REAL-TIME TABLET-BASED VIRTUAL REALITY IMPLEMENTATION TO FACILITATE TUNNEL BORING MACHINE STEERING CONTROL IN TUNNEL CONSTRUCTION

Sheng Mao, Xuesong Shen, Ming Lu, & Xiaodong Wu
Department of Civil and Environmental Engineering, University of Alberta, Canada

ABSTRACT: *On the majority of tunneling projects, steering a tunnel boring machine (TBM) currently relies on a laser station which projects a laser beam onto a laser target board mounted on the TBM. However, laser target boards lack accuracy and reliability, thus potentially contributing to quality defects and increased risks of schedule delay and budget overrun in tunnel construction. This research has developed a cost-effective, real-time solution called "virtual laser target board (VLTB)" to substitute for physical laser target boards in guiding TBM during construction. Through integrating automation control mechanisms, innovative computing algorithms, and wireless network technologies, the VLTB technology transforms a popular survey tool, the robotic total station, into a construction control robot which precisely tracks and positions the TBM. By applying an enhanced point-to-angle computing algorithm, VLTB calculates the exact coordinates of the cutter head center on the working TBM in millimeter-level accuracy. The invisible cutter head center is projected onto a "virtual laser target board" on a tablet interface in relation to the as-designed alignment. Based on field testing, VLTB is found to be able to lend real-time, relevant assistance to TBM operators and tunnel surveyors. Compared to other advanced technologies in the market, VLTB provides a simpler and more flexible solution to ensure tunnel alignment control and enhance quality and productivity performances in tunnel construction.*

KEYWORDS: *Tunnel Construction, Tunnel Boring Machine, Virtual Reality, Mobile Computing, Machine Control and Guidance, Robotic Total Station.*

1. INTRODUCTION

In tunnel construction, the operator steers the tunnel boring machine (TBM) from the launching shaft to the receiving shaft. The steering control is a challenging process, as the operator can barely utilize any references as landmarks to drive the TBM along the designed path. In reality, the operator and the surveyors fully cooperate and follow a specific protocol. The surveyors are responsible for setting up a series of geospatial benchmarks from the entrance shaft to the point near the working TBM, while the operator will guide the TBM following a laser beam the alignment of which is consistent with the design and is calibrated based on surveyors' benchmarks. In the current practice, the surveyors establish a laser beam parallel to the tunnel alignment; the laser leaves a footprint on a laser target board mounted on the TBM. When the TBM is on the designed path, the laser dot is supposed to fall on the center of the target board. Thus, the operator merely follows the laser footprint in advancing TBM.

Nonetheless, this process is not as reliable or accurate as desired. Steering TBM by following the laser footprint is analogous to hiking in a forest by following the sun. There are several factors affecting the outcome. First, the information available for the operator is scarce. The operator barely knows where the TBM is headed, nor the exact position of the TBM in the tunnel. The operator has to imagine the TBM position and attitude in the tunnel and made decisions based on guts feelings. Second, the reliability of the system cannot be verified on demand. The accuracy of guidance is decided by the parallelism of the laser beam to the tunnel alignment, and in practice, the parallelism is difficult to be verified. Slight displacement of the laser will result in a magnified deviation on the laser target board, causing TBM to stray beyond the error tolerances. After all, the process heavily depends on interpretation and verification by surveyors. The surveyors need to interpret TBM's rough position and attitude by counting the quantity of concrete blocks already installed and checking inclinometers on the TBM. They also need to interrupt the construction and verify the parallelism of the laser regularly. Moreover, as it is error prone and time consuming to relocate and calibrate the laser, surveyors intend to reduce the frequency of moving the laser station. However, advancing the TBM further away from the laser source yields even lower precision in laser projection; as the distance grows, a trivial mistake to the laser will lead to a much more significant error in TBM guidance control.

Citation: Mao, S., Shen, X., Lu, M. & Wu, X. (2013). Real-time tablet-based virtual reality implementation to facilitate tunnel boring machine steering control in tunnel construction. In: N. Dawood and M. Kassem (Eds.), Proceedings of the 13th International Conference on Construction Applications of Virtual Reality, 30-31 October 2013, London, UK.

As such, TBM needs to be shut down more frequently to allow surveyors to check or move the laser system, severely undermining the productivity of tunnel construction.

In short, the operator needs to visualize the status of the TBM in relation to the as-designed tunnel alignment in real time; however, the laser system is not effective or reliable to provide the critical guidance as desired. In this paper, we describe an innovative system resulting from recent research, which integrates automated surveying, communication, and visualization in order to lend decision support to both tunnel surveyors and TBM operators. In addition, the data will be recorded in real time and analytical results transferred via wireless networks from the tunnel to the above ground office. The core idea of the method is to survey the TBM status in real time and visualize the most relevant information on a virtual laser target board, thus helping the operator and surveyor to make sound decisions as tunneling operations continuously unfold.

Shen and Lu (2012) thoroughly evaluated current laser guidance methods, and categorized the tunnel guidance solutions into passive and active groups. The classic laser system as described above is a passive laser system, and the laser is maintained parallel to the tunnel alignment and points at a laser target board. The laser can only show the deviation of the TBM from the alignment, while rolling and pitching angles are determined by inclinometers installed on TBM. Note the critical yawing angle is not detectable in the commonly available laser system. In a modified version, the target board is replaced by two special target boards, with the front board being transparent. As such, laser will leave footprints on both boards and the yawing direction can be computed from the horizontal deviations of the two laser footprints (Shen and Lu, 2012).

The yawing angle is very critical and irreplaceable for the operator to control where the TBM is headed (turning right or left). Active laser systems focus on how to improve the passive laser systems and try to measure yawing and pitching angles automatically (Shen and Lu, 2012). The two popular commercial solutions are from tacs GmbH (tacs GmbH, 2004) and VMT GmbH (VMT GmbH, 2003). Both enhance the dual-target-board design. In tacs GmbH system, the positions of laser footprints are first captured by digital cameras, then deviations of footprints are determined by image processing software (Shen and Lu, 2012; tacs GmbH, n.d.). In contrast, VMT GmbH turns the front and back target boards into light-sensitive devices. In a similar way, the deviations of the laser footprints are measured directly on the boards, and then the processing software calculates the path of the laser (Shen and Lu, 2012).

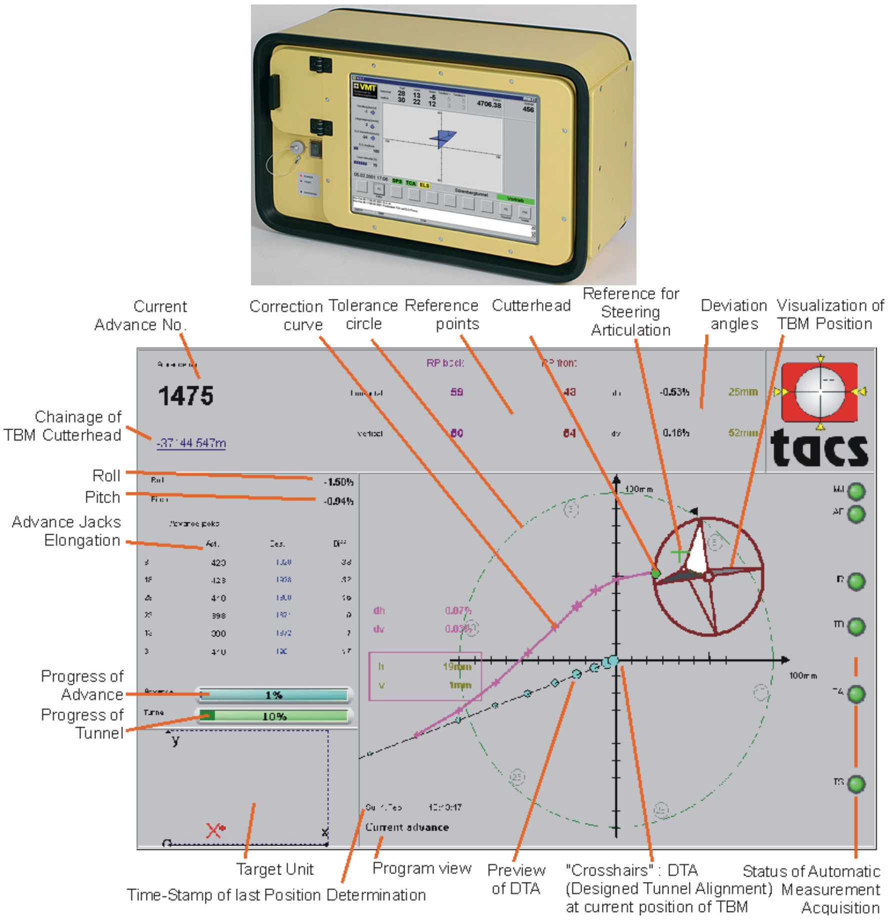


Fig. 1: Software interfaces from VMT GmbH (up) (courtesy of VMT GmbH, 2003) and tacs GmbH (down) (courtesy of Tacs GmbH, n.d.)

Both passive and active laser target boards provide the basis to further develop methods for visualizing TBM deviations, designed to assist the operator in steering the TBM. Liang and Lu (2010) developed a three-dimensional visualization system for the TBM, which can visualize the attitude of the TBM as well as the relative location between the TBM and existing pipelines. In particular, the system provides an intuitive view of heading control jacks of the TBM (Liang and Lu, 2010). The real time 3D visualization system is complicated in terms of design and implementation and demands substantial computing resources. Thus, the present research turns to a straightforward, intuitive, and robust system design as desired by the operator and the surveyor in making real time decisions during the tunneling process. And to our best knowledge, no existing commercial solution is as elegant or capable yet.

2. SYSTEM ARCHITECTURE

2.1 Tunnel Alignment and Deviations

A tunnel is designed to follow a path in the underground space at a given depth. During construction, the surveyors will figure out the path as per the design and project the guidance on the laser target board in order to guide the operator of the tunnel boring machine. Inside the tunnel, the path is always defined as *tunnel alignment*, which passes through the centers of all the cross sections of the tunnel. For a straight tunnel, the alignment is simply defined as an arrow pointing from the start point to the end point, while occasionally, for a tunnel consisting of straight sections and curved sections, the alignment is much more complex.

While advancing the TBM, the operator ensures the actual path taken by the TBM center overlaps with the tunnel alignment as close as possible. When the TBM strays from the tunnel alignment, deviations between the expected center position and the actual position yield. The deviations are characterized by two components: the line deviation is the horizontal offset from the online position, and the level or grade deviation is the vertical offset. As shown in Fig. 2, the line and grade deviations are defined as horizontal and vertical displacement between Y axis of TBM body and the tunnel alignment.

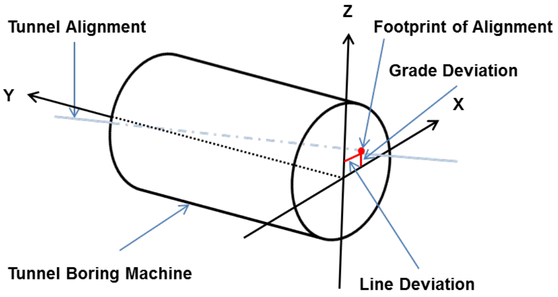


Fig. 2: Deviations of TBM

The operator is responsible for ensuring the deviation falls within a given tolerance, and the tolerance is chosen based on many factors. For example, the drainage tunnel is less tolerant (more stringent) than the traffic tunnel in terms of tunnel alignment control, as in a drainage tunnel the direction and speed of the storm water flow is affected by the tunnel alignment. Any “out of bounds” deviations may eventually affect the normal functionality of the tunnel.

After fixing the tunnel alignment, the surveyors need to define the corresponding laser path, which will be projected onto the laser target board installed on the TBM. However, the tunnel alignment is not always visible during the tunnel construction, as workers and equipment can easily occupy the space inside the tunnel and block the laser projection. Note the TBM is equipped with a gantry system at its backend, carrying supporting systems such as transformers, ventilation systems, conveyors and muck carts. The gantry system takes substantial space, making it impossible to project laser along the tunnel alignment. Therefore, the visible surveying and guidance window inside the tunnel is very narrow and often limited to a corner instead of the center of the tunnel cross-section.

2.2 Virtual Laser Target Board System

2.2.1 Design Overview

The VLTB system runs on an enhanced version of point-to-angle computing algorithm originally proposed by Shen and Lu (2012). The algorithm requires three prisms, which can be located anywhere in a solid object such as in a limited survey window near the top right corner of TBM. Despite the increased computational complexity, the real-time computing performance of the enhanced algorithm in terms of accuracy and response time has been maintained. By pre-registering the relative positions of the cutter head and three selected targets at rear end of TBM, the absolute center of the cutter head can be determined with the accuracy in the order of 1-2 millimeters based on real time TBM positioning. A vector linking two points in the underground space, namely the center of the cutter head and the center of the rear section of the TBM are projected on a virtual laser target board in order to visualize the TBM position and attitude. All the components in the system are connected through wireless networks. Both the operator at the frontend and the site foreman above ground are kept current of the tunnel as-built alignment and the actual construction progress in real-time.

2.2.2 Architecture

The virtual laser target board system is divided into three subsystems by functionality: the surveying subsystem, the communication subsystem and the control subsystem. As previously stated, the surveying subsystem comprises of target prisms and a robotic total station. The robotic total station is a total station enhanced with robotic control mechanisms and application programming interfaces (API). Users can control the robotic total station through the API and perform automation tasks such as target searching, tracking and surveying. In the surveying subsystem, the robotic total station locks the coordinates of the prisms by a pre-scheduled plan or on request from the control subsystem. The survey data are sent via the communication subsystem to inform the control subsystem.

As shown in Fig. 3, the system is connected by the communication subsystem (ZigBee wireless network). Operator sends survey commands and receives surveyed results through tablet-based interfaces of the control subsystem (a tablet computer). Note the guidance information is also shown on the tablet. On the other hand, the surveying subsystem (total station) receives survey commands, reads target prisms and broadcasts surveyed results via the ZigBee network. Above the tunnel, site server captures broadcasted results, and submits the changes to the database, which notifies 3D visualization programs to re-render the time-dependent 3D models.

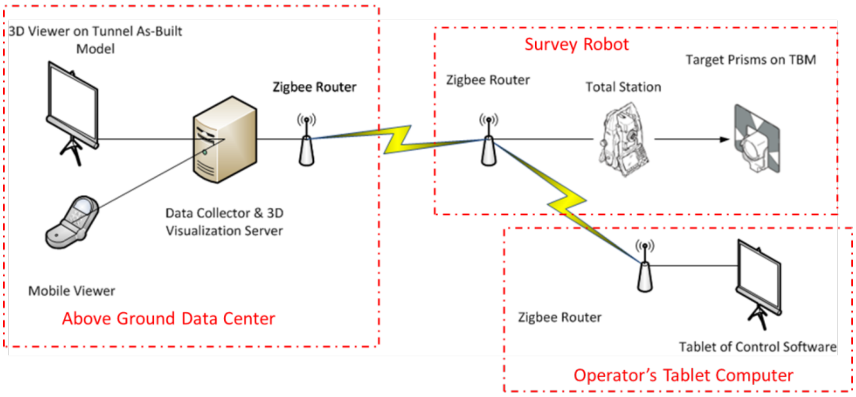


Fig. 3: System components and architecture

The communication subsystem is responsible for data communication, making the underlying data available to the user and the other subsystems. In different scenarios, the communication subsystem is configured differently, for example, for long-distance communication, ZigBee technology can be used, while for short-distance or low-latency scenario, Bluetooth technology can be employed instead. But for the other modules, the communication subsystem acts like a black box, and handles input/out data using standard input/output protocols. In tunnel construction, the survey premise will gradually move deeper in the tunnel with the advance of the TBM. As such, the distance between the data source and the above-ground data receiver continuously increases. As the mount of the robotic total station is relocated once every 200 m, the distance between the operator's tablet computer and the robotic total station gradually increases up to 200 m. In consideration of these constraints, a communication technology such as ZigBee that supports relay transmission is preferable.

The control subsystem handles user interaction, survey control, data persistence and failure recovery. It interacts with both surveyors and operators. For instance, surveyors can set up the coordinates of robotic total stations and target prisms through the system configuration interface; on the same interface, they can also check alignment deviations and schedule automatic surveys. For operators, they interact directly with the virtual laser target board (VLTB) interface and read the current steering guidance information. It is noteworthy the VLTB system installation is simple and doesn't require special laser receivers like those used in VMT and tacs systems; the system is a collection of inexpensive components or mature, off-the-shelf technologies.

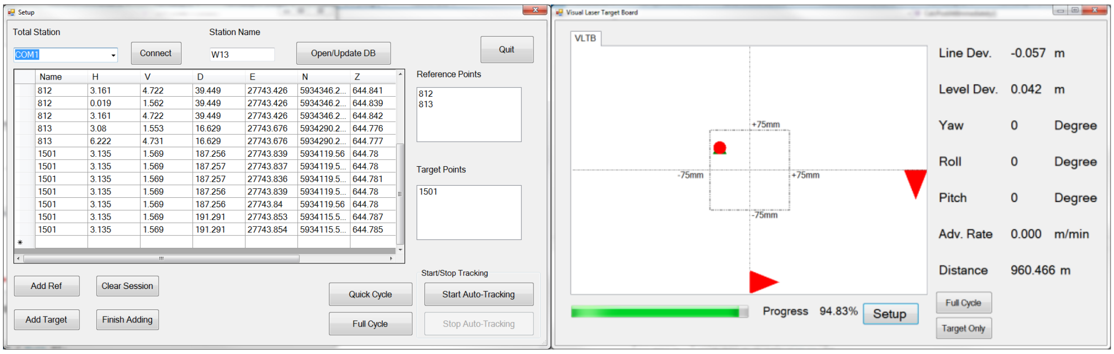
The software architecture of VLTB comprises of four different sub modules, and in the current version of the software system, all the four modules are implemented in the control subsystem (Shen and Lu, 2012). The four sub modules are:

- Total station control
- Data serialization and logging
- Data processing
- Data Visualization

As the communication subsystem is treated as a black box, all messages are broadcasted over the ZigBee-based wireless sensor network. The total station control module interprets the robotic total station control protocol, and the total station operates itself and controlled by commands issued from manufacturer-defined APIs. The data serialization and logging sub module preserves all incoming and outgoing broadcast messages, and keeps track of all the events for further integrity check and debug purposes. The data processing module is the core, which applies innovative algorithms to process surveyed data and produces results for support decision processes by surveyors and operators. The data visualization utilizes produced results and renders them in a more intuitive, role specific way in support of decision making and project control.

2.2.3 User Interface

There are two control panels in the VLTB system, one is for the operator and the other is for the surveyor. As shown in Fig. 4, the interface on the left is used by the surveyor and the interface on the right is used by the TBM operator. The surveyor can set up the total station, connect to the database, add or remove target/reference prisms and perform surveying through the interface. Meanwhile, the operator only needs to know the deviations of rear/head of TBM, and also the attitudes of the TBM. The information is neatly presented and the system runs automatically and maintenance-free.



Total Station: COM1

Station Name: W13

Name	H	V	D	E	N	Z
812	3.161	4.722	39.449	27743.426	5934346.2...	644.841
812	0.019	1.562	39.449	27743.426	5934346.2...	644.839
812	3.161	4.722	39.449	27743.426	5934346.2...	644.842
813	3.08	1.553	16.629	27743.676	5934290.2...	644.776
813	6.222	4.731	16.629	27743.676	5934290.2...	644.777
1501	3.135	1.569	187.256	27743.839	5934119.56	644.78
1501	3.135	1.569	187.257	27743.837	5934119.5...	644.78
1501	3.135	1.569	187.257	27743.836	5934119.5...	644.781
1501	3.135	1.569	187.256	27743.839	5934119.5...	644.78
1501	3.135	1.569	187.256	27743.84	5934119.56	644.78
1501	3.135	1.569	191.291	27743.853	5934115.5...	644.787
1501	3.135	1.569	191.291	27743.854	5934115.5...	644.785

Reference Points: 812, 813

Target Points: 1501

Line Dev. -0.057 m
Level Dev. 0.042 m
Yaw 0 Degree
Roll 0 Degree
Pitch 0 Degree
Adv. Rate 0.000 m/min
Distance 960.466 m
Progress 94.83%

Fig. 4: User Interface of the VLTB: Surveyor Version (Left) and Operator Version (Right)

Left image in Fig. 4 is the surveyor's interface. It allows surveyors to add and remove reference and target points, survey the TBM, and perform system self-check. Each target is given a unique name and stored with its metadata (the horizontal/vertical angle and slope distance) and its coordinates (coordinates on East, North, Zenith directions). A software session is used to preserve surveyors' setup when re-launching the interface; previously set data will be automatically loaded. Every time the surveyors relocate the robotic total station, they need to recreate a session to preserve the working environment.

The operator's interface is shown in the right image of Fig. 4. The two-dimensional diagram shows guidance information for the operator. In the diagram, the tunnel alignment passes through the center of cross, and is perpendicular to the observation plane (tunnel cross section). A red circle and a green triangle represent the rear end and the cutter head of TBM, respectively, while the vector connecting the two points represents the body axis of TBM. When the body axis of TBM is not along the tunnel alignment, the circle and triangle move away from each other. When the TBM stray away from the alignment, the circle and triangle move away from the center of cross in real time. The steering guidance is neatly simplified as a process to keep the circle and triangle within the square boundary and shorten the length of the body vector as much as possible. Moreover, the red triangle arrows suggest the direction of the next maneuvers for the TBM operator (turning right and downward as in Fig. 4), assisting operators in making decisions on steering control. The numbers on the right side of the interface show line/level deviations, yaw/roll/pitch angles, advancing speed of TBM and chainage distance of the TBM. Displaying such real time information is useful to keep track of the current TBM position status and the construction progress. Comparing related interfaces of commercial solutions (such as VMT and tacs), the VLTB interface simplifies the information shown to TBM operators and helps operators understand the status and make crucial decisions in an intuitive and straightforward manner.

2.2.4 Robustness Design

The underground construction environment is complicated, the space is confined, and the humidity is high. All these factors negatively affect the robustness and reliability of the tunnel guidance system. Consequently, the tunnel construction projects are vulnerable to system failures: A single failure may cause a huge impact on the progress and quality of construction, as the TBM cannot advance even an inch without reliable guidance

The five most critical bottlenecks of the VLTB system design are geometry of surveying, battery life, software logic, communication quality, and device deployment. The robotic total station is tasked to survey targets on the TBM along with two reference points with known coordinates on the tunnel wall. One of the concerns is the dispersion of the laser. As the tunnel advances away from the robotic total station, the laser footprint grows larger. If the two prisms are too close to each other, the total station can be confused and the measurements by the total station may be invalid. In tracking a smaller diameter TBM, it is very difficult to install the three prisms at positions on the TBM which are sufficiently apart from one another while falling in the narrow field of vision of the total station; therefore, the processing program will automatically choose corresponding algorithms based on how many target prisms are "surveyable", as shown in Fig. 5. Generally at least three surveyable prisms on the TBM allow the determination of exact 3D positioning of the TBM in the underground space; while one surveyable prism only yields the deviations of the end section of the TBM. Moreover, to obtain high accuracy results, the ideal geometric layout of prisms should be such that all the prisms fall in one plane perpendicular to the tunnel alignment (or the laser projection). In addition, the system is capable to perform automatic self-check, report any possible displacement, and carry out self-calibration operations of the total station as soon as possible.

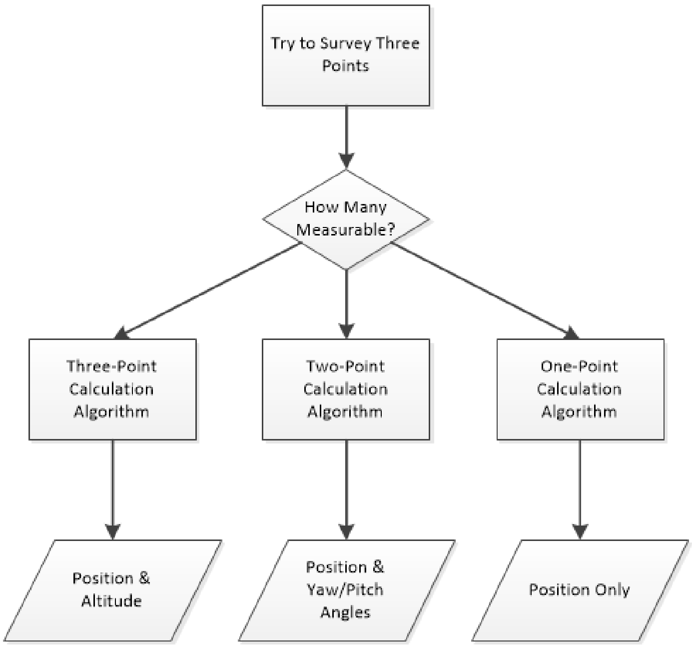


Fig. 5: System will automatically choose processing algorithm based on number of measurable targets.

The second problem is the battery management. The robotic total station, the tablet computer, and the wireless sensor network are all powered by batteries; any power failure is fatal to the entire system. Currently, several manufacturers of robotic total stations provide special external battery packs which can support the total station to continuously operate for over eight hours. Also, the tablet computer can be supported by the power supply inside the tunnel besides the TBM control panel. The Universal Serial Bus (USB) ZigBee nodes are powered through the USB interface of a laptop computer, and the standalone ZigBee nodes use external batteries as the energy source.

The third robustness problem is software logic. The software system uses both error codes and exceptions to protect the system integrity (Miller and Tripathi, 1997). The error codes are embedded in local logic and they represent known issues with the system. When the system receives error codes, it immediately triggers predefined actions, for example “waiting for next survey”. As for exceptions, they represent events that are not clearly predefined. For example, when some worker or equipment blocks the line-of-sight of the robotic total station, the survey process would fail and the system will receive a corresponding error code. In this case, the system automatically reinstates to a safe mode and alerts the operator or the surveyors about the situation.

The fourth problem is communication quality. There are dozens of wireless sensor nodes and the performance of each is influenced by battery, software bug, and other factors of the application setting. Currently, the system watches sending and receiving data from the wireless network, and observe time-out exceptions and message corruptions in communication. If errors and exceptions accumulate rapidly in a short time, the system probably suffers from failure in communication nodes, and such notification will be sent to operator. If the failure happens in a router node, it is more complicated to locate the node and it is not straightforward to identify which router has failed.

The last problem is deployment and it is most difficult to mount the tablet computer. The chamber of the TBM operator is confined and also the body of TBM is heated by all electrical and mechanical systems. Right now the tablet computer is put on the control panel but the heat can cause the tablet to malfunction.

3. EXPERIMENTS

The system was tested in an eight-foot drainage tunnel and field data were collected during the seven-month period from August 2012 to Mar 2013. The tests are divided into two phases: in the first phase, the system surveys the targets for several rounds and each round lasts for one hour, then the surveying results are regularly compared against surveyors’ independent checking results; in the second phase, the system runs continuously in the tunnel while the crew and TBM are working. The robustness of the system integration and automation in the field was tested in the second phase, and the system was capable to realize following functions:

- The wireless network was always online during the tests. The wireless coverage, interference, delay and batteries performed normally during the test. This test is to make sure that design and setup of the wireless network hardware system is valid in the tunnel setting.
- The total station surveyed the target prisms every five minutes. This test is to make sure the total station internal command server performs consistently with the wireless network and the control system.
- The control and computing module handled data and exceptions properly, for example, when the line-of-sight is blocked by anything or anyone, the total station should halt the current survey and a later retry is scheduled.
- The data receiver captured the surveyed data and submitted processed results to the database underpinning the three-dimensional visualization program.

During one field test, the system ran consecutively for two hours, and Table 1 shows the successful survey results. According to the logging system, all messages during the two hours were successfully sent and received, and it shows that the wireless network and the total station worked well in the test. Meanwhile, during the test, the line-of-sight was blocked by workers and the expander of TBM for a relatively long time, and the control system handled the situation properly, resulting in a blank survey history between 10:29 and 11:01. On the other side, the three-dimensional visualization program received computed results, and updated the rendered scene successfully.

Table 1: Continuously survey results of one target prism (H, V are in Radians, D, E, N, Z are in meters)

H	V	D	E	N	Z	Time
3.135	1.569	165.272	27743.705	5934141.545	644.722	13/03/2013 10:15:46 AM
3.135	1.569	165.288	27743.704	5934141.528	644.722	13/03/2013 10:21:36 AM
3.135	1.569	165.34	27743.706	5934141.476	644.721	13/03/2013 10:24:01 AM
3.135	1.569	165.381	27743.703	5934141.435	644.721	13/03/2013 10:25:07 AM
3.135	1.569	165.502	27743.705	5934141.314	644.721	13/03/2013 10:29:37 AM
3.135	1.569	166.1	27743.714	5934140.717	644.719	13/03/2013 11:01:26 AM
3.135	1.569	166.123	27743.714	5934140.694	644.72	13/03/2013 11:02:08 AM
3.135	1.569	166.184	27743.713	5934140.633	644.718	13/03/2013 11:04:16 AM
3.135	1.569	166.286	27743.715	5934140.53	644.721	13/03/2013 11:17:24 AM
3.135	1.569	166.286	27743.717	5934140.531	644.72	13/03/2013 11:19:40 AM
3.135	1.569	166.149	27743.713	5934140.667	644.72	13/03/2013 11:33:35 AM
3.135	1.569	166.149	27743.711	5934140.667	644.722	13/03/2013 11:34:42 AM
3.135	1.569	166.149	27743.713	5934140.668	644.721	13/03/2013 11:36:15 AM
3.135	1.569	166.152	27743.717	5934140.665	644.72	13/03/2013 12:06:51 PM
3.135	1.569	166.151	27743.715	5934140.665	644.722	13/03/2013 12:12:58 PM

Besides the field test, a mock-model based test was also rigorously conducted in a well-controlled lab environment in order to validate the accuracy of the system. As shown in Fig. 6, Point 1 is mounted at the center of TBM cutter head, and Points 2, 3 and 4 are mounted on the rear end of the TBM. In a real tunnel, Point 1 is not visible, and only points at the rear end can be surveyed. Before the test, relative coordinates of all four points were registered and recorded. In the test, every time the position and altitude of the TBM was changed, the total station surveyed the new coordinates of Points 2, 3 and 4, and the corresponding coordinate of Point 1 and the attitude of the TBM were calculated automatically. Then Point 1 was manually surveyed by the total station in the same positioning frame. The resulting coordinates were taken as ground truth to cross check the calculated coordinates, revealing one to two mm differences on average.

Fig. 6: The mockup TBM model for algorithm validation

4. CONCLUSIONS

This research has implemented the Virtual Laser Target Board (VLTB) system design based on an enhanced version of the point-to-angle computing algorithm proposed by Shen and Lu (Shen and Lu, 2012). It provides an accurate and intuitive solution to practicing effective construction engineering and management on tunnel projects. For surveyors, the system is not based on parallelism of the laser to the tunnel alignment, and therefore it is much easier to set up and relocate during construction. Also, the automatic self-check mechanism can report any displacement of the laser station (total station) at the earliest opportunity, reducing the heavy work load of performing regular checks by surveyors. This greatly shortens the time for quality control feedback and surveying tasks will not be necessary to interrupt the tunnel construction, leading to significant improvement in productivity.

And for TBM operators, the system requires no learning curve and provides them a neat and intuitive interface to work with. The interface is elegant and to the point compared with a three-dimensional visualization interface. When the system finds errors or exceptional situations, the operator can be alerted immediately. So the operator can carry out the challenging TBM-steering control measures with more confidence. Furthermore, with benefits of high accuracy and real-time feedback provided by the system, the operators can easily comprehend the TBM position and heading, and plan for optimal steering strategy in the immediate future during construction.

To guarantee system reliability, improving power use efficiency and self-debug ability of the ZigBee wireless sensor network are the issues to be addressed in the future. A possible solution is to change the communication mode from broadcast to point-to-point communication; thus, ZigBee sensor nodes can run on smart power-saving options and have longer battery life. As for the self-debug ability, when point-to-point mode is enabled, the system can iteratively query each sensor node and detect any malfunctioned ones. Nonetheless, the point-to-point mode cannot work directly with the robotic total station. A new system-on-chip control device can be an alternative solution to materialize the two-way wireless communication between a control tablet PC and the robotic total station.

5. ACKNOWLEDGEMENT

This research was substantially supported by Alberta Applied Research Funding program of TECTERRA (1108-UNI-008). The authors thank Mr. Siri Fernando, Mr. Tim Schneider, Mr. Chris Pratt, Mr. Grant Fox, 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.

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