AUTOMATION OF SHOTCRETE APPLICATION

R. Antretter
BEMO Tunnelling GmbH, Innsbruck, Austria
A. Sellemond
Vision Metrics GmbH, Munich, Germany

ABSTRACT: Accurate and smooth shotcrete surfaces – every tunneller's dream. Modern automated shotcrete-robots are able to shoot constant layers. It is now possible to apply variable layer thicknesses combined with profile accuracy to a defined geometry consecutively throughout the length of a tunnel. Compared to manual spraying the waviness of the final surface is reduced to an optimal extent and meets the requirements of the current German ZTV-Ing. The system is currently not intended for primary lining during excavation but for final and permanent surfaces.

1. INTRODUCTION

Restrictive demand of accuracy as well as the general wish of a tunneller's perspective of automation of the application of shotcrete led BeMo Tunnelling into cooperation with Vision Metrics with the goal of developing an automatic shotcreting system. The system should allow the application of a profile-controlled shotcrete shell onto an uneven surface. The system was not intended to replace the nozzleman during excavation works but to improve the final shotcrete shell's surface in terms of dimensional accuracy and waviness. One of the drivers to attempt to develop such a system was initiated by regulations in the German contractual document ZTV-Ing (ZTV-Ing., Teil 7 2026), which limit the acceptable surface quality of smoothing shotcrete to a 1:20 depth to base ratio, respectively to a 1:10 gradient.

Smoothing shotcrete is non-structural and needs to be applied as a separate layer (30mm thick, 4 mm grain size) of unreinforced shotcrete onto the surface of the structural shotcrete before installation of the waterproofing membrane. Limited efforts to achieve accuracy during time critical excavation works lead to the necessity of intensive smoothing processes to prepare the shotcrete surface properly. It can be necessary to grind high spots as part of the manual smoothing process. This is in combination with additional measures (e.g. pins) to make sure that no overspraying occurs as part of the smoothing shotcrete application. To conduct this task in an economical and time saving manner the idea of automated application was born.

Another motivation to develop an automatic system was and is work safety combined with the increasing lack of skilled nozzlemen.

2. STEPS OF DEVELOPMENT

Based on a Meyco Logica robot, designed around 25 years ago and capable of applying a constant shotcrete thickness automation engineers developed an appropriate control system for variable layer thicknesses. This machine was used for the development as a base since it was readily equipped with sensors at any articulation of the manipulator boom as well as within the cylinder for longitudinal movement and chain drive for the spray-lance. Details of the control's operating principle are presented in this paper (Antretter, R., 2025).

2.1 MILESTONES OF DEVELOPMENT THE BASE SYSTEM

A brief outline of the steps taken to make the system operational and initial experiences and their optimisation is provided below. This work took approximately one and a half years to complete, although not carried out continuously. Initially, an early version of a Logica arm was used, followed by a more sophisticated version based on a Meyco Potenza sprayer equipped with a Logica manipulator (with all sensors installed). This machine was used for trials starting in March 2025, after improvements based on the experience gained from the trials in March 2024 had been incorporated.

Milestones:

- - Creating of the first version of the control software and processing of survey data
- - Surveying of the machine and calibration of the sensors
- - Dry runs in the workshop
- - Construction site trials in 2024 at an outdoor mock-up
- - Interpreting the results and implementing improvements
- - Preparing the improved logic and incorporating the improvements
- - Construction site trials in spring 2025 at an outdoor mock-up, interpreting the results and developing improvements
- - Construction site trials in summer 2025 at an outdoor mock-up, see Figures 1 - 3 and moving to the tunnel after satisfactory results
- - Creating dimensionally accurate surfaces in the tunnel, on the sidewall and throughout the vault
- - Applying dimensionally accurate multiple layers to finalise the design of the shotcrete surface
- - Developing a solution for field transitions to ensure dimensionally accurate, smooth connections
- - Improving the machine's georeferenced calibration process after relocation

These stages are not yet complete. At the time of publication, work is carried out on a user-friendly visualisation of spray area selection and on a similarly user-friendly implementation of georeferenced positioning.

Figure 1: mock-up at Holsteintunnel Germany; control IT set-up in background right to the sprayer

2.2 RESULTS OF TRIALS AT THE MOCK-UP IN FRONT OF THE TUNNEL

At the Holsteintunnel (Autobahn A44, Kassel to Eisenach), BEMO and Subterra are excavating two parallel tubes of a 2 x 1,66 km long highway tunnels connected by cross passages, which were used for testing after the trials in front of the portals with a mock-up tunnel of the size of a cross passage (~5,5 m x 5,5 m).

After calibrating the machine to the concrete properties, multiple sections of the side wall and crown of the test stand were carried out, each with different spraying parameters in terms of application thickness, embedded elements (e.g. bolt heads) and spray bead spacing. It was found that the desired geometry was achieved very accurately and that inserts could be sprayed without underprofile and with a smooth surface (without bumps). In the next step, bumps were sprayed on to simulate the wavy profile of a manual spray application, and a levelling layer was applied over them. Even during application, it was visually apparent by the spray path velocity that the application was effectively levelling and that there was no inacceptable waviness on the resulting surface.

Figure 2: spray surface result at mock-up at Holsteintunnel Germany; a bolt head on the left part of the structure shows perfectly smooth overspray (the bolt plates at the shoulder of the structure were not intended to be sprayed in entirely)

A decisive factor is the concrete spread which was used in the range of 53 to 60 cm. Consistency regarding of continuous concrete quality is a major key to success; spreads (or corresponding slump values) outside of this range resulted in less accurate and poor spraying results regarding smooth overlapping of spray lines. An optimal distance between the spray lines for smooth overlapping was found to be 200 mm with this specific shotcrete on site. This parameter is dependent on concrete properties and needs to be determined out with any new recipe of newly tested shotcrete on site. A workflow was developed to specify the distance between the lines.

With deviations of about 20 mm to the intended geometry the results of the final optimised spray parameters looked encouraging, see Figure 3. Even though clogging problems arising from the kind of spraying in automatic mode in the crown area still had to be solved. It was discovered that the shotcrete tended to harden within the mixing chamber at the transition to the nozzle body which resulted in slight deviations of the spray jet alignment leading to application at unintended spots.

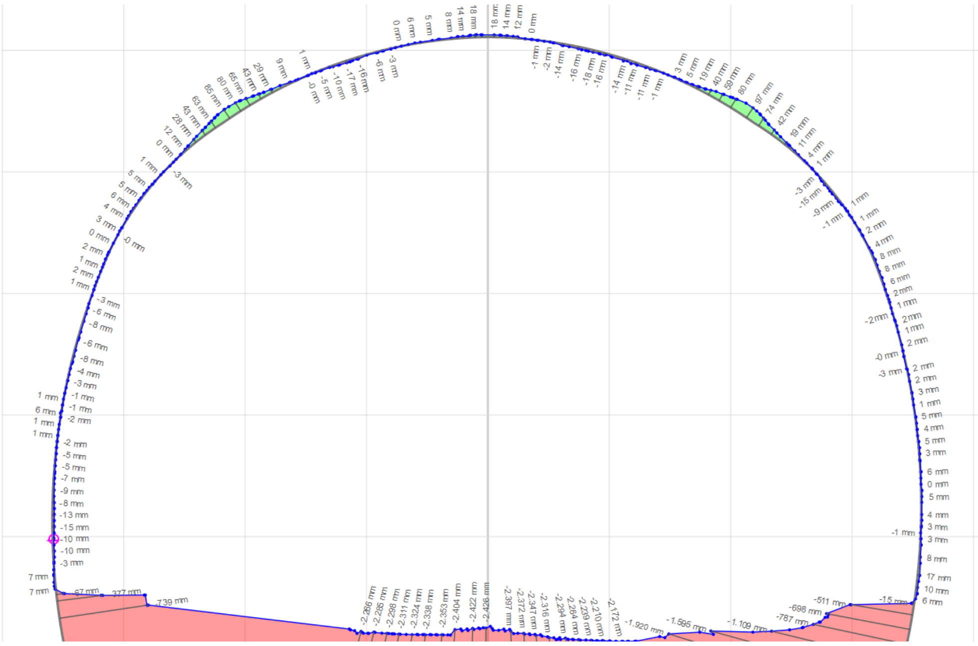

Figure 3: Scan of sprayed surface plotted against the set profil (the green areas above the shoulder must be disregarded since these are separations of side and crown and not intended to be sprayed)

2.3 TRIALS UNDER REAL CONDITIONS IN THE TUNNEL

Following the tests in front of the portal, work began in the tunnel to spray sidewalls of the bench to the intended geometry and smoothness in preparation for installation the waterproofing membrane.

The first section to spray was a rectangular area of the sidewall around 4 - 5 m vertical and 4 m in length which was dependent on the reach of the spray lance and extension. The area was located between the temporary invert and the utilities at the transition from crown to the sidewall, shown in Figure 4.

Figure 4: Scan of sprayed surface plotted against the set profil (the green areas at the shoulder were not intended to be sprayed)

The crown was already prepared for installation of the membrane, so that the vault was completed down to the invert by spraying both sidewalls. The smoothing shotcrete consisted of 0-4 mm grain size.

Results of application onto manually sprayed sidewalls confirmed the satisfactory experiences on the mock-up outside the tunnel.

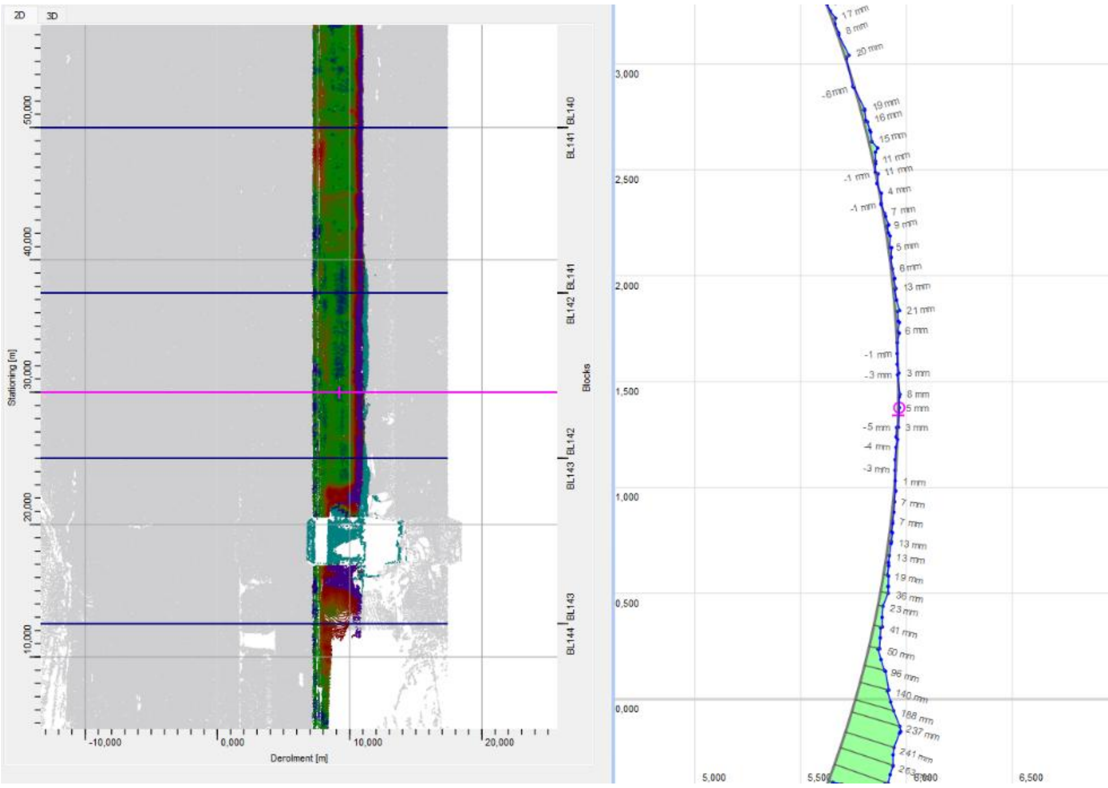

Figure 5: Tunnel band of the right sidewall after application; plot of cut shows final sprayed geometry compared to set geometry

Despite large thicknesses to be sprayed at some highly deviated spots in one go the final surface was close to the intended geometry with deviations below 20 mm, see Figure 5. Around 25 no. of areas had been sprayed consecutively only niches had been spared out.

Figure 6: Consecutive areas (blocks) of the sidewall; seams at transitions and herringbone pattern visible

Although the spray accuracy was satisfying in general the overlapping geometry at transitions was not satisfactory and the herringbone pattern visually inacceptable, see Figure 6.

The solution to the first problem led to a special technique in which the transitions are executed geometrically flawless by the control system. They were removed from of the operator's hands. Details cannot be disclosed at present due to pending legal patent matter. In any case, the control system suggests the best possible path planning to the operator for a smooth and geometrically invisible transition between the blocks.

Figure 7: Spraying a consecutive block adjacent to the one in the first third of the picture without visible seam at the transition

After testing various adjustments, a smooth surface transition could be achieved. It is important that the control is able to calculate the best solution at any applied layer thickness. That required some testing with improvements in stages, which can be seen in Figure 7.

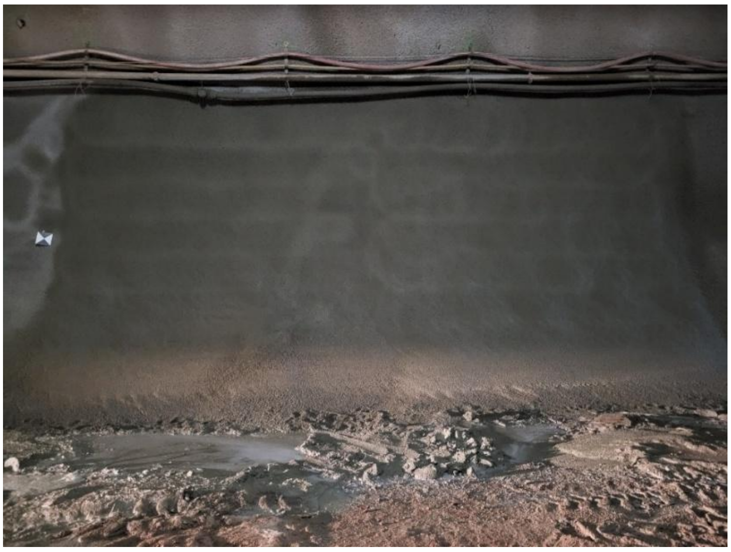

Figure 8: three block joints (the first located next to the surveying target) after execution of the final layer without visible herringbone pattern and with smoothly executed transitions

In order to avoid the herringbone pattern, which was unintentional and looked unusual to the eyes of a shotcrete specialist despite the precise geometry, an improvement also had to be made. In this case, the solution was a simpler one. A second spraying process was initiated, in which the nozzle spacing and application speed were increased. The thin layer thickness that is applied achieves a smooth, slightly smudged visual impression that is close to manual application and is visually appealing, see Figure 8.

3. EXECUTION OF THE FIRST VAULT IN A CROSS PASSAGE

With all lessons learned and lots of experience gained the first complete vault of a cross passage was executed. The cylindric part without the rising transition into the vault of the main tunnel only 12 m long was partitioned into three spray sections. There were several difficulties encountered during this project. Work had to be carried out from two sides, as the main tunnels had to remain passable. The spray robot was positioned at an angle to the longitudinal axis and tilted horizontally, and the machine had to be positioned at an angle to the longitudinal axis of the cross passage, see Figure 9. This meant that the machine was at an angle to the axes of the cross passage in all three dimensions, which the control system had to cope with.

Figure 9: position of spray-robot in cross passage ready to start spraying the first section on the opposite side

In order to enable a smart and reliable spraying process, the control system was equipped with a function that allows contours in the spray field to be recognised for path planning and tunnel profiles to be processed correctly, shown in the visualisation of the path planning in Figure 10.

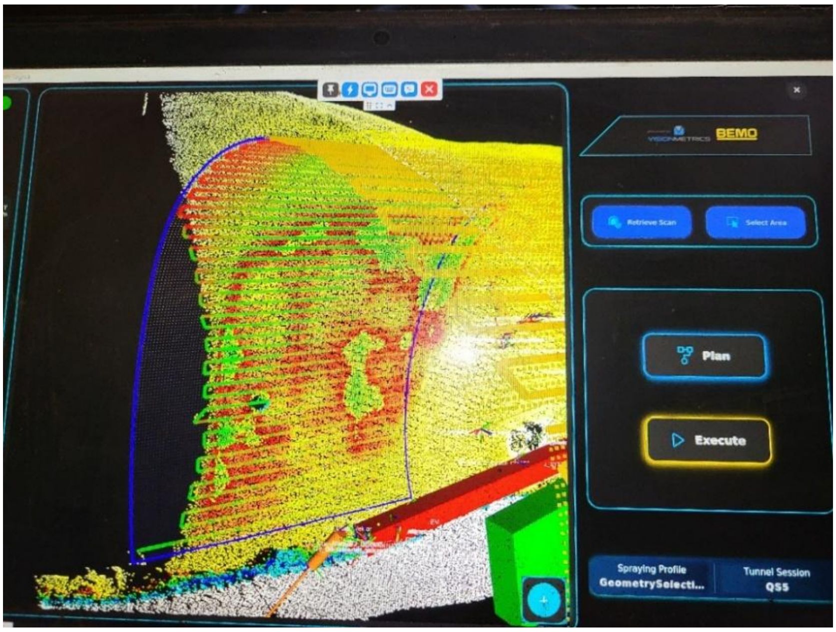

Figure 10: path planning visualisation mode; the lines within the blue spray field which interfere with the intersection edge of the cross passage and main tunnel are adjusted to the contour.

This feature made it possible to spray most of the intersection geometry precisely along the contour (shown in Figure 11), omitting only the rising transition in the crown (shown at the top of Figure 10), which was to merge into the main tunnel with a large radius.

On the inside of the cross section, which is to the left of the spray-robot's driving direction, the extreme angles to the axes of the cross passage caused the spray-lance to collide with the side wall. It became apparent that the attempt to maintain the spraying geometry by the control system caused the anti-collision criteria to be neglected. Correcting the behaviour of the control system was tricky, but it was possible to resolve the issue in the short term to complete the task and later adapt it permanently to the new circumstances.

Figure 11: spraying the geometry layer of the intersection part of the cross passage and main tunnel; see the rebound covering the invert

The application result of the geometry layer was satisfactory although less precise as already achieved. It is assumed that the worse accuracy is related to the extreme positioning angles of the robot (see Figure 12) of the geometry layer. The first spraying section with the intersection vault was still carried out on one side at a time, but in the following two spraying sections, the entire vault was sprayed from the left side wall to the right in one go.

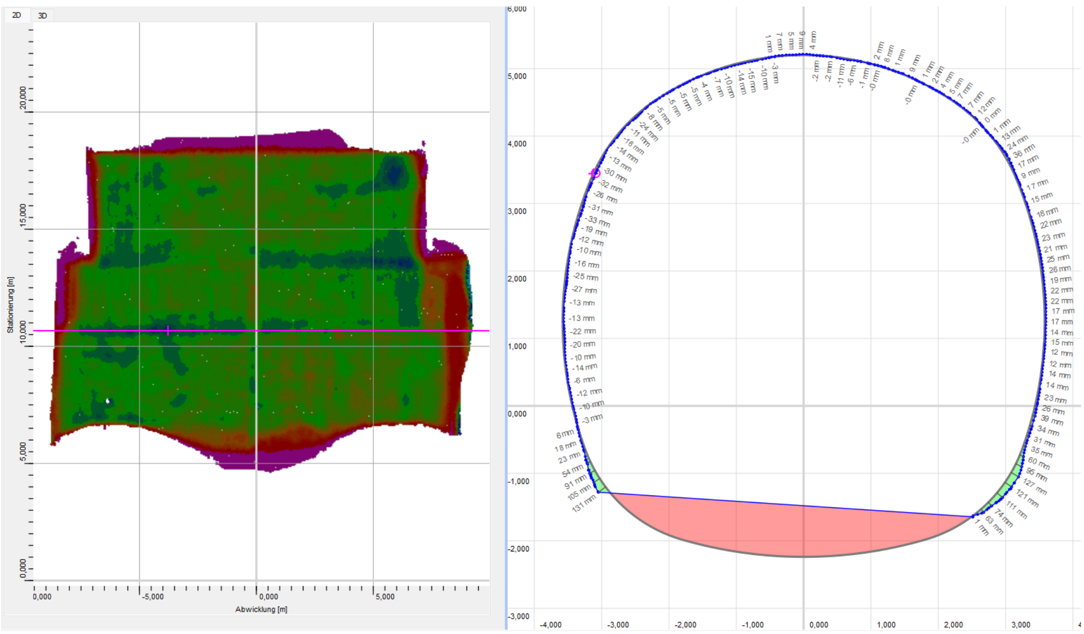

Figure 12: The cut shown was deliberately taken at an unfavourable position (block joint) to show the worst result is shown

With all spray surface inclinations, remarkably little rebound was observed (ref. Figure 11) thanks to the optimal settings for the nozzle distance (Melbye, T., Dimmock, R., Garshole, K. 1994). Weighing and recalculating the rebound during the mock-up tests yielded values of less than 10 % of the sprayed concrete quantity.

After spraying the final layer on the last of the three sections the entire cross passage was scanned and evaluated, see Figure 12, and the optical appearance is shown in Figure 13. The deviations on either side were less than 30 mm (average of -21 mm on the left and +22 mm on the right) and were minimal in the crown area. The profile appears to have been shifted slightly to the right, which was initially attributed to the extreme angles of the machine position, however, this needs to be investigated more closely.

Figure 13: optical appearance of the completed cross passage; the horizontal lines are unavoidable due to the automated process which does not quite allow human style pattern and has to be accepted

4. SPRAYING LARGE CROSS SECTIONS

One of the last critical trials was to test the boom behaviour with significant width and height. The main tunnels at the Holstein Project are 11,80 m wide and 9,50 m high. It was to be investigated how much the arm bounces when it has to work with a strong lateral and upward deflection.

Figure 14: finished two blocks with geometry layer from invert and sidewall and final layer from invert to the crown centreline close to the ducting

Bouncing of both boom and lance as well as of the heavy concrete hose during application was an issue but could be mitigated to an acceptable degree by adjusting of settings of hydraulic valve behaviour. The final appearance of the surface was satisfactory, however, see Figure 14.

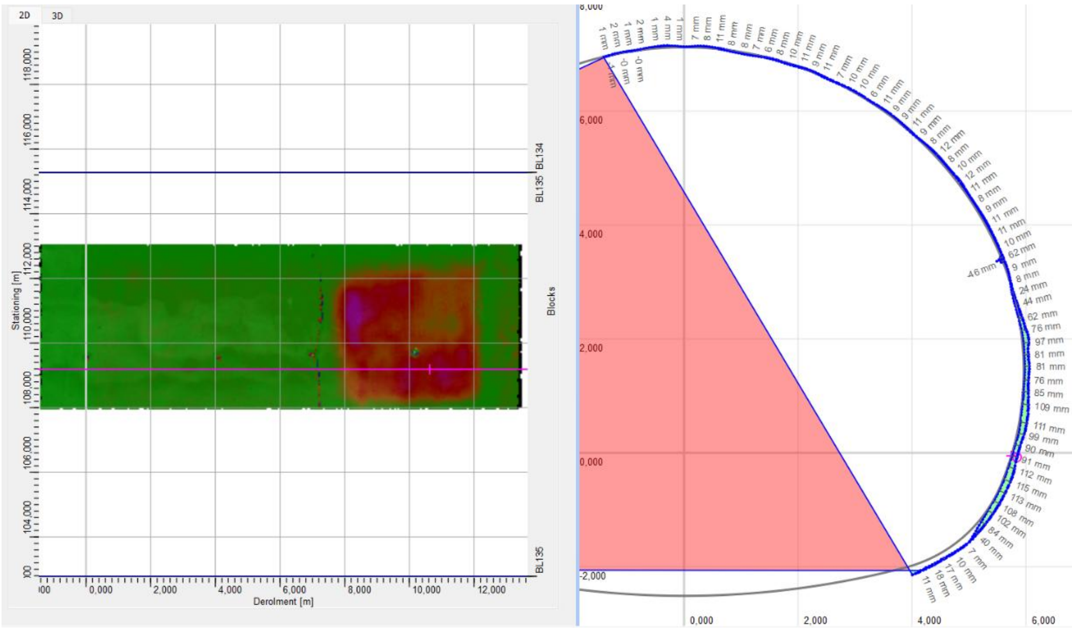

Figure 15: "Heat map" and cross section of the applied layers in the entire tunnel profile; The spot at -46mm indicates the position of the electric cable (the pink area in section to be disregarded)

In the crown, the final layer was applied very thinly to avoid underprofile, as the regulation layer had already been sprayed to the set tunnel geometry. The geometrical result was satisfactory, see Figure 15.

5. NEXT STEPS

Spraying the invert part unexpectedly turned out to be a difficult task as far as geometric accuracy is concerned. The reason was identified to lie in the kinematics of the spray head respectively in the arrangement of the concrete hose feed alignment to the spray head since its design is mainly intended to work in the upper half of a circular vault.

Figure 16: spraying the invert; noticeable is the gap right in the tunnel axis of the invert which has to be eliminated

At 180 degrees of the circle, the spray result showed a visible gap, and the two parts of the invert from the gap to the sidewalls showed different deviations from the set geometry, see Figure 16.

To solve the problems different solutions are being tested. One possible measure could be to reverse the installation direction of the nozzle head, so that the hose arrives centrally from above at the spray head and the movements are performed symmetrically on both sides.

In addition, work is currently underway to improve the user-friendliness of the software. To date, engineers have been involved in the development and have been satisfied with a complex operating sequence. Now that the main purpose of automation has almost been achieved, the task is to develop a quick and uncomplicated operating interface and workflow for operators who, supported by the control system, should not have to do much adjustment work to process the spray fields.

Further efforts will be made to the georeferenced positioning system of the machine in the tunnel. At present the exact positioning is executed by means of surveying points and a tachymeter which measures points at different boom positions after placing the support legs of the base machine. This process can be done by a trained operator in less than 10 minutes and has the potential to be automated as well during relocation of the machine, so that no time on the critical path must be spent for. The target is to achieve operation with only the operator and a second person which does all the cleaning, helps with malfunctions and relocation of the machine for continuous operation.

6. CONCLUSION

Efforts to achieve practical automation of profile-accurate shotcrete application can be considered successful in principle. With the current state of development, long tunnel sections can be processed accurately and economically, allowing the waterproofing membrane to be applied immediately afterwards. Reinforcement can also be applied directly to the vault without any adjustments, as it is dimensionally accurate. Development will continue on the basis of practical experience alone. Further applications could be:

- Shotcrete final linings
- Multi-layered shotcrete shells
- Tunnel rehabilitations

BEMO/Vision Metrics have already submitted documentation to achieve invention protection by various patents.

LITERATURE

Antretter, R., RETC 2025, Automatically Controlled Shotcrete Application, p. 958.

Melbye, T., Dimmock, R., Garshole, K. 1994, Spritzbeton für die Felssicherung (Sprayed Concrete For Rock Support), deutsche Fassung der 11. überarbeiteten Ausgabe der englischen Originalausgabe vom Dezember 2006, p. 225.

ZTV-Ing., Zusätzliche Technische Vertragsbedingungen und Richtlinien für Ingenieurbauten, Teil 7.

Ing., Rainer, Antretter: Author1

BEMO Tunnelling GmbH, Innsbruck

rainer.antretter@bemo.net

Dipl. Ing., Alexander, Sellemond: Author2

Vision Metrics GmbH, Munich

a.sellemond@vision-metrics.de