2)：72 - 80.
[10]谢雄耀,卢晓智,田海洋等.基于地面三维激光扫描技术的隧道全断面变形测量方法[J].岩石力学与工程学报,2013,32(11):2214 - 2224.(Xiongyao XIE,Xiaozhi LU,Haiyang TIAN,et al.Development of a Modeling Method for Monitoring Tunnel Deformation Based on Terrestrial 3D Laser Scanning[J]. Chinese Journal of Rock Mechanics and Engineering, 2013,32(11):2214 - 2224.)
[11]许正文,姚连璧.基于稳健估计的直接最小二乘椭圆拟合[J].大地测量与地球动力学，2008，28(1)：77 - 80.(Zhengwen XU，Lianbi YAO. Direct least square robust estimation method for ellipse fitting[J]. Journal of Geodesy and Geodynamics，2008，28(1)：77 - 80.)
[12]朱曙光,何宽,周建郑.徕卡三维激光扫描系统在建筑物精细建模中的应用[J].测绘通报,2018(2):154-156. (Shuguang ZHU,Kuan HE,JianZheng ZHOU. Research on the Application of Leica 3D Laser Scanning System in the Fine Modeling of Buildings[J]. Bulletin of Surveying and Mapping, 2018(2):154-156.)
[13]师海.三维激光扫描技术在施工隧道监测中的应用研究[D].北京:北京交通大学,2011.(Hai SHI. Application research of three—dimensional laser scanning technology in the construction tunnel monitoring[D].Beijing:Beijing Jiaotong University, 2011.)
[14]袁夏.三维激光扫描点云数据处理及应用技术[D].南京:南京理工大学,2011.(Xia YUAN. Data processing and application technology of 3 D laser scanning point cloud[D].Nanjing: Nanjing University of Science & Technology,2011.)

BIOGRAPHICAL NOTES

Zhi WANG

Senior engineer, and registered surveyor. In 2011, he graduated from Tongji University, majoring in geodesy and Surveying Engineering, with a master's degree in Engineering. Has been committed to the urban rail transit engineering spatial data acquisition and precision measurement Research, study and popularize the application of 3 D laser scanning technology in subway measurement, ancient building protection, and the construction of real 3D in China. He has published more than 50 papers.

CONTACTS

Zhi WANG
Organisation：Qingdao Surveying & Mapping Institute
Address：No.189, Shandong Road, Shibei District, Qingdao City
City：Qingdao
COUNTRY: China
Tel. +86 18766220625
Email: grooveboy@126.com