REAL-TIME AS-BUILT TUNNEL PRODUCT MODELING AND VISUALIZATION BY TRACKING TUNNEL BORING MACHINES

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ABSTRACT

Tunnel Boring Machines (TBMs) are widely used for tunneling in urban areas because of their high advance rate, precise as-built profile and minimal impact to buildings and traffic on the ground. For a tunnel built by a TBM, there are strict requirements on alignment control and safety. To meet these requirements, it is important to monitor the position of the TBM. In the current practice, the TBM position data, including advance distance and line and level deviations, are reported manually to the managers on a daily basis. To interpret and analyze the position data, the managers also need to refer to various construction drawings. This practice is untimely, inefficient, and error prone for decision making. To improve the current practice, an automatic approach for real-time as-built tunnel product modeling and visualization is proposed, based on TBM position and orientation data autonomously sourced from the Virtual Laser Target Board (VLTB) TBM Guidance System developed at University of Alberta. Related information of the tunnel project, such as the as-designed alignment, soil layers, the ground, existing utility lines, is also visualized together with the model of the as-built tunnel. The modeling algorithm is presented step by step. Its application in a real-life drainage tunnel project is discussed and limitations are also identified.

KEYWORDS

As-built modeling, Visualization, Tunnelling, Construction

INTRODUCTION

The trend of global urbanization spurs the demand for more underground structures such as transit and utility tunnels. Due to their high advance rate, precise as-built profile and low impacts to buildings and traffic on the ground, shield machines or Tunnel Boring Machines (TBMs) are often preferred to other methods for tunneling in urban areas (Maidl, Herrenknecht, Maidl, & Wehrmeyer, 2012). However, managing a tunneling project using a TBM is not an easy task. There are strict requirements on quality and safety. For a typical 8-foot (2.438 m) diameter drainage tunnel, the City of Edmonton (2012) specifies that the tolerance of the as-built centre line deviating from the as-designed is 150 mm, which is about 6% of the diameter of the TBM, and that of the grade of the invert (the lowest point of a vertical cross-section of a tunnel) is even smaller, just about 89 mm. Besides, it is paramount to avoid the TBM from hitting existing underground facilities such as utility lines, transit tunnels, piles and deep foundations, as the stake of the TBM hitting them is too high.

To meet the requirements mentioned above, one important task is to monitor the position of the TBM, which is the key factor to the spatial position of the as-built tunnel. In the current practice, the TBM position data, including advance distance and line and level deviations, are reported manually to the managers on a daily basis. This practice is untimely, inefficient, and error prone for decision making in the following two aspects. First, we are not able to know the TBM position in real time. In other words, there is a time lag (in hours or days) between the actual time when the TBM reaches a certain point and the time when the mangers know it. Second, we are not able to intuitively “see” the TBM, the as-built tunnel, and the surrounding soils and utilities. To interpret and analyze the position data, the managers also need to refer to various construction drawings.

To improve the current practice of managing and monitoring a tunnel project, an automatic approach for real-time as-built tunnel product modeling and visualization is proposed, by applying Virtual Laser Target Board (VLTB) TBM Guidance System developed at University of Alberta for data acquisition and transmission and Microsoft XNA game engine for modeling and visualization. Related information of the tunnel project, such as the as-designed alignment, soil layers, the ground, existing utility lines, is also visualized.

In the following sections, first, several as-built modeling techniques that represent state of the art are reviewed and their advantages and limitations are also discussed. Then, the system architecture of the proposed modeling approach is briefly introduced, and the modeling algorithm is also presented. To validate the feasibility of the modeling approach, a case study in a real-life drainage tunnel project in Edmonton, Alberta is carried out. The limitation of the proposed approach and future improvement are also discussed.

REVIEW OF AS-BUILT MODELING TECHNIQUES

With recent developments in Remote Sensing and Information Technology, as-built modeling has been the interests of many scholars in the construction domain. Their efforts can be categorized mainly into two groups, Photogrammetric/Computer Vision based modeling and Laser Scanning based modeling.

Photogrammetry is the process of determining geometric properties (e.g. distances and dimensions) of objects of interest from photographs. Major advancements in computer vision and image processing have made the process more and more automated (Klein, Li, & Becerik-Gerber, 2012). It has been tested for modeling of buildings and bridges (Kersten, Pardo, & Lindstaedt, 2004; Riveiro, Jauregui, Arias, Armesto, & Jiang, 2012), and several attempts have also been made to evaluate and increase its accuracy (Dai & Lu, 2010; Bhatla, Choe, Fierro, & Leite, 2012).

Laser scanner is an instrument that measures the outline of an object, by emitting laser beams to the object, collecting the reflected beams, and calculating the distances between the laser scanner and the points on the object that laser beams hit on. A laser scanner is able to emit and collect thousands of laser beams in a second, and form a dense point cloud that depicts the surface of the object (Klein et al., 2012). Fekete, Diederichs, & Lato (2010) reported their study on applying laser scanning for the as-built modeling and other geotechnical and operational applications in a drill and blast tunnel.

The two techniques are relatively complementary. Photogrammetry is portable and low-cost, but it requires manual 3D data retrieval and its spatial resolution is low; on the contrary, laser scanning is able to retrieve 3D data automatically and provide a high spatial resolution, but it is non-portable and expensive (Zhu & Brilakis, 2009). However, neither technique is the ideal candidate for the as-built modeling of a tunnel built by TBM method, whose as-built information is generally collected by surveying the invert of installed tunnel sections. Figure 1 shows the interior of a typical drainage tunnel in North America. The dark environment, narrow and long geometry of the tunnel and uniform materials of concrete lining segments make it hard to apply photogrammetry for as-built modeling, while the ventilation pipe and rails form obstacles for laser scanning as construction is ongoing, which makes this technique applicable only after the tunnel is completed. Besides, complete as-built modeling by laser scanning is still expensive and not yet commonplace. Thus, instead of applying these modern and widely-accepted as-built modeling techniques, why not further utilize the position and orientation data of the TBM resulting from an automated tracking and positioning technology?

Figure 1 – Typical environment in tunnels built by TBMs

PROPOSED MODELING APPROACH

System Architecture

The overall system architecture for the proposed modeling approach is shown in Figure 2. It mainly consists of two components, a MySQL database and a visualization program built on Microsoft XNA Framework. To successfully model the as-built tunnel and its surrounding environment in real time, we divide data into two categories, namely, "static" data and "dynamic" data. Static data are design parameters derived from construction drawings and geotechnical reports, which include the as-designed tunnel alignment, soil layers, the ground, and other related information, and are manually inputted to the database. Dynamic data refer to the position and orientations of the TBM, which are sourced from the VLTB TBM Guidance System and autonomously inputted by a data feed program. Refer to Shen, Lu, Fernando, & AbouRizk (2012) for more information about how the VLTB TBM Guidance System works. With all the related information stored in the Database, the visualization program reads data from it, creates models of the as-built tunnel, the as-designed tunnel, and the surroundings, and displays these models.

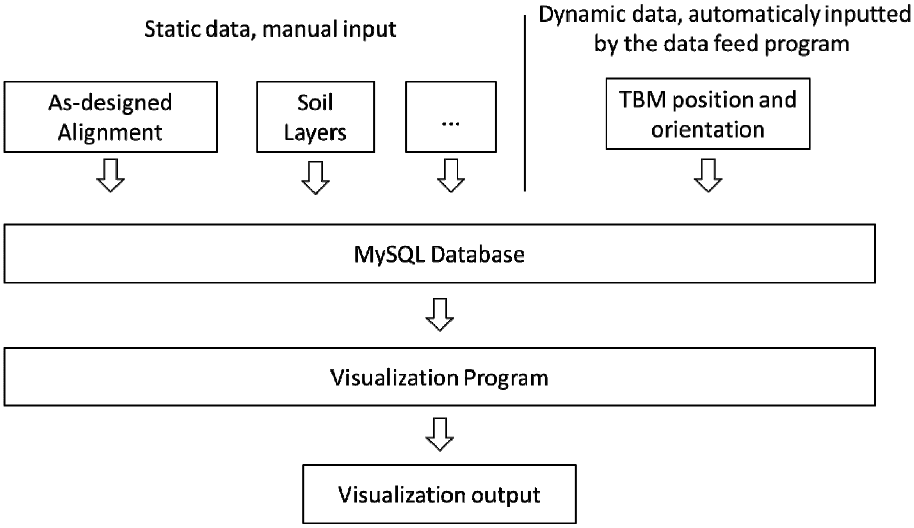

Figure 2 – System architecture

Geometric and Mathematic Foundations

Coordinate Systems

Three Cartesian coordinate systems (i.e. frames) are defined, namely, the local geodetic frame (F_n), the TBM's body frame (F_b), and the tunnel frame (F_t), as shown in Figure 3. The local geodetic frame, with the origin fixed in a particular location and the three axes along the east, north, and geodetic zenith, is usually the standard frame in construction surveying. The TBM's body frame is fixed on the center of the TBM, with (1) Y-axis along the TBM's advance direction, (2) X-axis perpendicular to the Y-axis and parallel to the horizontal plane, and (3) Z-axis perpendicular to both X-axis and Y-axis and pointing upward (Shen, Lu, & Chen, 2011). In addition, the tunnel frame is also defined, with (1) the origin on the starting point of the tunnel (2) Y-axis along the projection of the as-designed tunnel advance direction at the starting point on the horizontal plane (3) Z-axis along the geodetic zenith, and (4) X-axis the cross product of Y-axis and Z-axis.

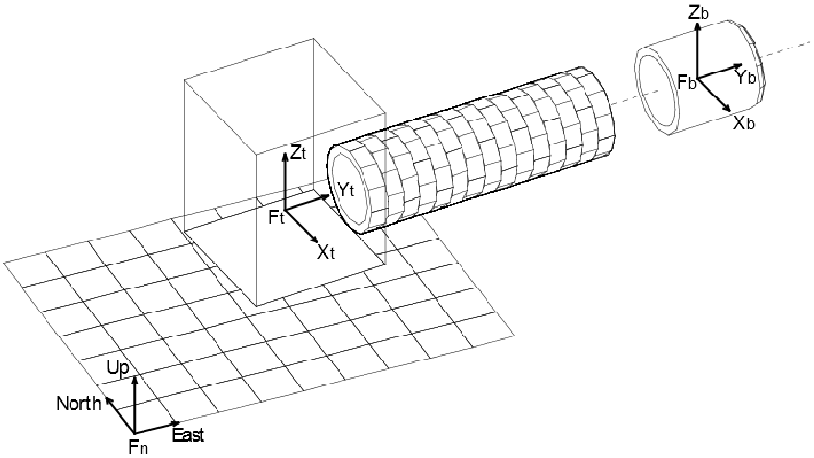

Figure 3 – The local geodetic frame, TBM's body frame and tunnel frame

The reason why we define multiple frames, instead of one single frame, is that spatial information of different objects stored in the database are referenced to different frames. For instance, the position of the TBM is measured in the local geodetic frame, while soil layer diagrams are usually drawn in the tunnel frame. In other words, there is no frame in which we can directly use existing position and orientations data to model all the objects.

Frame Transformations

As mentioned above, different objects are referenced to different frames. In order to draw them on the screen, we make the tunnel frame as our base frame, and transform point coordinates in other frames to the tunnel frame. For simplicity, we apply homogeneous coordinates and affine transformations that are common practices in 3D Computer Graphics (Guha, 2011). In the general form, a transformation from frame A to frame B can be expressed as Eq. (1):

$$\hat{p}_B = F_A^B \hat{p}_A \tag{1}$$

Where F_A^B is a 4×4 homogeneous transformation matrix, and $\hat{p}_A$ and $\hat{p}_B$ are homogeneous coordinates of point p in frame A and frame B, respectively. It's worth mentioning that $\hat{p}_A$ and $\hat{p}_B$ are 4×1 column vectors in the form of $(x \quad y \quad z \quad 1)^T$, in which x, y and z are three axis coordinates of point p in a certain frame and the element 1 is intentionally added for homogeneous transformations.

Interpolating the position and orientations of the TBM

The position and orientation data we retrieve from the VLTB TBM Guidance System are discrete, which means that we can get the data at specific time (e.g. 2012-08-24 13:17:30), not continuously. However, when we model the as-built tunnel, we may need such data between two points of time. Thus, interpolation of the position and orientations of the TBM is required.

Compared with other construction equipment such as excavators or trucks, the body of the TBM is relatively static. As mentioned in Shen et al. (2012), a typical advance rate of a TBM is 5m/shift (8 hours per shift), on average $1.74\times10^{-4} m/s$, which is almost negligible. The three-axis orientations of the TBM are also quite stable. According to a field test in Shen et al. (2011), the maximum fluctuation on the three orientation angles of a TBM over a 0.3m advance was just about 1 degree.

With such low velocity and fluctuation on orientation angles, there is no need to apply complex interpolation algorithms such as spherical linear quaternion interpolation that is commonly used in computer graphics for interpolating rotations. Simple linear interpolations of the three rotation angles and the position of the TBM are sufficient to achieve satisfactory modeling and visualization effects.

Modeling Algorithm

In a real construction site, the tunnel is built by installing concrete segments behind the TBM section by section, just like a masonry wall is built by laying bricks layer by layer. However, based on current data availability of the VLTB TBM Guidance System, we are not able to precisely track the installation of each concrete segment, nor can we track the installation of each segment ring. All we can do is to make the best use of the position and orientation data of the working TBM to approximately model the as-built tunnel.

The modeling algorithm is illustrated in Figure 4, and can be described as followings:

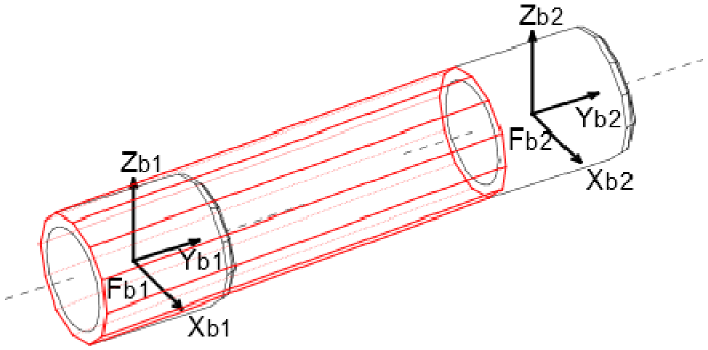

Figure 4 – Illustration of the modeling algorithm

Given the TBM's body frame F_{b1} at t1, we may draw a circle at the rear plane of the TBM. The diameter of the circle equals to the as-designed inner diameter of the tunnel and the center of the circle lies on the center of the rear plane of the TBM. In frame F_{b1} , this circle can be analytically denoted as Eq. (2):

$$\begin{cases} y = y_0 \\ x^2 + z^2 = \left(\frac{d_0}{2}\right)^2 \end{cases} \qquad (2)$$

Where y_0 equals to the y coordinate of the center of the rear plane of the TBM in frame F_{b1}, and d_0 is the as-designed inner diameter.

To efficiently model the tunnel on the screen, the circle in Eq. (2) is approximated by regular polygons. The vertices of the polygon can be given as Eq. (3):

$$\begin{cases} y = y_0 \\ x = \cos\left(\frac{i}{N} \times 2\pi\right) \times \frac{d_0}{2} \\ z = \sin\left(\frac{i}{N} \times 2\pi\right) \times \frac{d_0}{2} \end{cases} \tag{3}$$

Where $i = 1, 2, 3 \ldots N\text{-}1$, N is the total number of sides of the polygon. Note that regardless of the location and orientations of frame F_{b1}, the x, y and z coordinates of vertices with the same parameter $\frac{i}{N}$ in F_{b1} remain the same.

Similarly, given another frame F_{b2} at t2, we may define another polygon in frame F_{b2}, with the same expressions as in Eq. (3).

Next, we transform points in the two polygons defined above from their corresponding TBM body's frames to the tunnel frame. By linking the corresponding points on the two polygons, we may draw a wireframe model to represent the as-built tunnel, shown as the red polygon cylinder in Figure 4.

It's worth mentioning that the wire frame model is not the final visualization product. To achieve satisfactory visualization effect, we first interpolate the TBM's body frames in a series of equally spaced points along the trajectory of the TBM. Then, a conceptual wireframe model of polygon cylinders is built based on the position and orientations of the interpolated frames. After that, Boolean operations are made between models of soil layers and the as-built tunnel. In the end, to achieve desired visual effects, textures are attached to the models.

CASE STUDY

Project Description

A drainage tunnel project of the City of Edmonton, WESS Stage W13, is chosen as the test bed for the VLTB TBM Guidance System as well as the as-built modeling approach proposed in this paper. The tunnel is built along 151 Street, from 99 Ave to 93 Ave of the city. The total length is 1012.6 m at grade 0.1% and the outer diameter is 2340 mm (about 8 feet). The tunnel is built by an 8-foot Tunnel Boring Machine.

TBM Guidance Systems

A traditional laser guidance system was used as the primary tool for positioning the TBM, while the VLTB TBM guidance system was tested periodically for validation. The results of our field testing are shown in Table 1, revealing that the differences between the survey results from these two TBM guidance systems are acceptable, and the VLTB guidance system is reliable. Note: (1) results from the laser system used in practice do not represent the true deviations (30-40mm errors according to experienced tunnel surveyors) but reliable benchmarks to cross check VLTB results; (2) Due to limited line of sight, the VLTB guidance system is not able to determine the orientations of the TBM in this project.

Table 1 – Results of field testing

Date	VLTB		Laser		Difference	
	Line Deviation	Grade Deviation	Line Deviation	Grade Deviation	Line Deviation	Grade Deviation
10/08/2012	-25	1	-5	-20	-20	21
24/08/2012	6	15	5	15	1	0
30/08/2012	-46	-17	-5	-15	-41	-2
13/09/2012	7	-63	15	-30	-8	-33
21/09/2012	-6	-48	0	-20	-6	-28
26/09/2012	-2	-32	6	15	-8	-47
03/10/2012	-9	-21	10	20	-19	-41
21/11/2012	15	-18	0	-40	15	22

Implementation of the visualization program

Before the first field test, design information of W13 project is manually entered into the database. During each test, new position data of the TBM are automatically inputted to the database. As orientation data are not available, we assume that the Y-axis in the TBM's body frame is always parallel to the as-designed alignment, and the rolling angle (rotation of the TBM around its Y-axis) is always 0. The visualization output is shown in Figure 5, which demonstrates the feasibility of the approach proposed.

Date: 2012-10-19
Time: 16:12:57 MDT
Line Dev: -76 mm
Grade Dev: 12 mm
Distance: 571.639 m
Progress: 56.4%

Figure 5 – Visualization Output

CONCLUSIONS

The as-built information is critical for managing a tunnel project. In recent years, several technologies, such as laser scanning and photogrammetry, have been successfully tested in the construction industry for different applications. However, these technologies are not suitable candidates for modeling the as-built tunnel built by TBM method in a rapid, cost-effective fashion. In this paper, we propose a new as-built modeling approach, by tracking the position and orientations of the TBM over time. A case study in Edmonton was conducted to demonstrate the feasibility of the proposed approach.

However, several other factors that may affect the shape of the as-built tunnel is neglected, such as the deformation of the tunnel under ground pressure, installation errors of concrete lining segments, etc. To test the accuracy of the proposed as-built modeling approach, the authors plan to conduct a field survey of the inner profile of the as-built tunnel for sampled tunnel sections and cross check against the as-built models resulting from tracking the TBM.

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