New technologies in concrete spraying for tunnel construction

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ABSTRACT

Concrete spraying is one of the most demanding tasks in underground mining and tunnel construction. The quality of the sprayed concrete variates critically between operators, and talented operators are difficult to find. New technologies such as computer-assisted boom control, scanning technology, and VR simulators can help to improve the concrete spraying process.

The automation of the concrete spraying boom, ranging from controlling the boom with one joystick only to spray along a virtual line to fully automatic spraying of a predefined area, allows the operator to keep the optimum parameters such as stand-off distance and spraying angle over a long period.

The onboard scanner provides immediate feedback on the layer applied, ensuring that the minimum thickness of the concrete layer required for safe underground operation is applied while minimizing overspray costs. The client's increasing demand for documentation of the work from the excavated profile through the various layers to the final spraying is readily available without the need for additional measuring equipment and personnel that would slow down the progress of the advance.

Today's VR technologies allow for immersion in various underground environments while using the original controls such as radio remote control and the real machine's user interface. Different training modules offer both beginners and advanced operators safe and efficient training in different scenarios.

Remote drive systems, which allow the operator to move the concrete spraying machine from the remote control, offer advantages in terms of safety and ergonomics for operators, which positively affects productivity.

INTRODUCTION

The sprayed concrete industry was traditionally considered a relatively low-tech area of expertise for digitalization and modern technology. Indeed, concrete itself, additives, and equipment have developed hugely since the early days of dry spraying with a handheld nozzle. However, the application itself is still often seen as manual labour and craftsmanship that only a few can learn to master after years of practicing through trial and error.

In the last two decades, exciting developments in the field of automation of the concrete spraying application could be observed, which at first only hesitantly found their way into tunnel construction but have now been widely accepted. This also includes the increasingly powerful surveying technology, which in addition to the control and optimization of the spray application, can also provide as-built documentation with minimum effort.

Concepts such as Digital Twins allow testing systems under development at a very early stage and very close to the real world, thus optimizing the development process. The same models are also available to train future users with an excellent connection to reality.

Moving equipment underground is a risky undertaking and often requires extra personnel. Remote drive systems allow operators to freely move around to get a good view of the equipment and eliminate the need to climb into the cabin reducing the physical strain and injure risk.

Managing novice operator training, developing professional operator excellence further, and controlling the whole sprayed concrete process's overall cost needs a holistic approach. Digitalization or modern technology alone does not offer easy tricks here. Combining a comprehensive understanding and process excellence can enable powerful tools to benefit the whole tunnelling industry.

COMPUTER-ASSISTED BOOM CONTROL

As invented by Carl Akeley in 1907, sprayed concrete was initially applied by manually holding and guiding the spraying nozzle. With the development of the wet-mix process in the 1950s and the demand for higher output resulting in increased weight of the nozzle systems, the mechanization from handheld to remote-controlled spray application with a manipulator or robot was introduced.

While the first spraying manipulators were still directly hydraulically controlled, remote controls were developed, which allowed, first wired and later wireless via radio, the control of the manipulators from a distance.

History of automated concrete spraying robots in brief

The first fully automated sprayed concrete robots were developed in the mid-90s. Research and development were mainly carried out by the Swiss Federal Institute of Technology in Zurich, Switzerland, and the Ruhr University Bochum, Institute for Structural Engineering in Aachen, Germany.

Through cooperation between industry and universities in Switzerland, control systems were developed, which allowed the operator to use the spray manipulator in different operating modes. This ranged from the purely manual operation of the individual joints of the robot to semi- and fully automatic spray application of selected tunnel areas (Honegger, et al., 1997) and (Honegger & Codourey, 1998).

The measurement with infrared laser range finders, which were initially used to scan the application area, took a lot of time due to the point-by-point measurement and only allowed a very coarse resolution of the application area. The 2D LiDAR sensors used later enabled the survey of a 360° profile over 3 m tunnel length in a few minutes.

In addition to the pure automation of the spray application, research was also conducted in the area of nozzle guidance, rebound behaviour, and compaction of sprayed concrete (Girmscheid, G. and Moser, S., 2001), (Moser, 2004) and (Guthoff, 1991).

The most advanced technology at that time in the field of concrete spraying for tunnelling, MEYCO Logica (Figure 1), was developed by the Swiss-based manufacturer of concrete spraying equipment MEYCO Equipment in cooperation with the Swiss Federal Institute of Technology in Zurich, Switzerland and brought to market in 2001.

Figure 1 - MEYCO Potenza with Logica boom including 2D LiDAR

In addition to sprayed concrete, other sprayable materials such as fire protection mortars and waterproofing membranes (Figure 2) were applied with the Logica booms.

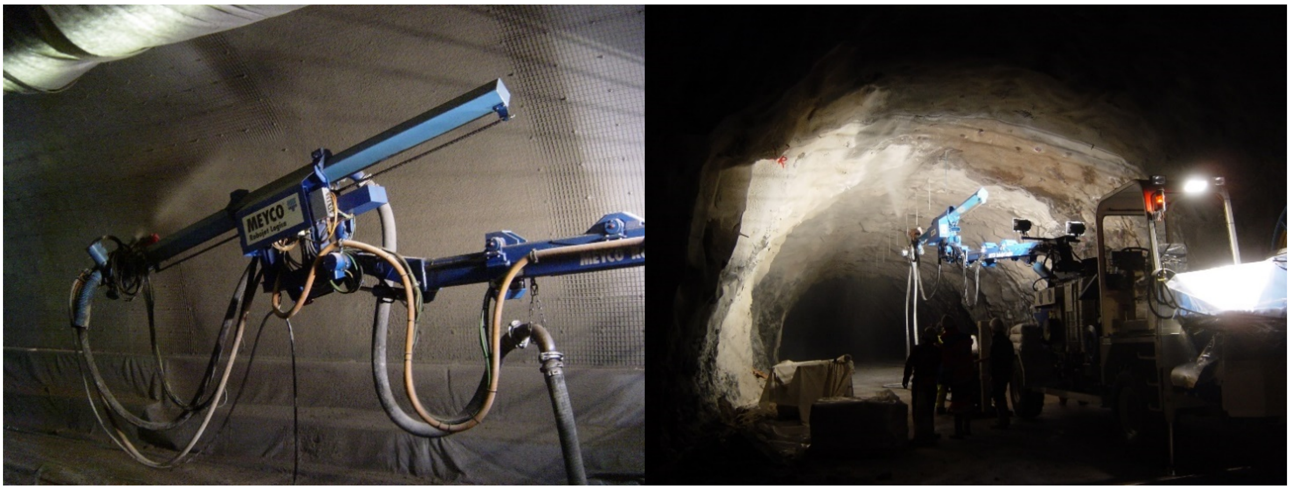

Figure 2 - Application of fire protection mortar and waterproofing membrane with MEYCO Logica

The profile data of the laser scanner usually are only available in the local machine coordinate system. To utilize the measured data even after the machine has been moved, MEYCO used in 2008 an external total station, which tracked and recorded the position of the LiDAR during the measuring process and thus allowed the georeferencing of the profile data.

Further investigations regarding the automation of standard spray manipulators and empirical tests regarding the accuracy of layer thicknesses were made at AITEMIN and CSIC with the support of the company Putzmeister (Nabulsi, et al., 2010). A more recent research project at the Institute for Advanced Mining Technologies at RWTH Aachen University in cooperation with GTA Maschinensysteme GmbH studied the use of Ultra-Wideband radio technology and inertial navigation for the determination of the position of the laser scanner and nozzle (Hartmann, 2018).

The automatic spray application available since 2000 has been successfully used in projects but is still waiting for the breakthrough. This was because the sensor technology used, especially the laser scanner had to be well protected against rebound and kept clean by the operator. The operator's expectations of a robot are also very high, and the willingness to adapt the spraying process is sometimes lacking. It has also been shown that the application of the exact layer thicknesses, such as required for a fire protection mortar and waterproofing membrane, has the biggest potential with this kind of spraying robot. Another decisive factor for the successful use of a spraying robot is that by automating the process, the stress on the operator can be massively reduced, and thus large areas can be sprayed over a long time without operator fatigue.

The Finnish company Normet Oy introduced 2017 the SmartSpray system, which provides computer assistance in the concrete spraying boom operation through coordinated control of the boom joints and point-to-point control modes.

Recently it was also reported that Chinese and Norwegian manufacturers of concrete spraying equipment are working on the automation of their concrete spraying systems.

Reasons to automate the spraying process

Concrete spraying is one of the most demanding tasks in underground mining and tunnel construction. The quality of the sprayed concrete variates critically between operators, and talented operators are difficult to find.

In addition to the basic requirements for a high-quality application of sprayed concrete, such as surface preparation, continuous concrete flow, exact dosing of the accelerator, and correct amount of compressed air, the following key elements play an essential role:

1. To reduce the rebound to a minimum, the nozzle must point perpendicular to the surface (Figure 3).
2. To achieve a good compaction of the concrete on the surface, the stand-off distance between the nozzle and surface must be kept between 1-2 m (1.5 m is recommended).
3. The spraying process should always take place from bottom to top, allowing especially when spraying thick layers, the previous sprayed concrete to support the next layer, and to prevent spraying of areas that received rebound.

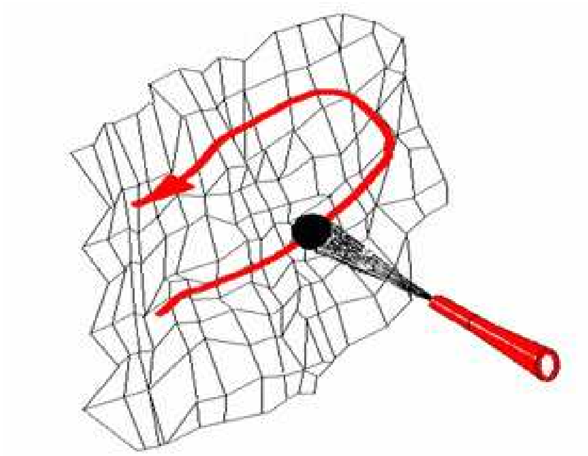

Figure 3 - Perpendicular orientation of the spray nozzle over an undulating surface

Normet's SmartSpray system (Figure 5) provides different degrees of automation to address the importation factors for applying high-quality sprayed concrete.

Especially for inexperienced nozzle operators, it is difficult to control the individual joints of a spray manipulator simultaneously to maintain the nozzle at the correct distance and spray angle. The SmartSpray Lite control system manages the movements of the spray manipulator except for the spraying nozzle. This means that the operator only must guide the spray nozzle over the surface at the optimum angle and distance, which is a great relief.

In the next degree of automation, the SmartSpray Pro system's control system guides the spray nozzle along a virtual line previously defined by two points (Figure 4). This further simplifies the work of the operator and is particularly helpful if the profile to be sprayed is rather regular, for example without major irregularities such as Polyethylene (PE) insulation mats installed on rock bolts. The spraying nozzle travels automatically back and forth along a straight line between the two defined points. The operator controls the virtual line or segment using only one joystick to move it to the next segment while keeping the distance to the surface.

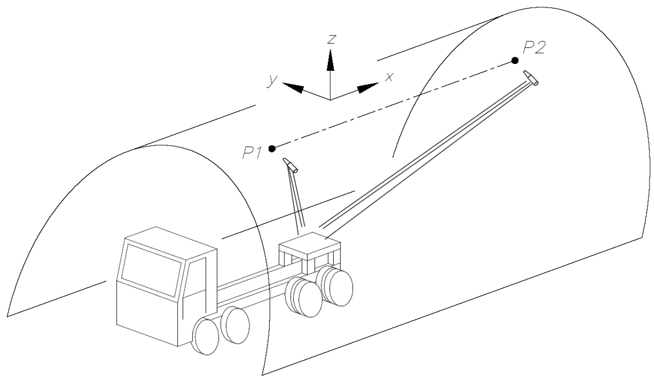

Figure 4 - Movement of the nozzle along a virtual line

If the tunnel profile and spray area are known, the SmartSpray ProPlus control system can automatically travel the predefined area while maintaining the optimum spray distance, spray angle, and nozzle speed over the surface. Because the flow rate is synchronized with the spray nozzle's speed, a consistent, accurate layer thickness of concrete is achieved.

Figure 5 - Normet SmartSpray spray boom

Future development and trends

For some years now, a general trend towards more automated processes has been observed in tunnel construction. Like self-driving trucks, automatic charging of blast holes and fully automatic application of sprayed concrete and other sprayable materials such as fire protection mortar and waterproofing membranes will become available.

Especially in countries where sprayed concrete is accepted as permanent rock support, spraying to the designed profile will become more important in the future, as one machine can spray both the initial and the final lining at once. Computer-controlled application is a flexible solution for rapidly changing profiles such as found in metro stations and hydropower projects.

Automation can also reduce the need for personnel to work in dusty, noisy, and potentially dangerous areas by making it possible to monitor the spraying process from an air-conditioned and soundproof location.

Benefits of automated spray application

Thanks to the high degree of automation of the spraying process, it is possible for the nozzle operator to achieve high-quality application and high spraying performance simultaneously over a long time without any signs of fatigue.

The rebound can be minimized by using the optimum spraying parameters, and thus the environmental impact is reduced. Covering the entire rock surface with optimized parameters ensures that the minimum layer of sprayed concrete has been applied, increasing safety. Because the nozzle operator can monitor the application process from a safe distance, he is less exposed to dust and noise emissions of the spraying process.

SCANNING TECHNOLOGY

Introduction

During recent years, the tunnelling industry has seen the outmarch of several integrated data collection systems that monitor and record the surroundings and different elements of the tunnelling processes. Lately also sprayed concrete has joined the league with onboard scanning and layer thickness monitoring systems. These systems not only work to merely show the applied layer thicknesses but also bring significant improvements to process efficiency, safety, operator training, documentation, reporting, and communication between project stakeholders.

Layer thickness control

Whether sprayed concrete is applied for initial safety to secure the progress of tunnel excavation or as a permanent sprayed concrete lining, being able to apply the desired layer thickness, and only that, is key to producing safe, cost-efficient, and high quality sprayed concrete linings. To achieve the designed support for the rock or soil mass above and around the tunnel opening, the sprayed concrete lining needs to meet all the requirements – correct concrete mix properties, application and conditions, hydration, and layer thickness.

Most of these factors can and need to be monitored before or during the actual process, but traditionally the layer thickness has been checked only after the application. Though highly experienced spraying operators can develop their skills to monitor and adjust the layer thickness visually and according to the sprayer operating values, this is very inconsistent considering the differences between operators, concrete spraying machines, concrete mix designs, and conditions regarding rock surface and atmosphere. Visual monitoring also completely cannot document and verify the realized layer thicknesses. Furthermore, highly experienced operators are rare natural resources, and training takes years of work.

Traditionally the layer thickness has been either controlled locally by installing gauge wires or studs (Figure 6) here and there on the surface to be sprayed or afterward by probe drilling. The issues with both methods are that they are highly labour-intensive and slow tasks, are subject to human errors, only offer layer thickness info very locally from individual points and recording the results can only be done manually. Drawing conclusions from these local measurements to cover the whole sprayed surface is iffy and risky, and even large areas with too thin layer thickness can be left unnoticed. Also, probe drilling afterward means that re-spraying for this area needs to be arranged separately if insufficient layer thicknesses are found. This is hugely inefficient, costly, and adds up to the total schedule of the spraying operations. Probing through the fresh concrete, for example with a knife, is just plain unacceptable due to the obvious safety risks of fresh concrete slabs falling on the operator.

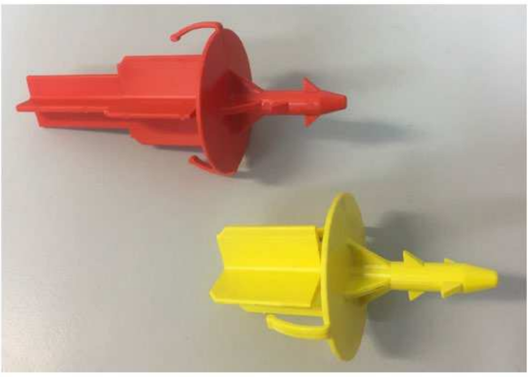

Figure 6 - Thickness gauge studs

Modern surveying technology brings new possibilities to layer thickness monitoring and control. Laser scanning is a proven technology in underground conditions and is already widely utilized to produce as-built documentation data in many fields of industry and construction. By integrating laser scanning technology combined with a layer thickness analysis system and a competent user interface to a concrete sprayer, the full potential can be harnessed. At its simplest, a laser scanner based layer thickness control system measures the surface to be sprayed just before and after the application, calculates the applied layer thickness perpendicular to the surface, and creates a report of the sprayed area according to the pre-settings made by the user.

Instead of giving layer thickness information from a few individual points to be written down on a paper days after spraying, digital mapping produces full coverage layer thickness analysis to be viewed and utilized already during the spraying process (Figure 7). Possible under-spraying will be noticed right away, and corrective actions can be taken without further delay. With a proper system integrated into the concrete spraying machine, the freshly sprayed concrete lining will be checked for under- and over-spraying and fully documented within minutes of application – before the operator has wiped the dust off his visor.

Figure 7 - Normet SmartScan scanner unit and user interface

The benefits of digital layer thickness control are most significant in projects where

- Safety is a matter of high priority
- The project schedule is tight
- Material and labour costs are high
- Sprayed concrete is used as final lining, or demand for quality is otherwise high
- Demands for as-built documentation are high
- Invoice basis for sprayed concrete linings between contractor and client is m^2 or otherwise measurable units of approved lining

The incomparable improvement in layer thickness measuring accuracy and coverage comes with added responsibilities, though. While the desired sprayed concrete structure thicknesses can be achieved far more easily and accurately, it must be taken to account that the theoretical laser scanning accuracy exceeds the accuracy of sprayed concrete application. Whereas laser scanning reaches the measuring accuracy of less than 5 mm in actual conditions, the grain size of typical sprayed concrete mix is often 8 mm, and even the most skilful and careful application comes with a small allowance. This merely means that the tolerance allowed to sprayed concrete layer thickness needs to be based on the properties of the application, not the properties of the measuring method.

Layer thickness monitoring systems based on laser scanning or other technologies can be either standalone or integrated into the spray rig. Whereas the standalone systems can be positioned more freely and do not always need to be used during the spraying, the integrated ones are specifically designed to work hand in hand with the spraying, controlling and documenting the layer thickness during the process. Also, integrated systems do not need separate personnel to operate them, and the effort required to perform the scanning during spraying is minimal.

Integrated systems can also be designed to interact with the sprayer control system to optimize the process on a more comprehensive level and to produce valuable data that is not possible to retrieve in any other way. In the future, an integrated layer thickness monitoring system can also be seen working together with an automated boom control system, creating an intelligent autonomous sprayer capable of producing high quality sprayed concrete linings based on internal quality control.

Standards for the determination of sprayed concrete layer thickness

Monitoring and proving the sprayed concrete layer thickness are regulated differently in different regions globally, but laser scanning is not yet widely recognized on standardization level as a layer thickness assessment method. In some underground construction forerunner countries, national regulations or major constructor guidelines accept laser scanning as a method for proving the layer thickness, and practices on how to comply with higher-level regulations have been written in either the national guidelines or project documentations. An example of this is Finland, where the European standard (EN 14488, 2005) is followed, and national guidelines for sprayed concrete (BY63 Ruiskubetoniohjeet, 2015) details how laser scanning can be used to assess the sprayed concrete layer thickness to comply with the standard.

(EN 14488, 2005) describes methods for the determination of the thickness of sprayed concrete on a substrate after spraying. In fresh concrete, a depth gauge is pushed into sprayed concrete, and the thickness is measured. In hardened concrete, holes or cores are drilled to the substrate. The depth of the holes or extracted cores is then measured to evaluate the concrete layer's thickness. A drill pattern consisting of five holes, spaced in two lines of three at right angles (600 ± 50) mm, should be used (Figure 8).

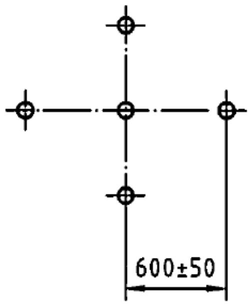

Figure 8 - Drill pattern EN14488-6

Standards quite often do not describe or define the area to be tested, the extent of testing or the requirements regarding the results. The use of laser scanners results in a much denser local resolution of sample points, making it challenging to transfer to the manual method with probe drilling. The national guidelines in Finland (BY63 Ruiskubetoniohjeet, 2015) stipulates for example the following acceptance criteria for laser scanning based thickness control:

- On 80% of the sprayed area, the layer thickness must meet or exceed the required layer thickness
- On 20% of the sprayed area, the layer thickness can be no more than 25% less than the required thickness
- The areas which are below the target thickness cannot be larger than 20 m^2 in size

To standardize the test procedures for determining the thickness of the sprayed concrete layer, local regulations are often implemented. These can be country-specific but can also be negotiated between client and contractor. They usually define the area that needs to be tested, the extent of testing, and the requirements regarding the results.

The underground construction industry should work together and promote more advanced technologies such as profile scanning to lay the foundation for regulating bodies to implement these into standards and regulations.

Layer thickness control system in operator training

It is often recognized that the operator experience and motivation to produce good results efficiently have a significant effect on the quality and total cost of sprayed concrete lining. It is also true that often the operator and application-related factors are the ones that have the most fluctuation. This issue is not solved by recruiting only experienced professionals – they do not just happen to emerge in sufficient numbers nearby when needed. Skills and understanding come through both experience and training, as in all highly technical and complicated expertise fields. If experience is gained purely through working with the concrete spraying machine, it will surely gradually build-up, but it comes at a slow pace, with safety risks, and with a high cost caused by all the wasted material and correcting errors along the way. Also, experience gained only through application often lacks the invaluable theoretical and economic knowledge behind the sprayed concrete operations. This does not necessarily slow the pace of the actual spraying, but it can significantly limit the operators' understanding of the effects of his or her actions and choices to the end-result and cost of the sprayed concrete lining.

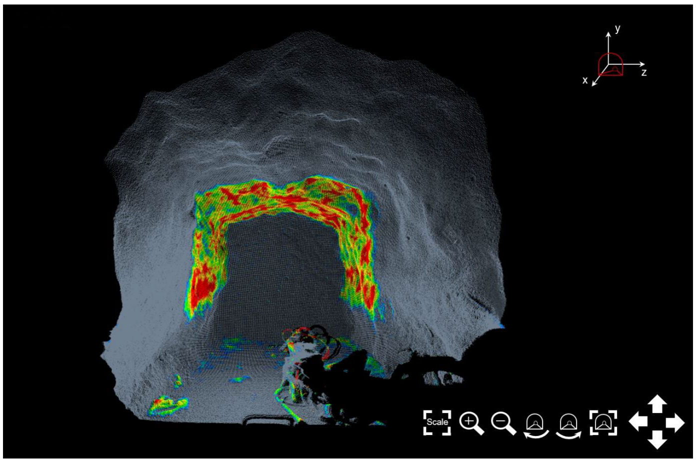

Figure 9 - Graphical User Interface

As the number of underground projects increases together with quality requirements, new ways to steepen the learning curve of new spraying operators are welcome. Even though in the end nothing completely replaces the experience gained through hours and hours of actual application on a real concrete sprayer, those otherwise slow, risky, and costly first steps are better taken safely in a classroom. When the candidate is ready to start training with a real machine, tools that help them find the right movements, and adjustments to produce consistent quality, sprayed concrete lining is extremely helpful. A thickness measurement system integrated into the spray rig works with the operator giving him or her instant feedback (Figure 9) on the application's success, helping to achieve the right touch significantly faster than with traditional methods. The layer thicknesses can be checked as often as needed during spraying until the operator starts to get the hang of it when the scanning frequency can be brought down to the standard level of scanning only the initial and final layers.

As-built documentation in modern tunnelling projects

As-built documentation can be utilized in modern tunnelling projects in many ways. Traditionally some kind of documentation has been used to verify that the excavated and supported surfaces are where they should be and that there are no underbreaks that might interfere with for example structures, pipelines, or the use of the underground space. More and more the documentation is also used as a basis for engineering these upcoming structures and technical applications as a basis for different calculations and even for invoicing in contracting. These purposes increase the requirements of as-built documentation regarding coverage, accuracy, and pace of delivery. In many applications the as-built documentation should be available to be used as soon as possible after the structure to be measured has been finalized.

The development of as-built documentation has followed the development of surveying equipment and solutions. Digital as-built documentation has been possible for years with a Total Station but recording one point at a time was slow and thus, producing not more than individual cross-sections was efficient enough. With the development of 3D laser scanning technology, the underground as-built documentation has taken a giant leap forward as producing dense point clouds of uneven surfaces today is a matter of minutes. From the point cloud data, several different types of illustrations and data extractions can be made (Figure 10). Point cloud data sets can also be made compatible with data models, such as 3D-models.

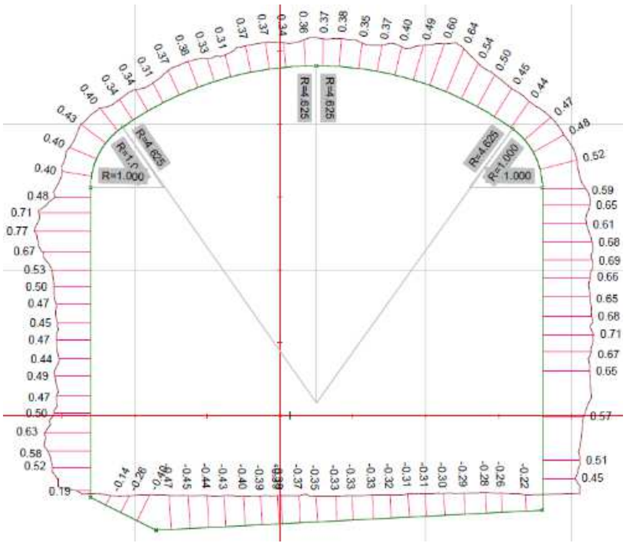

Figure 10 - As-built cross-section extracted from laser-scanned point cloud data

3D modelling has been used for some time now in construction projects to manage and execute the actual design engineering, illustrating the design work and coordinating different design branches, such as fitting the electrical, heating, ventilation, and air conditioning (HVAC) and pipeline designs to structural blueprints. Underground construction has been lagging on the development, but lately, tunnelling projects have started using more and more 3D modelling. In addition to design work, 3D models are a convenient and functional way of communicating between project stakeholders. The visualization is often faster and easier to grasp than a set of traditional 2D blueprints. A typical example of this is a situation where a change to some upcoming structure or technical appliance needs to be made, and as-built documentation is required to evaluate whether there is enough room or if more excavation is required. As-built documentation can also be used for future material consumption and structural strength calculations etc. The more up to date the models are, the more value they bring to all stakeholders during the project.

In general, it's often enough during the structural phase on construction projects that the communication is done on design-level blueprints or 3D model as finalized structure tends to be – if not identical – at least dimensionally very close to the designs. Nonetheless, in underground construction, the structural phase consists of excavating soil or rock, which is always an inaccurate method.

The tooling allowances of different excavation methods and conditions vary from some centimetres to even meters. This is often not an issue and depending on the use of the underground space a certain tolerance between the theoretical and actual excavated surface is allowed. Nonetheless, being aware of the difference between the theoretical and actual surfaces makes the future design work easier, faster, and more cost-efficient and reduces the number of changes required on-site in the upcoming construction phases. In modern underground construction projects, the stakeholders call for as-built documentation data already during the structural phase – in our case excavation – to be added to the 3D-model to align it with real dimensions and shapes of the underground space.

Traditionally this means that the contractor must carefully plan the as-built documentation surveying sequences to accommodate the project's needs. The sequence cannot be too long to avoid delays in providing the documentation, nor can it be too short to avoid high costs, schedule effects, and preparations for each surveying round. Traditional surveying of the completed surfaces always more or less interrupts the work in the heading in question. Also, Total Station surveying, or laser scanning is rather labour-intensive and often requires the surveyed data to be manually processed and added to the data models.

Now, if the philosophy of periodically gathering as-built data only from structures that are finished is developed to continuously adding new data of the work in progress, the situation where the 3D model is practically up-to-date and can be all the time utilized by all stakeholders of the project can be achieved. To keep the costs and schedule effects of this minimal, the onboard scanning system of a concrete sprayer is ideal for producing the as-built documentation data. Once the sprayed concrete surface is approved and declared finished, the as-built documentation can be simply tagged as final.

Methods to georeferenced profile data

For some projects, it is sufficient that the measured profile information is only available in the local coordinate system during the current spray application, which means without moving the machine. However, it is often necessary to transform the profile data into the project coordinate system or world coordinates. There are at least two methods available to georeference the measured profile data.

The first method is to locate two prisms mounted on the concrete sprayer from an external Total Station and use them together with the angle information from the inclinometers to transform the profile data into the project coordinate system (Figure 11).

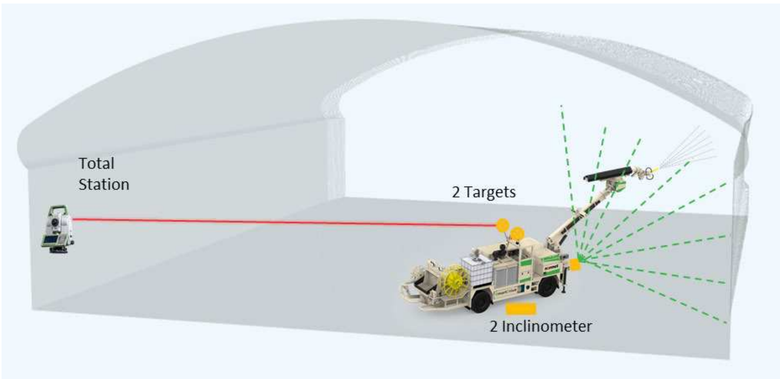

Figure 11 - Georeferencing with external Total Station

The second method uses an additional sensor installed on the spraying carrier facing rearwards and locates the targets mounted on the tunnel walls (Figure 12). With the known position of at least four targets in the local coordinate system, the sensor's position can be determined, and the profile data transformed into the project coordinate system.

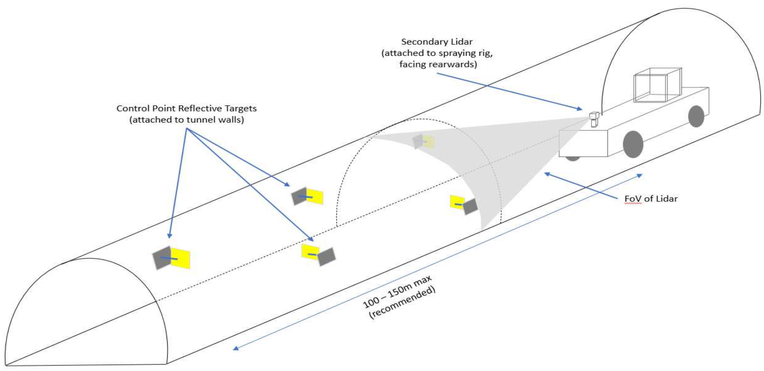

Figure 12 - Georeferencing with a secondary LiDAR sensor

Both methods make it possible to assign the measured profile data to its unique location and use them for various evaluations, such as comparing excavated vs. theoretic tunnel profile and as-built documentation purposes.

Depending on what purposes the georeferenced scan data will be used for, it needs to fulfill specific accuracy requirements. The accuracy of laser scanning itself is quite impressive given the uneven microstructure of the sprayed concrete surface, but the georeferencing method needs to be accurate enough not to deviate the point clouds from the chosen coordinate system more than allowed in relevant regulative documentation. Requirements for as-built documentation accuracy can be significantly higher, for example, in railway tunnel projects than in sewer tunnels or hydroelectric projects. Therefore, as requirements vary, the most feasible georeferencing method and technology must be evaluated and chosen to fit the project's needs.

Market overview scanning technology for sprayed concrete application

The cooperation between Putzmeister and Leica Geosystems resulted in the Geokret 2.0 system (Figure 13) combining the Leica BLK360 Imaging Laser Scanner with a tablet and associated software. The operator must place the laser scanner on a tripod on the floor next to the machine. The measuring process is started from the tablet, and the acquired data is transferred wireless to the tablet. The post-processing of the data takes place in a survey-grade package (3DReshaper).

Figure 13 - Putzmeister Geokret 2.0

GroundProbe adapted their GML product (Figure 14), which was initially designed for geotechnical convergence monitoring to detect rock and ground support movement with sub-millimetre accuracy, as a live guidance system for the concrete application to measure the concrete thickness. The high speed/high accuracy laser scanner is installed on a tripod on the floor next to the concrete spraying machine and needs to be operated by a surveyor in parallel to the concrete application.

Figure 14 - GroundProbe GML

Bever Control AS uses a similar kind of system to navigate drilling jumbos, consisting of a laser rangefinder that scans the tunnel surface with individual measurements. The scanning system (Figure 15) is installed at the back of the machine and consists of a graphical user interface displaying surface plots of the applied concrete thickness.

Figure 15 - Bever 3D Profiler

Australia-based Murray Engineering offers the OptiME 3D Shotcrete Optimizer (Figure 16), which combines an industrial 2D LiDAR with a belt drive to acquire 3D data. A rugged tablet PC with a touchscreen display enables the user operation and provides a graphical visualisation of the colour-coded point cloud data. The system can be installed onto a concrete spray rig or operated as a standalone device. The built-in wireless connectivity enables remote operation in hard-to-reach or hazardous locations.

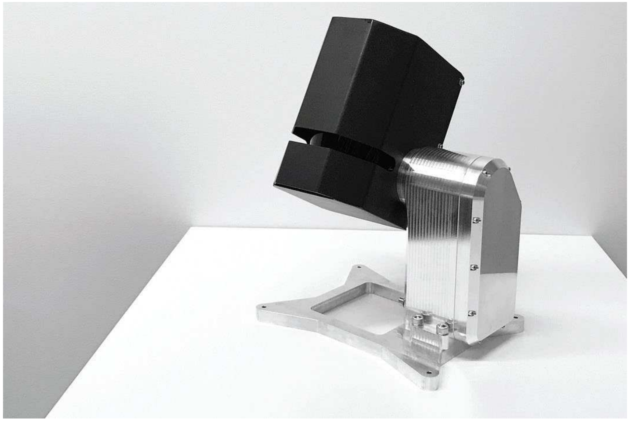

Figure 16 - Murray Engineering OptiME 3D Shotcrete Optimizer

Normet's SmartScan system (Figure 17) was developed for harsh underground environments to calculate and display the applied concrete thickness. The unique registration algorithm detects changes in the scanner's position between the scans utilizing features in unaltered areas to align the point clouds recorded against each other. This allows compensation for movements of the spraying platform, such as the sinking of the support legs.

Since the tunnel profile measurement is rarely carried out at rectangular to the surface, triangles are generated from the individual measuring points, which are then used to calculate the concrete layer thickness. This additional process requires more computing time but increases the overall accuracy and precision of the system.

The 3D scanner, mounted in a protective housing on the concrete sprayer, is well protected against rebound and is quickly available for the next scan without the risk of damage when installed externally or placed on the floor next to the concrete spraying machine. Developed for operators with a one-touch operation, which can be learned in a few minutes. The software allows on- and offboard evaluation and storage of profile data, including generating reports with thickness distribution and concrete volume calculations.

Figure 17 - Normet SmartScan

VR SIMULATORS AND DIGITAL TWINS

Fast development in virtual reality (VR) technology is known to many through different entertainment applications. Combined with advanced software and computing power, it serves as an incomparable multi-tool throughout the sprayed concrete process life cycle from the early stages of equipment and application development to training the operators and optimizing the whole concrete spraying process.

VR training simulators

As already mentioned, experienced sprayed concrete operators come in limited numbers, and verifying operator's skills using scalable measures is challenging. The operator is often the single most significant variable in a comprehensively optimized sprayed concrete process to produce high quality safely and cost-efficiently.

The non-profit organization EFNARC has worked for years to bring and maintain the quality of sprayed concrete worldwide on a high level and has launched its Nozzleman Certification Scheme in 2009. Continuous development of demands for absolute safety, consistent high quality and efficient operation has led to fast development in sprayed concrete equipment and materials. This sets requirements for the tools to train and certify the operators. EFNARC C2 nozzleman training and qualification scheme have been established to answer these needs, and training in the VR environment is key to the scheme.

VR based solutions have already found their place in many applications in industry and entertainment, and the technology behind is well proven. When combined with a high-performance computer and professionally engineered simulation software, today's VR training simulators are on a level where incredibly realistic simulation is achieved (Figure 18) (Figure 20).

Figure 18 - Normet VR simulator hardware and operator view through the VR glasses

Most experienced spraying operators claim that to become one, the ability to accurately see and comprehend movement and surfaces in three dimensions is crucial. This is often referred to as "having the eye" for spraying. This practically means that an operator needs to control and navigate the spray boom at a fast and consistent pace in three dimensions to produce a steady flow of concrete, keeping the nozzle's angle and distance towards the surface to be sprayed optimally at all times. Simultaneously, the operator needs to monitor the equipment operating parameters, the build-up of the concrete layer on the surface, and his movement minding safety and visibility. No wonder concrete spraying is often considered to be the most challenging task amongst underground processes.

All this means that the training environment for novice operators must be as close to real tunnel conditions and working with a real concrete sprayer that practicing the complicated tasks and getting the real feel of operating the equipment is possible. Otherwise, the new operator will have to grab the remote of the actual sprayer quite unprepared.

In addition to accurately simulating the environment and the concrete sprayer, a proper VR simulation also includes the whole application process with all its variables. All factors affecting the quality of the sprayed concrete structure such as the concrete build-up at the surface, accelerator dosage, concrete and airflow are simulated just as in a real application. The candidate learns the navigation of the spray boom and the effects of their actions. A wrong spraying angle leads to low quality, and too long spraying on the same spot will cause the sprayed concrete to fall to the ground. Moving to a better position around the concrete sprayer improves the visibility and safety of the operator.

Having an easily attainable training and assessment environment also gives contractors and training bodies better possibilities to evaluate the operator and set requirements for qualifications. The need for operator qualifications is recognized for years, but setting requirements comes with a responsibility to offer tools to fulfill them. A qualification system should not backfire on the contractors in the form of having to take excessive measures to fulfill the requirements, but to benefit all in form of increasing ability to produce high quality sprayed concrete structures more efficiently, cost-effectively, and most important of all, safely.

Digital Twins in R&D

In general, Digital Twin (DT) is seen as a concept for a digital representation of a real system so that the DT corresponds to the real system with high accuracy. These digital twins modelled of the physical objects can perform equal actions to the real counterparts.

VR simulators or DT are not only utilized for end-user training but also extensively in the research and development (R&D) process. Practically the Digital Twin is used during the whole product life cycle – from the design phase to development, manufacturing training, service, and marketing (Figure 19).

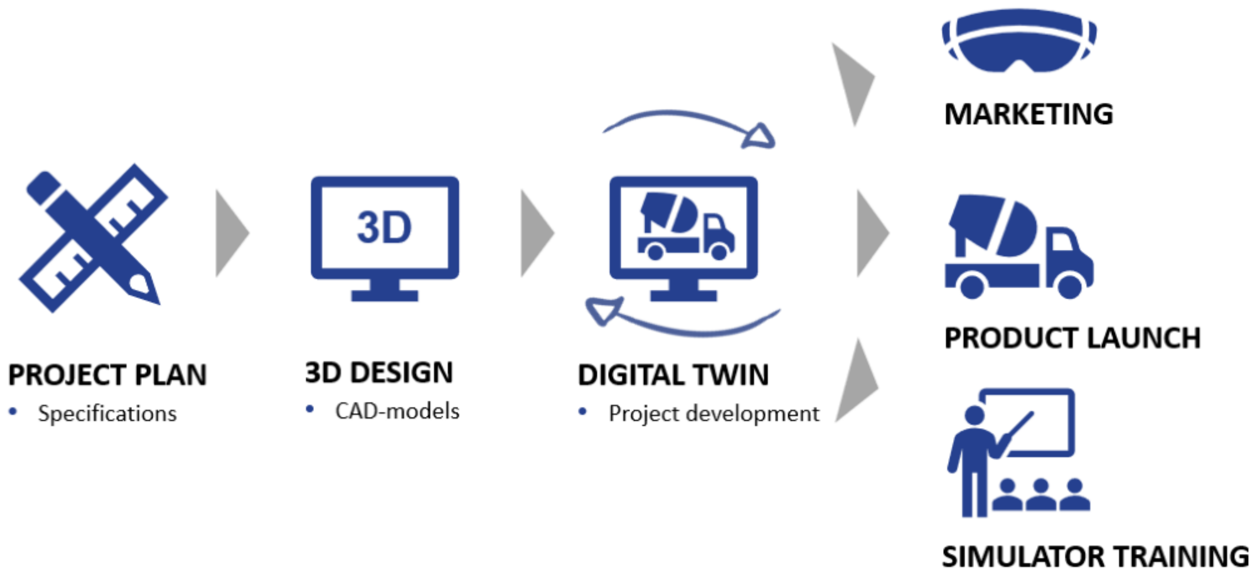

Figure 19 - Example of Digital Twin utilization in practice

At the beginning of the design phase, several concepts of a new machine or object are created. It is practical to create a virtual model from different concepts in many cases and simulate these concepts in the digital twin environment to save time and resources in the development phase. For example, designing new concepts of different types of boom structures or cabins or conceptualizing hydraulics or material structures in the digital world reduces the development time and material costs extensively. Iterations done in the Digital Twin simulators are much more efficient than building real prototypes and thus shortens the time-to-market in the development of new machines.

After the conceptual design phase, the detailed engineering and design of the overall system begin. At this phase, the digital twin of the whole machine is implemented. During the development phase, the Digital Twin is already utilized to optimize structures, get feedback from end-users, and develop the control system hardware and software. Usually, several iterations are taken in the virtual environment during the whole system design.

The level of automation and autonomously operated machines are increased rapidly in mining and tunnelling applications. For example, when implementing more automated features for boom control, highly advanced software algorithms must be iteratively developed and extensively tested in a real system. For this, Hardware-in-the-Loop (HIL) simulators are used to integrate the real control system into the counterpart. Testing new features such as automated spraying in the simulator does not require facilities, concrete, additives, and other materials and personnel. The process model and algorithms are part of the Digital Twin simulator, enabling the developers to test new algorithms safely and cost-effectively in the virtual environment.

During the engineering phase, the digital counterpart can be already presented to customers. After finalizing the product design, the system is used for training service and end-users with the VR capabilities.

Figure 20 - Normet Concrete Spraying VR simulation at an exhibition

REMOTE DRIVING SYSTEMS

Moving machinery in confined spaces and low lighting conditions such as found in underground operations is a significant risk of injury to the operator and damage to the equipment. Also, an assisting person is often needed to move a machine safely, which on the one hand, drives up personnel costs and runs counter to the general trend towards reducing personnel underground. Repeated access to the driver's cabin causes physical strain on the operator and carries the risk of long-term physical harm.

When applying thin layers of material, the equipment must be moved at short intervals between the application areas. As this interrupt the spraying process, the time required to move the machine is critical.

Safety when moving machines

As a result of tunnel construction, the lighting can be insufficient, space is rather limited, and the ground conditions poor. This often leads to considerable risks while moving machines underground. Even though the driver's cabin is often positioned elevated in the middle of the machines, the view of the surroundings and the machine's dimensions is limited.

After positioning the machine in the working area, the stabilizers must be extended, which is often done without a good view as the stabilizers' controls are not at the same location (Figure 21).

Figure 21 - Lowering the stabilizer in confined spaces and climbing down from the cabin

The limitation of the boom reach sometimes requires the repositioning of the machine. This can take place under freshly sprayed concrete, which is a severe safety issue. It also happens that machines must be moved over ramps or in unsafe areas. The option to move the equipment from a safe position can mitigate the risk of injuries by falling concrete or uncontrolled machine movements.

Reversing a concrete sprayer around a bend or with the power cable and water hose still connected, requires an additional person that ensures that the connected lines are pulled to the side, so they are not rolled over and damaged.

The driver's cab's access can sometimes be rather narrow and to use the handles and steps correctly requires the operator to remove the remote control before climbing the cabin. As operators tend to jump from the machine or ladder to the ground on the way down, injuries to knees and ankles and their long-term effects on health are common.

Climbing into the driver's cabin repeatedly to move the vehicle can be very strenuous to the machine operator, especially during long shifts.

Speed of application

Applying a thin layer of sprayed concrete onto PE insulation mats for fireproofing is considered a high-speed application (Figure 22). For this application, which can be found in Nordic countries such as Norway and Sweden, the application speed is critical. As any spraying manipulator has its physical limitations in reach, the time required to move the machine to its next application area greatly impacts the overall efficiency.

The concrete spraying boom typically used for this application can cover from one position in a tunnel with 10.5 m width and 6.0 m height a working area of 7 m in tunnel axis. The final thickness of 7 cm is applied in 3 layers, which happen at different passages. In a shift of 10 h, 200 m^3 of sprayed concrete are applied. Since the work shift also includes breaks, the average conveying capacity is on average 20 m^3/h.

A layer thickness of 20-25 mm and a profile circumference of 20 m result in 3.3 m^3 sprayed concrete over 7 m of the tunnel. Using the average output of 20 m^3/h, this results in about six spraying segments per hour.

The application is typically executed from a truck-based machine with enough power to drive the necessary concrete spraying aggregates such as concrete pump, compressor, and spray manipulator from the diesel engine. As the truck cannot be moved with the diesel engine's operating speed, the compressor must be stopped first to disengage the power take-off (PTO) at the diesel engine. The vehicle can then be moved, the PTO engaged, and the aggregates brought up again to operating speed. This process takes approximately three minutes and occurs six times per hour, which equals 30% less spraying.

The remote driving system available for this machine can reduce the time to move the machine drastically and eliminates the need to get in and out of the cabin.

Figure 22 - Spraying of PE insulation mats

Remote-controlled driving

Modern underground machinery is often equipped with radio remote controls, which allow the operator greater freedom of movement (Figure 23). The same machines consist of industrial bus systems such as CAN bus to control and monitor drive systems such as diesel engines and drive trains. In the case of a mobile concrete sprayer, the movement of the spray boom is carried out via hydraulic valves, which often communicate via a bus system with the control system.

If the vehicle's steering is now integrated into the existing control systems, remote-controlled driving of the carrier can be achieved with little effort. Due to the vehicle's remote-controlled maneuvering and the associated risks, the risk assessment must be renewed or updated.

The local regulations for remote-controlled machines, which often contain additional safety elements and a speed limit, must always be observed.

Figure 23 - Remote controlled concrete spray manipulator in a shaft with limited space

Conclusion

The possibility to move the vehicle from the remote control has many advantages:

- Reduces the risk of injury to the operator and damage to the machine due to better visibility
- The vehicle can be moved without an assistant, reducing operating costs and exposure to safety hazards
- Reduces the physical strain on the operator
- Provides a good view of the various machine elements and the application area
- Speeds up the repositioning of the machine, thus improve productivity

CONCLUSIONS

Computer-assisted boom control can improve the overall quality of the spray application by reducing rebound to a minimum while achieving good compaction of the concrete on the surface. Especially inexperienced nozzle operators benefit from the computer-assistance, allowing them to focus on the spray nozzle to achieve high spraying performance over a long time without any signs of fatigue.

The layer thickness control provides instant feedback of the applied sprayed concrete layer to the operator allowing immediate corrective measures and delivering the as-built documentation without extra effort.

A digital representation of a real system in the form of Digital Twins provides many benefits for end-user training and the research and development process.

Moving equipment underground is a risky undertaking and often requires extra personnel. Remote drive systems allow operators to freely move around to get a good view of the equipment and eliminate the need to climb into the cabin reducing the physical strain and injure risk.

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REFERENCES

BY63 Ruiskubetoniohjeet, 2015. Helsinki: Concrete Association of Finland Guidelines for Sprayed Concrete.

EN 14488, 2005. *Testing sprayed concrete - Part 6: Thickness of concrete on a substrate.* Brussels: European Committee for Standartization.

Girmscheid, G. and Moser, S., 2001. Fully Automated Shotcrete Robot for Rock Support. *Computer-Aided Civil and Infrastructure Engineering,* p. 200–215.

Guthoff, K., 1991. *Einflüsse automatischer Düsenführung auf die Herstellung von Spritzbeton,* Bochum: Ruhr.

Hartmann, T., 2018. *A Leap Toward Automation in Shotcreting,* Minneapolis: Society for Mining, Metallurgy and Exploration.

Honegger, M. & Codourey, A., 1998. *Redundancy Resolution of a Cartesian Space Operated Heavy Industrial Manipulator.* Leuven, ICRA98, Int. Conf. on Robotics and Automation.

Honegger, M., Schweitzer, G., Tschumi, O. & Amberg, F., 1997. *Vision Supported Operation of a Concrete Spraying Robot.* Toowoomba, M2VIP.

Moser, S. B., 2004. *Vollautomatisierung der Spritzbetonapplikation – Entwicklung der Applikations-Prozesssteuerung,* Diss. ETH Nr. 15621: ETH Zurich.

Nabulsi, S., Rodriguez, A. & Rio, O., 2010. Robotic Machine for High-Quality Shotcreting Process. In: *ISR 2010 and ROBOTIK 2010.* Munich: VDE, pp. 1137-1144.