Earthwork Volumes Estimation in Asphalt Pavement Reconstruction Using a Mobile Laser Scanning Systerm

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***Abstract* — This paper presents a novel method for estimating earthwork volumes in asphalt pavement reconstruction using a mobile laser scanning (MLS) system. First, based on the static targets, this method registers two point cloud datasets into the same coordinate system, which respectively are acquired in the reconstructing road before and after asphalting. Next, road surface points are detected from each point cloud using a curb-based method, and further divided into a set of blocks. Afterwards, the blocks are perpendicularly partitioned into grids, where two surface features are extracted using the RANSAC. Finally, the volume of each grid is calculated according to these two surface features. The proposed algorithm has been tested on two sets of point clouds acquired by a RIEGL VMX-450 MLS system in the reconstructing road before and after asphalting. The results demonstrate the accuracy and efficiency of the proposed algorithm in estimating earthwork volumes.**

Index Terms – Mobile laser scanning, point cloud, earthwork volume estimation, asphalt pavement reconstruction, road surface detection

I. Introduction

Earthwork volumes based on which contractors are paid for highway construction are usually used in determining the economic distribution of earthwork [1]. It is one of the most important components in estimating highway construction costs. Accurate estimation of earthwork volumes is essential because disagreements on the estimated volumes often cause the owner and the contractor to look to courts for settlement [2]. Therefore, a good method for accurately estimating earthwork volumes is essential.

Many models for accurately estimating earthwork volumes have been intensively studied in literature. The average end area model and prismoidal model [3] were commonly employed for estimating earthwork volumes. The prismoidal model gave an exact volume for linear profiles, while the average end area model generally overestimated the volume. A mathematical model that provided the exact volume of curved roadways with linear profiles between stations was developed in [4]. Based on triple integration, this model assumed that the ground cross slope was constant between stations. In [5], a Monte Carlo based model was proposed for estimating earthwork volumes of curved roadways. Using terrestrial laser scanning (TLS) technology, a detailed model before and after construction was created in [6], and earthwork quantities were calculated by comparing the triangular irregular network (TIN) of the original terrain to that of the accomplished project. 3D laser scanning and global positioning system (GPS) were used to acquire landslide data and to compute earthwork volumes in [7]. In this method, original 3D contour of the area and the landslide digital terrain model (DTM) were first obtained, and the DTM based on the base point was overlapped to the original contour at the same coordinate position and direction. Next, the volumes of collapse were estimated by the difference between the terrain features before and after landslide.

In recent years, the society has witnessed a rapid development of mobile laser scanning (MLS) systems which can acquire dense and accurate point cloud data with high pulse repetition rates. The MLS has been successfully used in many fields such as industries, arts, and engineering, due to its capability of acquiring data accurately and densely [8], [9]. The benefits of using laser scanners on construction field are the rapid raw data acquisition, easy levelling process, fewer human errors, and reliable reference for engineers. Therefore, MLS techniques are suitable for this study to compute earthwork volumes.

In this paper, we propose a novel method for estimating earthwork volumes from MLS point clouds. First, two point cloud datasets are respectively acquired by the RIEGL VMX-450 MLS system in the reconstructing road before and after asphalting. For estimating the whole earthwork volumes, the two point clouds are then registered into the same coordinate system based on the static targets coexisting in both point clouds. Next, a curb-based method [10] is used to detect road surfaces for each point cloud and further divide them into blocks. Afterwards, each block is perpendicularly partitioned into a set of grids, where two surface features are extracted using the RANSAC [11]. Finally, the volume of each grid is calculated according to these two surface features. The experimental results demonstrate the accuracy and efficiency of the proposed algorithm in estimating earthwork volumes from MLS point clouds.

II. Methodology

The proposed method contains four steps: registration, road surface detection, surface feature extraction, and earthwork volume calculation.

A. *Registration*

The two point clouds are collected in different missions, and the environments, sensors, scanning trajectories, and the positions of the GPS base station are all different, thereby resulting in coordinate misalignment in the resultant point cloud data. Therefore, the two point clouds need to be registered at first. Let $P = \{p_1, p_2, \dots, p_n\}$ and $Q = \{q_1, q_2, \dots, q_m\}$ be two point clouds in R^3. The goal of the registration algorithm is to find a rigid body transform α composed of a rotation matrix R and a translation vector t that best aligns the data Q to the model P. Hence, the new data $Q' = \{q_1', q_2' \dots, q_m'\}$ can be calculated as:

$$q_i' = Rq_i + t \qquad i = 1, 2, \dots, m \tag{1}$$

Here, we select the same static targets, such as signposts, bus stations, and light poles, from these two point clouds as references to align them into the same coordinate system, as shown in Fig.1, (a) and (b) show two point cloud datasets, from which the rigid body transform can be calculated using four group points; (c) displays the result of registration. After registration, the two point clouds are transformed into a consistent global coordinate framework.

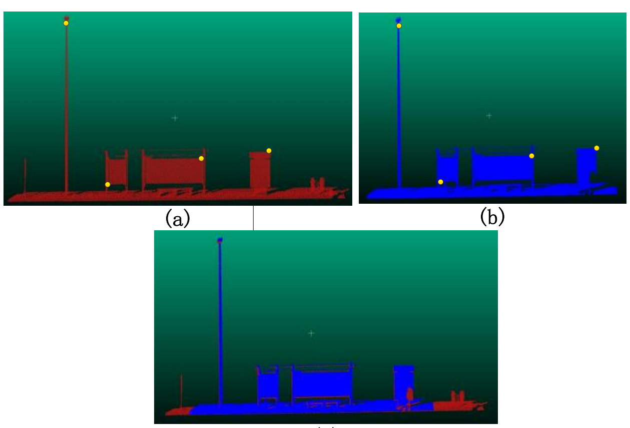

Fig. 1. Point cloud registration: (a) and (b) two point clouds with the same static targets (colored in yellow) coexisting in both of them, and (c) the registration result.

B. *Road surface detection*

In this paper, we apply a curb-based method for extracting road surfaces [10]. This method first uses the vehicle trajectory data to cross-section the raw MLS data into a set of blocks $Block_i$ (i=1,2,…,n) at a constant interval (R_t). Within each $Block_i$, a corresponding profile $profile_i$ is transversely sectioned with a certain width (W_g). Then, curb corners are estimated via slope and elevation-difference thresholds to separate road from non-road points within each profile. A mathematical formula can be described as follows:

$$\forall p_i : \begin{cases} if\,(S_{slope} > S_T)\,\&\,(G_{\min} \le G_i \le G_{\max}) & curb\ candidate \\ otherwise, & non\text{-}curb\ point \end{cases} \tag{2}$$

where S_{slope} denotes the slope of two consecutive points; S_T is a given slope threshold; G_i denotes the elevation-difference of a point and its neighbour; $G_{\min}$ and $G_{\max}$ are the minimum and maximum thresholds.

After identifying all curb corners from the profiles, a B-Spline fitting algorithm is applied to generate two smooth road edges. Finally, road surfaces are separated from non-road points based on the fitted road edges. A visual example of the detected road candidates is shown in Fig. 2, where (a) shows a raw MLS data and (b) illustrates the segmentation result of road and non-road points.

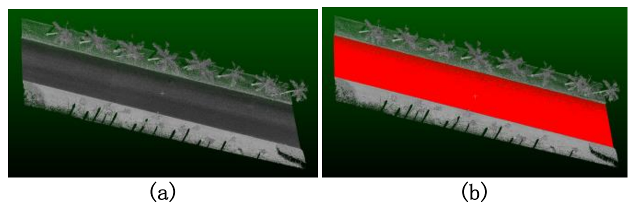

Fig. 2. Illustration of road surface segmentation result: (a) a raw MLS data and (b) the segmentation result of road and non-road points.

C. *Surface feature extraction*

After registration and road surface detection, the two point clouds are partitioned into a set of blocks with consistent global coordinate framework and two road surfaces.

Within each block, we first select the points belonging to the point cloud dataset acquired in reconstruction road after asphalting. The plane fitted by these points using the RANSAC [11] is selected as the base plane. Then, we transform the normal of the base plane to the z-axis of the coordinate system. Next, the merged road surface data are vertically partitioned into grids $grid_j$ in the XY-plane, as shown in Fig. 3. Finally, the RANSAC is used to detect these two plane shapes in each grid, as shown in Fig. 4.

After this step, the surface features composed of the width w, length l, and two plane normals F_1, F_2 in $grid_j$ of the block can be determined.

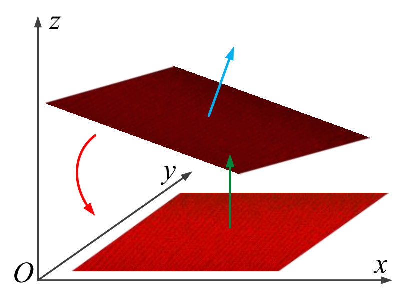

Fig. 3. A base plane whose normal was transformed to z-axis of the coordinate system.

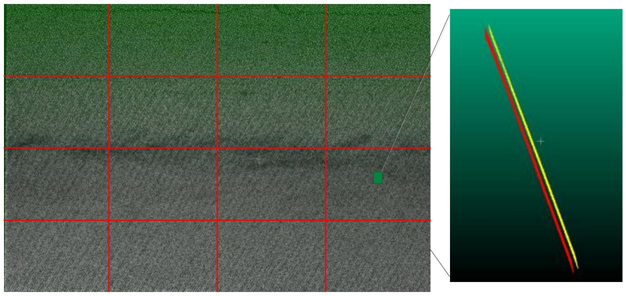

Fig. 4. Illustration of road block grid partition (left) strategy and two road surface profiles of a grid (right).

D. *Earthwork volume calculation*

The earthwork volumes can be calculated based on the extracted surface features in each grid. The angle between these two surfaces is calculated as follows:

$$\theta = \cos^{-1}\left(\frac{\| F_1 F_2 \|}{\| F_1 \| \| F_2 \|}\right) \tag{3}$$

where F_1 and F_2 are normal vectors of these two surfaces. If $\theta < 5^{\circ}$, these two surfaces are regarded as parallel, as show in Fig. 5. Then, the volume V_j of the jth grid is calculated as follows:

$$V_j = lwh \tag{4}$$

where l and w are the length and width of the grid, respectively; h denotes the thickness of the asphalt concrete. Otherwise, these two surfaces are not parallel, as show in Fig. 6. Then, the volume V_j of the jth grid is calculated as follows:

$$V_j = \frac{lw}{4}(h_1 + h_2 + h_3 + h_4) \tag{5}$$

where h_1, h_2, h_3, and h_4 denote the heights of AE, BF, CG, and DH, respectively. After the volume of each block is calculated, the whole earthwork volumes are calculated as follows:

$$V = \sum_i \sum_j V_j \tag{6}$$

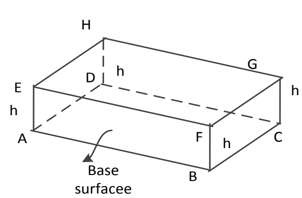

Fig. 5. A block with two parallel surfaces.

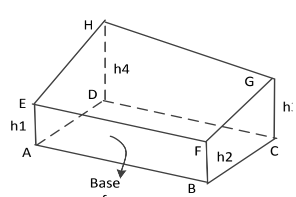

Fig. 6. A block with two unparallel surfaces.

III. Results and Conclusion

Two point cloud datasets acquired by the RIEGL VMX-450 system were used to test the proposed method. These two surveys were respectively conducted in a section of urban reconstruction road before and after asphalting in Xiamen, a port city in southeast China. Fig. 8 shows the survey scene images and the corresponding point clouds.

The RIEGL VMX-450 MLS system is integrated with 2 RIEGL VQ-450 laser scanners, an IMU/GNSS unit, Distance Measurement Indictor (DMI), and four high-resolution cameras, as shown in Fig. 7. The two scanners are symmetrically configured on the roof of the vehicle with a "Butterfly" configuration pattern whose field of view is 360 degrees and accuracy is within 8 mm (1 sigma standard deviation) with a maximum effective measurement rate of 1.1 million points per second and line scan speed of up to 400 scans per second. The average density of the point clouds on the road surface is approximately 4000 points/m^2. Therefore, these point cloud data provide promising data source for computing road thickness for earthwork volume estimation.

Fig. 7. The RIEGL VMX-450 MLS system.

To estimate earthwork volumes, two point clouds were selected from the surveyed data respectively acquired in the same section of a reconstruction road with a distance of approximately 1 km along the road. We adopted the WGS84 coordinate system for both point cloud datasets. As we known, the WGS84 coordinate system is a unified geodetic system for the whole world; therefore, we can rapidly calculate a rigid body transform α to align these two datasets by selecting several corresponding point pairs. After registration, the two point clouds were transformed into a consistent global coordinate framework. Then, a curb-based method was used to detect road surfaces and divided the road surface point cloud into a group of blocks. According to the sensitivity analysis, we kept R_t = 160, S_p= 0.05m, W_g = 0.2 m, G_{min} = 0.08 m, and G_{max} = 0.3 m for road surface detection. Next, we fitted a base plane using the RANSAC and transformed the normal of the base plane to the z-axis of the coordinate system. After coordinate transformation, each block was partitioned into a 4×4 grid with a 2-meter width and 2.5-meter length approximately. Finally, we applied the RANSAC again to detect surface features for each grid.

Using the formulas for calculating volumes, the whole earthwork volumes of the test data were estimated. Based on these two datasets, the earthwork volumes estimated using our proposed method was 440.955 m^3.

Many errors will affect the accuracy of the estimated earthwork volumes, such as manholes in the road, the rough surface of the road before asphalting, and the error of calculating the asphalt thickness. Among these errors, the error occurring in calculating the asphalt thickness is the most prominent. To verify the accuracy of the proposed method in measuring the thickness of the asphalt layer, a simulated experiment was conducted. Two point clouds were successively acquired using the RIEGL VMX-450 MLS system, and a cuboid-shaped stone was simulated as the asphalt layer of the road after asphalting, as shown in Fig. 9. Through accurate manual measurement, the thickness of the stone is 0.1013 m. By using the proposed method, the thickness of the stone is measured as 0.09677 m. Therefore, the simulated experiment demonstrated that our proposed method achieved a millimeter-level accuracy in estimating asphalt road thickness.

As seen from the results, we conclude that the proposed algorithm performs well and achieves an acceptable estimation. In addition, the proposed algorithm was implemented using C++ and executed very fast. Therefore, the proposed method can outperform the traditional surveying methods for accurately estimating earthwork volumes.

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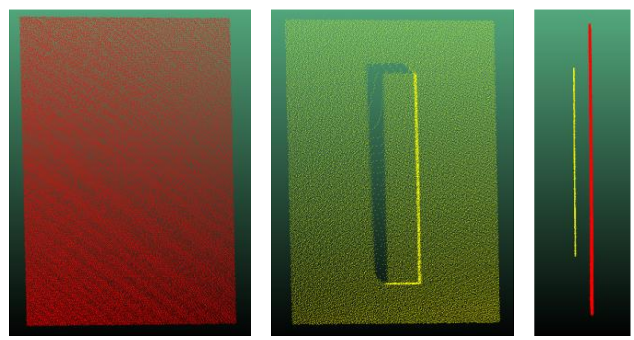
Fig. 8. Scene images and the corresponding point clouds acquired before (top) and after (bottom) asphalting.



(a) (b) (c)

Fig. 9. Point cloud data for the simulated experiment: (a) the point cloud simulated as road surface before asphalting, (b) the point cloud simulated as road surface after asphalting and (c) two surface profiles detected using the proposed method.