A FAST AND AUTOMATED METHOD FOR EXTRACTING TUNNEL CROSS-SECTIONS USING TERRESTRIAL LASER SCANNED DATA

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ABSTRACT: In tunnel construction, overcut along with undercut estimation is one of the most important factors to be considered before proceeding to the next operation. It is currently analyzed based on sparsely sampled points surveyed using a total station, but not much time is allowed for surveying and analyzing for economic reasons. A fast and automated method is presented to extract dense tunnel cross-sections using Terrestrial Laser Scanner (TLS) data. A 3D point cloud acquired from the TLS is converted to a two-dimensional planar image and skeletonized to estimate the tunnel centerline. Cross-sections are extracted orthogonal to the centerline. To evaluate the performance of the proposed method, it was applied to actual tunnel data and compared with the results from a conventional method using a total station. In the results, the cross-sections were extracted at center points corresponding to those of the conventional method. The proposed method proved itself to have advantages in terms of its ability to offer a detailed description and improve the efficiency of the processing time.

Keywords: *Terrestrial Laser Scanner, Tunnel, Cross-Section, Point Cloud, Hashing*

1. INTRODUCTION

The precise modeling of structures both under construction and after completion is important as it can be advantageous for those involved in construction management and assessment. The modeling should be done quickly and economically to keep up with the continually changing nature of construction sites. In the construction of tunnels, overcutting and undercutting are important factors to be estimated before proceeding to the next operation. These estimations are currently done based on sparsely sampled points surveyed using a total station. This approach requires a considerable amount of time. However, not much time is permitted for surveying and analyzing in construction sites. Another approach is based on triangulation using stereo images or a single image supplemented by line laser devices [1, 2]. Results from this approach prove that more sufficient points along a profile can be extracted faster. The precision can be, however, influenced by the imaging environment and automation is not easily achievable. At present, devices known as Terrestrial Laser Scanners (TLS) are receiving more attention in related fields due to their automated, swift and dense scanning capabilities [3-6]. The very large size of the scanned data is, however, a barrier to a fast process, and automation is not fully applicable in many cases. In the present study, a fast and automated method is presented to extract dense tunnel cross-sections using TLS data. The 3D point cloud acquired from the TLS is converted to a two-dimensional planar image and skeletonized to estimate the tunnel centerline. For efficient processing, the point cloud is loaded into a hashing-based indexing structure and searched to extract cross-sections orthogonal to the centerline. To evaluate the performance of the presented method, it was applied to an actual tunnel. The results were and compared to those of a conventional method using a total station.

2. METHODOLOGY

The proposed method is divided into two sections: estimation of the tunnel centerline, and extraction of the cross-sections. The overall flow of the method is shown in Figure 1.

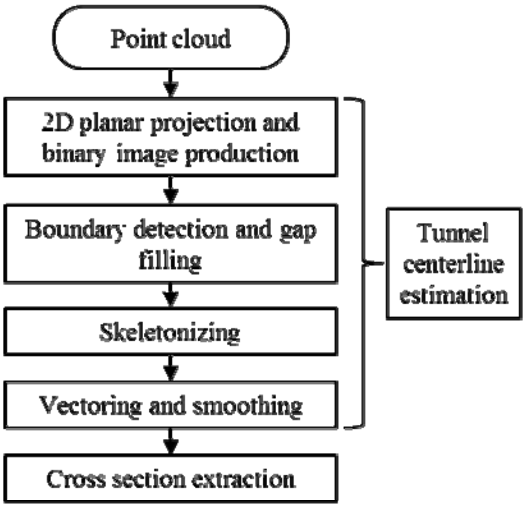

Fig. 1 Flow of the proposed method

2.1 Estimation of the Tunnel Centerline

Skeletonizing methods, popular in computer vision, medical visualization and feature representation, are applicable to centerline estimations of tubular objects. Tunnels, in general, have a tubular shape and can be simplified to a narrow and longish 2D object if projected onto a horizontal plane. A 3D point cloud of a tunnel, in the present study, is thus projected onto a 2D grid on a horizontal plane, and a binary image is created from the grid. A number of delicate methods [7-10] are applicable to a binary image to produce a skeletonized image that is 1 pixel thick. An open source code implemented in OpenCV was found to be useful in the present study. Before skeletonizing, any gaps in the binary image of the type that frequently occur due to occlusions during scanning should be removed unless a mass of coarse line segments is to be produced (Figure 2). For the reason, a boundary was traced from the binary image and filled in to produce a gapless image (Figure 3).

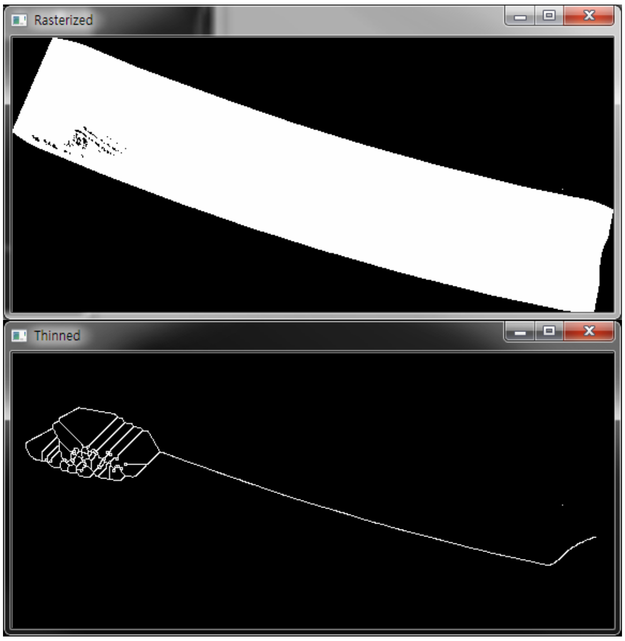

Fig. 2 Binary image containing gaps (upper) and skeletonized result of the image (lower)

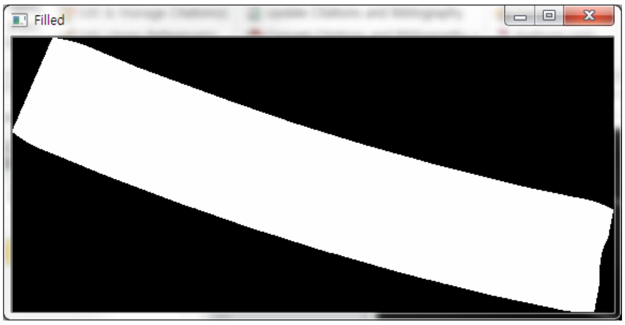

Fig. 3 Gap-filled image after boundary tracing

The result from skeletonizing, however, needs to be refined with a manual operation or with more complicated methods, as undesired line segments are frequently produced at the end of branches, which are common among other known methods (Figure 4).

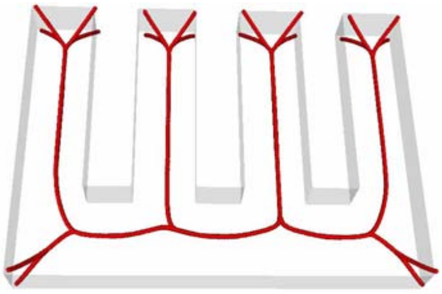

Fig. 4 A skeletonized result from [10]

The skeletonized image is vectorized to obtain the initial centerline, and the centerline is smoothed to straighten any over-bending segments (Figure 5). In the present study, vectorizing along with refining unwanted segments on the skeletonized image was done with ArcScan [11], an extension module of ESRI ArcMap. The method chosen for smoothing was Polynomial Approximation with an Exponential Kernel (PAEK) [12] as implemented in ESRI ArcToolbox.

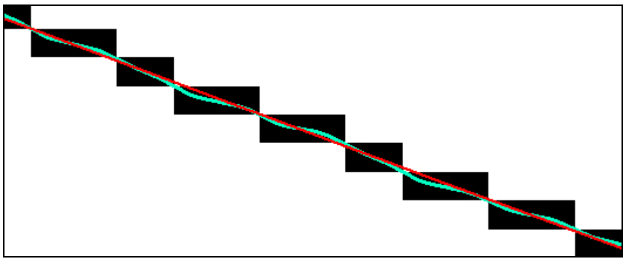

Fig. 5 Vectorizing and smoothing: the wavier line denotes the vectorized result of the 1-pixel skeletonized image, whereas the less wavy line denotes the smoothing result.

2.2 Extraction of Cross-Sections

Center points are estimated by evenly distributing points along the estimated centerline. Cross-sections are then extracted from the center points orthogonal to the centerline with a width *d* (Figure 6). To speed up the process, a hashing-based structure was adopted to index the point cloud. It restricts the search space to the finite colored cells shown in Figure 5. A hashing-based structure is defined as a 2D array of hashes (Figure 7). A hash stores a finite number of linked lists which cover evenly divided volumes in the vertical direction. A point can be retrieved from or inserted into a linked list which is searched with a key encoded from the z coordinate of the point of interest. The planar coordinates (*u, v*) and the key of a hash containing the point (x, y, z) are defined as follows:

$$u = Integer((x - x_{\min}) / n_{CS})$$
$$v = Integer((y - y_{\min}) / n_{CS})$$
$$k = Integer((z - z_{\min}) / n_{CS})$$

Here, ($x_{\min}$, $y_{\min}$, $z_{\min}$) denotes the minimum coordinates of the point cloud and n_{CS} refers to the size of the volume covered by the hash.

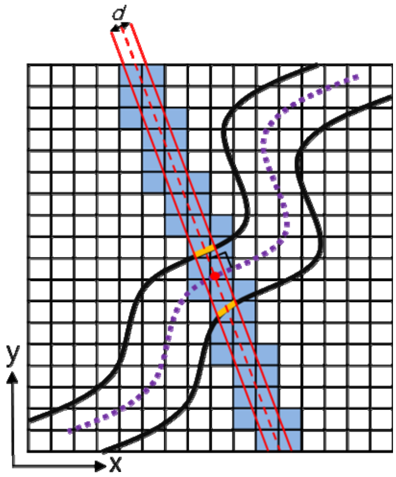

Fig. 6 Cross-section extraction

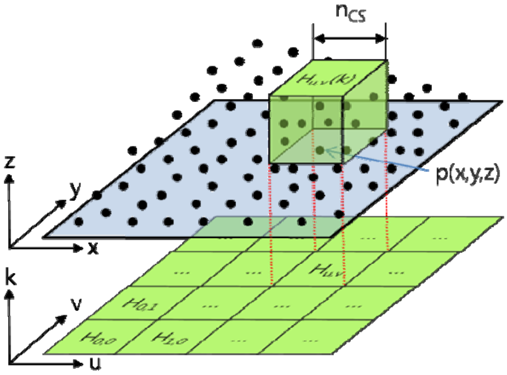

Fig. 7 Hashing-based structure

3. APPLICATION

The proposed method was applied to a point cloud scanned in a real tunnel. For comparison, the tunnel was again surveyed with a total station. Specifications of the test are shown in Table 1. The shape of the point cloud is depicted in Figure 8.

17 center points, using a total station, were surveyed and marked along the road centerline at 2m intervals (about 1.986m in horizontal distance). Each cross-section was surveyed by observing 21 points at 10° intervals from -10° to 190° from each center point.

The point cloud obtained by TLS was projected onto a horizontal plane and converted into a binary image of which the pixel size was 0.02 in x and y directions. Gaps in the image were removed with boundary tracing and filling inside the boundary. The binary image was skeletonized (Figure 9) and was vectorized to build a polyline between two ending points which had been manually selected. The polyline was smoothed to extract a series of vertices to represent the final centerline (Figure 10). Center points of the cross-sections were selected along the centerline at 1.986m intervals from a point at which the total station surveying was started. Finally, the cross-sections were extracted at a thickness of 1cm at the center points orthogonal to the centerline.

Table 1 Specifications of the Test

TLS	Scan Station 2, Leica Geosystems
Total station	GTS9001A, Topcon
Tunnel location	Sejong-Si, South Korea
Tunnel design (along centerline)	Length = 55.82m Radius of curvature = 252.50m Width = 10.52 m
Total station surveying	No. of observation: 17 (inside tunnel) No. of points: 21 points/station Surveying mode: non-prism
Laser scanning	No. of observations: 3 (2 outside and 1 inside tunnel) No. of points: 18,376,726 points (at least 1 point/2㎝*2㎝)
Processing environment	CPU: Intel Core2Duo E8200 (2.66GHz) Memory: 8.00GB OS: Windows 7 64-bit Tools: Visual Studio 2005, ArcGIS 9.3

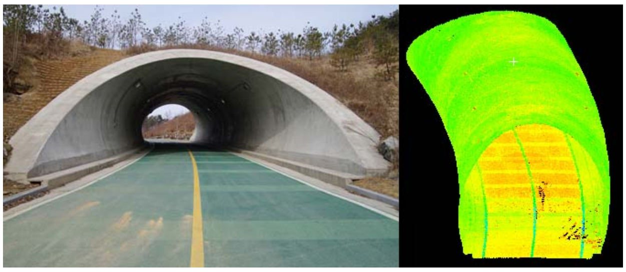

Fig. 8 Test tunnel

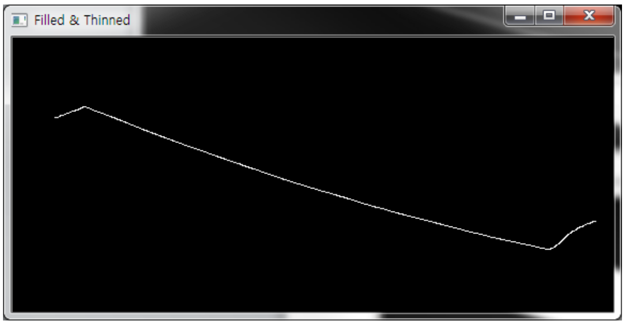

Fig. 9 Skeletonized image

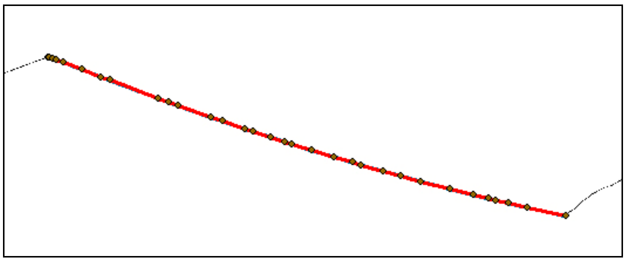

Fig. 10 Representative vertices of the centerline

Center points selected by the proposed method were compared with those of total station surveying (Table 2). The RMSEs of the planar discrepancies were estimated as 0.0176m in the x direction and 0.0462m in the y direction. The center points of the proposed method do not exactly coincide with but correspond within allowable limits to those of total station surveying. From the result, however, it cannot be concluded that the center points of the proposed method are accurate, as the center points of total station surveying were selected along a road centerline which does not necessarily coincide with the exact centerline.

Table 2 Comparison of the Center Points (unit: meter)

	TLS		Total station		Discrepancy	
ST	x	y	x	y	dx	dy
1	107.1956	99.1614	107.1956	99.1614	0.0000	0.0000
2	109.0701	98.5175	109.0508	98.4574	-0.0193	-0.0601
3	110.9377	97.8430	110.9100	97.7672	-0.0277	-0.0758
4	112.8065	97.1715	112.7786	97.1046	-0.0279	-0.0669
5	114.6859	96.5319	114.6556	96.4558	-0.0303	-0.0761
6	116.5666	95.8952	116.5408	95.8288	-0.0258	-0.0664
7	118.4511	95.2693	118.4292	95.2148	-0.0219	-0.0545
8	120.3413	94.6611	120.3258	94.6232	-0.0155	-0.0379
9	122.2422	94.0876	122.2272	94.0406	-0.015	-0.047
10	124.1448	93.5192	124.1382	93.4974	-0.0066	-0.0218
11	126.0483	92.9540	126.0516	92.9656	0.0033	0.0116
12	127.9610	92.4213	127.9632	92.4228	0.0022	0.0015
13	129.8781	91.9037	129.8770	91.8912	-0.0011	-0.0125
14	131.7936	91.3807	131.7976	91.3818	0.004	0.0011
15	133.7112	90.8649	133.7200	90.8820	0.0088	0.0171

16	135.6377	90.3836	135.6430	90.3992	0.0053	0.0156
17	137.5709	89.9302	137.5750	89.9386	0.0041	0.0084
RMSE					0.0176	0.0462

The cross-sections from the proposed method include even more points than those from total station surveying (Table 3). This implies that the proposed method provides a more detailed description of the scene, as shown in Figure 11.

Table 3 No. of Points in the Extracted Cross-Sections

ST	TLS	Total station	ST	TLS	Total station
1	1584	21	10	10791	21
2	1193	21	11	4703	21
3	1242	21	12	2403	21
4	1264	21	13	1840	21
5	1715	21	14	1463	21
6	2629	21	15	1340	21
7	4939	21	16	1494	21
8	11822	21	17	1459	21
9	22055	21	Total	73936	357

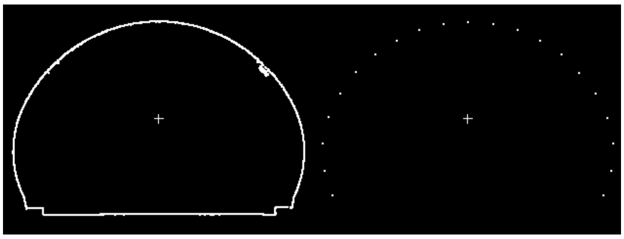

Fig. 11 Extracted cross-section at station 11 (left: TLS, right: total station)

Surveying and processing times are shown in Table 4. Most of the time was required for the surveying activities, while data processing required relatively less time. Some operations were not considered, as they can vary according to the skillfulness of the operator.

The overall time consumption of the proposed method was estimated to be less than half that of total station surveying. If more cross-sections are to be extracted, however, the gap is expected to widen. To extract 64 cross-sections, for example, no more surveying is necessary for the proposed method. More time is only necessary for cross-section extraction – from 6 seconds to 10 seconds. To extract the same number of cross-sections with total station surveying, a major time increase will arise during cross-section surveying, from 255 (=15x17) to 960 (=15x64) minutes.

Table 4 Surveying and Processing Times (unit: minute)

	TLS		Total station	
Surveying	Outside scanning	45(=25+20)	Center point selection	60
	Inside scanning	85	Cross-section surveying	255 (=15x17)
	Instrument installation	not estimated	Instrument installation	not estimated
Processing	Scan registration	not estimated	Reporting results	not estimated
	2D projection to skeletonizing	<1		
	Manual editing to vectorizing	5		
	Smoothing to centerline completion	<1		
	Cross-section extraction	<1		
Total		138		315

4. CONCLUSIONS

Terrestrial Laser Scanners (TLS) are becoming more popular in tunnel surveying, but the considerable size of the scanned data and difficulties in automation remain as problems to be solved. A fast and automated method is presented here to extract dense tunnel cross-sections using TLS data. To evaluate the performance of the proposed method, it was applied to a real tunnel, and the results compared with those of a conventional method using a total station. In the results, the center points of the cross-sections could be extracted from the corresponding locations of the conventional method. The proposed method proved to have advantages in that it offers a detailed description and saves time.

The authors are currently considering a strategy to adjust the center points of cross-sections using the extracted cross-section points themselves. A more thorough assessment of the method proposed here is also being considered in which the centerline is surveyed more accurately through the use of planned drawings.

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