Real-time In-Situ Technology for Shotcrete Construction

By Benny Chen, Christian Reich, Peter Ayres, and Nicholas Carter

Construction of sprayed concrete lining (SCL) ground support across the world utilizes the construct, verify and rework cycle. This methodology typically requires survey verification of the as-built result against design for each stage of the ground support installation. However, processing and analyzing the measurement data is a time consuming and often intensive manual process. Often once the survey information is available the construction crew will have already left, this will require rework on the next cycle.

Leveraging the latest in high-density LiDAR and high-speed computing technologies, provides the ability for construction crews to receive near real-time feedback of their SCL construction against design. This potentially can significantly improve the efficiency and quality of SCL reinforcement, while reducing waste in construction.

Construction Challenges

In a typical shotcrete application stage, the thickness of shotcrete applied is highly dependent on the skill and experience of the nozzlemen. Upon completion of the shotcrete placement the compliance of the sprayed concrete thickness with the design requirements is not known until after a survey is completed. The survey results highlight areas of over spray (excessive thickness) or under spray (deficient thickness), resulting in shotcrete wastage or costly rework.

For example, during application of shotcrete nozzlemen often use bolt tips as guidance to allow them to gauge the approximate depth of their placement. The nozzleman's experience plays a large role in ensuring that the correct thickness is achieved. However, to reduce the amount of under spray sections and prevent rework the nozzleman may choose to place more shotcrete than required.

In many tunnel and cavern projects, the design profile of the tunnel or cavern is critical and requires strict thickness tolerances during SCL construction to ensure the as-built sections fall within the design profile specifications. In these types of construction, both under spray and over spray could result in non-compliance which then requires very costly and time-consuming rework. Often depth pins and string lines are installed in the area to provide guidance to the nozzlemen, allowing them to visually gauge when they have achieved profile. The process of installing depth pins and string lines are time consuming and labor intensive. This significantly increases the time and cost of construction. Once installed, the nozzlemen will have to estimate the placement thickness between the string lines, which once again is heavily dependent on the skill and experience of the nozzlemen.

STATE OF THE ART CONSTRUCTION TECHNOLOGY

Since the introduction of the Building Information Modeling (BIM) standards, governments around the world are rapidly adapting BIM for their construction projects. This is evident in countries including Hong Kong, Singapore, Norway and Sweden. Figure 1 show the core BIM construction workflow where design and authoring of the architectural and tunnel designs are done in 3D CAD software, such as Revit and Civil3D, where a full 3D model of the completed section is created. This is followed by the Virtual Design and Construction (VDC) process where a complete construction simulation is run using the CAD models. This helps validate the both the construction process and the schedule. Clash detection is also accomplished with the design model to detect any potential design conflicts before the construction plan is approved.

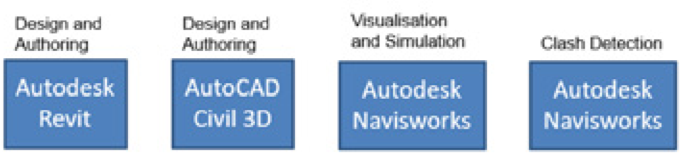

Fig. 1: BIM Construction Workflow

BIM construction is one of the key reasons for the use of laser scanner technology. 3D Laser scanners are used to scan as-built construction elements. Scanning is typically carried out by a survey team where the laser scanner is deployed in the excavation heading to collect the as-built scan data. This scan data is then brought up to the project office, where a powerful desktop computer analyses the data in a georeferenced coordinate system. This point cloud data set often requires some manual processing to correct for measurement errors and to correlate with the design data. The entire process is required before producing a report that can be used for analysis and then feedback to the construction crew. This process typically takes between 2 to 4 hours per station. Hence, the use of such technology in civil constructions are limited.

Since 2016 the rapid adoption of high-speed embedded computing platforms, like Field-Programmable Gate Array (FPGA) and Graphics Processing Unit (GPU) processor cores for embedded systems, advanced data processing has become prevalent. These technologies allow battery-powered devices to achieve computing performance of one trillion floating-point operations per second (1teraFLOPS). Part of this rapid adoption is due to the global development of algorithms and processor cores for machine learning platforms and real-time autonomous vehicle projects.

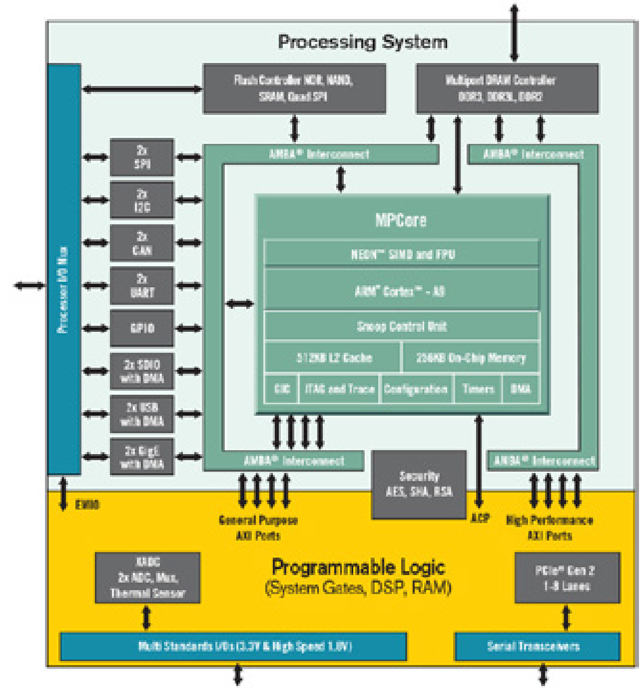

Fig. 2: Xilinx FPGA Architecture

By using FPGA based System-on-Chip (SoC) technology, similar to the Zynq-mp processor core technology that can deliver teraflops of computing performance, computationally intensive signal processing algorithms can be implemented in the hardware using the Programmable Logic portion of the system (see Figure 2). The Programmable Logic area, in yellow, allows the computer designer to create custom digital signal processing cores, like GPUs, and execute them in parallel, allowing high speed processing of large datasets. The Programmable Logic area also has the benefit of having dedicated memory banks that support concurrent access, unlike conventional computer memory access, via a common bus architecture. The architecture above makes it possible to process high-density data, like the 3D point cloud data produced by laser scanners in real-time.

REAL-TIME IN-SITU MEASUREMENT TECHNOLOGY

Real-time in-situ measurement technology refers to a portable measurement device equipped with onboard high-speed computing capabilities to deliver live or near real-time high-resolution information. One example is the production of information such as deformation or shotcrete thickness results in 3D. Figure 3 shows the comparison between using a conventional LiDAR against an in-situ LiDAR technology, in this case the Geotechnical Monitoring LiDAR (GML).

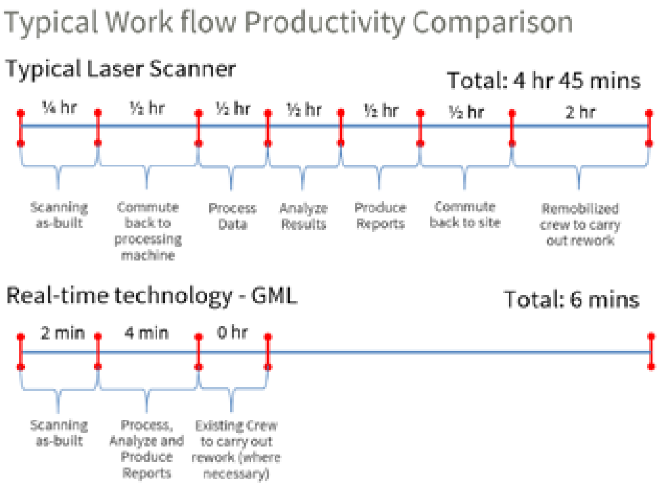

Fig. 3: LiDAR vs In-situ LiDAR Workflow Comparison

Fig. 4: Geotechnical Monitoring LiDAR (GML)

In the above comparison, the ability to analyze and report the desired construction results automatically and in minutes has the potential to significantly change SCL construction processes.

GEOTECHNICAL MONITORING LIDAR (GML) TECHNOLOGY

The GML technology was designed and developed by GroundProbe, a mining technology company that supplies slope stability monitoring radar systems such as the SSR-XT for the mining industry. Figure 4 shows the GML system as a complete standalone battery-operated LiDAR solution, that was designed to be a one person operation. This technology is equipped with an onboard high-speed computing device and signal processing software, that can produce high density point cloud information in real-time.

MEASUREMENT ACCURACY

The first proof of suitability for the new technology was to verify the measurement accuracy for shotcrete thickness measurements, against the existing total station pick up by survey control.

The GML was deployed in various control environments in a tunnel project to verify the thickness measurements. The first method was to compare the results of existing shotcrete thickness reports produced by the survey pick-ups against the thickness reported by the GML scanner. In this process, the GML was setup next to the total station during conventional pickup to scan the excavated sections before any shotcrete was installed. Upon installation of the bolts and shotcrete, both the GML and the total station were redeployed to complete the final as-placed scan. These results were tabulated in typical profile section views as per Figure 5.

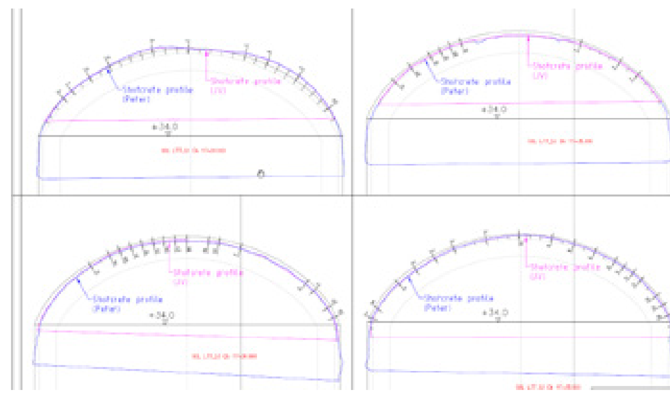

Fig. 5: GML & Total Station Comparison Results

In Figure 5, the GML results are in blue and the results of the total station survey are in pink. Results can be seen in all four scans, the GML results were almost identical to the total station measurements.

In another verification test, core samples were drilled to check the thickness against the GML measurements. In this test, the GML was deployed to scan the section before any shotcrete was installed. Once the shotcrete had been placed and cured the drill rig was deployed to drill four test holes, where the depth of the cores were measured. These four holes were marked on the tunnel surface to allow the user to locate the holes in the GML data.

Figure 6 shows the drill results in the GML SSR-Viewer software. The image was produced by the GML data and clearly shows the marked holes. For each marked hole a group of points were selected, creating the annotated figures shown in the figure. An average thickness measurement was computed for each of the annotated group of points and displayed in the charts.

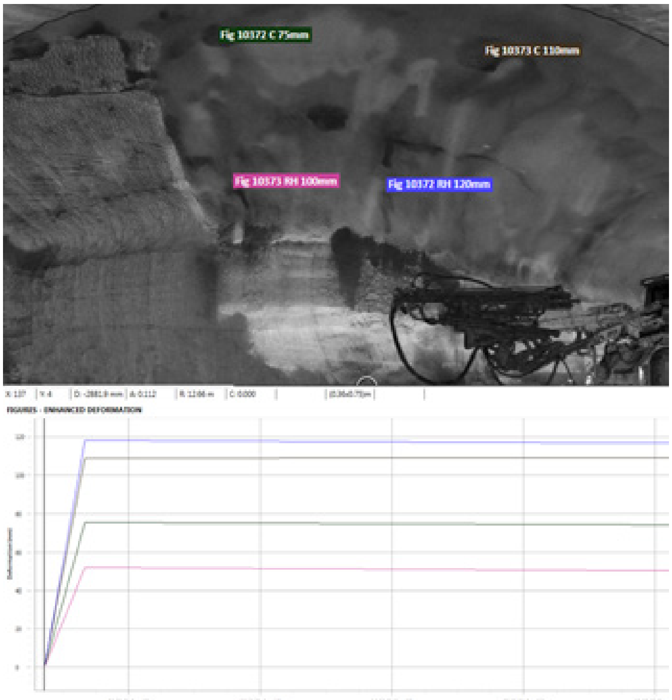

Fig. 6: GML & Drill Test Comparison Results

Table 1 shows the core sample measurements, against the GML measured results, for the placed shotcrete thickness. The GML thickness measurements were accurate to within 1-2 mm (0.04 to 0.08 in.). However, there was a large discrepancy with the results for Fig 10373RH, as notated in the table below. This was subsequently investigated, and it was found the core samples had not been measured correctly.

Figure Name	Drilled Results	GML Results
Fig 10373 C	110mm	109.3mm
Fig 10372	75mm	75.4mm
Fig 10372 RH	120mm	118.2mm
Fig 10373 RH	100mm	52mm

Table 1: GML & Drill Test Comparison Results Table

CHECK AGAINST DESIGN PROFILE

When operating in Profile Mode, the GML can import BIM CAD models into the device and automatically calculate the deviations against the design model. This allowed the construction crew to have real-time feedback of their work while in the tunnel. Figure 7 shows an example of the software operating in Construction Guidance Mode in a tunnel excavation operation.

In Figure 7, the grey point cloud is the scan data and it overlays the different design profile data, shown in purple and blue. The software automatically calculates the distance (in millimeters) to and from the selected profile lines, to produce the deviations in a hot-cold heat map.

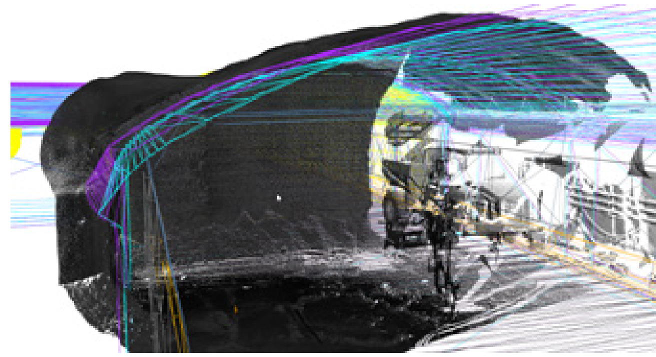

Fig. 7: GML Profile Mode

LIVE SHOTCRETE SPRAY GUIDANCE

The following case study was based on data from an Australian tunneling project in 2018. The project used GML for managing the shotcrete thickness for the primary lining ground support in a road header cut tunnel.

The typical construction issue faced in this project was the amount of shotcrete being ordered for each cut. Quantities were based on a calculated estimation, often with large amounts of excess material being ordered to accommodate rebound and the spraying skill of the nozzlemen. During the spraying stage, the nozzlemen have depth pins to gauge the spray thickness, hence the final sprayed thickness varies widely depending on the skill of the nozzleman.

In this project, the GML was used to provide in-situ feedback to the nozzlemen to guide them to spray to the required design thickness. Since the GML was introduced in a later stage of the project it was challenging to change the operating procedure. This required significant planning to be able to train and guide the nozzlemen to spray to the correct thickness. Using the GML system helped to reduce the overall shotcrete usage for the project.

In the early stages of implementation, the GML was used to characterize the quality of shotcrete application by the different nozzlemen. Figure 8 shows the typical spray quality before use of the GML to guide the nozzlemen. The shotcrete thickness in the images were represented with red for areas under design thickness, purple for areas over design thickness and green for areas with the desired design thickness. As illustrated in in Figure 8a, the sprayer was able to cover the bolts correctly but left large areas under sprayed between the bolts. Figure 8b, shows the opposite. Often the nozzlemen would overspray the entire area just to ensure there were no under spray areas resulting in using significantly more shotcrete than necessary.

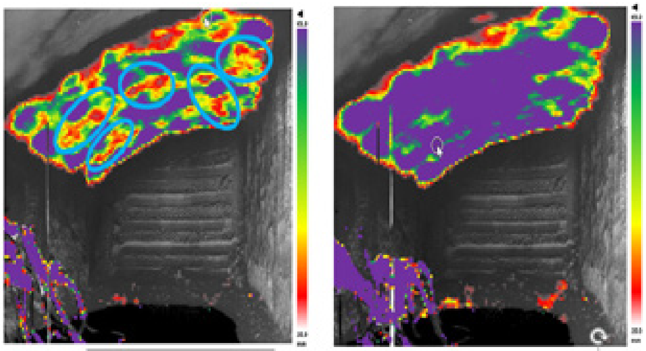

Fig. 8: Detection of overspray and under spray of shotcrete

During the first four weeks of the project, after buy-in from the site engineers, foremen and nozzlemen, the project started seeing improvement in the spray quality. The sprayer was able to use the GML guidance to cover up the thin spots as seen in Figure 8b. However, there were still some amount of overspray. Figure 9 shows an example where the nozzlemen was able to detect thin areas and rectify them immediately using the GML.

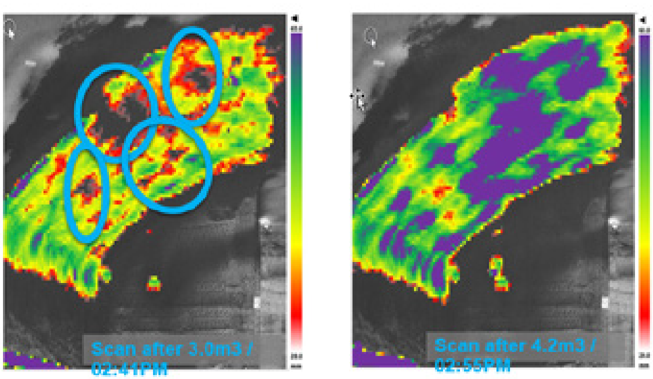

Fig. 9: Nozzlemen guided to fix up thin spots in shotcrete application

Shortly after the first month, the majority of the nozzlemen were able to use the GML to guide their shotcrete placement to reduce the amount of over spray. Figure 10 shows the reduction of overspray areas. In this example, the nozzlemen were able to reduce 33% of shotcrete usage by using the GML. More importantly, this was achieved within two weeks.

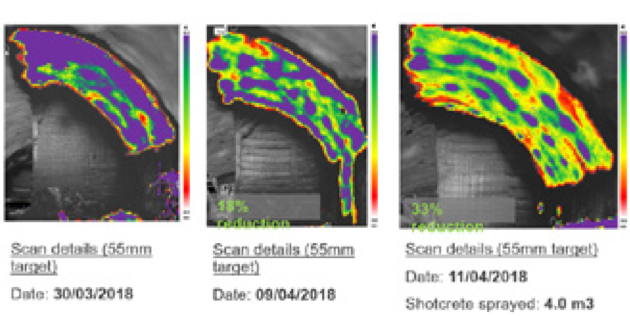

Fig. 10: Reduction of shotcrete usage

The GML was used in the project for a total of eight months and after the first month using the GML the project was able to reduce the shotcrete material orders by 30% for the remaining seven months of operation.

SHOTCRETE FINAL LINING CONSTRUCTION

The following case study was based on data from another Australian tunneling project between March and May of 2019. The project utilized GML for controlling the shotcrete spraying process for the tunnel-wide, final lining, to reduce or eliminate rework due to shotcrete not meeting the required minimum thickness.

In this final lining shotcrete application, shotcrete was sprayed continuously between cross passage (CP) to cross passage, completing a 390 ft (120 m) section at a time. This required the shotcrete rig and crew to move 13 to 20 ft (4 to 6 m) each time, to complete shotcreting the entire section. Given the design requirements for thickness and the tunnel design profile, depth pins and string lines were installed as guides prior to the spraying of the final shotcrete lining. The string lines were installed by a crew of two operators, one surveyor and the use of Mobile Elevated Work Platform (MEWP). The installation took the crews approximately two shifts to complete each section. Figure 11 shows a tunnel section that has the depth-pins and string-lines installed.

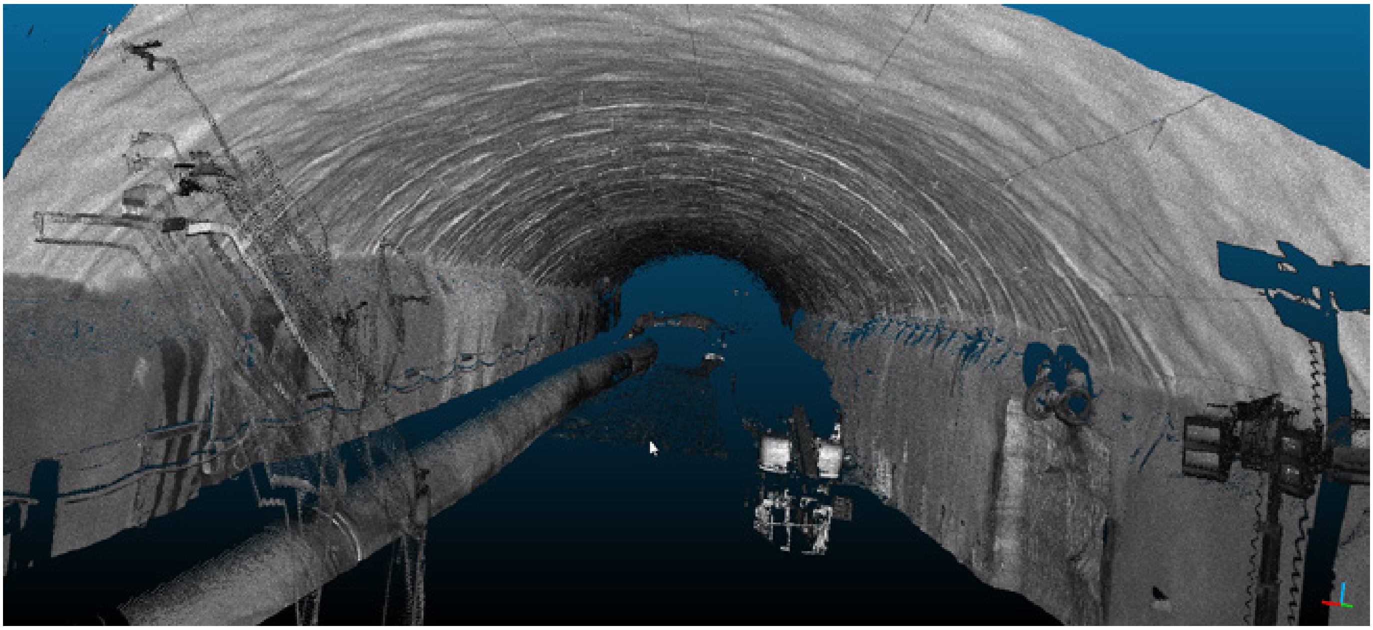

Fig. 11: Depth-pin and string line installation in tunnel section

Prior to the use of GML, the nozzlemen were using the string lines as a guide to spray the desired thickness and profile. Once the spray was completed, the section was surveyed to verify the shotcrete placement against the design profile and required thickness. The project ran for months and found there were too many thin spots that required rework, despite the installation of depth pins and string lines. The GML was then deployed simply as a verification tool to capture the construction baseline. Figure 12 shows a typical rework issue on the project.

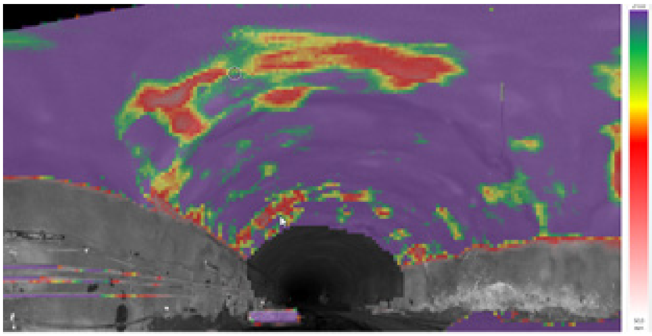

Fig. 12: GML scan showing under spray sections in Red

Figure 12 shows thin spots represented in the hot color palette (red) and over sprayed sections in the cold color palette (purple). The thin spots were spread across the entire sections requiring significant amounts of rework and verification by dedicated rework crews.

GML DEPLOYMENT CHALLENGES

The first key question regarding deployment of the technology was whether it can operate in cycle, particularly during the SCL stage of the tunnel construction process, to monitor spray conformance.

During spray conformance monitoring, the GML is typically deployed next to the front stabilization jack of the shotcrete rig and remains in place during the entire spray sequence. This position allows a wide scan area to be captured with minimal obstruction from the shotcrete rig. The GML completes a baseline scan under two minutes before the shotcrete operator starts to spray. Once the shotcrete operator is satisfied with the first pass, the boom is lowered, and a second scan is captured. As shown in Figure 13, the results are then presented to the shotcrete operator on a tablet to indicate any areas that have not reached the required thickness. The scanner operator then uses a laser pointer or cap lamp to guide the shotcrete operator to respray the thin areas. Once both operators are satisfied, a final scan is taken to confirm the results.

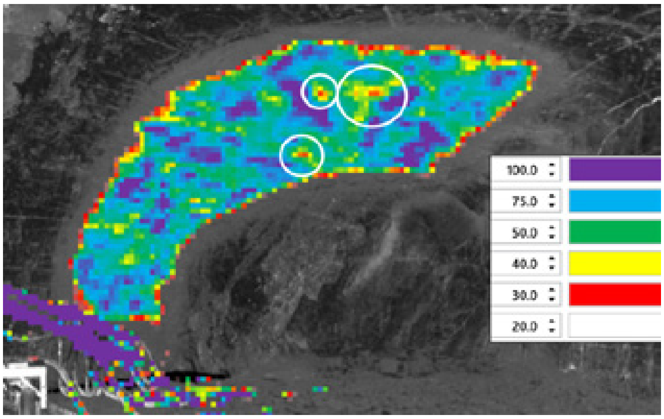

Fig. 13: GML Scan Color threshold for spray thickness

The other key issue was the nature of the final lining spraying process, were the shotcrete rig and crew needed to advance at every 13 to 20 ft section. This required the GML to be relocated with the rig to operate in cycle. The GroundProbe team worked closely with the shotcrete crew along with engineers to develop a shotcreting sequence that allows the GML to operate in cycle. Leveraging the rapid processing capabilities of the GML, the system was able to operate without delay for the majority of the construction.

Given the support of the engineering and final lining team, and lots of teamwork, the project was able to begin to achieve the desired results within the second week of deployment. Figure 14 shows the desired spray result. In Figure 14, it can clearly be seen that there were no thin spots and the reduction of over sprayed sections was significant.

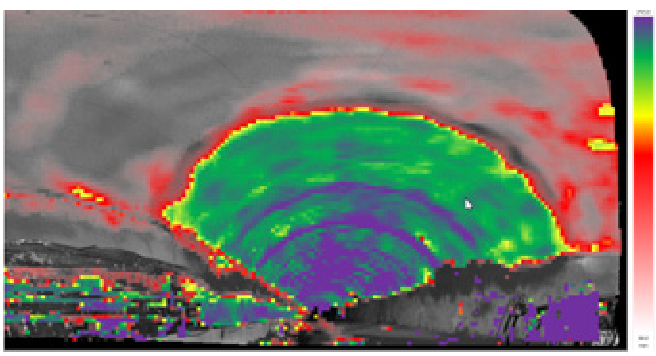

Fig. 14: GML guided spray with zero non-compliant thin spots

This was a considerable improvement on the project and the technology was introduced to cover more areas of final lining construction within the project. Inside the initial two months of deployment, the final lining teams were able to complete 2.6 miles (4.2km) of final lining construction without rework, significantly reducing the amount of shotcrete material used for the project.

Conclusion

The rapid progression of powerful embedded computing and LiDAR technology enables the development of near real-time in-situ scanning solutions. These advances allowed application of the new technology into SCL construction operations and enabled modifying current practices to achieve improved safety, quality and cost savings.

The rapid advancements in computing technology is certainly a key enabler, allowing technology designers to develop tools that could significantly evolve the mining and construction industry. However, the success of such technology relies heavily on the people operating in the industry. Our experience shows that the success of the case studies referenced in this paper, depended heavily on the engagement of the engineering and construction crews, especially the nozzlemen. One of the biggest challenges faced was the management of change in the construction processes. Effective communication and a collaborative approach, to reach a desired solution, was critical to the success of introducing the changes. Leveraging the experience of the foreman and nozzlemen also was a key element in the development of the technology and the construction process.

Finally, project management teams also play an important role in fostering the development of innovative technologies by adopting them at an early stage of a project. This is critical for any emerging technology to achieve the desired potential, and to incrementally change the current state of the art.

Acknowledgement

We would like to thank the excavation and final lining teams mentioned in this article, especially the nozzlemen and site engineers for their contribution to the technology. We would also like to thank the monitoring team from 21MT, led by Christian Reich, for their highly skilled operators that helped to train and integrate the GML technologies into the construction projects.

References

1. Chen, B.; Mares, D.; Carter, N.; Ayres, P.; Voysey, G., 2020, "Leveraging Super-Computing and High-Density Lidar Technologies for Real-Time Verification and Rectification of Tunnel Construction Against Design," *ITA–AITES* World Tunnel Congress AND *46th General Assembly.*

2. Bergmann, N. W., 2005, FPGA-Based reconfigurable system-on-chip. Very Large-Scale Integration System-on-Chip (VLSI-SoC2005), Perth, Australia, 17-19 October, 2005. Perth, Australia: International Federation of Information.

3. D. Lv, X. Ying, Y. Cui, J. Song, K. Qian and M. Li, "Research on the technology of LIDAR data processing," 2017 First International Conference on Electronics Instrumentation & Information Systems (EIIS), Harbin, 2017, pp. 1-5. doi: 10.1109/EIIS.2017.8298694.

4. Processing. Altameemi, A. A., & Bergmann, N. W. (2016). Enhancing FPGA softcore processors for digital signal processing applications. 2016 Sixth International Symposium on Embedded Computing and System Design (ISED), 294–298. https://doi.org/10.1109/ISED.2016.7977100

5. Zynq-mp-core-dual.png (800×900). (n.d.). Retrieved 18 September 2019, from https://www.xilinx.com/content/dam/xilinx/imgs/block-diagrams/zynq-mp-core-dual.png.

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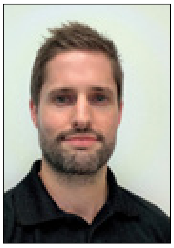

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