 ISBN 978-0-85825-002-4

Automatic and real-time positioning of vault and full round tunnel shutters based on camera sensor units

M. Jarvis
VMT Tunnel Guidance, Melbourne, VIC, Australia

S.Wojtkowiak & N. Mattburger
VMT GmbH, Bruchsal, Baden-Württemberg, Germany

ABSTRACT: Traveller Formwork Gantries or Shutters are used for the secondary lining in both conventional and mechanised tunnelling, but current processes involve low levels of digitalisation and automation. Shutter positioning relies on conventional surveying with Total Stations, often causing delays. Setup and concrete pouring are typically documented on paper, later digitised in the office, which limits productivity and performance analysis. This paper presents the development of an automated measuring system designed to speed up shutter setup and reduce labour demands. Prototype systems have been trialled on vault and 360° shutters in Germany, Poland, England, and Australia to evaluate site acceptance and assess time and labour savings. While surveying teams have responded positively, end-user feedback is mixed. Additionally, discussions are underway regarding real-time onsite data capture, aiming to eliminate paper reporting, reduce redundant data entry, improve data collection efficiency, and streamline verification and evaluation processes for better site management.

1 INTRODUCTION

Traveller Formwork Gantries, also known as Arch Forms or Shutters are essential for the secondary lining phase in both conventional and mechanised tunnelling projects. This phase involves constructing the final tunnel lining, which requires high geometric precision and structural integrity. In recent years, the positioning and alignment of shutters have been conducted using conventional surveying techniques, primarily manual procedures such as block axis nail calibration or use of Total Stations. While reliable, these methods are time-consuming and iterative, often leading to significant waiting times for the production team and reducing overall workflow efficiency.

Accurate setout and calibration are critical, as the shutter must be precisely positioned to meet strict design tolerances. This includes both the alignment along the tunnel axis and control of roll (rotational positioning), vertical height, and potentially lateral offset. Achieving this correct spatial configuration is essential to ensure formwork is ready for the next concreting cycle and meets quality standards.

Work processes including shutter positioning, alignment verification, and concrete pour status are typically documented manually with pen & paper. These records are then transcribed into digital formats at a later stage in the site office. This approach introduces delays, data redundancy, and the risk of transcription errors, while also limiting the availability of real-time performance metrics. Furthermore, systematic tools for evaluating productivity, cycle times, and construction progress are scarce, restricting opportunities for process optimization.

Improving these workflows is both a technical challenge and an opportunity to innovate within the tunnelling industry. Despite the critical role of the inner lining in achieving a durable and safe tunnel structure, the complexity and importance of this stage are often underestimated in comparison to tunnel excavation. Emerging technologies and automation strategies now aim to modernize this area – enhancing precision and efficiency of formwork positioning while improving safety, reducing manual labour demands, and enabling better decision-making through real-time data acquisition and analysis.

2 TRADITION MEETS NOVEL APPROACH

The standard work cycle of a Traveller Formwork Shutter includes the steps of installing reinforcement, shutter advance, positioning of the shutter, concrete pour and concrete curing / hardening. When the curing process is fulfilled, the shutter may relocate and advance to the next block. Relocation and setup require support of a Surveyor to controls the position of the shutter.

In former times, a Surveyor would stakeout and install block axis nails on the floor along the planned axis and determine "asbuilt" coordinates. Work processes were recorded with pen and paper, the Surveyor handwriting within their field book. The height of each installed nail was compared to design and a delta height manually calculated.

A plumb-bob or plumb-line would hang down from the formwork carriage. To locate the shutter the plumb line would be orientated about the block axis nail. This comes along with a waiting time until the pendulum effect of the plumb line is complete. To control roll of the shutter, two block axis nails may be staked out at similar lateral offset from the centre of the shutter axis.

If the shutter must be positioned within the "gap" between two blocks, plumb lines are also required on the backside of the formwork traveller. As the shutter is iteratively positioned to account for roll, vertical or horizontal, the pendulum effect of the plumb line must be allowed to finish.

A more recent approach is an iterative measurement by a Surveyor via Total Station and prisms. Reference points are welded on the steel frame of the traveller, with adapters used to mount prisms. Total Station orientation is determined via free stationing using coordinates of the tunnel survey network. Two prisms left and right sided remain to local coordinates in the shutter coordination system. The Total Station measures e.g. the left prism to locate the coordinates. For the roll the prism on the other side is measured too. The shutter is moved according to the results and the iteration of measuring the prisms until the right position of the shutter is verified. Handwritten notes may be replaced by a tablet or controller with software to import data such as a coordinate file. The controller may be wirelessly linked to the Total Station via Bluetooth. The Foreman or Leading Hand references the tablet for shutter positioning and moves the shutter iteratively according to the data output.

The modern approach seeks to improve setup time of the shutter for a faster advance in the tunnel. A sensor unit is used to determine the forward position of the shutter. Each unit consists of two measuring cameras and one dual-axis inclinometer. The sensor unit is firmly mounted on the steel frame of the traveller as high as feasible, close to the upper formwork cap. Based on two incoming camera images and the roll values of the inclinometer, software used photogrammetric intersection to determine the traveller shutter axis in relation to the theoretical block axis.

At the beginning of the project a comprehensive machine measurement is needed to calculate the traveller axis and local coordinate system, plus the relative position of the formwork shutter and cap. Reference points are welded to the steel traveller to enable faster positioning during system commissioning. After installation, a calibration measurement is used to determine the position of each camera relative to the traveller coordinate system, values known as "assembly dimensions".

In preparation, the Surveyor must stakeout block axis holes to represent design alignment of the secondary lining. Each location is defined by a hole drilled into the base concrete slab and a standard Survey "spigot" screwed within. These locations supersede the previously used block axis nails. Important to note, these Survey setout works may be completed off the critical path, at a time convenient for tunnel operations.

Each location is signalled via one visual bracket called a Ringed and Automatically Detected Marker. RAD-Markers are essentially a target (white with black imprints) designed so the measuring cameras can precisely detect their centre point. RAD-Markers are housed within an aluminium bracket, which screws down into the Survey spigot.

System data is transferred to the industrial computer within the Central Box and software calculates the spatial position of the shutter by means of image detection and transformations. The position relative to design is represented numerically in the positioning module and shows the operator which direction to move the shutter. The operator may choose between indicated corrections or deviations of the shutter axis in relation to the designed block axis. As soon as the cameras detect the RAD-Marker in the field of view, software calculates the deviations of the shutter from the desired position in three dimensions: chainage, horizontal to block axis and elevation). The dual-axis inclinometer ensures the roll of the shutter is determined and software visualization shows the deviation in roll. The calculated differences for chainage, horizontal and vertical deviation as well as roll are represented in the software in a numerical and graphical manner.

During concreting and curing, the position may be automatically recorded by user defined intervals. The position and deviations are continuously indicated to the operator. Due to the use of a tablet on which a visualization of the positioning system is running, the operator is not tied to a certain place and may set up the shutter in a remote-controlled manner.

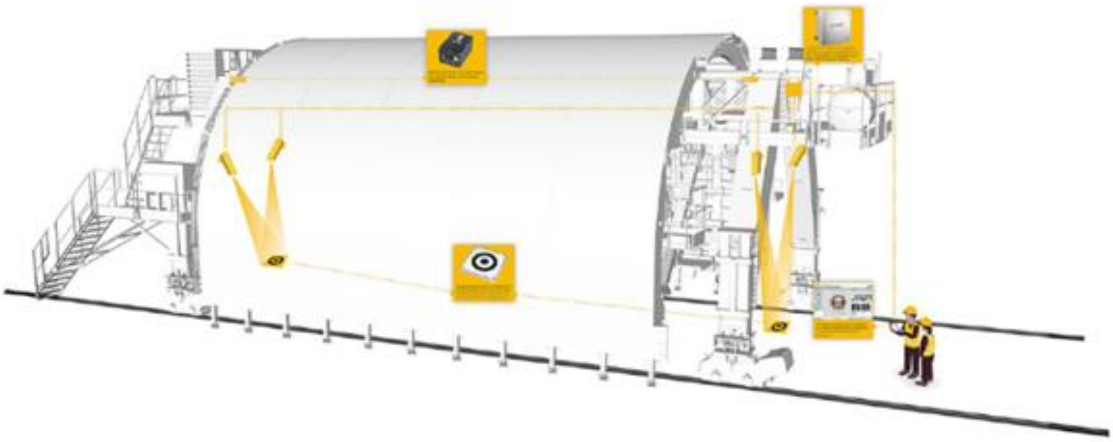

Figure 1. Overview of positioning system hardware and concept

3 TIME, COST & WORK FLOW

To assess validity and implications of the novel method, we compare both methods from various perspectives.

Table 1 provides a simplified comparison of the methods and some of their key parameters.

Table 1. Comparison of total station positioning method and novel method.

	Total Station Method	Novel Method
Quick and fast setup	Install prisms and setup Total Station	Once installed no further set up time/ RAD markers are relocated each block
Position determination	Using Total Station and prism – iterative procedure	Using camera-based sensor units / as backup system transferable to Total Station
Monitoring function during the processes	Manual process by Surveyor	Automated monitoring function via camera-based system configured in different intervals as needed
Use of specialized labour	Surveyor involved in set up phase and pre-pour check	Tunnel personal such as Foreman trained to manage system.

		Surveyor on call and for pre-pour check only
Time needed for setup	Up to one hour	Approximately 8-10 minutes
Digitalization and database handling	Handwritten and converted in office	Automated data upload from shutter position for automated Reports
Quality of the inner lining	No values	Monitoring improves quality process

Considering the roll of the shutters, the traditional setout of the shutter may have taken up to one hour and required a Surveyor with specialized equipment including Total Station and prisms. When the traditional method was employed, user must consider significant waiting time regarding the pendulum effect of the plumb-bob over each block axis nail. This must be considered after each iterative traveller movement. Where a dedicated Surveyor and Total Station are employed, each traveller movement requires new prism measurements and subsequent calculation are required until the shutter setup is completed.

The novel method demonstrates a reduction of setup time and supplements a full-time Survey team by enabling other personal to complete the process. Surveyors are required only to prepare the block axis position for markers and conduct a final pre-pour check for quality control. When RAD-Markers are repositioned, they are screwed in the pre-drilled holes and the camera detection recognizes the input of the software. As the shutter approaches the block joint and cameras visualise the RAD-Markets, all required correction values are calculated and displayed on the tablet. Thus, the shutter can be setup for a new cycle in minutes. Waiting time for the production team is mitigated and the Surveying team may focus on critical path tasks.

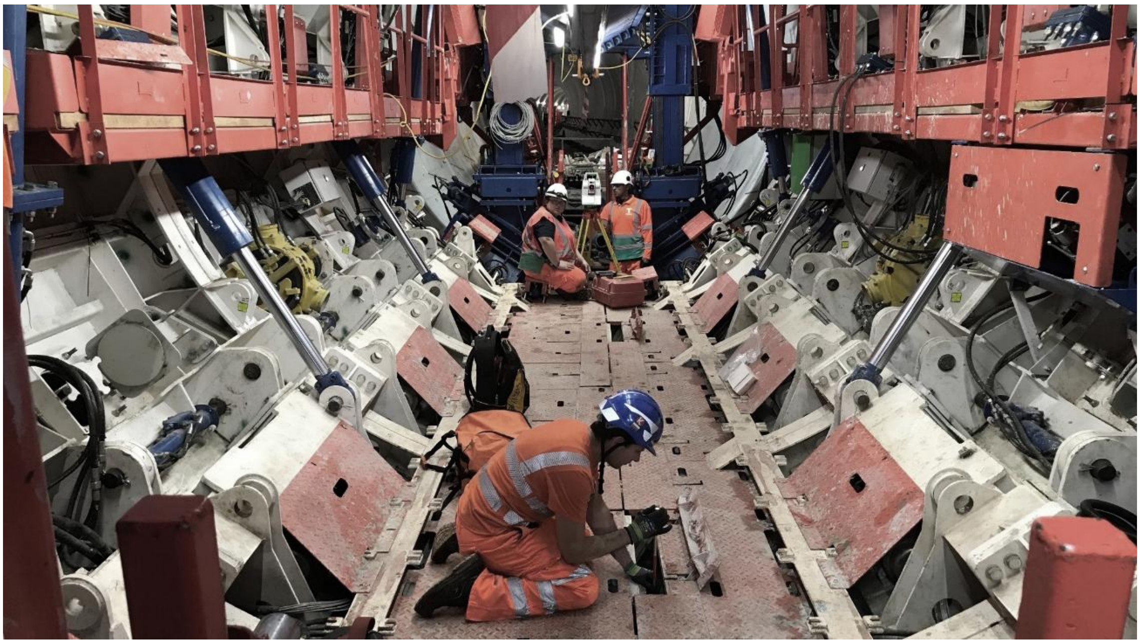

Figure 2. Survey personnel employ iterative total station positioning method

4 INNOVATION & DIGITIZATION

The traditional set up of the shutter does not include live positioning values. Once the shutter is setup, concrete cured and the shutter advanced, the cycle starts again. The novel method determines the current position of the shutter compared to the designed block axis in real-time. To achieve this, the system uses camera sensor units installed at within the steel traveller frame, connected to the shutter cap at the crown. Position and roll are continuously displayed to the operator. This allows an exact vertical and horizontal setup with relation to the design block axis that can be precisely controlled. The current chainage, block number and roll of the shutter complete the information that is important for the operator. The operator may select position display as either horizontal and vertical corrections, or deviations in relation to the block axis. Camera images are live streamed into the main system view, enabling errors to be recognized directly. The operator is in optimal control of necessary steering movements. The status of all system components is monitored live. Green status means all is normal, while warning colours yellow and red indicate system issues for immediate action.

Figure 3. Positioning main screen from operators view during setup phase of a shutter

Traditionally the Foreman or Leading Hand would note production information on paper in the field and record in the construction office at the end of shift. This process allows limited options for analyzing productivity and construction progress.

The novel monitoring method of the shutter position during the concreting process and acquisition of the position during the concreted blocks can be actualized in intervals for the recordings and for saving them in the database. Values are set by the user in the system configuration and may be written into the PLC of the machine manufacturer to enable automatic positioning of the shutter. The system provides full documentation of the positioning in a database and is the basis for reports, data exports (CSV, XLSX) or other analyses. It has the potential to mitigate or replace manual recording in the field and rework in the office.

The system software runs on a Windows-based industrial PC. The module and function access are controlled by robust user management. The high information content of the displayed data ensures an optimal control of the machine position to achieve uniform positioning of the shutter with small deviations from the block axis. The final shutter position is stored in the database and reported digitally for quality management.

Reference points welded into the shutter, with known coordinates in the shutter system, can be used to independently determine the shutter position through an independent measurement by means of the Total Station as well as with prisms and subsequent transformation in the software module.

5 LABOUR & PERSONNEL

The conventional method requires a Survey team to be involved in all processes along the tunnel network and shutter setting modes. Positioning the shutter requires personal and waiting times for the team until the final positioning is done by the Surveyors.
With the novel method Survey may prepare their works off the critical path, at a time convenient for tunnel operations. Their primary task is setout of block axis locations which represent design alignment of the secondary lining. Each location is defined by a standard Survey "spigot" screwed into a hole drilled into the base concrete slab. Surveyors prepare a coordinate file and upload on the tablet. These locations supersede the previously used block axis nails.
As the shutter advances to the next block, one of the production team must simply relocate a single RAD-Marker by screwing into the spigot. Surveyors are largely released from shutter setout and must only conduct a final pre-pour check for quality control. Waiting time for the production team is mitigated and the Surveying team may focus on critical path tasks.

To improve health and safety of site personnel the remote-controlled manner of the positioning system ensures that the operator is not tied to a certain place to complete the work. The operator may reference the positioning system from a safe and comfortable location. Support personnel are not required to climbing around the shutter gantry during setup to visually assess the position. Use of a Total Station and tripod is mitigated improving access along the tunnel alignment for personnel and plant.

Figure 4. Production personnel screw in a RAD-marker to pre-coordinated survey "spigot"

6 PROTOTYPE ANALYSIS & FUTURE WORKS

Prototype systems were evaluated on vault and 360° shutters in Germany, Poland, England and Australia. The goal was to gather experience on benefits with respect to time and labour efficiency, safety of personnel, plus listen to key users regarding potential improvements. Prototype systems were assessed in parallel to the standard setup cycle and reviewed against previously stated perspectives. Key improvements on the operational side include reduction of total setup time and the number of specialized personnel required. It was generally accepted that the camera-based sensor unit system improves most key parameters.

As there is naturally a cost to procure and commission such a system, some sites noted a greater benefit where more blocks were poured. Where 25 or fewer blocks were poured, the overall cost-benefit was reduced. As the total number of blocks increased above 30, the overall cost-benefit was significant.

As of 2025, manufacturers of Tunnel Boring Machines (TBM) use technologies that enable automated data acquisition and position determination of future advances. The secondary lining processes of conventional tunnelling are far behind.

Soon, comparable technologies will be available for conventional inner lining processes that are done by shutters, such as data acquisition and digital shift management reporting.

Positioning values may be written into the machine PLC and systems will support and integrated and automatic positioning of the shutter throughout the setup phase. This will apply to vault, arched and full-round shutters.

Data Management and Documentation will be streamline through automated documentation of the position, block reports, shift data management and an asbuilt of the shutter position prior to stripping formwork – all available in automated reports stored in the cloud.

The camera-based sensor unit enables a monitoring process to provide information regarding movement of the formwork during concrete pouring and curing. Additional sensors will deliver information regarding concrete temperature, pressure and load. Industry should anticipate that each positioning task will be automated to ensure each process is faster, safer and of higher quality.

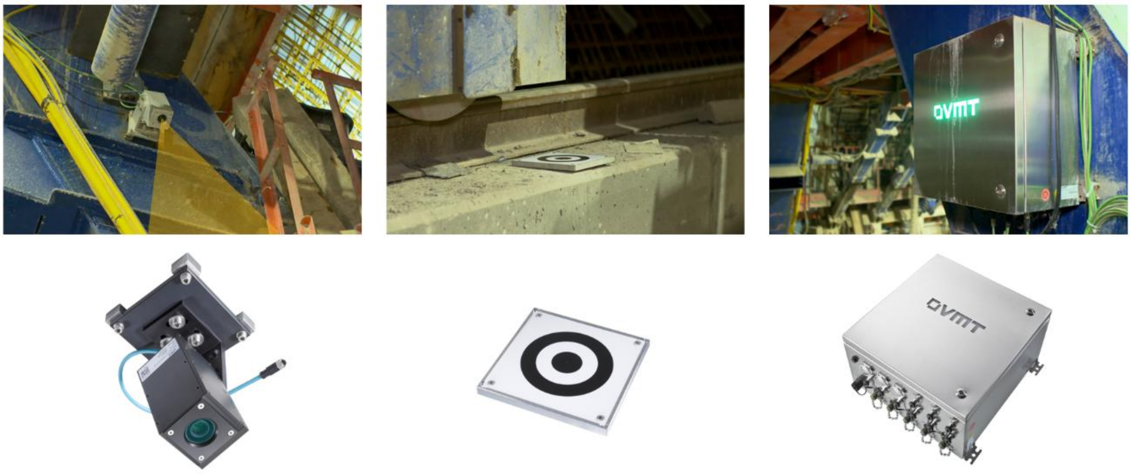

Figure 5. Sensor technology enables advances in automation, data management and reporting.

Each year the civil tunnelling industry aspires for greater implementation of 3D modelling and BIM technology to follow each process via a digital twin. The modern conventional construction site cannot be tracked in the same high standard as a the TBM method. While TBM construction sites have tools in the cloud to view the status of production in real time, the work of the inner lining with shutters may be loosely analysed via handwritten notes. To leverage technology currently utilized in TBM tunnelling, tenders for secondary lining must be modernized. Such topics should consider navigation support of shutter formwork, data integration with machine PLC's, automated reporting and shift data. Quality assurance and documentation topics should be supported by asbuilt block reports, concrete batch traceability, monitoring of concrete temperature, pressure and load during both concrete pouring and curing.

7 CONCLUSION

This paper has looked at the role of Traveller Formwork Shutters as used for secondary lining of conventional and mechanised tunnelling. We examined the task of positioning shutters by traditional methods and compared to a modern novel method with sensor units. By comparing both methods, this paper established the novel method enhances speed, safety, efficiency and cost-savings, plus greater possibilities around data acquisition and reporting. Furthermore, prototype testing on construction sites around the world have shown the waiting time in the positioning phase of the shutter can be mitigated, and the Survey team is released from critical path activities.

During the early years of underground tunnel excavation, works were performed with the simplest methods, rudimentary position control and a large workforce. Tunnel Boring Machines have embraced technology and evolved through more complex and automated methods. By contrast the secondary lining processes can be greatly enhanced. In the coming decades, one focus of tunnel construction will be the automation of the processes to increase the safety and efficiency. We seek to eliminate paper reports and redundant data entry, enhance data collection efficiency, enabling better evaluation, and streamlining the verification process for site management. In this context the camera-based positioning system is a development step which brings more automation and a reduction of personnel needed and makes an important contribution to this evolution.

8 REFERENCES

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