Integrated Approach to Machine Guidance and Operations Monitoring in Tunnel Construction

X. Shen[a], M. Lu[b], S. Mao[b] and X. Wu[b]

[a] School of Civil and Environmental Engineering, University of New South Wales, Australia
[b] Department of Civil and Environmental Engineering, University of Alberta, Canada
E-mails: x.shen@unsw.edu.au, mlu6@ualberta.ca, mao1@ualberta.ca, xwu10@ualberta.ca

Abstract -

Tunnel construction method using a tunnel boring machine (TBM) is commonly adopted for building underground infrastructure, such as railways, roads, sewers, or utility pipelines. TBM tunnelling entails precise guidance of the machine in the underground space, as well as effective construction management and project control. The research aims to address critical engineering and management problems during the course of tunnel excavation, including TBM guidance, automated as-built data acquisition, real-time data processing and 3D visualization. In this paper, we propose an integrated TBM guidance and operations monitoring solution for tunneling applications. A robotic total station is employed to automate the continuous processes of TBM tracking and guidance inside the tunnel. Wireless sensor networks are particularly implemented for on-site data communication. The results of TBM's position state, tunnel alignment and construction progress are processed and presented in straightforward, user-friendly interfaces on the fly. Working with the City of Edmonton, Alberta, Canada, the integrated system has been implemented in the construction of a 2.4-meter-diameter and 1-km-long sewage tunnel project and undergone seven-month field testing in 2013. The solution lends substantial support to TBM operators and project managers in making critical decisions on a near real-time basis.

Keywords -

Automation and Control; Tunnel Construction; Machine Control and Guidance; Wireless Sensor Networks; 3D Visualization; Project Management and Control

1 Introduction

Tremendous demands for sustainable development of urban areas have driven widespread applications of tunneling techniques for underground construction. The resulting subsurface infrastructure, such as metro railway networks, traffic tunnels, drainage and storm water pipelines, electricity cables and gas lines, etc., are vital to the economy and security of the community [1]. Compared against the conventional hand-digging and cut-and-cover methods, tunnel construction using a tunnel boring machine (TBM) is more preferable especially in well-developed areas, thanks to its enhanced productivity, safer environments provided to the working crews, and less disruption to surface activities [2].

For operators in the tunnel construction field, steering a TBM is like driving a vehicle in complete darkness. It is crucial to precisely position the TBM in the underground space, so as to guide its advancement closely along the as-designed alignment [3]. For tunnel quantity assurance, tolerances of alignment deviations in both horizontal and vertical planes are generally specified in tight margins, such as ±75 mm for the entire tunnel project [4]. However, unforeseen underground obstacles and variable geologic conditions present significant challenges to tunnel alignment control. In practice, it is not unusual that TBM operators and site managers are caught by surprise with excessive out-of-tolerance tunnel alignment errors. It will take weeks or longer time to determine the exact alignment deviations by surveying specialists, and then figure out a practical strategy to steer the TBM back on track. Sometimes, the TBM can be trapped in the ground, requiring considerable time, cost and effort for recovery; in worst-case scenarios, the TBM has to be abandoned due to prohibitively high cost and overwhelming effort in rescuing it.

TBM guidance control currently relies on a laser station which projects a laser beam onto a laser target board mounted on the TBM [5]. However, laser target boards lack accuracy and reliability, thus potentially leading to increased risk and uncertainty in tunnel construction [6]. Meanwhile, current manual methods for tunnel progress data collection undermine both efficiency and effectiveness of project management and control. The operations data, like tunnel alignment deviations and TBM's advance rate, are manually recorded by TBM operators and project manager on a daily basis. The resulting data are often kept as separate paper-based records, which need days or even weeks to be compiled, post processed and analyzed. The analysis results often come back too late to be helpful.

The research aims to address critical engineering and management problems during the course of tunnel excavation, including TBM guidance, automated as-built data acquisition, real-time data processing and 3D visualization. We propose an integrated TBM guidance and operations monitoring solution for tunneling applications. A robotic total station is employed to automate the continuous processes of TBM tracking and guidance inside the tunnel. Wireless sensor networks are particularly implemented for on-site data communication. The results of TBM's position state, tunnel alignment and construction progress are processed and presented in straightforward, user-friendly interfaces on the fly.

The remainder of this paper first reviews the current practice for TBM guidance, followed by a description of the integrated system design. Finally, field evaluation of the proposed system in a 2.4-meter-diameter and 1-km-long sewage tunnel project in Canada is presented.

2 Current Practice for TBM Guidance

Laser systems currently predominate in TBM guidance applications. Typically, a laser guidance system consists of a tunnel laser station and a laser target board. As shown in Figure 1, a laser station is mounted on precast concrete tunnel lining segment. The coordinate of the laser station is first determined by traditional tunnel surveying. The orientation and gradient of the laser beam are then calibrated to be parallel with the as-designed tunnel alignment. Figure 2 shows a laser target board installed on a TBM. When the laser beam is projected onto the target board, TBM operator can infer the current line and grade tunnel alignment deviations by reading offset of the laser spot from the centre of the target board.

Despite extensive applications and low cost of the traditional laser guidance systems, several major technical limitations contribute to relatively low accuracy and reliability of the technology, including (1) potential manual errors in initializing or calibrating the laser station, (2) dispersion and refraction of the laser beam over a long distance, and (3) difficulty to receive laser's projection over a long distance or due to excessive deviations of the TBM [6]. As such, maximum application distance for the laser guidance system is around 200 m. For long tunnel projects, the laser station needs to be relocated every 200 m of tunnel excavation. The surveying work for moving the laser station in the tunnel is tedious and time consuming, requiring a crew of specialist surveyors spending one hour to calibrate the laser beam, and around five hours to set up a new laser station. Meanwhile, all of the tunnelling operations have to be halted during this work process. As a result, the tunnelling productivity can be considerably undermined by operation and maintenance of the laser guiding system.

Figure 1. Laser station mounted on precast concrete tunnel liner

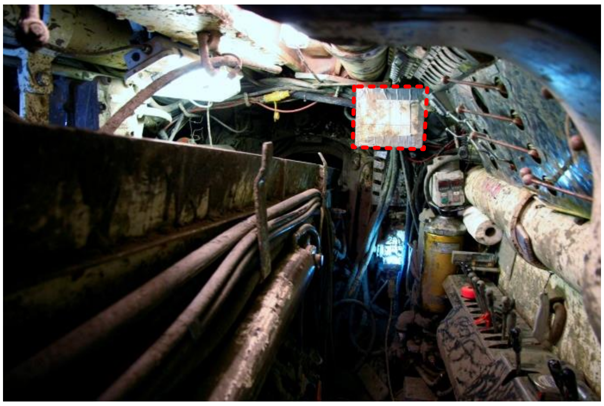


Figure 2. Laser target board installed on TBM

Corporations specialized in tunnel guidance have developed advanced laser guidance systems by integrating electronic or video laser target units to digitize the laser spot position on the target [7, 8]. On the down side, the high complexity in system design considerably increases the system's price tag and consumption cost, including system maintenance and technical service [6].

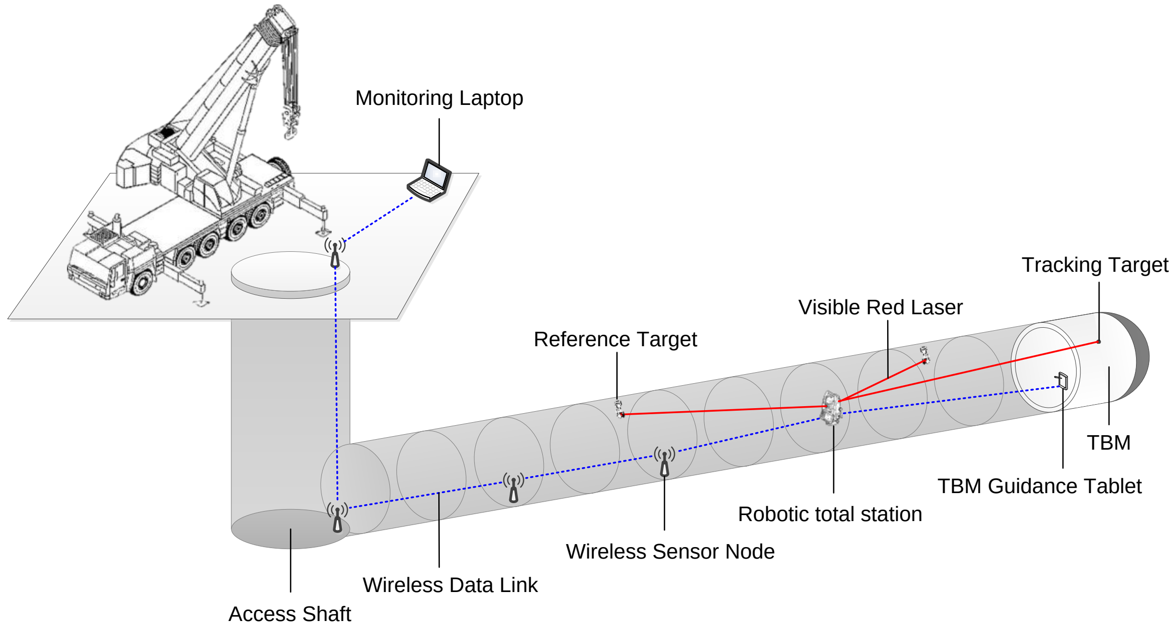


Figure 3. System design for the integrated TBM guidance and tunnel operations monitoring solution

3 Integrated System for TBM Guidance and Tunnel Operations Monitoring

An integrated solution is proposed in this research to automate TBM guidance and monitor tunnel operations in real time. The main functions include TBM positioning, wireless field data collection, online analytic data processing and visualization in a three dimensional (3D) environment. Given in Figure 3, a robotic total station is employed to automate the continuous processes of TBM tracking and spatial data collection inside the tunnel. Two reference targets with known coordinates are utilized to initialize and calibrate the total station inside the tunnel. The real-time position of the TBM in the underground space is then fixed accurately by the total station through continuously tracking a target installed on the TBM, as shown in Figure 3. Meanwhile, wireless sensor networks are particularly implemented for on-site data communication among the total station, TBM guidance tablet computer, and a monitoring laptop (see Figure 3). The analytical results of TBM's position state, tunnel alignment and construction progress are presented in straightforward, user-friendly 3D interfaces, which aid TBM operator and project managers in making critical decisions on a near real-time basis.

3.1 Surveying Automation and Real-Time As-Built Data Acquisition

The advanced surveying instrument of robotic total station is utilized in the research, serving as a critical geomatics tool for automated TBM positioning and as-built data collection. Compared against traditional surveying instrument, the robotic total station incorporated on-board computer, digital signal processing and self-driven motor. Therefore, sophisticated functions can be provided by the robotic total station, such as: (1) automatic target recognition, (2) automatic target tracking, and (3) programmability for computer controlled automatic surveying and data transmission.

The robotic total station is remotely controlled by a rugged tablet computer in the system. During tunnel operations, control commands are sent in wireless to trigger the surveying procedures, including automatic tracking of the target on the TBM, as shown in Figure 3. TBM’s coordinates with time stamped are returned in serial data package, which are further processed to derive the TBM guidance information in the tablet. Meanwhile, intelligent self-calibration functions are incorporated in the system design, by which the robotic total station can automatically detect any displacement of its own standpoint by checking two reference targets.

The low-cost and power-efficient wireless sensor networks are implemented for data communication inside the tunnel. As such, the total station can be wirelessly linked up with the tablet computer in the

TBM and the monitoring laptop on the surface. Figure 4 shows a prototype of the surveying automation system we developed in the Construction Automation Lab at the University of Alberta, Canada.

Figure 4. Robotic total station remotely controlled by a tablet computer through wireless sensor networks

3.2 Virtual Laser Target Board (VLTB) Program

A VLTB program is developed in house to automate TBM surveying and generate guidance information on the tablet computer. Three subsystems are integrated in the program, namely, the surveying subsystem, the communication subsystem and the control subsystem [9]. In the surveying subsystem, the robotic total station locks the coordinates of the target by a pre-scheduled plan or on request from the control subsystem. The survey data are sent via the communication subsystem to the control subsystem. The communication subsystem is responsible for data transmission through the wireless sensor networks infrastructure. The communication subsystem acts like a black box, and handles input/out data using standard serial data communication protocol. The control subsystem handles user interaction, survey control, data integrity check and failure recovery.

Figure 5 shows the VLTB user interface providing guidance information to the TBM operator. The as-designed tunnel alignment passes through the center of cross. A red circle and a green triangle represent the rear end and the cutter head of TBM, respectively (overlapped in Figure 5). The steering guidance is neatly simplified as a process to keep the red circle and green triangle within the square boundary as much as possible. Moreover, the red triangle arrows suggest the direction of the next manoeuvers for the TBM operator (turning right and downward as in Figure 5). The numbers on the right side of the interface indicate line-level deviations, yaw-roll-pitch angles, advancing speed of TBM and chainage distance of the as-built tunnel. The guidance information is updated in real time, assisting TBM operator making crucial decisions in an intuitive and straightforward manner.

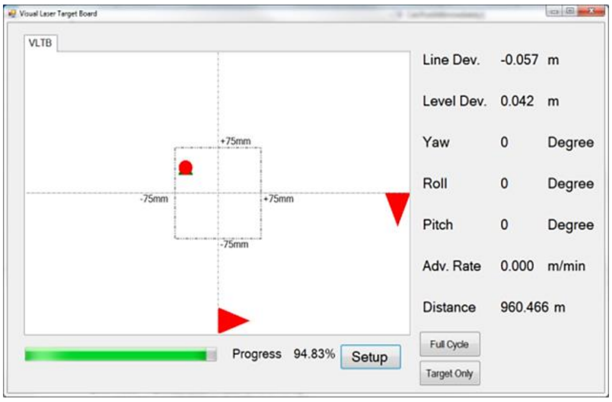


Figure 5. User interface of the VLTB program

3.3 Data-driven 3D Tunnel Visualization

A straightforward, user-friendly 3D visualization platform is further developed to present the analytical results of TBM's position state, tunnel alignment and construction progress [10]. The visualization program running on the monitoring laptop aids project managers in making critical decisions on a near real-time basis.

The architecture of the 3D tunnel visualization program is given in Figure 6. Two categories of input data are combined to model the as-built tunnel and its surrounding environment, including static data and time dependent data. Static data are design parameters derived from construction drawings and geotechnical reports, for instance as-designed tunnel alignment, soil layers, existing utilities, and other related information. These data are inputted to the database manually. Time dependent data refer to TBM tracking data, which are sourced from the VLTB system and are autonomously inputted by a data feed program. The resulting tunnel visualization interface is shown in Figure 7.

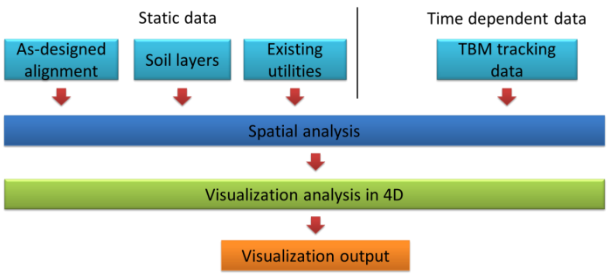


Figure 6. Architecture of tunnel visualization program

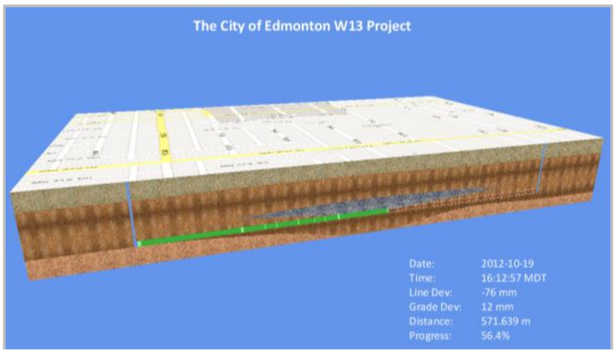


Figure 7. Real-time 3D visualization of tunneling progress

4 Field Evaluations

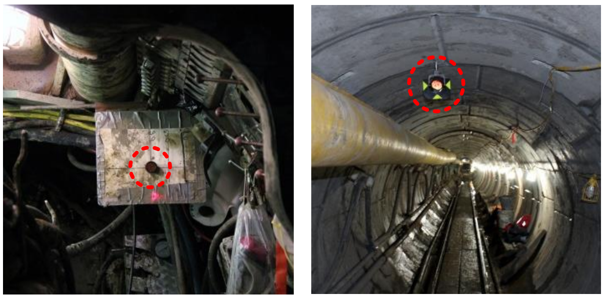
From August 2012 to March 2013, the integrated TBM guidance and tunnel operations monitoring system was implemented and underwent seven months testing on a 2.4-meter-diameter, 1-km-long sewage tunnel project (West Edmonton Sanitary Sewer - WESS, Stage W13) in Edmonton, Alberta, Canada. Figure 8 shows the LOVAT open-face TBM utilized in the project.

Figure 8. 2.4 m diameter TBM employed for the testing tunnel project

The robotic total station (model: Leica TS15) was mounted on the as-built tunnel liner using a specially designed surveying bracket, as shown in Figure 9. Constrained by the narrow surveying window available in the tunnel, one tracking target (model: Leica GMP101 mini prism) was installed at the center of the existing laser target board (see Figure 10a). Figure 10b shows one of the two reference targets (model: Leica GPR121 round prism) installed in the tunnel.

The maximum range to enable the automation function of the robotic total station for surveying the tracking target was found to be around 250 m inside the tunnel. Therefore, similar to the operations of the traditional laser station, the total station had to be moved forward from time to time as tunnel operations unfold. During the testing, the two reference targets were utilized to initialize the coordinates for a newly installed total station, which is enabled by a traditional surveying method called *resection*. As such, relocation of the total station can be completed within 30 min, as opposed to five hours required to move the laser station.

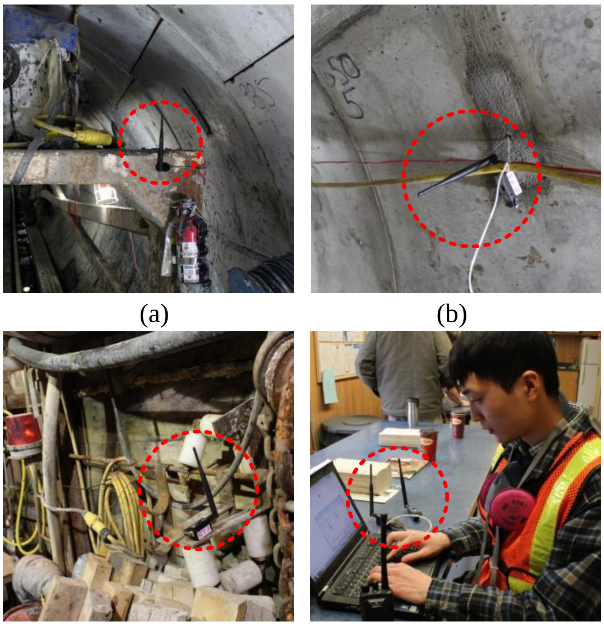
Figure 9. Robotic total station mounted in tunnel



(a) (b)

Figure 10. Surveying targets installed in the tunnel: (a) tracking target; (b) reference target

Wireless sensor nodes (model: SENA ZigBee ZS10) were deployed onsite every 150 m from the tunnel face along the tunnel lining segments, and access shaft to the surface trailer office, as illustrated in Figure 11a-d. A total of 12 sensor nodes established the wireless communication network covering the 1-km-long tunnel and the site on the surface. It is found from the extensive site testing that the wireless sensor networks can provide reliable data communication among the robotic total station, the tablet computer and the monitoring laptop. Figure 12 shows the tablet computer installed inside the TBM, which provided real-time guidance information to TBM operator during the testing.



(a) (b)

(c) (d)

Figure 11. ZigBee wireless sensor nodes deployed on site: (a) at rear end of TBM's trailing grantry; (b) along precast concrete tunnel liner; (c) at bottom of access shaft; and (d) in the site office

Table 1 shows consecutive testing results for 70 min on March 13, 2013. It is found the tunnel had been excavated over 934 m. The TBM advanced 0.809 m during this testing period, while the line and level deviations were maintained about 13 mm and 63 mm, respectively. It is noteworthy that some intervals of data were not available, e.g. 32 min between 10:29 and 11:01. This is mainly due to short period blockage of the line-of-sight by workers and tunnelling facilities. The VLTB program was designed to handle the situation properly, resulting in continuous operation afterward. When there are no readings from the system, a message will pop up and remind the TBM operator for checking the visibility of the tracking target.

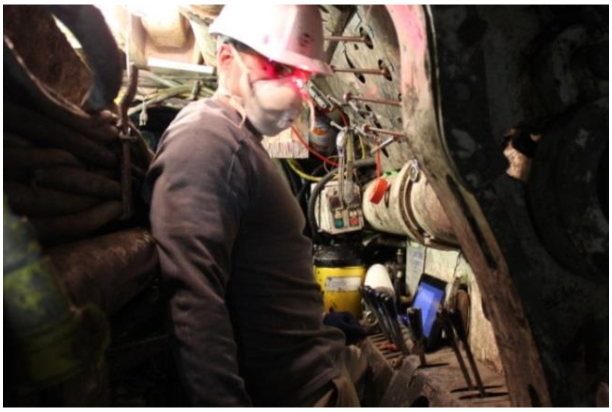


Figure 12. TBM guidance tablet computer mounted in the steering panel of the TBM

5 Conclusions

Today, utility and traffic tunnels are commonly constructed using the mechanized tunnelling method. Steering control of a TBM remains a challenging task due to complicated ground conditions, such as unforeseen obstacles and variable geologic conditions. Traditional laser guidance systems fall short in terms of accuracy and reliability. The lack of effective TBM guidance and operations monitoring solutions adds to high risks in executing tunnelling projects, potentially leading to out-of-tolerance alignment deviations, project delay and budget overrun, or even failure of the tunnel project.

An integrated system for TBM guidance and tunnel operations monitoring has been developed in this research. Through embedding automation control mechanisms and innovative computing algorithms, the

Table 1. Testing results on March 13, 2013

Date (yyyy/mm/dd)	Time (hh:mm:ss)	TBM coordinates (m)			Chainage (m)	Deviations (mm)	
		Easting	Northing	Elevation		Line	Level
2013/03/13	10:24:01	27743.706	5934141.476	644.721	934.514	15	-62
2013/03/13	10:25:07	27743.703	5934141.435	644.721	934.555	18	-62
2013/03/13	10:29:37	27743.705	5934141.314	644.721	934.676	17	-62
2013/03/13	11:01:26	27743.714	5934140.717	644.719	935.273	11	-65
2013/03/13	11:02:08	27743.714	5934140.694	644.72	935.296	11	-64
2013/03/13	11:04:16	27743.713	5934140.633	644.718	935.357	12	-66
2013/03/13	11:17:24	27743.715	5934140.53	644.721	935.460	11	-63
2013/03/13	11:19:40	27743.717	5934140.531	644.72	935.459	9	-64
2013/03/13	11:33:35	27743.713	5934140.667	644.72	935.323	12	-64
2013/03/13	11:34:42	27743.711	5934140.667	644.722	935.323	14	-62

system transforms a mature survey tool, the robotic total station, into a tunnelling control robot which precisely tracks and positions the TBM. Accurate TBM positions are automatically determined by the robotic total station, so as to derive line and grade deviations of tunnel alignment in real time. Meanwhile, intelligent self-calibration functions are incorporated in the system design, by which the robotic total station can automatically detect any displacement of its own standpoint by checking two fixed "landmark" points with known coordinates inside the tunnel. The low-cost and power-efficient wireless sensor network solution is implemented for data communication inside the tunnel. As such, the total station can be wirelessly linked up with a control computer on the surface, where data are analyzed to generate (1) real-time 3D visualization of the working TBM, (2) as-designed vs. as-built tunnel sections, and (3) any anticipated obstructions and geological information in the underground workspace.

Field testing of the prototype system on a 1-km-long sewer tunnel project in Canada validated the technical feasibility and effectiveness for real-time data acquisition. It is also found that the automation system can save on project shut-down periods for relocation surveying, from the current 5 hours to less than 30 minutes. Therefore, application of the new system would lead to significant enhancement of tunnelling productivity. The solution also lends substantial decision support to not only tracking the construction progress but also visualizing any tunnel alignment deviations on the fly. With sufficient project data accumulated, the cases and knowledge gained from the new solution can be used for industry training.

The future research will enhance system reliability through more field applications. Meanwhile, this research mainly investigated TBM guidance in straight tunnel alignment. Applications in curved tunnel sections deserve rigorous further investigations.

Acknowledgment

This research was substantially supported by the TECTERRA's Alberta University Applied Research Funding Program (1108-UNI-008). The writers thank Mr. Siri Fernando of the City of Edmonton for his vision and unreserved support. The writhers also thank Mr. Tim Schneider, Mr. Chris Pratt, Mr. Junhao Zou, Mr. Darsh Nawaratna, and Mr. Ray Davis of the City of Edmonton for facilitating field testing.

References

[1] Bernold L. Economic model to optimize underground utility protection. *Journal of Construction Engineering and Management*, 129(6): 645-652, 2003.

[2] Maidl B., Herrenknecht M., Maidl U., and Wehrmeyer G. *Mechanised shield tunnelling*, 2nd Ed. Ernst & Sohn, Berlin, Germany, 2012.

[3] Bickel J., Kuesel T., and King E. *Tunnel engineering handbook*, 2nd Ed. Springer, New York, USA, 2011.

[4] Megaw T. and Bartlett J. *Tunnels - planning, design, construction*. Halsted Press, John Wiley & Sons, New York, USA, 1981.

[5] Kavanagh B. *Surveying with construction application*, 7th Ed. Prentice Hall, Upper Saddle River, New Jersey, USA, 2010.

[6] Shen X. and Lu M. Development of virtual laser target board to tunnel boring machine guidance control. In *Proceedings of the 2012 ASCE International Conference on Computing in Civil Engineering*, Clearwater Beach, Florida, USA, 2012.

[7] Tacs GmbH. Summary of the acs guidance system. On-line: www.tacsgmbh.de, Accessed: 20/02/2014.

[8] VMT GmbH. TUnIS Navigation TBM laser. On-line: http://vmt-gmbh.de, Accessed: 20/02/2014.

[9] Mao S., Shen X., Lu M., and Wu X. Real-time tablet-based virtual reality implementation to facilitate tunnel boring machine steering control in tunnel construction. In *Proceedings of the 13th International Conference on Construction Applications of Virtual Reality (CONVR2013)*, London, UK, 2013.

[10] Wu X., Lu M., Mao S., and Shen X. Real-time as-built tunnel product modelling and visualization by tracking tunnel boring machines. In *Proceedings of the 30th International Symposium on Automation and Robotics in Construction and Mining (ISARC2013)*, Montreal, Quebec, Canada, 2013.