Automated Shotcrete Application in Tunnelling

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INTRODUCTION AND DEVELOPMENT

The tunnelling industry has again been working toward the automation of shotcrete application for some years now, after research and development stalled around 2005. Robots had been developed with the capability of applying a consistent thickness of shotcrete onto uneven surfaces. However, doing so did not improve the waviness of the original substrate, and the cost and limited possibilities to use such machines brought further development to a halt.

Stricter requirements regarding the waviness and accuracy of the shotcrete surface, coupled with a growing shortage of skilled shotcreters, necessitated further development. Such automation has the potential to address several fundamental challenges associated with conventional, manually controlled shotcrete spraying.

One of the primary objectives during shotcrete placement is to achieve a surface that is as smooth as possible and as close as possible to the specified geometry. In practice, however, the nozzle is usually controlled manually via remote control while the operator is positioned at some distance from the spraying location. Limited visibility and the strong dependence on operator experience often make it difficult to consistently meet the increasingly strict quality requirements for tunnel profiles.

Deviations from the geometry frequently result in extensive and costly rework, such as milling/grinding operations or manual surface corrections using repair mortars. These activities can significantly affect construction time and project costs and may even jeopardize the overall economic success of a project.

Against this background, a joint development project between BeMo Tunnelling GmbH and a development team from Vision Metrics GmbH was launched in February 2023. The goal of this collaborative effort was to develop a control system for fully automated shotcrete placement, to test it under real construction site conditions, and ultimately use the system on BeMo sites and to rent it out to third parties.

The basis for development was a conventional shotcrete robot originally designed for manual nozzle guidance via remote control. As part of the project, the machine was equipped with additional sensors and a newly developed control system (Fig. 1).

After completion of the mechanical and electronic modifications, development of the control software began, accompanied by initial practical tests. The first trials were carried out in a specially constructed test tunnel (Fig. 2) to evaluate fundamental functions and control logic under controlled conditions.

As development progressed and the core functional principles were successfully validated, further tests were gradually moved to real tunnel environments. During this testing phase, continuous adjustments were made to control parameters, hardware components, and the overall workflow. Through this iterative development process, the original concept evolved into a robust and practical solution suitable for construction site operations.

Fig. 1: Retrofitting the control system on an existing machine

Fig. 2: Test setups of the artificial tunnel profiles for the initial tests

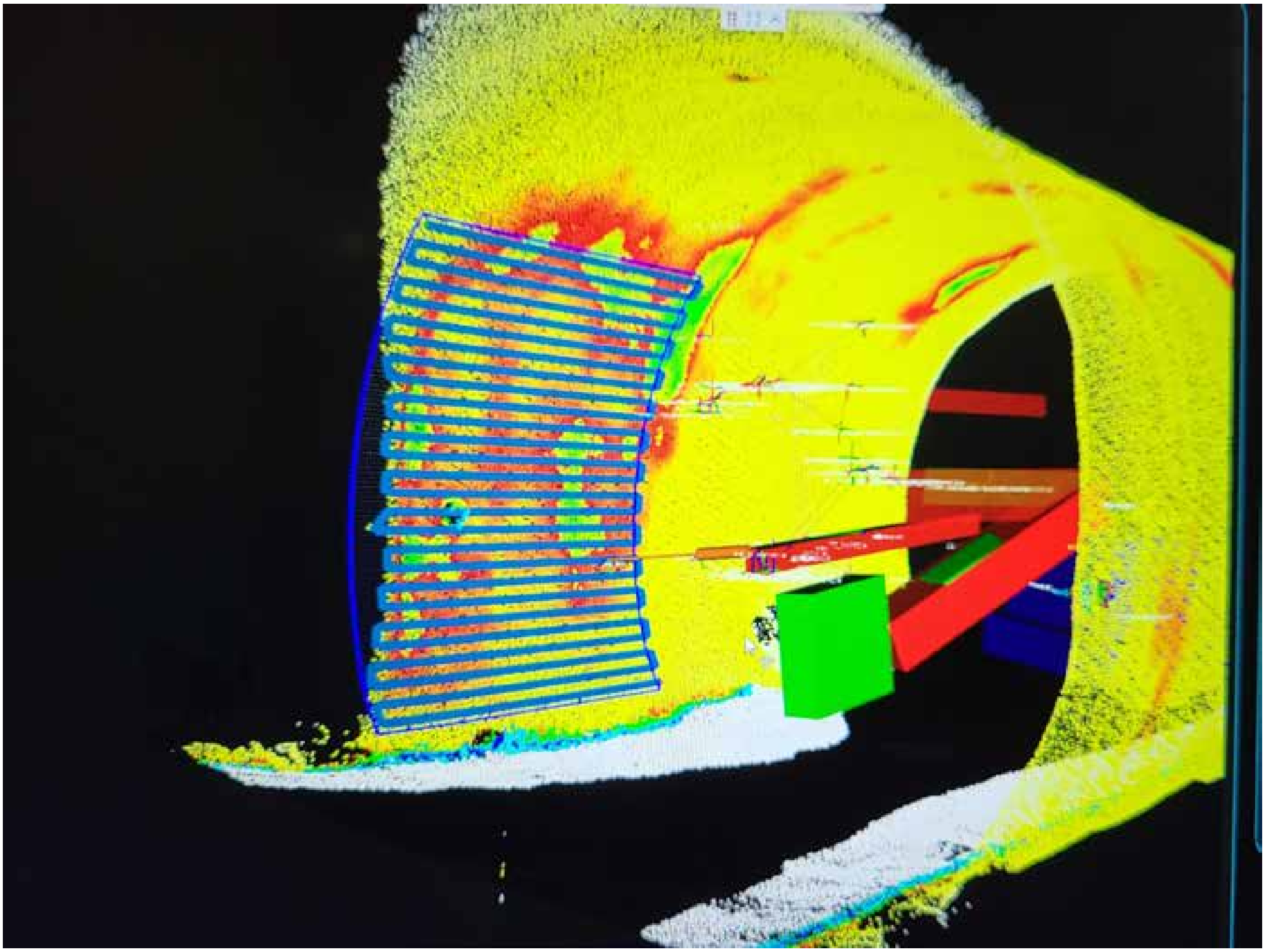


Fig. 3: Visualization of the tunnel scan, the machine position, the selected area, and the planned spraying path

WORKFLOW OF THE AUTOMATED SHOTCRETE PROCESS

To better understand the overall concept, the final workflow of the automated shotcrete process is described below. The process can be divided into the following consecutive steps.

SURFACE SCAN

At the beginning of the process, the machine must receive information about the locally required layer thicknesses. For this purpose, a three-dimensional scan of the existing tunnel surface is created before the spraying process begins. No scanning is performed during spraying; all geometric information required for the automated application is derived from the previously recorded surface scan.

The scan itself is not performed by the spraying machine but by conventional surveying instruments such as 360-degree laser scanners or total stations. After optional in post-processing, the data is imported into the machine control system.

During spraying, the required layer thickness is achieved while maintaining a constant spraying rate, typically between 10 to 16 yd^3/hr (8 and 12 m^3/hr). Instead of adjusting the material flow, the system controls the applied thickness by varying the movement speed of the robotic arm, and therefore the nozzle. Lower travel speeds result in thicker layers, while higher speeds produce thinner layers.

An important advantage of this approach is that surveying can be performed independently of the spraying operation. Tunnel sections can therefore be scanned in advance, for example, the day before spraying, reducing waiting times and improving the overall construction workflow.

MACHINE POSITIONING

In addition to the layer thickness information, the machine must also know its exact position in space. This is achieved by surveying the machine into the same coordinate system used for the surface scan. By aligning both datasets within a common coordinate system, it ensures the calculated layer thicknesses are applied at the correct positions in the tunnel.

SELECTION OF THE SPRAYING AREA

In the control software, both the machine and the point cloud of the surface scan are now georeferenced within the same coordinate system. The current machine position and the scanned tunnel surface are visualized accordingly (Fig. 3). Based on this representation, the operator can define the spraying area to be processed and select an appropriate parameter set for the control system that is adapted to the layer to be applied (for example, nozzle distance to the surface or spacing between spraying lines).

PATH CALCULATION AND START OF SPRAYING

After the spraying area has been selected, the control software automatically calculates a suitable spraying path. This calculation determines both the movement trajectories of the robotic arm and the corresponding travel speeds required to apply the locally required layer thickness.

Once the calculation is completed, the operator manually moves the robotic arm into a suitable position close to the starting point of the spraying path (shown in Fig. 3). The compressor and the concrete pump are then started, followed by the activation of the accelerator pump to initiate the automatic spraying process.

By positioning the nozzle to the invert and after some seconds spraying onto it, a stable shotcrete cone forms indicating appropriate accelerator dosing (the correct accelerator dosage rate has been determined previously during the pre-construction testing procedure of the concrete mixture). This allows the operator to visually assess the correct consistency of the concrete and to start the automatic spraying process.

A particularly critical aspect of continuous spraying operations is repositioning the machine and creating a smooth transition to the previously sprayed area. Within the control system, this has been addressed by designing the spraying paths so that transitions between adjacent spraying fields remain as inconspicuous (geometrically smooth) as possible.

However, achieving a homogeneous surface appearance does not depend solely on precise machine control. Other factors, such as accurate machine positioning, proper surveying, the properties and consistency of the concrete mixture, and the dosage rate of the accelerator also play an important role.

INFLUENCE OF CONCRETE CONSISTENCY AND ACCELERATOR DOSAGE

Throughout the course of the project, it became increasingly evident that the quality and consistency of the shotcreted concrete mixture have a decisive influence on the spraying result. In automated spraying, the requirements for the material properties are even higher than in manual nozzle operation, because the machine cannot visually assess the spray pattern and therefore cannot adjust the nozzle guidance during application.

Consequently, the system is not able to adjust the nozzle guidance based on the appearance of the freshly shotcreted concrete, for example, by increasing the nozzle distance to better distribute a mixture that is too fluid. For this reason, the correct adjustment of the material parameters before the automated spraying process begins is essential. It is therefore the operator's responsibility to ensure that both the concrete delivery rate and the accelerator dosage are correctly set before the spraying cycle begins.

In general, two key factors interact in this context: The quality of the concrete mixture and the dosage rate of the accelerator.

CONCRETE QUALITY

The term concrete quality encompasses several properties of the shotcreted mixture that together influence the spraying result.

Fig. 4: The appearance of sprayed surfaces when the shotcrete mixture is too fluid; a clearly visible pattern can be observed, which is often undesirable

SLUMP

A key parameter is the slump of the concrete. For shotcrete placement, a balance must usually be found between pumpability and sufficient stability once applied. The slump must remain consistent to ensure a uniform finish.

If the slump is too low, the required pumping pressure increases significantly. At the same time, the delivery rate becomes irregular, which can lead to fluctuations in the concrete flow at the nozzle. These fluctuations are directly reflected in the spray pattern and can negatively affect the surface quality (Fig. 4).

If the slump is too high, the concrete may exhibit inconsistent flow on the application surface because it does not set quickly enough. In such cases, the geometric accuracy of the applied layer may still be acceptable, but the visual appearance of the surface often does

Fig. 5: A sprayed area with good concrete quality; the pattern is still visible, but significantly less pronounced

not meet the required standards.

If the slump is within the optimal range, the spray pattern that would otherwise be visible also disappears from the surface (Fig. 5). However, some unevenness may remain in the lower part of the sprayed area if the start-up phase of the concrete and accelerator pump was not carried out with sufficient care, and the correct ratio of concrete to accelerator has not yet been established in the shotcrete stream.

ADMIXTURES AND FIBERS

Chemical admixtures and reinforcing fibers can also significantly influence the properties of shotcrete. Depending on the type and amount of these components, the pumping behavior and spraying characteristics of the concrete may change.

WORKABILITY TIME

Another important factor is the workability time of the concrete. Long transport distances or delays in the construction process may lead to noticeable differences in spraying quality between the beginning and the end of discharging a truck mixer. For this reason, careful coordination of site operations is essential to minimize waiting times after the concrete has been mixed.

Due to the large number of influencing factors in shotcrete placement, an initial calibration of the machine with the concrete to be sprayed needs to be carried out before the first operation. During this calibration, the machine parameters are adjusted to match the specific concrete mixture used on site.

ACCELERATOR

In addition to concrete quality, the accelerator dosage also plays a crucial role in the appearance of the sprayed surface. The accelerator dosage should always be adjusted to the concrete consistency and the layer thickness being applied. If the dosage is too low, parts of the fresh shotcrete layer can break away from the surface. Because the automated system does not receive feedback about such defects without an additional surface scan, these areas will usually need to be repaired manually afterward. This can also have implications for work safety.

Further, when the nozzle is flushed between spraying cycles, it is essential that the accelerator line is properly refilled before the next spraying operation begins. This ensures that the accelerator is mixed with the concrete

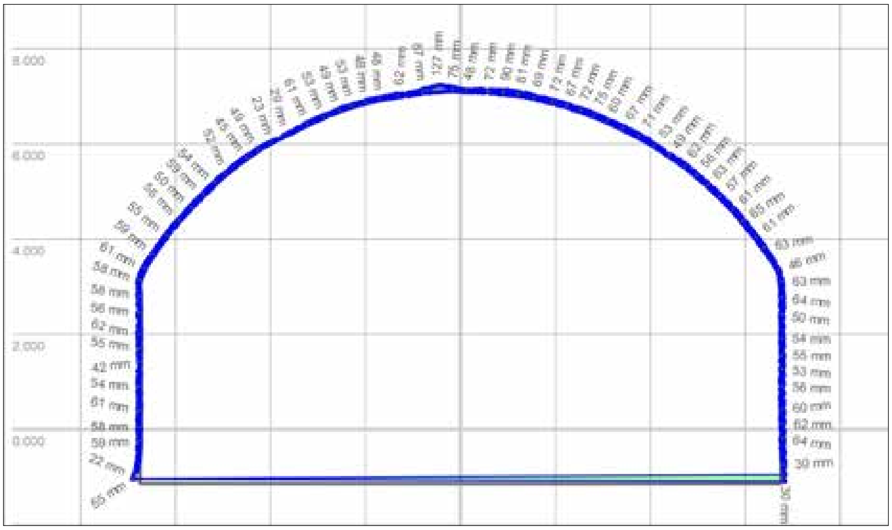


Fig. 6: Values indicate the applied layer thickness at each comparison point, ranging from 0.9 in. to 5.0 in. (23 mm to 127 mm)

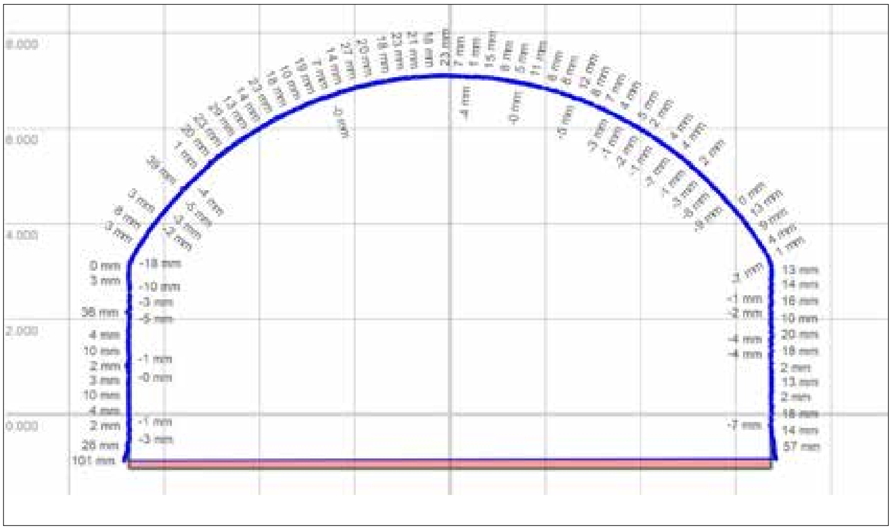


Fig. 7: Values indicate the deviation from the target profile at each comparison point, ranging from approximately -0.9 to +0.9 in

Fig. 8: Surface appearance during the execution of the automatic spraying process

Fig. 9: An even shotcrete surface, achieved using the automated spraying system

from the very beginning of the pumping process. Otherwise, the first sprayed lines can appear insufficiently set, because the concrete initially reaches the surface without sufficient accelerator.

It should be noted that these aspects are not specific to automated spraying but are equally important in conventional manual shotcrete application.

RESULTS FROM FIELD APPLICATION

Initial deployments of the automated shotcrete system in a tunnel environment have demonstrated that the developed solution is suitable for practical use. In most cases, deviations of approximately ± 0.9 in. (± 23 mm) from the specified design profile could be achieved.

Fig. 6 illustrates how the system is able to locally adapt the applied layer thickness. More material is applied in areas where the existing surface deviates significantly from the design profile, while areas closer to the design profile receive a thinner layer.

In the example shown, the applied layer thickness varies between approximately 0.9 in. and 5.0 in. (23 mm to 127 mm). This clearly demonstrates the system's ability to locally adapt the amount of material in order to reach the requirements of the target profile.

A further evaluation of the achieved surface geometry (Fig. 7) shows the actual deviations from the design profile after the spraying process. Apart from a few isolated outliers, the resulting surface remains within a tolerance range of approximately ± 0.9 in.

In addition, the visual appearance of the sprayed surface indicates that the automated process produces a uniform and even surface with very few visible irregularities (shown in Figs. 8 and 9).

CONCLUSION

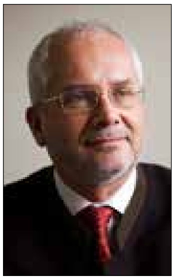
The development demonstrates that automated shotcrete application in tunnelling is technically feasible and can be successfully implemented under appropriate conditions. Certain challenges can also be mitigated at the design stage, for example, by avoiding sharp geometric transitions in the tunnel profile.

By combining precise surveying, digital process planning, proper design, and automated nozzle guidance, automated shotcrete placement can be performed more reproducibly and with much better geometric accuracy (waviness) than in purely manual operations. In particular, the system enables high accuracy in layer thickness across the entire tunnel profile, including the crown. This makes the method particularly suitable for applications with strict geometric tolerances, as well as for layers that require an even surface with minimal waviness, such as smoothing layers for waterproofing installation, shotcreted final linings, and tunnel rehabilitation (e.g. projects where existing tunnel final linings get replaced by shotcrete placement).

Soon, efforts will be made to incorporate control of the concrete pump into the control system to refine its capabilities. Further, a high-precision automatic calibration system for determining the spray robot's position will be implemented. This will save time when repositioning the machine.

The system and the spraying robot are already being rented to interested customers for suitable applications, including training provided by application engineers. A patent application has been filed for the main features of the control system.

__Igor Schweiggl__, M.Sc. is an application engineer at BeMo Tunnelling GmbH, focusing on the development and implementation of automated shotcrete application in tunnelling. He holds a master's degree in environmental and process engineering and has been closely involved in advancing robotic spraying technologies from concept to field application. His work combines practical tunnelling experience with a strong background in surveying and process optimization. He has contributed to the successful deployment of automated shotcrete systems on construction sites, with a focus on improving surface quality, geometric accuracy, and overall process efficiency in tunnel construction.



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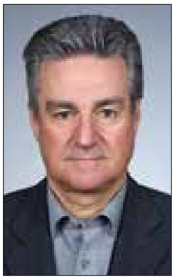
__Alexander Sellemond__, M.Sc. is the system engineer and managing director of Vision Metrics GmbH in Munich, specializing in the development of camera-based measurement technology. He holds a master's degree in electrical and information engineering from the Technical University of Munich, with a focus on power electronics and image processing. His professional background spans hardware and embedded software development, with experience at MTU Aero Engines, Siemens Corporate Technology in Munich, and in freelance engineering for startups and enterprise companies. His work combines expertise in computer vision, artificial intelligence, software engineering, and electronic system design.



Mech. Eng. __Rainer Antretter__ is employed with BEMO Tunnelling as head of the Mechanical Department, where he started in 1983. His early responsibilities included design of construction site facilities, water supply, wastewater disposal systems, excavation and muck-handling equipment concepts, design of rail-based mucking systems, tunnel ventilation systems, and compressed-air tunnelling systems. Appointed Deputy Head in 1996, he contributed to strategic and operational development and completed training to an HSE expert. Since 2006, he has served as Head of Plant Department, overseeing profitability, capital expenditure, and plant-related contracts while leading multidisciplinary engineering teams. He also provides expertise for international know-how transfer services with core expertise in mechanical systems for tunnelling, and he is driving the development of automated concrete spraying technology.

Dipl.-Ing. (FH) __Peter Dietrich__ is a senior tunnel engineer and project engineer at BeMo Tunnelling GmbH with more than 30 years of experience in the tunneling industry. He has extensive expertise in SEM/NATM tunneling and shotcrete-supported excavation, gained through numerous complex infrastructure projects in Europe, North America, and Asia. His work includes project management, construction supervision, and technical consulting in challenging ground conditions, particularly in urban environments. He has been involved in international know-how transfer projects and the implementation of advanced tunneling methods, contributing to safe and efficient excavation processes and high-quality shotcrete application in modern tunnel construction.