Measurement and analysis of long-tunnel cross-sectional deformation using multi-sensor integration

Qingquan Li\textsuperscript{a,b,*}, Qingzhou Mao\textsuperscript{a,b}, Qin Zou\textsuperscript{a,c} and Liang Zhang\textsuperscript{a,b}

\textsuperscript{a}Transportation Research Center, Wuhan University, Wuhan, China; \textsuperscript{b}State Key Laboratory for Information Engineering in Surveying, Mapping and Remote Sensing, Wuhan, China; \textsuperscript{c}School of Remote Sensing and Information Engineering, Wuhan University, Wuhan, China

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A long tunnel is a typical linear man-made infrastructure. The shape, especially the cross-sectional shape, and geometric parameters of the tunnel are very important for the safety of transportation. A multi-sensor integration approach is presented to survey the shape of the tunnel dynamically. With efficient collection of high-precision spatial points of structure surface, a laser scanner is widely used for measuring the structure’s three-dimensional geometric and deformation. In this article, two laser scanners and other position and orientation sensors, such as DGPS, IMU, and DMI, are integrated to form a MSI measuring system. With position and orientation sensors, the position and orientation of the laser scanners could be acquired dynamically, even in the tunnel where a GPS signal is out of reach. For fusing data collected from different sensors, data are generalized into a unified coordinate system. In our study, data from the laser scanner are first converted from the laser scanner coordinate system to the vehicle coordinate system. Then, vehicle coordinates are converted into geodetic coordinates by referencing the IMU coordinate. Calibrations are carried out in advance to obtain the parameters of conversion between coordinate systems. A time-domain tunnel deformation evaluation model is created on the basis of cross-sectional area change detection, where matching-based deformation detection (MDD) algorithm has been proposed for calculating the deformation area of two cross-sectional polygons. This article also reports a test to use MSI measuring system for Wuhan Yangtze River highway tunnel measurement. Results of the precision analysis verify the reliability of the proposed tunnel deformation evaluation model and the validity of the MDD algorithm.

Keywords: tunnel measurement; laser scanning; deformation monitoring; multi-sensor integration; POS

1. Introduction

Tunnel surveying and monitoring has always been a research focus in the field of traffic safety. From the 1960s, total station-based method (TSM) and convergence meter-based method (CMM) have been the main methods for tunnel monitoring. TSM provides a most general way to survey the shape of the tunnel, though with many deficiencies: (1) control points should be set, see Figure 1a; (2) the measuring work is affected by the dim light in the tunnel; (3) it is time-consuming and labor-consuming. CMM is a contact approach for tunnel measurement. It uses convergence meters to provide two-dimensional (2D) data of the measured points. Through the Data Bus, the measuring data are delivered to the tunnel monitoring system, with which a dynamic monitoring could be achieved. Chung \textit{et al.} (2006) applied CMM for Seoul metro tunnel monitoring. In their application, convergence meters were installed to each longitudinal section of the tunnel wall, which formed a convergence circle (see Figure 1b). Convergence circles recorded the geometric parameters of the tunnel sections. From analysis of the convergence data, the deformation level could be figured out. However, CMM has limitations. For example, measured points in CMM can only get 2D information. Moreover, as convergence circle should be configured in distance intervals, it is difficult to apply CMM in large-scale projects.

In the recent 10 years, tunnel surveying and monitoring techniques were rapidly developed. Miura \textit{et al.} (2001, 2005) and Tian \textit{et al.} (2006) introduced a method based on close-range photogrammetry (CPM) for tunnel surveying. To solve the problem that the light in the tunnel is very weak, a number of retro-reflection targets were employed. Each target point was supervised by two cameras, in other words, there would be two photos at each target point, which formed a stereo image pair for 3D measurement. Then, an interpolation operation was conducted to model the 3D shape of the tunnel (see Figure 1c). Unlike CMM 2D points, CPM target points have 3D coordinates, with which an intensive inspection could be achieved. But defects of CPM are that a huge number of retro-reflection target points are needed to confirm a considerable accuracy for tunnel monitoring, which is impractical.
A laser-scanner-based method for deformation measurement was applied earlier in this century. The laser scanner offers a highly effective method for collecting a massive volume of precise, high-resolution 3D points for measuring. Unlike traditional surveying techniques that collect hundreds of discrete data points over a period of several days, laser imaging is capable of capturing several million 3D points in just a few minutes (Lichti et al., 2000). Gordon et al. (2001, 2003) used terrestrial laser scanning method (TLSM) for structure deformation measurement. The laser scanners were fixed in advance. With high-precision spatially dense points, surface deformation of the structure could be observed. Similar experiments were done by Lovas et al. (2008) and Qiu and Wu (2008). Terrestrial laser scanner provides a noncontact approach for structure measurement; however, it is a static method, which limits its application. In this article, a multi-sensor integration method (MSIM) for tunnel surveying is presented. With DGPS, IMU, DMI, gyro theodolite, etc., the position of laser scanners could be gained dynamically. Therefore, the survey could be conducted even during the movement.

The rest of this article is organized as follows. Section 2 introduces the framework of MSI measuring system and describes the system calibration. Section 3 elaborates the principle of MMD algorithm. Section 4 reports our empirical study and results.

2. MSI measuring system and its calibration
2.1. MSI measuring system architecture

MSI measuring systems are equipped with POS (GPS, IMU), DMI (wheel encoder), laser scanners, etc. Figure 2 shows the layout of POS and two laser scanners. In the vehicle-loaded MSI measuring system, the onboard POS (GPS + IMU) is used to automatically acquire position data and orientation data of mobile platform, DMI (wheel encoder) is used for recording the distance the platform moves, and the laser scanner gathers the information of spatial points of structure surface. All data are processed by the processing software mounted on the moving measurement system, including GPS data differential processing, GPS/IMU/DMI data fusion, and absolute laser rangefinder data calculation. The acquired data can be directly input into the spatial database after being processed, which can be further used to construct 3D models or to update the GIS database, and so on. Generally, a vehicle-loaded MSI measuring system includes a data collection module, a system calibration module, a data fusion and processing module, and a cartography management module (see Figure 3).

2.2. MSI measuring system calibration
2.2.1. Coordinate systems in MSI measuring system

Coordinate systems in the vehicle-loaded MSI mainly include
To make measuring data useful, all data collected by MSI should be adjusted to a uniform coordinate. As we use WGS-84 coordinate for results output, there should be several coordinate transformations. The process of transformation is given in Figure 4b. The mathematical model for transformation is

\[
\begin{bmatrix}
X_W \\
Y_W \\
Z_W
\end{bmatrix} =
\begin{bmatrix}
X'_L \\
Y'_L \\
Z'_L
\end{bmatrix} + \lambda_1 R_{imu}^{\text{veh}} \begin{bmatrix}
X_{imu}^{\text{veh}} \\
Y_{imu}^{\text{veh}} \\
Z_{imu}^{\text{veh}}
\end{bmatrix}
+ \lambda_2 R_{imu}^{\text{veh}} \begin{bmatrix}
X_{veh}^{\text{veh}} \\
Y_{veh}^{\text{veh}} \\
Z_{veh}^{\text{veh}}
\end{bmatrix} + \lambda_3 R_{L}^{\text{veh}} r
\begin{bmatrix}
\cos \theta \\
\sin \theta \\
0
\end{bmatrix}.
\]

\[
\begin{bmatrix}
X_{imu}^{\text{veh}} \\
Y_{imu}^{\text{veh}} \\
Z_{imu}^{\text{veh}}
\end{bmatrix}
\]

is the coordinate of LCCS origin in VCS; \[
\begin{bmatrix}
X_{imu}^{\text{veh}} \\
Y_{imu}^{\text{veh}} \\
Z_{imu}^{\text{veh}}
\end{bmatrix}
\]

the coordinate of VCS origin in ICS; \[
\begin{bmatrix}
X_{veh}^{\text{veh}} \\
Y_{veh}^{\text{veh}} \\
Z_{veh}^{\text{veh}}
\end{bmatrix}
\]

the coordinate output by POS at time \(t\); \[
R_{imu}^{\text{veh}}, R_{imu}^{\text{veh}}, R_{imu}^{\text{veh}}
\]

and \(R_{imu}^{\text{veh}}\) the rotation matrices; and \(\lambda_1, \lambda_2, \lambda_3\) the scale factors. \(X_{veh}^{\text{veh}}, Y_{veh}^{\text{veh}}, Z_{veh}^{\text{veh}}\) should be calibrated with calibration field indoor or outdoor before measuring practice.

2.2.2. Systems calibration

- **POS calibration**: POS system integrates GPS and IMU. To fuse GPS and IMU data to obtain the unification coordinate and speed information, before running POS, we must determine the GPS antenna phase center’s position in the IMU coordinate system accurately. These parameters can be measured accurately by a total station, and the closer the GPS antenna and IMU, the higher the precision and reliability are.

- **Laser scanner calibration**: Laser scanner can obtain the plane coordinates of the target points relative to the laser scanner center. To establish the 3D model as well as transfer the achievement to local Gaussian coordinates, we must demarcate the laser scanner center’s coordinates into the IMU coordinate system and the rotation of laser scan optical fiber axis related to IMU coordinate system first, then we can obtain the target points’ absolute geodetic coordinates with these parameters.

The calibration results are given below.

1. Coordinate of GPS phase center in ICS

Caliper was used for measuring the rough coordinate of GPS phase center in ICS, which can be later used for initial data in precise calibration. The calibration results are listed in Table 1.

2. Transform parameters (LCCS to VCS)

When the laser scanner is fixed, the scan-plane
should be coinciding with the XOZ plane of VCS. So, directions of the two coordinate systems’ Y-axis are consistent.

The angle between the right laser scanner’s polar axis and the downward perpendicular of the vehicle’s bottom plate is 7.2° by calibration.

Transform parameters of the right LCCS to VCS are

Offset parameters [X-offset, Y-offset, Z-offset] = [0.065 0.000 0.000]
Error rate [ΔX  ΔY  ΔZ] = [0.005 0.005 0.005]

The angle between the right laser scanner’s polar axis and the downward perpendicular of the vehicle’s bottom plate is 7.5° by calibration.

Offset parameters [X-offset, Y-offset, Z-offset] = [-0.0650 0.000 0.000]
Error rate [ΔX  ΔY  ΔZ] = [0.005 0.005 0.005]

(3) Transform parameters (VCS to ICS)
To simplify data processing, IMU is installed with axis pointing direction consistent with that of VCS. So the rotation matrix is a unit matrix. Then calibration should be achieved by measuring the coordinate of CVS origin in ICS. Table 2 shows their coordinate values.

Table 1. Coordinate of GPS phase center in ICS.

<table>
<thead>
<tr>
<th>Axis direction</th>
<th>X (m)</th>
<th>Y (m)</th>
<th>Z (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>0.000</td>
<td>0.000</td>
<td>0.015</td>
</tr>
<tr>
<td>Error rate</td>
<td>0.020</td>
<td>0.020</td>
<td>0.020</td>
</tr>
</tbody>
</table>

Table 2. Coordinate of VCS origin in ICS.

<table>
<thead>
<tr>
<th>Axis direction</th>
<th>X (m)</th>
<th>Y (m)</th>
<th>Z (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>-0.310</td>
<td>0.650</td>
<td>0.050</td>
</tr>
<tr>
<td>Error rate</td>
<td>0.002</td>
<td>0.002</td>
<td>0.001</td>
</tr>
</tbody>
</table>

3. MDD algorithm for tunnel cross-sectional deformation detection

3.1. Cross-sectional area-based tunnel deformation evaluating model

Tunnel deformation includes longitudinal strain and cross-section deformation. This article mainly researches the cross-section deformation. The cross-section of the tunnel’s body should possess the same parameters during design time. But because of the difference of rocky composition and pressure along the tunnel, deformation may happen among different cross-sections, which is called spatial deformation. In addition, the shape of the same cross-section will also deform with time, which is called temporal deformation. In this article, a ratio δ is used as a relative indicator evaluating the tunnel cross-sectional deformation.

Here,

\[ \delta = \frac{|A(RCS) + A(TCS) - 2f(A(RCS \cap TCS))|}{A(RCS)} \]

where \( A(RCS) \) is area of referenced cross-section (RCS); \( A(TCS) \) the area of target cross-section (TCS); \( f(A(RCS \cap TCS)) \) the function about area of overlapped part between RCS and TCS.

The bigger the δ, the more possible the tunnel cross-section deforms.

For spatial deformation analysis, randomly select \( n > 5 \) cross-sections and calculate their areas S. Then fetch the cross-section whose area is closest to average area S as RCS and others as TCS.

For temporal deformation analysis, fetch the previously measured cross-section as RCS and this time measured cross-section as TCS.

3.2. MSI measuring system calibration

The traditional method of tunnel cross-section deformation monitoring is defined as

\[ f(A(RCS \cap TCS)) = \max(A(RCS \cap TCS)) \]

Thus, \( \delta = \frac{|A(RCS) + A(TCS) - 2\max(A(RCS \cap TCS))|}{A(RCS)} \)

It calculates the biggest overlapped area \( \max(A(RCS \cap TCS)) \) between TCS and RCS by translating and rotating the TCS while RCS is fixed.

But this traditional method has two main drawbacks:

(1) The algorithm’s efficiency is low. To obtain the biggest overlapped area, the translation parameters and rotation parameters must be iteratively computed, which may be time-consuming;

(2) It could not ensure the two sections matching perfectly even if the overlapped area is the largest, which may result in wrong judgment.

3.3. Matching-based deformation detection (MDD) algorithm

Considering the two points, the MMD algorithm is proposed, as described in Algorithm 1.

To calculate the difference between two cross-sections, we use MDD algorithms. An example to illustrate MDD is given in Figure 5, in which (a) and (b) show two
cross-sections, named RCS and TCS; (c) shows their match points under the constraint line. A constraint line is used to segment the original image and to indicate which part is for matching and which part is for adjustment. As shown in the figure, the deformation at the tunnel’s sidewalk ladder and inflexion is smallest, so these points could be used as match points to achieve the matching of target cross-section and reference section. To search these match points between two images, a shift-matching algorithm is employed here. With match points, we could adjust TCS to RCS. Then their part under constraint line would be nearly the same, and the difference could be calculated by observing the part above the constraint line. Figure 5d shows the difference between RCS and TCS after adjusting TCS to RCS.

Now, $f(A(RCS ∩ TCS))$ can be defined as

$$f(A(RCS ∩ TCS)) = A(RCS ∩ MDD(TCS))$$

Thus, $\delta = \frac{|A(RCS) - A(TCS) - 2A((RCS ∩ MDD(TCS)))|}{A(RCS)}$.

4. Experiments, analysis, and conclusion

Wuhan Yangtze River highway tunnel is typically a linear architecture, located between Wuhan Yangtze River Bridge and Wuhan Second Yangtze River Bridge, and it is the first wear-river tunnel on the Yangtze River. The tunnel starts at Pingjiakou, Hankou district, and ends in the east side of Youyi Avenue, Wuchang district, with a total length of 3630 m. This tunnel includes two tunnel lines. Both the lines set two lanes, with a width of 7 m, net height of 4.5 m, and a designed speed of 50 km/h (Figure 6).

With a heavy load of river water above and a huge traffic flow inside, the tunnel cannot avoid deformations. So the periodical measuring and monitoring of the tunnel is necessary.

The measurement platform used by the Intelligent Vehicle Research Center of State Key Laboratory of Information Engineering in Surveying, Mapping and Remote Sensing of Wuhan University is based on Chery Tiggo, as shown in Figure 7. It is equipped with a Novetal’s IMU and a GPS antenna on the rear of the vehicle top, and these two together compose a POS system through NMEV receiver. One SICK laser scanner is installed on each side of the middle of the vehicle top. For convenient data collection, computers are placed in the vehicle; meanwhile the display monitors are set next to the codriver seat.

4.1. Measuring experiment and result analysis

In this study, we conduct an experiment for tunnel deformation monitoring. The tunnel scanned with 3D spatial points is shown in Figure 8, where (a) is the overall view of the

Figure 5. Using MDD algorithm to get difference of two cross-sections. (a) RCS, cross-section at 508.50, first time; (b) TCS, cross-section at 508.56 m, second time; (c) match points under the constraint line; (d) an overlay view of RCS and TCS after doing adjustment to TCS.
tunnel with render color, (b) is part of the tunnel indicated by the yellow lines, (c) is another view on (b), and (d) is the inside view of the tunnel.

Seventeen pairs of cross-sections are randomly selected for accuracy analysis. The statistic data are listed in Table 3, in which column 1 denotes the index of the selected sections, column 2 denotes the area difference of each section pair, columns 3 and 5 denote the location of each section, and columns 4 and 6 show the area difference $\delta$. With these data, we first investigate the repeatability of the proposed method. Then, we analyze the correlation of the 17 sections in each measurement activity.

Table 3. Cross-section data.

<table>
<thead>
<tr>
<th>Section index</th>
<th>$\Delta$</th>
<th>Distance (m)</th>
<th>$\Delta$</th>
<th>Distance (m)</th>
<th>$\delta$</th>
</tr>
</thead>
<tbody>
<tr>
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<td>0.0091</td>
<td>700.120</td>
<td>0.0128</td>
</tr>
<tr>
<td>2</td>
<td>0.0030</td>
<td>805.900</td>
<td>0.0111</td>
<td>730.076</td>
<td>0.0121</td>
</tr>
<tr>
<td>3</td>
<td>0.0028</td>
<td>851.060</td>
<td>0.0102</td>
<td>790.148</td>
<td>0.0109</td>
</tr>
<tr>
<td>4</td>
<td>0.0032</td>
<td>866.160</td>
<td>0.0093</td>
<td>835.011</td>
<td>0.0124</td>
</tr>
<tr>
<td>5</td>
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<td>881.079</td>
<td>0.0133</td>
<td>850.106</td>
<td>0.0084</td>
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<tr>
<td>6</td>
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<td>895.038</td>
<td>0.0106</td>
<td>865.173</td>
<td>0.0107</td>
</tr>
<tr>
<td>7</td>
<td>0.0027</td>
<td>910.192</td>
<td>0.0134</td>
<td>880.149</td>
<td>0.0122</td>
</tr>
<tr>
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<td>925.109</td>
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<td>9</td>
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<td>0.0114</td>
<td>1285.171</td>
<td>0.0109</td>
</tr>
</tbody>
</table>

1. **Repeatability.** From Figure 9(a), we can find that, to all pairs, area difference ratio is smaller than 0.0033. If we use laser scanner with higher precision (precision of our laser scanner is 0.01 m), a better result could be gained. In this article, a ratio $\delta$ is used as a relative indicator evaluating the tunnel cross-sectional deformation.

2. **Correlation.** Figure 9b and c shows that the area difference ratio of cross-sections in each scanning case are lower than 0.015. The tunnel cross-sections are similar in shape. However, there are still some relatively big differences happening at some places. On ground truth, that is because of the decoration in the tunnel, namely the transportation equipments such as droplights, cameras, bracket, and so on.

4.2. **Conclusion**

In this article, we have proposed an efficient tunnel-measuring approach based on multi-sensor integration technology. The contributions of the MSI measuring system are threefold. First, it offers a MSI framework for measuring system. In this framework, sensors could be adopted referring to their function. Second, the MSI measuring system provides an efficient way for tunnel measuring. Compared with traditional methods, MSI could gain multi-information simultaneously, which includes tunnel longitudinal profile, tunnel cross-section, and tunnel plane toward. Third, a match-based deformation detection algorithm is presented for tunnel cross-section difference calculation.
Figure 9. Cross-sectional data analysis. (a) Temporal deformation, (b) spatial deformation analysis I, (c) spatial deformation analysis II.

References