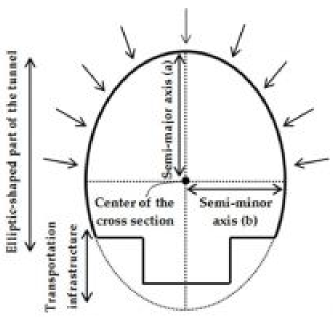
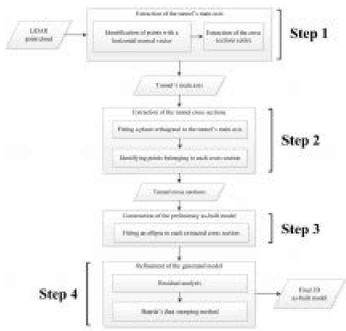
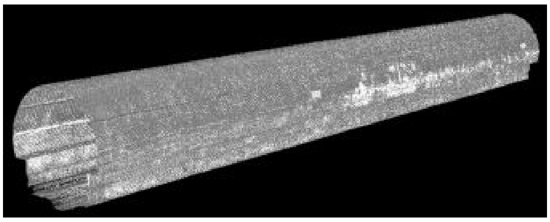
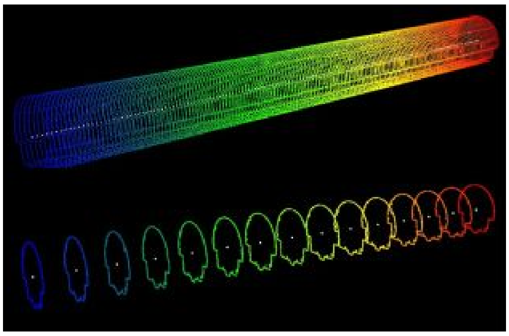
FROM POINT CLOUDS TO CROSS-SECTIONAL DIMENSIONS

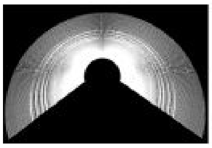
Automated Modelling of Tunnels

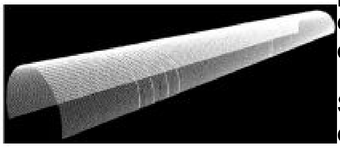












Tunnels must be regularly monitored to meet safety requirements and to prevent excessive deformation or displacement. Tunnels are currently monitored by measuring a few benchmarks using total stations or other surveying instruments. These techniques are effective and precise, but also slow and expensive. In the case of rail tunnels, for example, the regular train schedule is disrupted whenever land surveyors have to operate inside the tunnel. This article presents a novel automated method for the geometric modelling of tunnels from mobile Lidar point clouds with sub-millimetre precision. The models can be employed for maintenance, project management and enhancement of future designs.

Safety of transportation corridors including roads and train tunnels is of great concern. Due to the weight load of the terrain above, tunnels start experiencing deformation and displacement as soon as they have been constructed. Therefore, they must be regularly monitored to meet the safety requirements. In the present context, monitoring is described as the detection of deviations from the designed geometric shapes. Accurate measurements obtained from modelling of tunnels allows for quantifying deformation and displacement, which may trigger immediate or longer-term maintenance efforts. Deformation and displacement can be identified by comparing the geometric models of a tunnel from two or more epochs. Modelling also helps to monitor progress in the construction phase which is a necessity for project managers. The construction progress can be monitored by comparing the as-built model of a tunnel under construction with the as-designed model. Furthermore, as-built models can be employed for detecting imperfections or even flaws in the design of a tunnel which provides input for improving future designs.

Lidar

The conventional methods, based on traditional land surveying, are time-consuming and hence expensive. In contrast, mobile laser scanning (MLS) or Lidar allows the fast collection of precise, highly redundant measurements which are crucial for monitoring of tunnels. A one-kilometre length of tunnel can be captured within a minute and the acquired data contains millions of three-dimensional (3D) data points. Furthermore, as an active sensing technology, Lidar does not suffer from the poor lighting conditions in tunnels either. However, Lidar point clouds are typically large, which makes the manual processing time-consuming and costly. Thus, the key to fully exploiting the potentials of MLS point clouds is to automate the data processing. Integrating the beneficial properties of MLS with automated data processing significantly decreases the time and costs involved in monitoring of tunnels. As a result, deformation and displacement analysis can be performed more frequently, which in turn results in early detection of sagging tunnel segments, detaching construction materials and other deteriorations. This enhances underground transportation safety.

Geometric Modelling

Transportation tunnels have a standard tubular shape, often with a circular or elliptic-shaped cross section. A circle is a specific form of an ellipse with equal semi-major and semi-minor axes. Hence, for a wide range of tunnels, the cross sections can be modelled as ellipses. Cross sections can be divided into the top part and the bottom part comprising the transportation infrastructure (Figure 1). Even though both parts are under terrain weight load, the top part is subject to greater deformation since the bottom part acts more rigidly due to its larger dimensions. Therefore, only the top elliptic-shaped part is considered when modelling the tunnel.

Workflow

The method is composed of four steps which all are executed automatically (Figure 2). The first step identifies the main axis of the tunnel. In the second step, points belonging to cross sections are extracted. The preliminary as-built model is created in the third step. Residual analysis and Baarda's data snooping method are then applied for the detection and elimination of outliers in a sequential procedure. Once outliers are eliminated, the final model is created from the outlier-free data in the fourth step. The use of least squares adjustment enables the quality of the generated model to be assessed as the standard deviations of the semi-major axis, semi-minor axis, area and eccentricity of the cross sections.

Test

A Velodyne HDL 32E scanner mounted on a rail car scanned 155 metres of a one-way underground rail tunnel while the train was moving at a speed of 65km/h. The capturing of the point cloud, containing over six million points, took about ten seconds. The tunnel has an arbitrary horizontal orientation with an approximately 7° vertical slope. Although the point cloud contains geometric and intensity information, only geometric information was used for data processing. Figure 3 shows an oblique view of the dataset. By applying the method to the point cloud, the tunnel's main axis was calculated (Figure 4). Furthermore, 1,551 cross sections were extracted at 10cm intervals. For visualisation purposes, the extracted cross sections are depicted at 1m and 10m intervals in Figure 5. The 3D coordinates of centre and 3D orientation direction (normal vector) of all cross sections were also computed.

As-built Model

Figure 6 shows the constructed as-built model. As a result of the modelling, the area, eccentricity, semi-major and semi-minor axes of all cross sections and their standard deviations were calculated. Table 1 displays the means and standard deviations of the dimensional parameters of cross sections, i.e. semi-major axis, semi-minor axis, area and eccentricity. The eccentricity is a function of semi-major axis and semi-minor axis and has no unit. The dimensions of the cross sections were computed with a standard deviation equal to or less than 0.2mm and their areas were calculated with a standard deviation of 3cm^2. Calculation of the standard deviations of both axes is crucial for detecting deformations along only one axis, since such deformations are not reflected by other parameters like eccentricity or area. Additionally, the average normal distance of data points from the generated model (average absolute error) was 1.2cm.

Statistics	Mean	SD
Semi-major axis	785.08cm	0.2mm
Semi-minor axis	775.09cm	0.1mm
Area	95.5838m^2	3cm^2
Eccentricity (unit-less)	0.17606	0.00002

Table 1, Statistics of the extracted cross sections.

Concluding Remarks

The automation level of this method is notably higher than that of other methods, which all apply non-linear mathematical models with ten unknowns, requiring further complicated constraints. By using a linear model with two unknowns, this method is able to achieve a reliable estimate of the modelling parameters in a single run, which improves the computational efficiency. Moreover, the method is applicable to tunnels with any horizontal orientation and degree of curvature as it makes no assumptions, nor does it use any a priori knowledge about the horizontal direction or curvature of tunnels. Although transportation tunnels may have different cross-sectional shapes, ellipse and circle are two of the most common ones. The approach is applicable to any type of tunnel or underground transportation corridor with a circular or elliptic-shaped cross section.

Further Reading

Arastounia, M. Automated As-Built Model Generation of Subway Tunnels from Mobile LiDAR Data. *Sensors*, *16(9)*, 1486; DOI: 10.3390/s16091486.