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Automated and Efficient Extraction of Highway Tunnel Lining Cross-sections Using Terrestrial Laser Scanning (TLS)

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Over the past years three-dimensional (3-D) laser scanning technologies play an important role in civil engineering. In particular, man-made structures 3-D spatial information extraction methodology is one of the major fields of application of terrestrial laser scanning technology. In this paper, an automated and efficient method for extracting highway tunnel lining cross-sections using terrestrial 3-D laser scanning system is presented. First, the tunnel point cloud acquired from terrestrial laser scanner is registered based on the control network (CN) method and least-squares optimization, ensures minimization of the target-to-target registration errors. Then the 3-D tunnel point cloud is projected onto a horizon plane, converted to a two-dimensional (2-D) planar image, and skeletonized to estimate the tunnel 3-D centreline. The orientation of tunnel cross-section, which are orthogonal to the centreline, is defined to be in terms of the centreline. Finally, the cross-sectional planes are determined for every interval. The proposed method was implemented on concrete highway tunnel monitoring project on the G25 highway, in Jiangsu Province, China, and proved itself to offer advantages, including detailed description and improved surveying automations and data processing efficiencies.

Keywords: Terrestrial laser scanning (TLS), highway tunnel, tunnel cross-section, point cloud, monitoring, control network (CN), least-squares optimization, civil engineering

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1 INTRODUCTION

As scientists, civil engineers and planners require ever more detailed information about the requirement for accurate three-dimensional (3-D) mapping of road structures is likely to increase considerably in the years to come. The technology available for providing road 3-D mapping may be applied from the ground using static instrumentation or an air based platform. Advanced digital mapping tools and technologies are so-called 3-D laser scanners are enablers for effective e-planning, consultation and communication of users' views during the planning, design, construction and lifecycle process of road. The regeneration and transformation of cities from the industrial age to the knowledge age is essentially a 'whole life cycle' process consisting of: planning, development, operation, reuse and renewal. In order to enhance the implementation of road solutions during the regeneration and transformation of cities, advanced digital applications can have a significant impact.

There are many brick-lined tunnels in the Nanjing-Hangzhou urban agglomeration serving a variety of purposes from railways to highways. These tunnels are subjected to degeneration such as sapling, perished mortar and loose bricks during their service life. Ground stress and movement can cause significant deformations to the tunnel structure and lining. If this goes unnoticed and without remedial maintenance severe disruption to the tunnel use can occur. Regular and frequent monitoring to diagnose any deterioration is of major importance. Decision making can be supported by numerical modelling to analyse and predict mechanical behavior of the tunnel. The monitoring of the geometric shape of tunnels has always provided a challenge for the surveying community. Their size and shape has required 3-D measurements to be collected to enable a full understand of the tunnel geometry. In the past, this has been split often into a cross-sectional shape and a longitudinal direction. The long narrow nature of most tunnels provides limited scope for some forms of survey measure where as it can be difficult to achieve a strong survey geometry.

Recent years have seen the emergence of 3-D terrestrial laser scanning (TLS) system, which offers the advantage of acquiring accurate 3-D information of objects in a short operational time [1]. They provide several benefits over conventional sources of data acquisition in terms of accuracies, resolutions, attributes, and automation [2]; therefore, applications of TLS technology are rapidly expanding with decreased costs and increased accuracy. This technology is currently applied in various fields, including ice shape measurements [3], automated railway tracks extraction [4], urban roads extract [5–7] and underground engineering surveys [8, 9]. The use of the TLS technique has also become popular in tunnel engineering [10–14] due to the various advantages over conventional geodetic devices. The main advantage of using TLS rather than traditional surveying methods is that information can be obtained on the geometry of the tunnel along its entire length rather than on specific sections, usually at intervals of several meters; hence, any of the sections of a tunnel can be modelled and represented for research purposes. TLS has been receiving more attention, particularly in the areas of tunnel management [15, 16], tunnel 3-D modelling [17], tunnel monitoring techniques [18–20], and tunnel deformation analyses [21–24]. In these cases, however, the method of fixing a tunnel centreline, on the basis of which cross sections are extracted, was not treated or presented in detail. Instead, the centreline from a drawing was adopted, or the line was manually drawn. It is doubtful whether these approaches can adequately represent the exact centreline because there often are discrepancies between a drawing and an actual tunnel.

The objective of this paper is to develop an automated and efficient method for extraction of dense tunnel cross-sections using TLS system. The paper is organized as follows: the proposed method that includes tunnel point cloud data registration, tunnel central line estimated, and tunnel cross-section extracted in Section 2. Section 3 discusses the tunnel measurement case study, followed by Section 4 with the conclusions and recommendations for further research.

2 METHODS

2.1 Outline procedure

In this section a method developed for automated and efficient extraction of tunnel lining cross-sections using TLS technology is described. The proposed approach comprises three steps: (i) tunnel point cloud registration based on control network (CN) method and least-squares optimization; (ii) estimates the tunnel central line using the RANSAC (RANdom Sample Consensus) algorithm; and (iii) the cross-sectional planes are determined for every interval.

2.2 Tunnel point cloud registration

TLS faces challenges, when applied to elongated construction such as tunnel, as such application requires numerous scans to complete a whole feature. The point cloud sets acquired by TLS are referenced to different local frames, each associated with a corresponding scanner location. Therefore, a registration process based on the CN method is needed to align and merge these individual scans relative to a common reference frame. A CN may cover a small area by using a local coordinate frame that allows us to position the features in relation to the CN reference frame, or cover a large area by consisting of a few well-placed and precise-established control targets. CN registration will determine the relative positions of the point clouds that it connects in series, and if tied to control targets based on a common reference frame, the positions may be referred to that frame. From these computed relative positions, full-scale scans can be measured for layout of tunnel.

To cover the whole tunnel during reference measurement based on CN, numerous temporary scanning positions are needed, taking into account the field of view specifications of the used terrestrial laser scanner (GX; Trimble, Inc.) with a field of view of $360° \times 60°$. To enable the registration of the measurements from these scanning positions into a single point cloud, Trimble white-and-green targets ('Reference Target' which printed on water-proof polyester paper and determines the exact location of the cross-section for the further processing of each measurement) attached on tripod are set up equally spread over the tunnel in a line. Four targets used in one scanning station so that there are at least two overlapping targets between two scanning positions. This large number of overlapping targets ensures a solid registration and minimization of the target-to-target registration errors based on a least-squares optimization (<1 mm registration error). The exact centre of each white-and-green target is recognized by the processing software (Realworks Survey) and one of these targets is indicated as the so-called 'Master Control Target', which determines the exact location of the cross-section for the further processing.

2.3 Three-dimensional (3-D) centrelines extraction

The tunnel point clouds are projected onto the *XOY* plane, from which we extract the boundary points of both sides of the tunnel. An algorithm for boundary point extraction is proposed using a moving window. A circular window with a predefined radius that is centred at the point of interest M. All points within the window are considered the neighbouring points of point M. The polar angles of the neighbouring points are computed relative to point M. We then calculate the differences between consecutive polar angles. If point M is a boundary point, the difference Δfi+1,i between boundary points Mi and Mi+1 is much larger than the difference Δfi,i−1 between boundary point Mi and interior point Mi-1. Therefore, once the difference is greater than a predefined threshold, point M is labelled as a boundary point. The boundary lines of a tunnel usually contain segments of straight lines, curves and transition curves, which are parameterized as follows:

Straight line:

$$y = ax + b \tag{1}$$

Transition curve:

$$y = cx^3 + dx^2 + ex + f \tag{2}$$

Curve:

$$y = gx^2 + hx + k \tag{3}$$

where a and b are the parameters of a straight line; c, d, e and f are the parameters of a transition curve; and g, h and k are the parameters of a curve.

The boundary line fitting process includes the estimation of multiple models. To ensure the robustness of the fitting, the RANSAC algorithm is used to estimate the parameters of the three models. Instead of using as much data as possible to obtain an initial solution and attempting to eliminate the invalid data points, RANSAC uses as small an initial data set as is feasible and enlarges this set using consistent data when possible. The RANSAC paradigm contains three unspecified parameters: (i) the error tolerance, which is used to determine whether a point is compatible with the model; (ii) the number of subsets to attempt; and (iii) the threshold t, which is the number of compatible points and is used to define that the correct model has been found. The determination of these three parameters is discussed in the introduction to RANSAC.

After the initial model is detected, RANSAC is used to robustly estimate the optimized model parameters. Two, four, and three points are used to estimate the model parameters to fit a straight line, a transition curve and a curve, respectively. The criterion used to identify outliers is based on the deviations of the tested points from the fitted model. The inlier boundary points of a certain model are classified as a segment that is used in the following global optimization. The final optimal parameters are computed by the least-squares adjustment using the obtained inlier points.

After fitting the boundary lines, the boundary points are evenly resampled. To extract the centreline of the tunnel, a much-desired extension of the presented skeletonization method would be to generalize it to the 3-D case; however, the 2-D boundary lines parametrization presented above is not straightforward to generalize to 3-D. The main reason behind the above is the difference between the topological and ordering properties of 2-D curves and 3-D surfaces. The 2-D skeletonization method for the computation of 3-D centrelines is exploited. Centrelines are curves as defined and not surfaces as the true 3-D skeletons. A point belongs to the centreline if there exists a sphere, centred in this point, which touches the boundary at opposite sides (as compared to any two points, in the case of skeletons). 3-D centrelines are computed as follows. First, the 2-D skeletons are extracted of each axis-parallel 2-D plane of the 3-D volume point cloud. This produces three sequences of 2-D skeletons, and three volumes, corresponding to the three directions, called the X, Y, and Z skeletons. Then, these volumes are intersected, voxel by voxel, and obtain the 3-D centreline of the initial object. The idea behind the above approach is that the voxels in the intersection belong, locally, to three axis-aligned 2-D skeletons. These voxels are thus at maximal distance from the boundary line, measured in the three orthogonal planes. This is a simplification of the general case where one would have to measure the distance to the boundary line along any arbitrary plane, three orthogonal circles are used instead of a sphere. The above is often a sufficient approximation for the typical snake-like objects for which centrelines are usually computed.

2.4 Cross-section extraction

After estimating two boundary lines and computing a centreline on tunnel point cloud, a cross-section to be orthogonal to the centreline of the tunnel is determined. According to the design of the tunnel, it can be assumed that each tunnel section approximates a cylindrical shape. Therefore, the longitudinal axis (centre axis) of the best-fit cylinder is considered to represent the axis of the tunnel section. In order to obtain a closed polyline as cross-section instead of a much smaller collection of individual points, a mesh of the point cloud of the tunnel section is calculated. The cross-section is defined perpendicular to the tunnel longitudinal axis and its exact intersection on the tunnel section is fixed by the 'Reference Target' (Trimble white-and-green target). The definition of 'Reference Target' for each monitored tunnel section allows a same location of the cross-section between the different consecutive monitoring measurements. The cross-section results in a polyline, representing the mesh surface of the measured tunnel surface and including all the measured detailed information.

3 CASE STUDY AND DISCUSSION

3.1 Scope and location

The twin tunnels named Tizishan is located in G25 highway near the Jiangsu Province, China. Each tunnel has a total length of 332.00 m, a height of 8.15 m and a width of 14.05 m, and is shown in Figure 1. In order to validate the method herein presented, it was applied to the one tunnel of them. A TLS acquisition survey were planned. The laser point cloud data acquisitions were performed using the laser scanner described above and shown in Figure 2, which can collect millions of points for photo-realistic resolution. To survey the environment in 3-D over a range of 5 to 350 m, a laser beam sweeps the visible surfaces, field of horizontally and vertically view over $360° \times 60°$. The location of the scanner positions was planned to minimize the number of survey stations and to avoid possible omissions. In fact, for the measurement of the tunnel area, sixteen stations were required. The survey by TLS was also important for geometrical registration of reference targets. To be noted that one station maximum distance is about 40 m, from back target to front target, as shown in Figure 2.

3.2 Measurement and discussion

The objective is to measure the highway twin tunnels using the TLS system based on the CN method. The CN method facilitate the measurements of highway twin tunnels in one aspect. Multiple scans complete the overall

FIGURE 1
Photograph of the Tizishan twin tunnels on the G25 highway, Jiangsu Province, China.

FIGURE 2
Photograph of the terrestrial laser scanner used in this work *in situ*. The front targets are in the red box and the distance between the terrestrial laser scanner to target is less than 20 m.

highway tunnel measurements for two long strip ribbons. Since the shape of each tunnel is consistent, analysing the results of the final registration is useful and extendable. The scanning scene shows the approximate distribution of scanners and targets along the tunnels. Normally the distance between stations is 15 to 20 m, and the scanner from the one of either side of tunnel is 1 to 3 m, as shown in Figure 3.

(a)

(b)

FIGURE 3
Photographs showing details of the tunnel measurement environment for (a) the terrestrial laser scanner work station and data acquisition of tunnel concrete surface, and (b) data acquisition of the reference target.

(a)

(b)

FIGURE 4
Photographs showing details of the reference target station: (a) foresight or back sight reference targets mounted on tripods; (b) reference targets attached to the concrete surface with special highly adhesive glue to guarantee the further use of these targets during the control measurements.

From each scanning position station (*cf.* Figure 4), the point cloud covers the whole field of view of the terrestrial laser scanner: 360° horizontal × 60° vertical continuous single scan. The density of these point clouds varies, depending on the time, observed object, surveying environment and type of measurement. For this case study is a control measurement in highway environment. For each surveying station would cost 20 minutes, the density of scanning points was set at a point every 5 mm at the maximum distance of

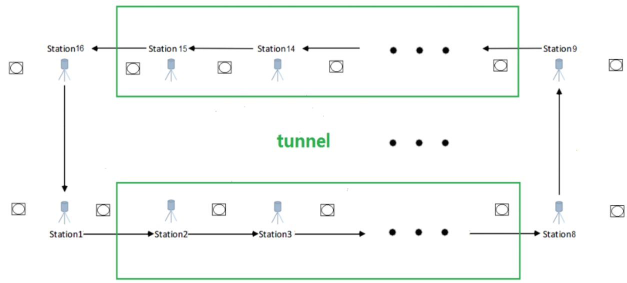

FIGURE 5
Schematic representation of the scanning positions and the targets.

about 20 m on the concrete surface of the scanned tunnel ring. For a reference target object scanning would cost 10 minutes, the scan mode was set at 'refined scan mode'. During the optimized processing of the point clouds from measurements immediately after placement, resulting in a point cloud resolution of at least 5 mm was imported in the laser scan processing software (Realworks Survey). The original scanning resolution for measurements immediately after placement did significantly contribute to the necessary level of detail or accuracy, so in the future, a point every 5 mm at the maximum distance would be sufficient for measurements immediately after placement; moreover, the overlap of these scanning positions in this type of measurements increases the point density to a level comparable with the control measurements. This resolution offers enough details to filter and extract the point clouds and to automatically identify the white-and-green targets by the software (Realworks Survey). The used terrestrial laser scanner specifications mention a 12 mm position accuracy at 100 m and a 7 mm distance accuracy at 100 m. The standard deviation of Trimble targets acquisition is <1 mm. The modelled surface precision is ± 2 mm.

The length of single tunnel is about 332 m and two scanning trips (lines of scanning position) are laid in parallel cross both tunnel. To cover the whole tunnel section during the CN measurement and to limit the incidence vacancy of the tunnel point cloud, sixteen scanning positions are needed, taking into account the field of view specifications of the used terrestrial laser scanner. Redundant observations are obtained outside the tunnel. The specific conditions for the scanning positions and targets, illustrate the schematic diagram of the scanning positions and the locations of the targets and the schematic diagram of registration, shown in Figure 5. All scanning positions are eventually shown as the chain distribution, ensuring the greatest degree of reliability for the scanning position registration based on CN method. To ensure the stability of the local scanning position registration, at least four targets (two back targets and two front targets) are laid between the two adjacent scanning

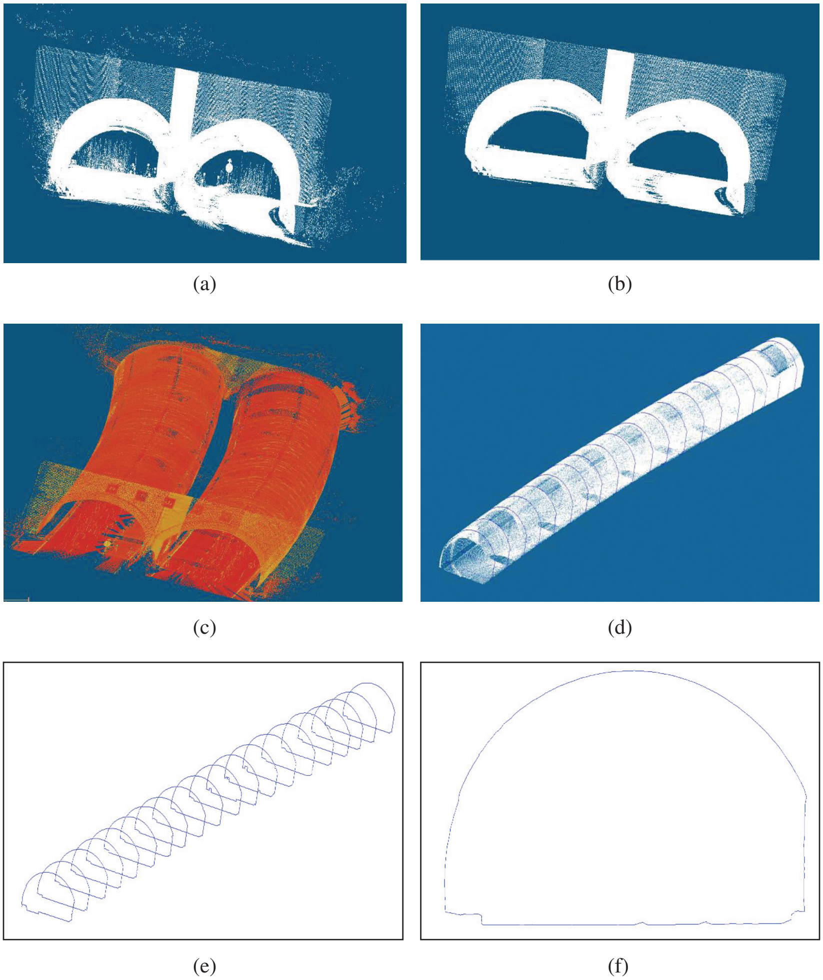

FIGURE 6
Extraction of the tunnel lining cross-section with point cloud processing: (a) original tunnel point cloud; (b) tunnel point cloud after filtering process; (c) bird's-eye view of twin tunnels point cloud; (d) cross-sections fitting of the tunnel point; (e) overview of all extracted cross-sections; and (f) enlarged view of single tunnel lining cross-section.

positions. The spatial locations of the targets are evenly distributed and considered in the scanner angle of incidence in the layout process for the targets.

The process of extraction of tunnel lining cross-sections include three steps as follows:

(i) Registration for all point clouds of scanning stations, noise points from wires and pipelines are clearly present in the data (*cf.* Figure 6(a));
(ii) Filtering the original tunnel point clouds, resulting in pure point cloud without any noise (*cf.* Figure 6(b)); and

(iii) As mentioned in Section 2, our proposed algorithm can theoretically extract tunnel lining cross-sections at any interval from the terrestrial point clouds (*cf.* Figure 6(c)). We implemented the cross-section extraction experiments at a 15 m interval. The total computational cost of the cross-section extraction was less than 20 minutes. The candidate cross-sectional points were extracted using the straight line that was orthogonal to the centrelines of the tunnel within a vertical plane at a 1^{o} interval (see Figure 6(d)). An overview of all extracted cross sections is shown in Figure 6(e). For tunnel inspectors, besides the acquisition, processing and recording of data, it is decisive to have an easy access to the latter. In this scope, if an exhaustive assessment of the structure had been performed, all details with tunnel identified can be output from the tunnel lining cross-sections model, with all relevant information linked. This geometric reference model can be later consulted using a user-friendly graphic interface. To serve as example, Figure 6(f) shows a reference image of the identified detail information incorporated in the tunnel lining cross-sections model obtained by TLS.

4 CONCLUSIONS

An approach of the method developed by terrestrial laser scanning (TLS) technology, aiming at extracting concrete tunnel lining cross-section, has been demonstrated herein. The overall tunnel linings pattern can be obtained and recorded using this automated and efficient method. The local analysis of the extracted tunnel cross-sections allows measurement of their width, length and orientation. These features show that the proposed method can be an important aid in the definition and optimization of maintenance interventions of concrete tunnels. Compared to traditional methods, the main advantage of developed method is the automatic processing of information, resulting in higher speed, efficiency, reliability and both quantity and quality of data. In addition, a comprehensive database is created and can be recorded in geometric reference models.

TLS technology requires access for positioning the reference stations and an exhaustive survey of the structure, which involves the use of various survey lengths to reach the required resolution. The terrestrial laser scanning proved to be suitable for the geometry survey of structures and build geometric reference models, including information regarding reference points, essential for details characterization. Presently, the method is applied to exposed concrete surfaces and presents the following main limitations: (i) the nonoperation on surfaces with dirty stains that hide details of survey object; and (ii) the exhaustive scan survey needed to achieve the required resolution. In the first case, the limitation is transverse to all existing methods. In the second case, the use of robotized equipment for data acquisition, such as an unmanned aerial vehicle (UAV), represents an attractive and cost-effective tool. Still, the significant technical challenges and the definition of proper protocols, in order to ensure the required precision and accuracy of results, are currently under evaluation.

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