Tunnel boring machine positioning automation in tunnel construction

Xuesong Shen [1], Ming Lu [1*], Siri Fernando [2], and Simaan M. AbouRizk [1]

[1] *Department of Civil and Environmental Engineering, University of Alberta, Edmonton, Alberta, Canada*
[2] *Design and Construction, Drainage Services, City of Edmonton, Edmonton, Alberta, Canada*
** Corresponding author (mlu6@ualberta.ca)*

Purpose Tunnel construction using a tunnel boring machine (TBM) entails precise machine positioning and guidance in the underground space. In contrast to traditional laser-based machine guidance solutions, the proposed research aims to develop an automation alternative to facilitate TBMguidance and as-built tunnel alignment survey during tunnelling operations. **Method** A fully automated system is proposed, in which a robotic total station is employed to automate the continuous process of TBM -tracking and positioning in the 3D underground working space. ZigBeebased wireless sensor networks are applied for wireless data communication inside the tunnel. A camera is mounted on the telescope of the total station to capture online operational videos. Real-time survey data are thus acquired, processed and displayed on a tablet PC on the fly, resulting in: (i) TBM's precise coordinates in the underground space; (ii) three-axis body rotations of the TBM; (iii) tunnelling chainage progress; and (iv) line and grade deviations of the tunnel alignment. **Results & Discussion** For proof-of-concept, a prototype TBM-positioning automation system has been developed in-house for laboratory testing. The accuracy testing was conducted by the automation system and a specialist surveyor independently. The differences between the two sets of surveying results were less than 2mm, which sufficiently validated the high accuracy of the automation solution. In April 2012, the prototype will be field tested on a 2.4 m diameter and 1,040 m long drainage tunnel project in Edmonton, Canada.

Keywords: *automation, tunnel construction, TBM, machine control and guidance.*

INTRODUCTION

For operators in the tunnel construction field, steering a tunnel boring machine (TBM) is like driving a vehicle in complete darkness. The current practice for TBM guidance largely relies on traditional laser guidance systems which project a laser point onto a target board fixed on a TBM. Limitations of the practice, however, potentially contribute to the high risks in executing tunneling projects, such as out-of-tolerance alignment deviations, project delay and budget overrun. Particularly, unforeseen underground obstacles and variable geologic conditions further complicate tunnel alignment control. It is not unusual that TBM operators and site managers are caught by surprise with excessive out-of-tolerance tunnel alignment errors[1]. It may take weeks or longer time to determine the exact alignment deviations by survey specialists. Sometimes, the TBM can be trapped in the underground space, requiring considerable time, cost and effort for recovery; in worst-case scenarios, the TBM has to be abandoned in the ground due to prohibitively high cost of rescuing it.

This research aims to develop an automation system for TBM positioning and guidance. A fully automated solution is proposed, in which a robotic total station is employed to automate the continuous process of TBM tracking and positioning in the three dimensional (3D) underground working space. ZigBee-based wireless sensor networks are applied for wireless data communication inside the tunnel. Real-time survey data are thus acquired and processed on the fly, resulting in: (1) tunneling chainage progress; (2) line and grade deviations of the tunnel alignment; (3) three-axis body rotations of the TBM; and (4) precise coordinates of any invisible points on TBM in the underground space. Further, the solution provides multiple role-based user interfaces and lends real-time, relevant assistance to TBM operators, tunnel surveyors, and project managers in making critical decisions.

The remainder of this paper is organized as follows: First, the pros and cons of the traditional laser guidance system are evaluated. We then illuminate system design of the proposed automation solution, followed by a tunnel estimation case to contrast improved and current work processes. Main findings and the practical applicability of the research are summarized in conclusions.

TRADITIONAL LASER GUIDANCE SYSTEM

Laser guidance systems have predominated in tunneling applications for many decades. Generally, a laser station is firmly fixed inside the tunnel, projecting a laser point onto a laser target board mounted on the TBM, as shown in Figure 1. Based on the offsets of the laser spot on the target board, the TBM operator infers the current line and grade tunnel alignment deviations.

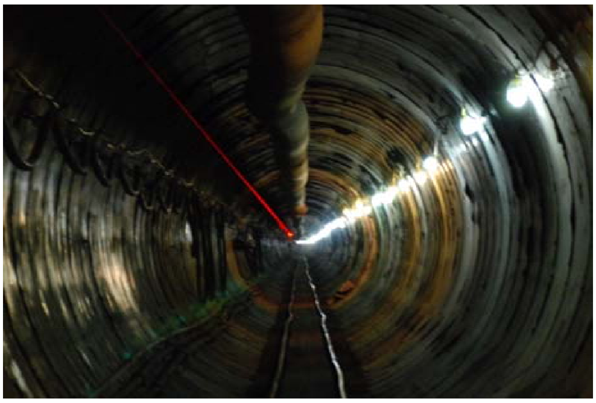


Fig.1. Guiding laser beam inside tunnel

TBM's three-axis orientations in the underground space are crucial to machine steering control. Coupled with the traditional laser system, a two-axis bubble leveler is commonly installed on the TBM to gauge its rotation angles of pitch and roll in vertical planes. Meanwhile, the advancing direction of the TBM (yaw in the horizontal plane) can be determined through installing a transparent front target along with the rear laser target board (see Figure 2).

(a) *(b)*

Fig. 2. Laser target boards mounted on the TBM: (a) transparent front target, (b) rear target

One of the major limitations associated with the traditional laser guidance system lies in relatively low accuracy and reliability due mainly to three factors, namely: (1) potential manual errors in initializing or calibrating the laser beam's alignment, (2) dispersion and refraction of the laser beam over a long distance, and (3) difficulty to receive laser's projection because of excessive TBM deviations[2]. Typically, the maximum application distance for the laser guidance system is around 200 m. Besides, the laser beam's alignment toned to be frequently calibrated by specialist surveyors (at least once every other day). As a result, the tunneling productivity can be considerably undermined by operation and maintenance of the laser guiding system.

In order to facilitate tunnel alignment control, commercial companies have developed advanced TBM guidance systems by integrating sophisticated mechanical, optical and electromagnetic subsystems[3]. Tight space constraints and harsh work conditions in the tunnel may not satisfy system installation requirements. On the down side, the high complexity in system design may compromise system reliability while considerably increasing the system's price and consumption cost, including system maintenance and technical service[4].

TBM POSITIONING AUTOMATION SYSTEM

The proposed TBM positioning solution combines four functions: (1) TBM tracking automation through surveying-computing integration; (2) wireless data communication enabled by ZigBee-based wireless sensor networks; (3) "virtual laser target board" program for TBM guidance; and (4) real-time visualization of tunnel construction in a 3D environment.

TBM tracking automation

The system employs a robotic total station to realize an automated, continuous process of TBM tracking and spatial data collection inside the tunnel, as illustrated in Figure 3. TBM's coordinates as well as its line and grade deviations from the as-designed tunnel alignment are computed in real time. By use of a limited quantity of tracking targets fixed on the TBM, the three-axis orientations of the TBM in the underground working space are computed by applying innovative "point-to-angle" algorithms, without the need of using any gauges (such as levelers, gyroscopes, inclinometers and compasses)[1,4].

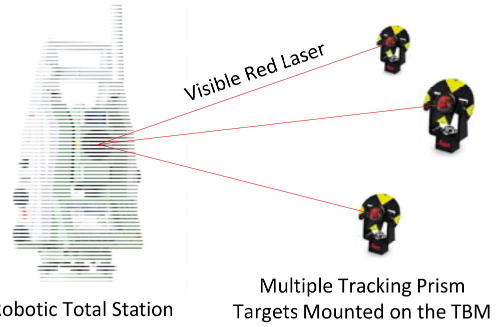


Fig.3. Automated target tracking for TBM positioning and orientations computing

Wireless data communication

Wireless sensor networks are purpose-deployed in the system design, enabling on-site data communication between key components of the TBM tracking system, namely, the total station, a control laptop computer in the underground tunnel, as well as a monitoring computer on the surface.

ZigBee-based wireless sensor networks are deployed in this system. In general, the emerging wireless sensor networks technology provides a smart, cost-effective and energy-efficient network infrastructure, which consists of a group of intelligent sensor nodes that can wirelessly communicate with one another. ZigBee represents a global specification for wireless sensor networks based on the IEEE 802.15.4 standard[5]. Typically, the battery life of a ZigBee sensor node is around several months, which can be further extended to years under the "sleep" operation setting (analogous to setting a computer to the sleep mode).

In the field implementation of the proposed solution, a control laptop computer is placed adjacent to the steering panel of the TBM. One ZigBee wireless node is linked with the robotic total station through a serial data cable, the other ZigBee node with the USB interface is plugged in the control laptop, as shown in Figure 4. Real-time surveying results are transmitted to the computer, while remote control commands are forwarded to the total station through the same wireless data communication channel.

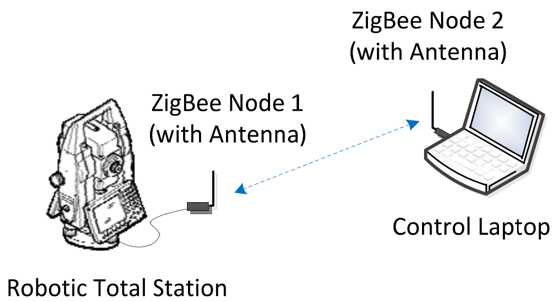


Fig. 4. Wireless sensor networks for data communication between the robotic total station and control laptop

Virtual laser target board program

A unique interface of the software system is a "virtual laser target board", which is displayed in the control computer to guide the TBM. Four fundamental modules are integrated in the program, including (1) total station communication module (TSCM): this module handles wireless communication between the control laptop computer and the total station; TSCM controls the total station operations by executing preprogrammed point tracking and surveying commands, and translates the feedback from the total station in its "machine language" for further computing; (2) tracking and positioning computing module (TPCM): this module forms the core of the whole system and it computes TBM's positions and attitudes from the coordinate data of the surveyed points. The computing results are passed over to the data publishing module; (3) analytical data publishing module (ADPM): the purpose of this module is to connect a data producer (for example TPCM) to a data consumer (for example the user interface module). It stores all analytical results in a queue and propagates any updates to all subscribers; (4) role based user interface module (RUIM): users of different roles have different user interfaces and each user interface has its own policy to render data.

The main user interface is designed for the TBM operator, which mimics a traditional laser target board the operator is familiar with, as shown in Figure 5. This user interface consists of (1) two perpendicular lines in the center of the screen and the crosshair indicating the as-designed alignment of the tunnel project; (2) two points onto the screen representing the current positions of the two center points at the tail and the head sections of the TBM, which are practically invisible in the underground space; (3) a square box which defines the TBM deviation tolerance limits. If the two points are both enveloped inside the box, it means at the current moment the TBM's alignment deviations are well controlled within the specified tolerances. The Euclidean distances from the tail/head point to the two perpendicular lines define accurate measures of line and grade deviations of the tunnel alignment.

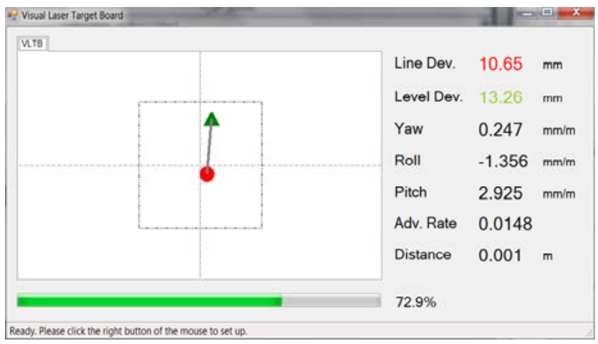


Fig. 5. Interface of virtual laser target board program

3D visualization of tunnel construction

A user-friendly 3D platform is provided in the system in order to visualize analytical results describing the TBM's real-time position state, the tunnel design and the construction progress. It aids project managers in making critical decisions on a near real-time basis. The tunnel design and tunneling process are visualized in three steps: (1) before the construction phase, relevant environment data, like ground topography, strata information, geotechnical parameters, and the as-designed tunnel alignment are modeled in the system; (2) during the construction phase, the system reads TBM real-time positioning data and animates the construction process. The difference between the as-designed alignment and the as-built alignment can be readily visualized through 3D computer graphics, thus allowing project managers and engineers to monitor what is happening underground in an intuitive VR environment; (3) after the construction phase, the tunnel alignment control process and the as-built tunnel alignment can be reviewed, while the TBM operator's experience can be captured for performance assessment and training purposes.

Figure 6 visualizes a simulated tunnel project. The progress of tunnel construction is presented in the complicated underground space, where the different colors of as-built tunnel sections indicate the quality of the tunnel alignment (green – within tolerance; red – out of tolerance).

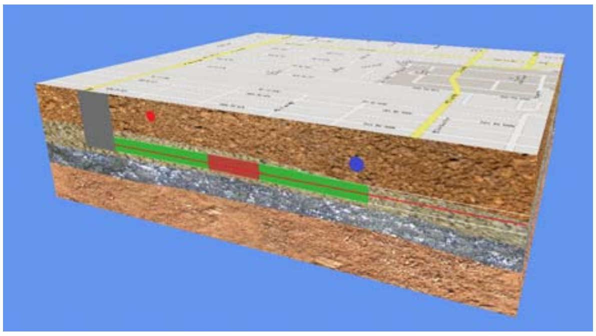


Fig. 6. Real-time 3D visualization of tunnel construction

PRODUCTIVITY AND COST PERFORMANCE ANALYSIS

In this section, a case study of evaluating productivity and cost performances on tunnel construction by use of the two alternative TBM guidance systems is presented. Suppose a 1,000-meter-long tunnel is to be built, total project time and direct construction cost are estimated for the traditional laser system and the proposed automation system, respectively.

The tunnel crew consists of one Tunnel Supervisor, one Tunnel Forman, one TBM Operator, one Crane Truck Operator, two Tunnel Laborers (level II) and four Tunnel Laborers (level I). A survey crew consists of three surveyors, as given in Table 1. The tunnel crew works 8 hours/shift, 1 shift a day, 5 days a week. The survey crew works on the site by appointment only. Based on the use of the traditional laser system on previously completed tunnel projects and productivity analysis using historical data, the average production rate is determined to be 5 m/shift, which factors in different types of delays in connection with survey checking and alignment control.

Table 1: Crew and equipment cost information

Quantity	Job	Hourly salary[6]
1	Tunnel Supervisor	$ 33.544
1	Tunnel Forman I	$ 28.554
1	TBM Operator	$ 26.915
1	Crane Truck Operator	$ 25.536
2	Tunnel Laborer II	$ 25.936
4	Tunnel Laborer I	$ 25.148
3	Surveyor	$ 24.573
Quantity	**Equipment**	**Hourly rental fee**
1	TBM	$ 315.000
1	Crane Truck	$ 120.000

For the traditional laser system:

- "Routine survey": In every 10 m TBM advances, a shutdown for 1.5 hours is necessary for routine checking of laser alignment by the survey crew;
- "Relocation survey": In every 200 m a shutdown for 5 hours for laser station relocation and laser realignment by the survey crew is necessary, which includes any "routine survey" if needed;
- "Misalignment shutdown": In every 800 m a potential shutdown for 1 week is required to fix TBM misalignment issues by the tunnel crew.

Note: the surveyors are only paid based on the number of hours they spend on survey checking and laser realignment services; while the equipment rental fee is charged based on time of availability on the site. Meanwhile, during non-productive shutdown periods, the tunnel crew would work on tunnel maintenance while still being paid by their hourly rates.

Given the average production rate of 5 m/shift, the total project time by use of the laser system is determined as:

$$(1000/5)*8 = 1{,}600 \text{ h}$$

The cycles as required for routine survey, relocation survey and misalignment shutdown are determined as below, respectively:

$$1000/10-1 = 99 \text{ cycles}$$
$$1000/200-1 = 4 \text{ cycles}$$
$$1000/800 \approx 1 \text{ cycle}$$

Considering the overlap between survey services and misalignment shutdowns, durations for routine survey, relocation survey and misalignment shutdown are as below, respectively:

$$(99-4-1)*1.5 = 141 \text{ h}$$
$$(4-1)*5 = 15 \text{ h}$$
$$1*5*8 = 40 \text{ h}$$

The total shutdown time is 196 h. Therefore, actual tunneling time is 1,600-196 = 1,404 h.

Based on the information given in Table 1, the hourly wages for the tunneling and survey crews are calculated as $ 267.013 and $ 73.719, respectively. The direct labor costs for the tunnel crew and the survey crew are calculated as below, respectively:

$$1600*267.013 = \$\ 427{,}220.8$$
$$(141+15)*\ 73.719 = \$\ 11{,}500.164$$

Since the equipment rental fee is charged based on time of availability on the site, the equipment rental time is estimated as:

$$(1600/8)/5 = 40 \text{ weeks} = 6{,}720 \text{ h}$$

The direct equipment rental cost is:

$$6720*(315+120) = \$\ 2{,}923{,}200$$

In total, the direct project cost is $ 3,361,920.964.

For the proposed automation system:

- "Routine survey": In every 50 m TBM advances, a shutdown for 1 hour is necessary for routine checking by the survey crew;

- "Relocation survey": In every 200 m a shutdown for 2 hours is required for total station relocation by the survey crew, which includes any routine survey if needed;
- Shutdowns due to misalignment fixing are not required.

Assuming the same tunneling hours are required on the project when the automation system is applied, the actual tunneling duration is 1,404 h.

The cycles for routine and relocation surveys are:

$$1000/50-1 = 19 \text{ cycles}$$
$$1000/200-1 = 4 \text{ cycles}$$

Considering the overlap between survey services and shutdowns, the durations for routine and relocation surveys are:

$$(19-4)*1 = 15 \text{ h}$$
$$4*5 = 20 \text{ h}$$

The total shutdown time is 35 h. Then, the total project time is 1,404+35 = 1,439 h.

As such, the average production rate using the automation system is:

$$1000/1439*8 = 5.56 \text{ m/shift}$$

The direct labor costs for the tunnel crew and the survey crew are:

$$1439*267.013 = \$ 384{,}231.707$$
$$35* 73.719 = \$ 2{,}580.165$$

The equipment rental time is estimated as:

$$(1439/8)/5 = 36 \text{ weeks} = 6{,}048 \text{ h}$$

The direct equipment rental cost is:

$$6048*(315+120) = \$ 2{,}630{,}880$$

Therefore, the direct project cost is \$ 3,017,691.872.

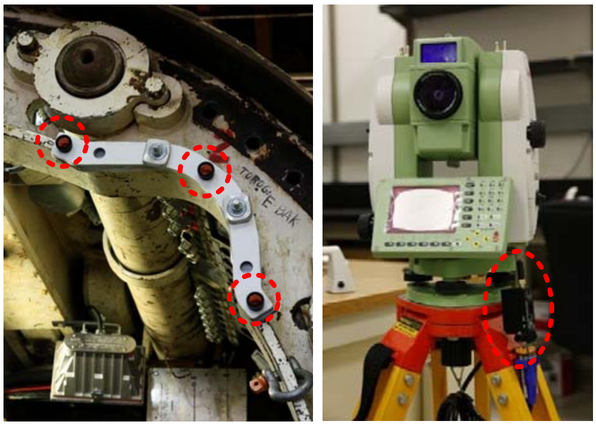
Table 2 compares the total project times, the direct construction costs and the average production rates for the two TBM guidance systems. When the automation system is applied to replace the traditional laser system, the contractor would save \$ 344,229 on the direct construction cost. Meanwhile, it is estimated that 10.1% shorter project duration and 10.2% lower direct cost would be achieved, while the average production rate would be increased by 11.2% to 5.56 m/shift.

Table 2: Productivity improvement and cost savings by use of the proposed automation system

	Laser system	Automation system	Comparison
Project time	1600 h	1439 h	-10.1%
Direct construction cost	$ 3,361,921	$ 3,017,692	-10.2%
Production rate	5 m/shift	5.56 m/shift	11.2%

SYSTEM PROTOTYPING AND FIELD TESTING

A prototype of the proposed automation system was developed in-house at the University of Alberta. The automation prototype mainly consists of three mini tracking targets (model: CTS Leica Compatible Mini Prism 65-1500M), a robotic total station (model: Leica TCPR1203+) and three ZigBee wireless sensor nodes (model: SENA ProBee ZS10 and ZU10), as shown in Figure 7. In close collaboration with the Design and Construction Section of the City of Edmonton, the new solution is scheduled to be implemented in a 2.4 m diameter and 1,040 m long drainage tunnel project in Edmonton, Canada for field performance evaluation from the end of April 2012.



(a) (b)

Fig.7. Prototype of the TBM positioning automation system: (a) three tracking targets mounted on a 2.4 m diameter TBM, (b) robotic total station linked with a ZigBee wireless node

CONCLUSIONS

Increasing demands for better underground infrastructure have spurred tunnel construction all over the world, within which the TBM tunneling method is the most commonly applied. The lack of effective TBM guidance solutions, however, potentially contributes to increased risks and uncertainties in tunnel construction

In this research, we have developed an automation solution for TBM positioning, which integrates automation control mechanisms, innovative computing algorithms, and wireless network technologies. Meanwhile, the multiple role-based user interfaces lend substantial decision support for TBM operators, tunnel surveyors, and project managers to track the construction progress as well as visualize any tunnel alignment deviations on the fly.

The project estimation case study indicates by adopting the proposed automation system tunneling productivity would be improved by 11.2% against using the traditional laser system. The resulting project duration and the direct construction cost would both be reduced by about 10%. The realistic system performances and the productivity improvement will be further validated through conducting extensive field experiments of the automated TBM positioning system at Edmonton, Canada starting from the end of April 2012.

Acknowledgments

This research was substantially supported by the TECTERRA's Alberta University Applied Research Funding Program (1108-UNI-008). The writers thank Mr. Sheng Mao and Mr. Xiaodong Wu of the University of Alberta for their deliberate effort and significant contribution in system development. The writhers also thank Mr. Tim Schneider, Mr. Chris Pratt, Mr. Rick Edge, Mr. Darsh Wimal Nawaratna, Mr. Michael Yu, Mr. Ray Davis and Mr. Junhao Zou of the City of Edmonton for their help in conducting field trials.

References

1. Shen, X.S., Lu, M., Chen, W., "Tunnel-Boring Machine Positioning during Microtunneling Operations through Integrating Automated Data Collection with Real Time Computing", *Journal of Construction Engineering and Management*, Vol. 137(1), pp. 72-85, 2011.
2. Thomson, J., "Pipe Jacking and Microtunneling", *Blackie Academic & Professional*, London, 1993.
3. Tacs GmbH, "Summary of the acs Guidance System", www.tacsgmbh.de, April 15, 2012.
4. Shen, X.S., Lu, M., Chen, W., "Computing Three-axis Orientations of A Tunnel-Boring Machine through Surveying Observation Points", *Journal of Computing in Civil Engineering*, Vol. 25(3), pp. 232-241, 2011.
5. Baronti, P., Pillai, P., Chook, V.W.C., et al., "Wireless Sensor Networks: A Survey on the State of the Art and the 802.15.4 ZigBee Standards", *Computer Communications*, Vol. 30(7), pp. 1655-1695, 2007.
6. City of Edmonton, "2009-2010 Collective Agreement between the City of Edmonton and Canadian Union of Public Employees Local 30", 2010.