Journal of Traffic and Transportation Engineering(English Edition)

2014,1(5):325-337

Applications of terrestrial laser scanning for tunnels: a review

Weixing Wang[1,2,*], Weisen Zhao[2], Lingxiao Huang[2], Vivian Vimarlund[3], Zhiwei Wang[2]

[1] *Royal Institute of Technology, Stockholm, Sweden*

[2] *School of Information Engineering, Chang'an University, Xi'an, Shaanxi, China*

[3] *Department of Computer and Information Science, Linköping University, Linköping, Sweden*

Abstract: In recent years, the use of terrestrial laser scanning (TLS) technique in engineering surveys is gaining an increasing interest due to the advantages of non-contact, rapidity, high accuracy, and large scale. Millions of accurate 3D points (mm level accuracy) can be delivered by this technique with a high point density in a short time (up to 1 million points per second), which makes it a potential technique for large scale applications in engineering environments such as tunnels, bridges, and heritage buildings. Tunnels, in particular those with long lengths, create great challenges for surveyors to obtain the satisfactory scanned data. This paper presents a short history of TLS techniques used for tunnels. A general overview of TLS techniques is given, followed by a review of several applications of TLS for tunnels. These applications are classified as: detecting geological features of drilling tunnels, monitoring the geometry of tunnels during excavation, making deformation measurements, and extracting features. The review emphasizes how TLS techniques can be used to measure various aspects of tunnels. It is clear that TLS techniques are not yet a common tool for tunnel investigations, but there is still a huge potential to excavate.

Key words: terrestrial laser scanning; tunnel; deformation measurement; cross-section extraction; measurement planning

1 Introduction

In recent years, the use of terrestrial laser scanning technique in engineering surveys is gaining an increasing interest due to the advantages of non-contact, rapidity, high accuracy and large scale. This technique delivers millions of accurate 3D points (mm level accuracy) with a very high point density in a short time (up to 1 million points per second), which makes it a valuable alternative or complementary technique for classical topographical measurements based on total station or digital photogrammetry. The terrestrial laser scanning can still deliver very accurate points even in the situations where other topographical techniques are

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[*] **Corresponding author:** Weixing Wang, PhD, Professor.
E-mail: wxwang@chd.edu.cn.

difficult or impossible to use.

The digital photogrammetry is inapplicable under some extreme conditions, such as the drilling tunnels, but the laser scanning is applicable in these complex situations. The measurement with a total station is also an option, but the advantage of the laser scanning is obvious: instead of focusing on the rather limited number of specified points, the laser scanning delivers millions of 3D points in a complete monitored tunnel section.

Recently, the improvements of this technique regarding the speed, accuracy, software algorithms, and the fall in price have introduced a high potential of large scale applications in highly demanding engineering environments such as tunnels, bridges, and heritage buildings. Tunnels, in particular those with long lengths, create great challenges for surveyors due to difficulty to obtain the satisfactory geometry of the scanned data.

The high resolution point clouds provided by laser scanning techniques have several applications in construction of tunnels (Decker and Dove 2008; Fekete et al. 2010; Fekete and Diederichs 2013; Roca-Pardiñas et al. 2014), such as construction survey of tunnels (Kong and Ou 2013), extraction of cross-section (Han et al. 2013) or feature line (Yoon et al. 2009) of tunnels, and deformation measurement of tunnels (Gordon and Lichti 2007; Han et al. 2013b).

2 Terrestrial laser scanning

2.1 LiDAR techniques

The core technology of the terrestrial laser scanning is the LiDAR technique, which is used to obtain the distance of each object point from the lens. The acronym LiDAR stands for light detection and ranging. The laser system produces and emits a beam (or a pulse series) of highly collimated, directional, coherent, and in-phase electromagnetic radiation. When the light reflected by the surface of an object is received, the system can calculate the range by the flight time and acquire the reflectivity of the surface. Fig. 1 shows one example of the laser scanners, and Fig. 2 illustrates the principle of the laser scanning technique. There are two different methods of range determination: phase and pulse (Jaboyedoff et al. 2012). The former is more accurate in range but suffers from a limited range. Alternatively, the latter can measure in a greater range. Therefore, the latter is implemented in most TLS used for the measurement of civil construction.

Fig. 1 An example of laser scanner

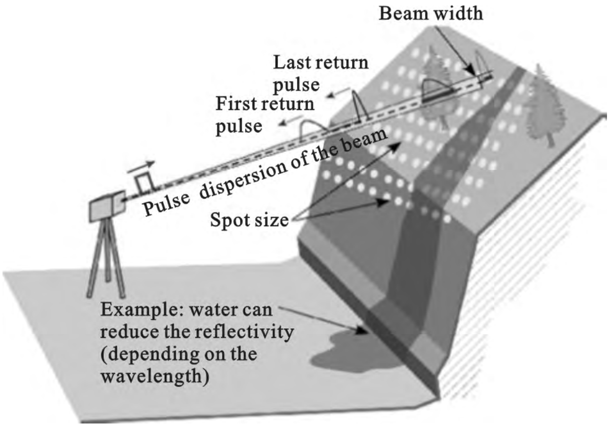


Fig. 2 Principles of laser scanner data acquisition

2.2 Measurement principle

A laser scanner consists of a transmitter/receiver of the laser beams, a scanning device and a timing device (Fig. 2). The scanner sends out laser pulses then receives and records the reflected signals. The timing device measures the time of flight (Δt), with which the scanner can compute the distance d

$$d = \frac{c\Delta t}{2} \tag{1}$$

where c stands for light speed.

Knowing the direction and the angle of the light (cos(α) , cos (β) , cos(γ)) allows determining the relative position (x, y, z) of a reflective surface to the device.

$$\begin{cases} x = d\cos(\alpha) \\ y = d\cos(\beta) \\ z = d\cos(\gamma) \end{cases} \tag{2}$$

2.3 Accuracy, resolution, and point density

The typical accuracy of a laser instrument is ±4 mm, within the maximum distance of about 300 m. Nevertheless, the instrumental accuracy is usually lower in practical applications due to unfavorable conditions such as bad weather conditions (rain or fog) , very low reflectivity of the object surfaces, and very bright ambient conditions, etc.

The resolution of the laser scanner usually declines with the distance due to the laser beam divergence. For example, the laser's spot dimension of the HDS6100 (one type of laser scanner) increases 3 mm when the distance increases 50 m. The details are listed in Tab. 1.

Regardless of the increasing of the laser's spot dimension, the scanner records the center of the spot as a point; therefore, the point density is lower than 1 mm even in the maximum distance.

Tab. 1 Comparison between two laser scanners

Scanner type	Lecia scan station 2	Lecia HDS6100
Scan method	Pulse	Phase
Range	1-300 m	1-79 m
Speed	50000 point per second	500000 point per second
Resolution	6 mm/50 m	3 mm/50 m

2.4 Registration of point cloud

To obtain a 3D model of a construction, the scanner must scan in different positions. The several point clouds acquired from different positions require registration to constitute the entire 3D model. The typical method is to place some targets that can be recognized by the scanner before scanning. The scanner can mark the targets as specific points and we can register different point clouds with the targets they share.

2.5 Short overview

TLS appeared at the end of the 1990s (Heritage and Large 2009) . This instrument is an evolution of the electronic distance meter (EDM) and total station, which benefits a lot from the earlier airborne laser scanning developments. In recent years, the terrestrial laser scanning technique has experienced great advances, which has been successfully applied in a number of diverse fields such as restoration and conservation of historical buildings (Fort-González et al. 2002; Herrera et al. 2009; Weritz et al. 2009; Riveiro et al. 2011) , monitoring and modelling of geography (Derron and Jaboyedoff 2010) , measurement of civil constructions (González-Aguilera et al. 2008; Qiu and Gao 2010; Reveiro et al. 2012) , deformation monitoring (Tsakiri et al. 2006; Monserrat and Crosetto 2008) , and mapping of 3D city models (Pu and Vosselman 2006) .

The measurements of tunnels were discussed in the beginning of 2000s (Schulz and Ingensand 2004) , and were first performed in 2006 for drilling tunnels (Lemy et al. 2006) and as-built tunnels (Van Gosliga et al. 2006) .

3 Applications of laser scanning in tunnelling

In order to ensure safety, long term stability, and quality control in modern tunnelling operations, the acquisition of geotechnical information about encountered rock conditions and detailed installed support information are required. The limited space and time in an operational tunnel environment make the acquiring data challenging. The laser scanning in a tunnelling environment, however, shows a great potential.

The first study of excavating tunnel was proposed by Lemy et al. (2006). In this study, as shown in Fig. 3, Lemy et al. (2006) used a laser scanner to acquire the 3D data of an excavation surface in a tunnel. The displacement of excavation surface is determined by comparing the point clouds obtained at different times.

Fig. 3 Laser scanning of excavation surface of tunnel

The study showed that the laser scanning is a promising technique with a great potential to be used for the collection of data required for the excavation of tunnels. The use of laser scanners allows for effective management of time and access constraints encountered typically during rock engineering projects since it quickly provides a realistic and permanent representation of excavation surfaces. Moreover, it requires only a reduced number of physical targets to be installed for data referencing purposes. Hence, it is particularly well adapted to the study of inaccessible and unstable surfaces as mapping, which can be carried out at any time from a safe location regardless of lighting conditions.

In 2009, Fekete et al. used laser scanning techniques in some projects of drill and blast tunnels in Oslo. Fekete et al. obtained detailed rockmass and excavation information without costly delay or disruption of the construction workflow. With the data they did some useful operational applications: support evaluation, scaling assessment, potential leakage mapping, analysis of structurally controlled overbreak, structural discontinuity evaluation, discontinuity spacing and 3D models, surface characterization, identification of discrete, and textural geological features.

In 2010, Fekete et al. proposed another application of the laser scanning for stability analysis of tunnels in blocky rockmass. In this study, the laser scan data was used to create block models of the rockmass (Fig. 4), which improved the excavation of the tunnel by showing the undercut and overcut. Moreover, a workflow was designed for integrating the laser scanning data into geotechnical tunnel analyses.

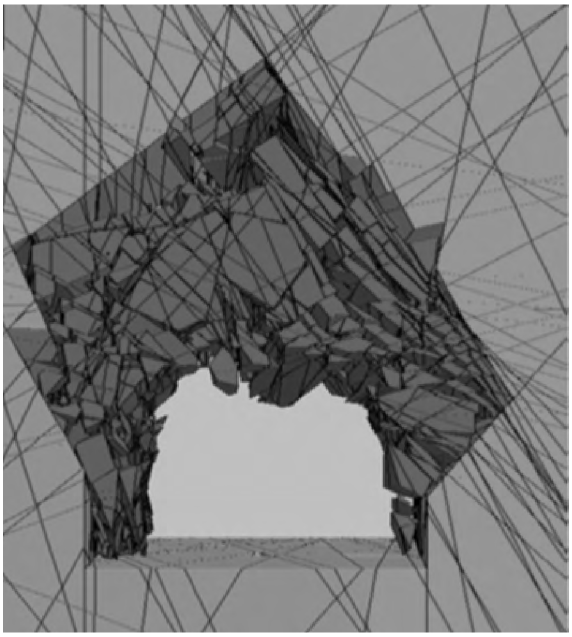


Fig. 4 Block model of rockmass

In their work, they focused more on the geologic situations of tunnels. While in the research of Gikas (2012) in Greece, he paid more attention to the geometry of tunnels. At first, Gikas stated the coordinate system: the z-axis defines the direction of local vertical, the y-axis lies on the horizontal plane pointing towards the magnetic north, and the x-axis completes the right handed orthogonal coordinate system. With this coordinate system, accurate and reliable coordinate transformations can be used for the point cloud registration.

Instead of mapping the geological features of a tunnel, Gikas aimed at profile and volume computations, which required a larger scanning range and the less point cloud resolution. Thereby, he made the scan locations more sparsely, which led to the faster acquisition time together with the less data volume. No matter how far the two adjacent scan locations are, they are planned to overlap. In this regard, the points lying within the overlapped area are used to stitch the individual scan areas together to form a continuous 3D scan image.

When the scan locations are stated, some special targets are placed in the overlap area. The coordinates of these targets are known in the coordinate system, with which the point clouds can be transformed to the absolute position. With the point clouds data, Gikas presented three example applications in the geometric documentations of tunnels: the tunnel surface documentations including the information at the excavation face, cross-section and volume calculations during support measure operations, and a geometric documentation of the metal arch formwork.

In these studies, the potential and applications of the laser scanning technology for collecting high-fidelity data to support tunnel construction activities have been thoroughly examined. The capability of the laser scanning to provide a precise and accurate 3D mapping of the excavation site enables the construction to be more transparent, faster, and more reliable compared to the data obtained from traditional surveying approaches. Also, this capability benefits the tunnel engineers for the better understanding and controlling the various issues (geological, structural, etc.) arising during construction.

4 Applications of laser scanning in as-built tunnels

The surveying and mapping of tunnels are crucial for the optimal use after construction and in routine inspections. Most of these applications focus on the geometric information of the tunnels extracted from the laser scanning data. Two kinds of applications are widely discussed: deformation measurement and feature extraction. Several representative applications are shown below.

4.1 Deformation measurement

The traditional deformation measurement in an underground environment is performed with a series of permanent control points installed around the profile of an excavation, which is unsuitable for a global consideration of the investigated area (Nuttens et al. 2012) . Using laser scanning for deformation analysis provides many benefits as compared to traditional monitoring techniques. The change in profile is able to be fully characterized and the areas of the anomalous movement can easily be separated from overall trends due to the high density of the point cloud data. Furthermore, monitoring with a laser scanner does not require the permanent installation of control points, therefore the monitoring can be completed more quickly after excavation, and the scanning is non-contact, hence, no damage is done during the installation of temporary control points.

The main drawback of using laser scanning for deformation monitoring is that the point accuracy of the original data is generally the same magnitude as the smallest level of deformations that are to be measured. To overcome this, statistical techniques and three dimensional picture processing techniques for the point clouds must be developed.

The feasibility of the tunnel deformation monitoring using TLS was firstly discussed by Lindenbergh et al. (2005) . In his study, the accuracy of one newest laser scanner, Lecia HDS3000, was tested. The analysis of the accuracy demonstrates that it is possible to design a measurement device in which the deformations need to be monitored.

The first investigation of deformation analysis of tunnels with the laser scanning was performed in 2006 (Van Gosliga et al. 2006) . In the work, Van Gosliga et al. suggested the method of cylinder fitting for the deformation analysis of tunnels.

Before deformation analysis, the tunnel model is fitted to a point cloud consisting of several registered terrestrial laser scans using a linear iterative least square approach, which results in approximately optimal values for the tunnel model (Fig. 5) .

The deformation analysis consists of two parts: the first part is comparing the tunnel data in some epoch with a designed model. The second part is to test whether the deformation occurred between two epochs of tunnel measurements.

The comparing processes are simple. First, it transforms the points cloud (x, y, z) into a cylindrical coordinate system (ρ, ϕ, z) as shown in Fig. 6.

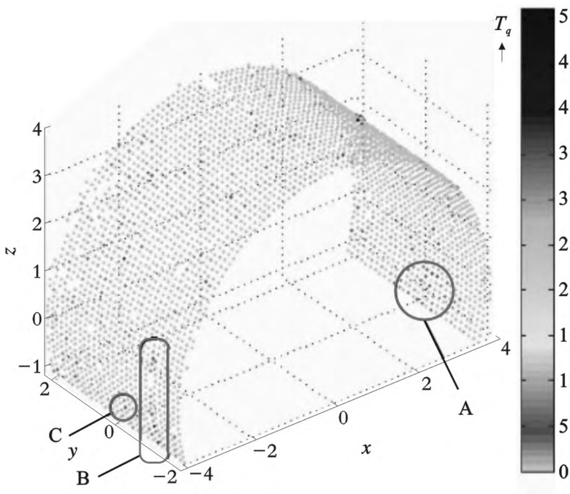


Fig. 5 Deformation detection

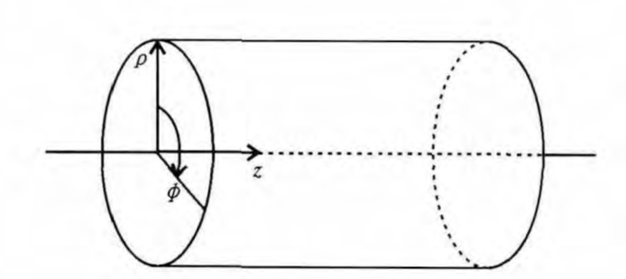


Fig. 6 Cylindrical coordinate

$$\begin{cases} \rho = \sqrt{x^2 + y^2} \\ \phi = \arctan(y/x) \\ z = z \end{cases} \tag{3}$$

In this way, the all deformations occur along the range coordinate. Second, the value of ρ at location (z, ϕ) is obtained by averaging all observations within a grid cell

$$(z_0 - \Delta z, z_0 + \Delta z) \times (\phi_0 - \Delta\phi, \phi_0 + \Delta\phi)$$

Third, the difference of the range coordinate between two epochs in the same grid point is determined. At last, the deformation points are tested by a stability test to remove the measurement noise.

Lindenbergh et al. (2009) made an attempt at the accuracy and precision in a millimeter level in quantifying deformation. This work presented two major steps towards obtaining sub-noise level accuracy in surveying applications using the terrestrial laser scan data. The first step aimed at obtaining a point cloud of the optimal quality for each measurement epoch. The second step consists of an adjustment and a testing procedure that identifies deformation by gaining benefits from both data redundancy and individual point quality.

There are some other studies on tunnel deformation analysis using LiDAR technique (Vezocnik et al. 2009; Nuttens et al. 2010; Delaloye et al. 2012; Walton et al. 2014), most of their methods fit the tunnel to a typical geometric model (e. g. circular cylinder, elliptic cylinder, or a more complex model that follows the ideal design plan). It is easier to conduct the deformation analysis using these parameterized models, but some details may be neglected during the modeling process.

Han et al. (2013a) presented an efficient approach for the deformation detection. First, the 2D tunnel profile geometry is extracted from the raw laser scanning data. Then by applying a minimum distance projection (MDP) algorithm, point correspondences are established so that the deformation signals along the given profile can be immediately identified. Based on the results of the simulation and a real case study of a highway tunnel, this approach is proven to be an efficient and accurate solution for monitoring tunnel deformations. However, the benefits of the 3D data have not been fully exposed.

Han et al. (2013b) improved the technique to a real 3D approach which detected the 3D deformation directly from the point clouds. The associated uncertainties could be reduced by avoiding the 3D to 2D profile projection. The MDP algorithm was then estimated directly using 3D dispersed point clouds so that any deformation signal along the entire tunnel surface can be immediately identified. Furthermore, a rigorous covariance propagation approach was introduced to provide explicit quality indications on the obtained solution.

In this approach, the point correspondence between the points on the reference (non-deformed) and deformed surfaces is established by the MDP algorithm directly from the 3D datasets. First, a point k on the deformed surface is selected. Its distance to all points on the reference surface is computed to find the nearest three points (k_1', k_2', k_3') to the point k. Then the coordinates of the projected point k', on the reference surface, can be computed using the following equations

$$x_{k'} = x_k - \frac{an(k - k_1')}{a^2 + b^2 + c^2} \quad (4)$$

$$y_{k'} = y_k - \frac{bn(k - k_1')}{a^2 + b^2 + c^2} \quad (5)$$

$$z_{k'} = z_k - \frac{cn(k - k_1')}{a^2 + b^2 + c^2} \quad (6)$$

The vector n stands for the face normal of the plane formed by the three points k_1', k_2', k_3'. The parameters a, b, and c are the orthogonal coordinates of the vector n.

$$n = (a, b, c) = (k_2' - k_1') \times (k_3' - k_1') \quad (7)$$

The projected point k' on the reference surface should have a minimum distance to point k and is regarded as the most probable correspondence point of k. Finally, the MDP distance representing the spatial displacement of point k can be computed by

$$S_{\mathrm{MDP}} = \sqrt{(x_{k'} - x_k)^2 + (y_{k'} - y_k)^2 + (z_{k'} - z_k)^2} \quad (8)$$

The deformation signals along the entire surface can be obtained if every point on the deformed surface is processed, see Fig. 7.

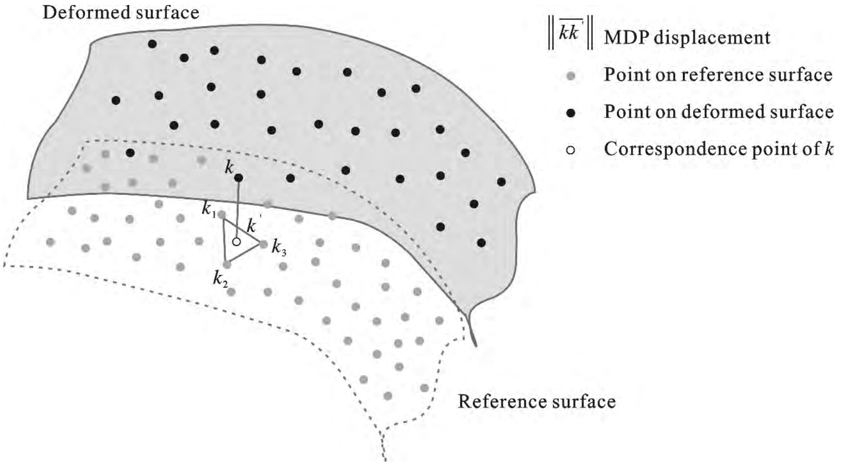


Fig. 7 Illustration of MDP algorithm

A real case analysis using this approach was performed in a highway tunnel in Taiwan. This fast and automatic approach was easy to implement with fewer analysis steps and less quality loss compared with the earlier approaches. Furthermore, this approach is a surface-based analysis that determines both the magnitude and distribution of the deformation signals, which enables a comprehensive evaluation of tunnel dynamics.

The laser scanning technique has a great potential in deformation measurement of tunnels, but the computational burden of analyzing millions or billions of 3D points costs more time than the other measurement steps. This problem can be overcome with the rapid development of computer technology and the improvement of algorithms.

42 Feature extraction

It is necessary to extract some features of a tunnel for the acceptance inspection and the tunnel mapping, such as the cross-section (Delaloye et al. 2014) , the centerline, and the installations like rail and pipe (Qiu and Wu 2008) .

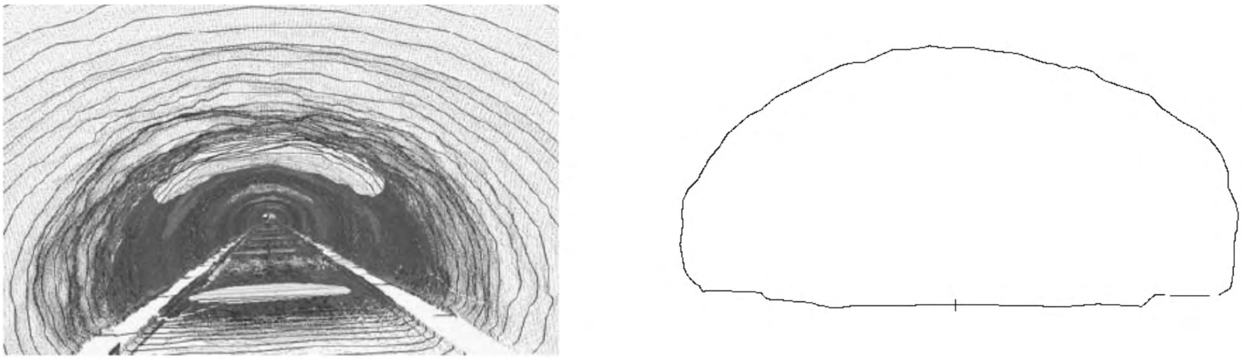
The first application using the terrestrial laser scanning for feature extraction was performed in 2006 (Lam 2006) . With the point cloud from a terrestrial laser scanner, Lam studied a workflow to survey geometric tolerance of tunnels for controlling aspects of tunnel shape and providing displacement vectors of the finished components in construction. This study described how to select a suitable laser scanner, the calibration method, the procedures for acquiring survey data by instrument in the field. And it depicted the computational algorithm of computer software needed for registration, fusion and error analysis of multimodality and range images, so that the point cloud obtained by instrument was applied effectively in assessing the various geometric tolerances of tunnel structures in as-built surveying. The testing results were listed in Tab. 2.

The assessment of geometric tolerances is based on the extraction of the tunnel profile cross-section, surface form and column eccentricity. Comparing these three features with the ideal design plan, the profile tolerance, the form deviation and the straightness tolerance of a column axis are computed depending on the requirement of the accuracy of the assessment.

Seo et al. (2008) developed a tunnel cross section management system using the terrestrial laser scanning, which can be practically employed for determining the cross-section of tunnels more promptly and accurately. One example is shown in Fig. 8.

Tab. 2 Types and characteristics of geometric tolerances

Feature type	Type of tolerance	Characteristic
Individual feature	Form	Straightness, flatness, cylindricity
	Orientation	Angularity, perpendicularity, parallelism
Related feature	Location	Position, concentricity
	Runout	Circular runout, total runout
Undetermined feature	Profile	Line profile, surface profile



(a) View

(b) Final result

Fig. 8 Example of extracting cross-section

First, high-density 3D data was obtained in a prompt and accurate manner using a terrestrial laser scanner. The data processing was then conducted to promptly determine arbitrary cross-sections at 0.1, 0.5, and 1.0 m intervals. A laser scanning technique was also used to quickly and accurately calculate the overbreak and underbreak of each cross-section along the entire tunnel length. As the developed system utilized vast amounts of data, it was possible to promptly determine the shape of arbitrary cross-sections and to calculate the overbreak and underbreak more accurately with the higher area precision. An economic analysis of various techniques for determining the tunnel cross-section revealed that this measurement system was also outstanding from an economical perspective. It is expected, therefore, that the system will not only enable more efficient and cost-effective tunnel drilling management and monitoring, but also will provide a basis for future construction and management of tunnel cross-sections.

Yoon et al. (2009) developed a trial model of a laser-based tunnel scanning system to facilitate an automated tunnel inspection process. The scanning system consists of a rotary-type laser scanner and a rail guided vehicle to deliver the scanning data containing x, y and z coordinates. An algorithm was studied to extract installations on the liner and the physically damaged parts of a tunnel liner using the geometric and radiometric features of the scanning data. This algorithm was tested and evaluated by using the scanning data set from an operating railway tunnel and a concrete box with various diameters of pipes attached on one wall of the box. Due to the mechanical and laser sensor limitations, the developed system was limited with respect to the identification of cracks and installations. The accuracy of this system is 5 mm.

Han et al. (2012) developed an automated and efficient method for extraction of tunnel cross-sections using TLS data. First, the point cloud of a tunnel was projected onto a horizontal plane to produce a binary image. Then the image was processed with the boundary tracing and filling to remove the holes produced in sparsely scanned regions that were far-off-nadir or occluded from the scanner. With a skeletonizing algorithm, the object in the image was transformed to a 1-pixel-thick line, which was the extraction of the centerline after vectorizing and smoothing. Finally, as shown in Tab. 3 and Fig. 9, the cross-sections were extracted according to the points of the centerline.

Tab. 3 Comparison of surveying and processing times min

Category	TLS		Total station	
	Activity	Time	Activity	Time
Surveying	Outside scanning	45(25 + 20)	Center point selection	60
	Inside scanning	85	Corss sectional surveying	255(15 × 17 stations)
	Instrument installation	60(20 × 3 stations)	Instrument installation	85(5 × 17 stations)
Processing	Scan registration	Not estimated	Reporting results	Not estimated
	2D projection to skeletonizing	< 1		
	Manual editing to vectorizing	5		
	Smoothing to centerline completion	< 1		
	Initial cross-sectional plane estimation to	< 1		
	Final cross-sectional production			
Total		198		400

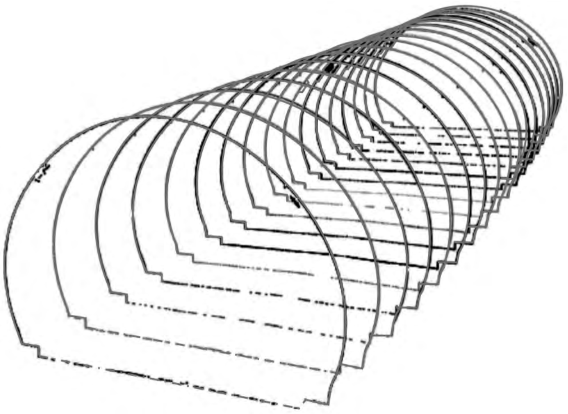


Fig. 9 Extracted cross-sections

Han et al. (2013) tested their method on a subway tunnel comparing with the total station method. The TLS method obtained 147023 points of a cross-section in about 200 minutes, however, it took 400 minutes to acquire 357 points of the cross-section by the total station method. Obviously, the terrestrial laser scanning had great advantages both in accuracy and speed comparing with the total stations. And the scanning time would certainly be improved. Overall, this method was proved to offer the advantages of detailed description and time savings.

Nuttens et al. (2014) introduced a methodology for the ovalization monitoring of circular tunnels based on the laser scanning, as shown in Fig. 10, they implemented it in a train tunnel project in Belgium. In this project, the reference measurement was carried out immediately following construction of the tunnel section, which consisted of three scanning positions in one section because the space was limited by the construction equipment. The control measurement took place in the following three months, when the space was free and only one scanning position was needed.

However, the processing of the laser scanning data is formed in two parts: the extraction and the evaluation of the cross-section. The former results, in a polyline, represent the triangulated surface of the measured tunnel and include all the measured detailed information. In the latter, the radius values of the cross-section are calculated and the values of the control measurements are compared with those of the reference measurements.

This method can detect the changes of the cross-section under millimeter. The results of such a systematic monitoring program allow contracting engineers to validate the theoretical models and to compare with the actual behavior of large diameter shield tunnelling in soft soil. It is highly valuable because very few measurements at this early stage of a tunnel construction are available to evaluate the performance and accuracy.

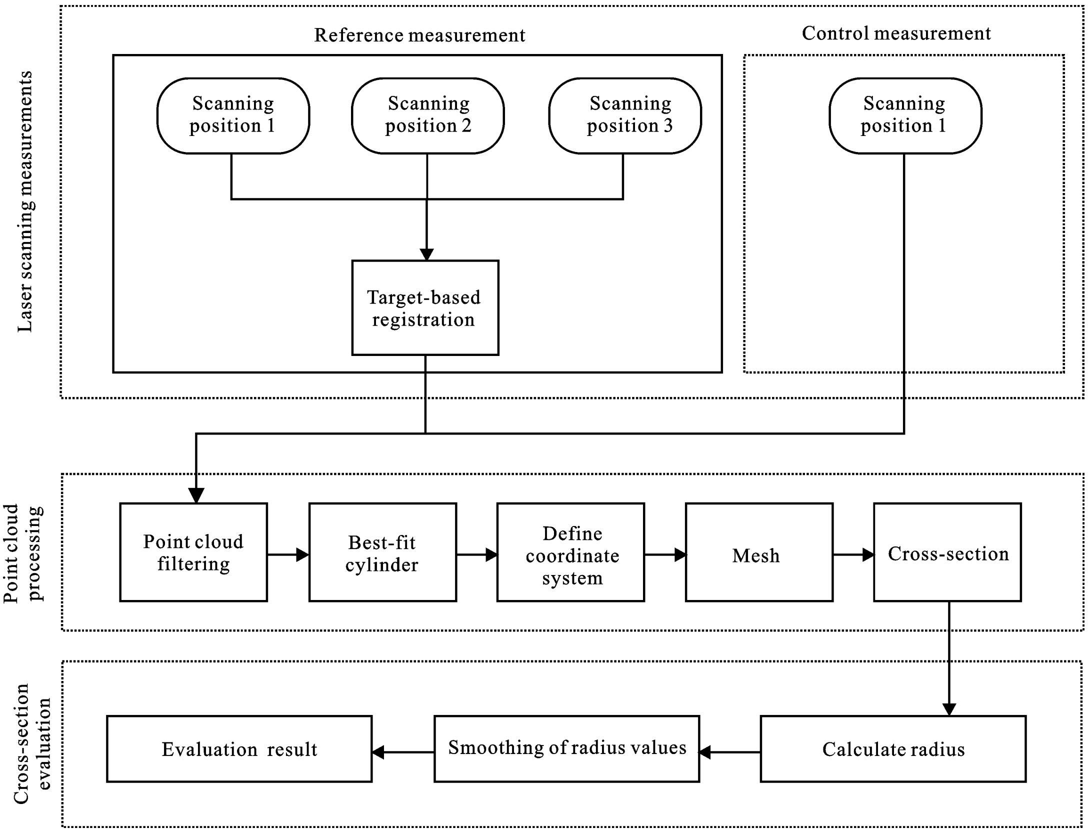


Fig. 10 Measurement and processing methodology

5 Measurement and analysis

Although there are lots of applications using the terrestrial laser scanning, the measurement planning is seldom considered, and mostly limited to cost minimization by scanning to the maximum range of the scanning equipment. However, other factors besides distances that substantially influence the accuracy of the measurements tend not to be taken into account when planning data capture, such as the size of the laser footprint, the incidence angle, the scanning density, and the geometry of the tunnel itself.

Argüelles-Fraga studied the impact of the location of the scanner, the incidence angle, the footprint size and the scanning density on geometric verifications of circular cross-section tunnels (Argüelles-Fraga et al. 2013) . He also suggested a data capture methodology designed to optimize tunnel scanning tasks using TLS. His methodology is based on theoretically estimating the position of the laser spot on the tunnel surface. The distance from the scanning position to each point on the tunnel wall can be theoretically calculated with the radius of the circular section, the laser scanner height, the distance from the tunnel centre to the scanner, and the laser scanner measures horizontal and vertical angles.

Argüelles-Fraga also discussed other three factors affecting measurement accuracy: point density, incidence angle, and footprint size. Considering with these four factors, he did an approach to determine the distance and angular intervals which yield a specific accuracy for a minimum scan time. In order to validate his method, a simulated tunnel scan and real tunnel scan were carried out. The results visually showed the influence of the factors above on the scan accuracy. In other words, tunnel geometry, scanner position, scanning density, incidence angle, and footprint size are closely related factors that could affect the results of the measurements.

Pejic (2013) gave an optimal solution for surveying tunnel geometry using the laser scanning technology to reliably inspect railway tunnels and create as-built documentation. This methodology provides the optimization of scanning parameters, scans registration, georeferencing approach, and the survey control network design. The maximal size of the scanner shifting along the tunnel alignment is primarily conditioned by the factors including the incidence angle of the laser beam and the point density distribution. Pejic introduced the so-called arbitrary georeferencing approach in the long tunnel scanning that controlled the point cloud geometric distortions to the required limits and contributed to time and material resources savings. The optimal design of the survey control network ensures the required positional accuracy and the reliability of the measurements, together with a cost effective approach to the tunnel surveying.

This method was tested by the empirical results of the modelling and profiling of 12 tunnels in a single track railway. The lengths of these tunnels were from 60 m to 1260 m, with a total length of 3.5 km. Due to the specific geometry of the case study tunnels, the maximal favorable laser incidence angle was 78° with a distance of 13 m, and consequently the optimal size of the scanner shifting along the tunnel alignment was 26 m. The survey control network was designed with the condition that the optimal reliability factors were within the required limits for engineering networks. A priori estimation of the control network positional uncertainty and posteriori adjustment results show that the achieved positional accuracy of the control points is approximately five times higher than the requested absolute accuracy of the tunnel model. On the largest tunnel example it was shown that the arbitrary georeferencing approach assured that the optimal registration error size was within the requested limit.

Based on Argüelles-Fraga's study, Javier proposed the influence analysis of range and angle of terrestrial laser scanning measurements incidence on tunnel inspection in 2014. In this study, a methodology to build an error model of TLS measurements was suggested.

Simulating errors on the point cloud measured with a TLS system is possible to analyze the effect of the errors due to the distance to the object and the angle of incidence on tunnel inspection. For the maximum distance recommended for tunnel inspection, the errors are mainly due to the angle of incidence.

Conclusions concerning the influence of the position of the scanner on errors were also extracted. Mostly, the suitable position should be the center of the tunnel, the error distribution along cross-sections is homogeneous, and the maximum errors are fewer than that when the scanner near the tunnel gable (a common position in practical situations) . When the scanner is near the tunnel gable, the error distribution is not homogeneous along the same cross-section and greater errors would occur on the wall near the scanner, due to the angle of incidence. However, when a surface is fitted to the point cloud, these inconveniences are countered in tunnel inspection due to the higher density of points on the wall near the scanner.

6 Conclusions

Above synthesis and considerations show that the terrestrial laser scanning is increasingly being used for tunnels, becoming a powerful tool for both construction and maintenance management. In near future, the laser scanning will probably be a standard tool for geologic and geometric analysis for tunnels. As the technique is also progressing, more accurate and inexpensive TLS devices will appear with more extensive applications. Nevertheless, the huge amount of data will remain a problem since the computers need to be more powerful with increasing data acquisition capacity as it already needs hours to process the data for some simple applications.

The real challenge is to develop some advanced methods with more complex image processing algorithms. In most of the current applications, it is necessary to process the scan data with some simple algorithms, ignoring lots of potential information. There is the possibility to develop a standard workflow for the optimal use of the capacities of laser scan instruments. There is still a huge potential to excavate in tunnel data in the future.

Acknowledgments

This research is financially supported by Special Fund for Basic Scientific Research of Central Colleges (No. 2013G2241019), Shaanxi Province Science & Technology Fund (No. 2013KW03), and Xi´an City Science & Technology Fund (No. CX1252(8)).

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