3D laser scanning and surveying adjustment in traffic infrastructure management

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Abstract: In view of difficulties in automatic and refined management of traffic infrastructure, road lamps and signboard in the test road section are taken as examples, an application framework for automatic and refined management of traffic infrastructure is proposed by using 3D laser scanning technology combined with GPS (Global Positioning System) and QGIS (Quantum Geographic Information System). The advantages of 3D lidar sensor, such as high precision, strong anti-interference ability and good real-time performance are fully used. Through data fitting by using total least squares method, digital management of infrastructure is carried out and its precision is high. Combined with GPS and QGIS, the spatial information of infrastructure is developed. In this way, manpower and efficiency of management of infrastructure are saved and improved.

1. Introduction
At present, low degree of automation and refinement are problems of traffic infrastructure management. The traditional manual detection is time-consuming and laborious, and the degree of automation and refinement is not enough, which can not meet the development needs of traffic infrastructure management in the future. As a new data acquisition way, 3D laser scanning technology has the advantages of high precision, good real-time performance, strong anti-interference ability and high efficiency[1], which is widely used in road point cloud segmentation[2], calculation of forest canopy area[3], landslide analysis[4], and analysis of tunnel deformation monitoring[5], etc. However, there is little research on the application of 3D laser scanning technology in traffic infrastructure automation and refinement management. In reality, many tests rely on manpower. For the reason above, application framework of 3D laser scanning technology in traffic infrastructure management is designed, which focuses on using advanced 64-line 3D lidar sensor equipment to collect point cloud and processing the point cloud data. Data processing is divided into two aspects, one is fitting the point cloud data of transportation infrastructure, getting its state equation in space, and recording it in digital form. The other is calculating the geographical location of transportation infrastructure, recording and managing the location information by combining GPS and QGIS.

There are some advantages of this framework as follows:
(1) Compared with two-dimensional camera, the data collected by the 3D lidar sensor contains depth information and strength information, which is more comprehensive and rich, and data quality and accuracy are also higher. Moreover, the 3D lidar sensor is not affected by light and has better environmental adaptability; and
(2) Compared with modeling, data fitting can extract more information of traffic infrastructure; compared with RFID (radio frequency identification) technology\cite{6}, the real-time performance of this technology is better, and the status information of infrastructure can be updated in real time; and
(3) Combined with GIS and GPS technology, not only the storage and management of traffic infrastructure data is more convenient, but also the spatial information can be utilized, which provides great convenience for managers.

2. Methods

The structure design of framework proposed in this paper is shown in Figure 1. The whole framework is composed of three layers: perception layer, network layer and application layer. The perception layer belongs to the device side, which is the front end of the overall framework. 3D lidar sensor collects the point cloud, which will be transmitted to the network layer. The network layer belongs to the algorithm side, which is the data processing part. One part of data processing is data fitting. The total least squares method is taken as the fitting criterion, the point cloud data is fitted and the central coordinate information will be extracted. The other one part is calculating the geographical location. Combined with GPS, the spatial position information can be obtained and transmitted to the application layer. The application layer belongs to the platform side, storing the traffic infrastructure information and facing to the managers.

![Figure 1](image1.png)

**Figure 1** Overall structure of traffic infrastructure management application framework

2.1. Perception layer

2.1.1. 3D lidar sensor

The perception layer is responsible for information acquisition of traffic infrastructure. Main equipment used in the perception layer is a 64-line lidar sensor, the model is HDL-64E. The physical image of lidar sensor is shown in Figure 2.

![Figure 2](image2.png)

**Figure 2** Physical picture of HDL-64E

The sensor is composed of upper and lower two laser blocks, 64 laser transmitters and 64 laser receivers totally. The upper and lower laser blocks are respectively equipped with 32 laser transmitters and 32 laser receivers. The laser transmitters are divided into two parts and assembled on both sides of
the 32 laser receivers. The upper and lower laser blocks rotate as a whole. The performance parameters of the lidar sensor are shown in Table 1.

| Parameters of lidar sensor |
|-----------------------------|
| Lidar sensor model          | HDL-64E               |
| Horizontal perspective      | 360°                  |
| Horizontal angle resolution | 0.08° ~ 0.35°         |
| Vertical view               | -24.8° ~ 2°           |
| Vertical angle resolution   | 0.4°                  |
| Perspective update rate     | 5Hz ~ 20Hz            |
| Measurement points per second | 1300000 ~ 2200000  |
| Measuring range             | 120m                  |

2.1.2. Visualization tool of point cloud: Veloview
Veloview is a kind of point cloud data reconstruction software, which can visualize and process 3D data captured by HDL-64E in real time. The measurement results of lidar sensor are returned in 3D position information and attribute data, such as laser ID, point ID, azimuth, timestamp, etc. The real-time point cloud image displayed by lidar sensor in veloview is shown in Figure 3. As can be seen from Figure 3, in addition to the real-time point cloud image, the point ID, 3D coordinates (X, Y, Z), azimuth, distance, intensity, laser ID, vertical angle and other information can also be checked.

2.2. Network layer

2.2.1. Criterion of data fitting
As for data fitting, traditional least squares (LS) method only considers the measurement error of the observation value. For the data measured by the lidar sensor, there are measurement errors existing in both coefficient matrix and observation value, so the traditional least squares method can not be used as the fitting criterion, but the total least squares(TLS) method is appropriate, which considers both measurement errors [7]. The difference is shown in Figure 4.
2.2.2. Total least square model and its solution

As for linear equation system $BX = L$, the error of coefficient matrix $B$ is set $E_B$, and the error of observation $L$ is set $E_L$. In this case, the linear equations can be written as:

$$ (B - E_B)X = L - E_L $$

Equivalent to:

$$ ([B \ L] - [E_B \ E_L]) \begin{bmatrix} X \\ -1 \end{bmatrix} = 0 $$

Among formula (2), $B \in R^{m \times n}$, $L \in R^{m \times 1}$, $X \in R^{n \times 1}$, $\text{rank}(B) = n < m$. $m$ is the number of observation value and $n$ is the number of unknown parameters.

Set $C = [B \ L], \Delta = [E_B \ E_L]$, formula (2) can be written as:

$$ (C - \Delta) \begin{bmatrix} X \\ -1 \end{bmatrix} = 0 $$

Singular value decomposition of $C$ can get:

$$ C = U \Sigma V^T $$

Among formula (4), $U = [\bar{u}_1 \ \cdots \ \bar{u}_m] \in R^{m \times m}$, $V = [\bar{v}_1 \ \cdots \ \bar{v}_{n+1}] \in R^{(n+1) \times (n+1)}$, $\Sigma = diag\{\sigma_1, \cdots, \sigma_{n+1}\}$, $\sigma_1 \geq \cdots \geq \sigma_{n+1} > 0$. The rank of augmented matrix $C$ is $n+1$ because $\sigma_{n+1} \neq 0$. According to Eckart-Young-Mirsky matrix approximation theorem [8][9], The best approximation matrix $[[B \ L]]$ of matrix $[B \ L]$ must be decomposed into:

$$ [[B \ L]] = \bar{U} \bar{\Sigma} \bar{V}^T $$

Among formula (5), $\bar{\Sigma} = \text{diag}(\bar{\sigma}_1, \cdots, \bar{\sigma}_n)$.

The constraint criterion of the total least squares method is:

$$ \sigma_{n+1} = \min_{\text{rank}([B \ L])=n} \|[[B \ L] - [[B \ L]]\|_F $$

Among formula (6), $\|\cdot\|_F$ is Frobenius norm.

Its correction is:

$$ [B \ L] - [[B \ L]] = \begin{bmatrix} E_B & E_L \end{bmatrix} = \sigma_{n+1} \bar{u}_{n+1} (\bar{v}_{n+1})^T $$

$\bar{u}_{n+1}$, $\bar{v}_{n+1}$ are the $n+1$ column of matrix $U$ and $V$ respectively. So it is easy to get that the rank of the residual error $[E_B \ E_L]$ is 1. So:

$$ [[B \ L]] \begin{bmatrix} X \\ -1 \end{bmatrix} = 0 $$

Then the total least squares solution of unknown parameters can be obtained from the $n+1$ column of $V$, which is:

$$ X = \begin{bmatrix} X_{-1} \\ -1 \end{bmatrix} = \begin{bmatrix} -1/v_{n+1} & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & -1/v_{n+1} \end{bmatrix} \begin{bmatrix} v_{1,n+1} \ \cdots \ \ v_{n+1,n+1} \end{bmatrix}^T $$

So the total least squares solution is:

$$ X = \begin{bmatrix} X_{-1} \\ -1 \end{bmatrix} = \begin{bmatrix} -1/v_{n+1} & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & -1/v_{n+1} \end{bmatrix} \begin{bmatrix} v_{1,n+1} \ \cdots \ \ v_{n+1,n+1} \end{bmatrix}^T $$

According to the steps above, the collected data can be processed programatically.
2.2.3. Selection of calculation tool
Matlab is selected as the calculation software, and the calculation results are presented in the form of three-dimensional scatter diagram and optimum fitting result diagram.

2.3. Application layer
QGIS is selected as the application layer of the framework. As one kind of GIS, there are many advantages in QGIS, such as user-friendly interface, supporting cross platform and operating system, and supporting dozens of GIS data file formats. In addition to supporting rich data formats, data visualization, editing and analysis are also supported by QGIS, which is convenient for managers to query and meet the needs of management. OpenStreetMap online map can be imported and 4326 GCS_GPS_WGS_1984 geographic coordinate system is selected in QGIS. The interface of software is shown in Figure 5.

3. Experiment

3.1. Test road section
Xinmin Road of Tsinghua university, longitude from 116.32448 to 116.32456 and latitude from 40.00000 to 40.00109, is taken as the test road section. Display on OpenStreetMap in QGIS is shown in Figure 6 and live picture is shown in Figure 7.
3.2. Test vehicle

Digital road integrated acquisition vehicle, mounted with lidar sensor HDL-64E is shown in Figure 8.

The coordinates of GPS can be regarded as the absolute position of lidar sensor. Relative position of traffic infrastructure can be obtained by the lidar sensor. Thus the absolute position of traffic infrastructure can be calculated.

4. Results & Discussion

4.1. Point cloud data in perception layer

The point cloud data collected by HDL-64E is shown in Figure 9. When selected, the point cloud will be highlighted immediately. Then, the data information such as 3D coordinates, azimuth and distance of the point cloud to be detected can be extracted as the original data for data fitting.
4.2. Calculation results

4.2.1. Fitting results of road lamps

The fitting algorithm of point cloud data in Matlab is shown in Figure 10.

```matlab
data = load('C:\Users\MrShi\Desktop\veloviewdata\lamp.txt');
n=size(data);
mean(data,1)
axis([-12 -11 8 9 -2 2]);
F=@(p)arrayfun(@(n)norm(cross(data(n,:)-
[p(1),p(2),p(3)],...
[p(4),p(5),p(6)]))/norm([p(4),p(5),p(6)]),[1:size(data,1)]);
p=lsqnonlin(F,[data(51,:),data(12,:)-data(51,:)]);
hold on;view(3);grid on;
t=linspace(0,6);
plot3(data(:,1),data(:,2),data(:,3),'g.');
plot3(p(1)+t*p(4),p(2)+t*p(5),p(3)+t*p(6));
title(sprintf('The fitting line
is: \( (%g, %g, %g) + (%g, %g, %g)t \)',p))
xlabel('X')
ylabel('Y')
zlabel('Z')
```

Figure 10  Algorithm of data fitting in Matlab

The fitting criterion of total least square method is the least square sum of the vertical distances from all points to the fitting line. Fitting result was shown in figure 11.

Figure 11  Fitting results of road lamp 1
(0.0327011, -0.0608082, -3.68312) is the direction vector of spatial straight line fitted by data of road lamp 1, which means when the height decreases by 3.68312m, X increases by 0.0327011m and Y decreases by 0.06082m. The angle between the direction vector and the XY plane is $\tan^{-1}\left(\frac{3.68312}{\sqrt{0.0327011^2 + (-0.0608082)^2}}\right) = 88.926^\circ$. 89.125º is the actual angle between the road lamp 1 and the ground. So the error is: \(\frac{89.125 - 88.926}{89.125} \times 100\% = -0.223\%\), which means high detection accuracy of this method.

(-11.793, 8.751, 1.208) (unit: m) is the coordinate of the lamp center after adding central coordinate extraction statement in algorithm. The origin is in the center of the lidar sensor base, whose height is 2.080m to the ground. So revised central coordinate \(\bar{Z}\) is: \(\bar{Z} = 1.208 + 2.080 = 3.288\) m. According to the GPS module, the longitude and latitude of the lidar sensor are (116.32463, 40.00030). Based on Geodesy, when the horizontal distance is less than 10km, the geoid or ellipsoid can be replaced by a horizontal plane, regardless of the influence of the earth curvature. On the horizontal plane, when the difference of X coordinate is 1m, the difference of longitude is 0.00001 degree, when the difference of Y coordinate is 1.1m, the difference of latitude is 0.00001 degree. The calculated longitude and latitude of the road lamp 1 are (116.32451°, 40.00038°). Similarly, the same processes are done on the other two road lamps in the test section of Xinmin Road as shown in Figure 12, and the fitting results are shown in Figure 13 and Figure 14.

Figure 12  The other two road lamps and one signboard (The signboard is marked with white dotted line frame and the road lamps are marked with red dotted line frame)

Figure 13  Fitting result of road lamp 2
(-0.081577,0.0365341,-2.34394) is the direction vector of spatial straight line fitted by data of road lamp 2. The angle between the direction vector and the XY plane is 
\[ \tan^{-1} \frac{2.34394}{\sqrt{(-0.081577)^2 + 0.0365341^2}} = 87.816^\circ \] . 89.236° is the actual angle between the road lamp 2 and the ground. So the error is: 
\[ \left( \frac{87.816 - 89.236}{89.236} \right) \times 100\% = -1.591\% \]. The calculated longitude and latitude of the road lamp 2 are (116.32450°, 40.00079°), and revised \( \bar{Z} \) is 3.283m.

\[0.0723541,-0.00413406,2.15206\] is the direction vector of spatial straight line fitted by data of road lamp 3. The angle between the direction vector and the XY plane is 
\[ \tan^{-1} \frac{2.15206}{\sqrt{0.0723541^2 + (-0.00413406)^2}} = 88.071^\circ \]. 88.965° is the actual angle between the road lamp 3 and the ground. So the error is: 
\[ \left( \frac{88.071 - 88.965}{88.965} \right) \times 100\% = -1.005\% \]. The calculated longitude and latitude of the road lamp 3 are (116.32449°, 40.00106°), and revised \( \bar{Z} \) is 3.285m.

### 4.2.2. Fitting result of sign board

Picture of signboard’s point cloud is shown in Figure 15.

Point cloud data of signboard is extracted and the fitting algorithm is shown in Figure 16, and the fitting result is shown in Figure 17.
The normal vector of the fitting plane is: \( \mathbf{a} = (9, -41.625, 1) \), and the normal vector of horizontal plane is: \( \mathbf{b} = (0, 0, 1) \). So the angle \( \mathbf{a} \) making with \( \mathbf{b} \) is: \( \cos^{-1} \frac{\mathbf{a} \cdot \mathbf{b}}{|\mathbf{a}| |\mathbf{b}|} = 89.968^\circ \). 88.875° is the actual angle between sign board and the ground, so the error is: \( \frac{89.968^\circ - 88.875^\circ}{88.875^\circ} \times 100\% = 1.230\% \), which means the fitting effect is optimal and the signboard is in good condition, and there is no inclined bending. The calculated longitude and latitude of the sign board are (116.32449°, 40.00070°), and revised \( Z \) is 2.563m.

The fitting results are listed in Table 2 as follows:
Table 2  Table of infrastructure information after fitting

| Category     | Longitude(°) | Latitude (°) | Central height(m) | Direction vector or normal vector | Angle with the ground(°) |
|--------------|--------------|--------------|-------------------|-----------------------------------|-------------------------|
| lamp         | 116.32451    | 40.00038     | 3.288             | (0.0327011,-0.0608082,-3.68312)   | 88.926                  |
| lamp         | 116.32450    | 40.00079     | 3.283             | (-0.081577,0.0365341,-2.34394)    | 87.816                  |
| lamp         | 116.32449    | 40.00106     | 3.285             | (0.0723541,-0.00413406,2.15206)   | 88.071                  |
| Signboard    | 116.32449    | 40.00070     | 2.563             | (9,-41.625,1)                     | 89.968                  |

4.3. Results displayed in application layer

The information obtained from Table 2 is displayed in the form of layer in QGIS, which is shown in Figure 18. Traffic infrastructure is displayed in the form of red dot, whose detailed information can be queried in open attribute table. Picture of the attribute table is shown in Figure 19.

Figure 18  Display of infrastructure in QGIS(marked in red dot)

Figure 19  Picture of the attribute table

5. Conclusions

In this paper, road lamps and signboards in the test section are taken as examples, an application framework of traffic infrastructure management is put forward based on 3D laser scanning. The framework is introduced comprehensively from the perception layer, network layer and application layer.
The advantages of 3D laser sensors, such as high precision, good real-time performance and strong anti-interference ability are brought into play well. Therefore two conclusions can be drawn as follows:

(1) This paper focuses on the application of 3D lidar sensor equipment in traffic infrastructure management, gives the specific usage of 3D laser scanning technology in automatic and refined management of traffic infrastructure, and expresses the status and location information of infrastructure in digital form through data fitting.

(2) Combined with the use of GPS and QGIS, the spatial information of infrastructure can be developed and utilized, and the data is collected by integrated acquisition vehicle instead of manual detection, which can save time and effort, improve the management efficiency, and provide a certain solution for traffic infrastructure management department in the future.

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