Robotic Shotcrete Applications for Mining and Tunneling

by Michael Rispin, Chris Gause, and Thomas Kurth

If a robotic applicator is mentioned in connection with mining or tunneling and shotcrete, what is meant is an apparatus used to hold and control a spraying nozzle.

Why should this be necessary when a man can do the same work?

Tunneling and mining development are intrinsically hazardous forms of construction. When shotcrete is used as initial temporary support after blasting, using a mechanical arm to extend into an unsupported area is a great enhancement to personnel safety.

A spraying manipulator is a hydromechanical, remote-controlled spraying unit for mechanizing and automating the application of shotcrete. It is suitable for use anywhere substantial quantities of wet- or dry-mix shotcrete will be applied, and it offers significant advantages in construction applications when manpower is exposed to potentially unstable, unsupported ground, rebound, or dust. Mounted on various kinds of carrier vehicles and able to achieve a reach of up to 47 ft (14.5 m), a robotic applicator saves the time and cost of erecting scaffolding where, due to the very size of the working area, it would otherwise be needed.

As this article will show, there are many combinations and permutations of configurations of robotic shotcrete applicators in use today in mining and tunneling.

A History of Robotic Applicators

Thirty years ago, the first shotcrete manipulators really were just nozzle holders. Over the next 20 years, numerous variations appeared in all parts of the world based upon cranes, drill jumbos, and lifts with a device enabling the nozzle to be attached. These assemblies were not designed for quick and nimble nozzle and arm movements, so efficient placing of quality shotcrete with a smooth finish on difficult substrate was extremely difficult, if not impossible.

Specialized shotcrete spraying manipulators began to appear in the early 1980s, by which time sprayed concrete had become an acceptable form of construction (if only by the dry-mix method). The most suitable of these dedicated units had features that are still standard today: spraying heads with universal movements, eight fields of motion, and the "parallel-lance" with great extension possibilities. These arms were generally mounted onto existing carrier vehicles—trucks and excavators were favorites. Features such as automation of movements of lance and nozzle holders were integrated into remote controls to help the nozzleman produce a better spraying pattern.

By the mid 1990s, with the proliferation of large-scale wet-mix spraying, the spraying manipulator had firmly established itself as a piece of equipment to be found on almost all large construction projects where shotcrete was used as a temporary or permanent support. But the demands made upon the manipulators had changed: the bar had been raised!

A mechanical device to hold a nozzle was no longer enough. New standards and economic constraints demanded more speed and efficiency in placement. To save time and money, this meant a manipulator had to be able to hold and control a nozzle and hose with diameters of up to 3 in. (75 mm) to enable the full capacity of the shotcrete pump to be used. This required robustness and operational dexterity to allow large amounts of shotcrete to be placed quickly and accurately, typically impossible with a converted placing boom. Remote controls were also developed, from hydraulic levers to electric operation with cables, and later radio remote control became a standard option.

This period in time also saw the development of the autonomous shotcrete spraymobile. These vehicles were trimmed from top to bottom with all the equipment necessary and with one aim in mind: quality shotcrete. Manipulators became very diverse and specialized as construction was customized to be exactly suited to application conditions, be it for large civil projects, tight mining tunnels, shafts, or even integrated into a tunnel boring machine (TBM).

Today, there's a demand for more quality and accountability in the results and the application process on site, hence even more automation is required. There is only one way these attributes can be assimilated into a robotic shotcrete applicator—through the use of computer technology.

By 2000 the first computer-controlled robots had appeared. Able to be programmed to spray an area automatically and keep records of the work, this advance opened up vast new possibilities in improving tunneling and mining safety, economy, and efficiency. Computer control eliminated the need for a nozzleman to work continuously close to the danger area. The required finished surface accuracy increased as the machine, coupled with the computer through laser measuring technology, worked much more precisely than a human. The fatigue and skill factor variables were removed from the equation.

Automation holds great advantages. In deep mines, for example, long traveling times and short shifts can be replaced with full employment of resources by a nozzleman who sits safely on the surface controlling processes through his man-machine-interface (MMI). Simpler units can be equipped with teach-in features that repeat various patterns. Work in hostile environments, such as a uranium mine, can now be tackled with much less risk.

The future will belong to these types of robotic shotcrete applicators, but there will also be place for the dedicated standard hydromechanical manipulator.

Robotic Spraying versus Hand Spraying

The benefits of mechanized shotcrete application can be evaluated by three categories:

1. Increased production;
2. Higher quality shotcrete in-place; and
3. Improved worker safety.

Increased Production

A multitude of reasons exist that allow increased production with the use of a shotcrete robot, most of which are due to the elimination of the human fatigue factor.

The predominant reasons are as follows:

- Increased concrete hose diameter. Some spraymobiles are equipped with 4 in. (102 mm) hoses. Hand nozzling will typically use a 2 in. (51 mm) hose diameter. The weight of shotcrete in the 4 in. (102 mm) line is equal to 12.3 lb/ft (18.3 kg/m). When you multiply this by 3 to 6 ft (1 to 2 m) of hose length often being supported by the nozzleman, combined with the compressed air supply, any person would quickly become exhausted.
- Fatigue also carries over to pumping rates or pump output. As the shotcrete output is increased, the nozzleman must also resist the increase in line surge that comes from temporary interruption of pumping while the swing tube changes cylinders and begins the next stroke. The nozzleman in a sense must act as shock absorber. In addition to pump surges, the compressed air 177 to 247 ft^3/min (5 to 7 m^3/min) for hand spraying, whereas robotic spraying involves 353 to 494 ft^3/min (10 to 14 m^3/min) with 7 bar pressure delivered to the nozzle body also applies a backward pressure that must be compensated for by the nozzleman. This additional fatigue factor is of course eliminated with mechanized spraying equipment.
- With the human fatigue factor eliminated, shotcrete volumes can increase dramatically. Hand nozzling volumes can range from 9 to 12 yd^3/hr (7 to 9 m^3/hr), while mechanized spraying can easily reach volumes of 26 yd^3/hr (20m^3/hr). This is particularly beneficial in larger diameter tunnels, stations, galleries, or when shotcreting for the final lining is being utilized.

Higher Quality Shotcrete In-Place

There are combinations of capabilities with mechanized spraying that allow shotcrete to be placed with improved in-place properties. Some of these are:

- Dedicated maximum air volume for optimum compaction;
- Lance mounting is automatically held parallel to the axis of the tunnel; and
- New robotic manipulating capabilities also allow for automated nozzle adjustments to be made to maintain proper standoff distance as well as nozzle angle to the substrate.

Improved Worker Safety

The contributions to a safer working environment via robotic spraying are clear. With use of a remote control, crews are able to remain in supported areas while letting the reach of the spraymobile apply shotcrete in the newly excavated areas. In areas that require a combination of rock bolts and shotcrete, the bolting crews can take advantage of working in a supported environment where an initial layer of shotcrete has been sprayed for temporary support.

State-of-the-Art Robotic Applicators

In producing top quality shotcrete, the best manipulator is still only one component of a system. The complete system is necessary if the manipulator is to be used to its full potential.

On large construction sites such as tunnels, it is imperative that the spraying set-up be installed and ready to start performing within minutes of the heading being ready for it. As soon as the spraying operation is finished, the equipment has to be removed so that the next work-cycle can begin. Furthermore, it is a common trend to execute different jobs simultaneously, which demands complete, self-contained equipment. For example, because a central air supply is seldom large enough to supply all site demands, the complete mobile therefore carries its own compressor.

Meyco Potenza

The Potenza is one of the better examples of a complete mobile unit for the spraying of shotcrete. This type of spraymobile has been setting the standard for shotcrete in tunnels and other areas of application using the wet-mix shotcrete method. They have become commonplace on many of the world's most important sites where sprayed shotcrete must be applied in large quantities without compromising quality.

The standard components of the complete mobile unit are:

- Robojet spraying manipulator
- Potenza shotcrete pump for the wet-mix process
- Integrated Dosa TDC accelerator dosing unit
- MEYCO Data for compiling operating and performance information
- Central power unit
- Chassis, four-wheel drive and steer, with stabilizers
- Cable reel
- Air compressor
- Nozzle system
- Liquid accelerator tank
- Water storage tank
- Working lights
- Water pump
- High pressure water cleaner
- Release oil pump

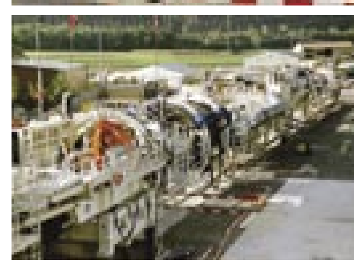
MBS-02E

The MBS-02E features most of the shotcreting capabilities outlined for the Potenza but is built as a smaller and more robust package designed for the smaller mining headings and the rigors of the North American underground mining environment. Most importantly, while its primary purpose is to spray shotcrete, it is also capable of quickly and efficiently traveling the underground tunnels and ramps in a typical mine in order to be efficient in its use in multiple headings.

The spraying manipulator, designated Meyco Minima, boasts a folding boom that retracts for tramming, yet is unfoldable in a 10 x 10 ft (3 x 3 m) heading, and offers a maximum spraying range of 29.5 ft (9 m) in height, 23 ft (7 m) lateral, and 26.2 ft (8 m) forward.

Due to frequently encountered, unexpected conditions in a mine, the spraymobile is also equipped with a shotcrete pump and hopper assembly that can be hydraulically positioned at various heights to adjust to any type of feed, typically from a transmixer, even when parked on uneven surfaces.

TBM Ring Construction Sprayer



A TBM can also be viewed as a carrier vehicle. Manipulators on TBMs should be, of course, part of an integrated system designed with the quality of the end product, that is, shotcrete, in mind. TBMs vary greatly in their individual construction, dictated by the geological environment where they are employed. This in turn influences the design of the manipulator. Space is at a premium and the logistics are difficult, so a manipulator must have the greatest possible movement but not clutter up the already crowded back-up rig. MEYCO has manufactured both ring construction type manipulators and centrally placed lance units according to local requirements. These units are always tailor made but should contain all the basic principles and components to enable movement, dexterity, and ease of handling for the nozzleman. A large ring, as shown previously, would be similar to equipment used in the Lötschberg Transalpino Project.

Shaft Robo

Shaft manipulators actually have a lot in common with ring constructions made for TBMs. The big difference is obviously the angle and direction in which the carrier vehicle, in this case a Galloway

stage, is either lowered or raised within a vertical excavation. Again, the manipulator must be an integral part of a coordinated shotcrete system. Depending on the diameter of the shaft, a centrally-mounted lance or a ring running around the stage would be used.

Meyco Oruga

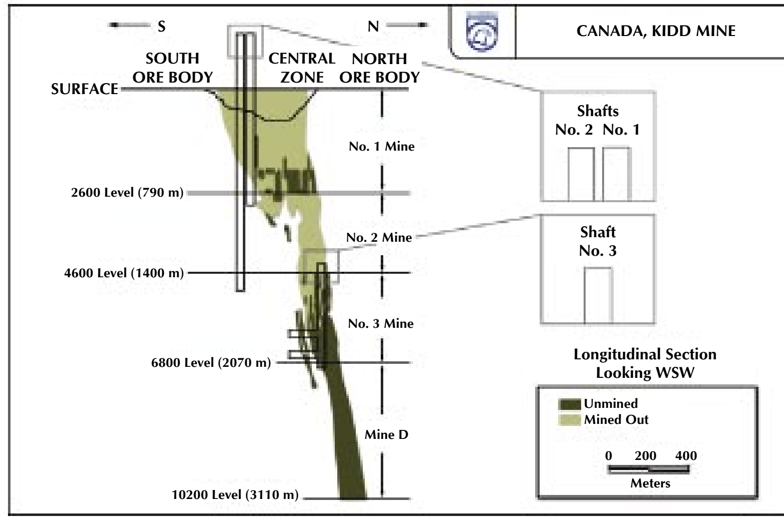
The Oruga is small and compact when driving around on its tracked carrier. It also has a reach of up to 7 yd (8 m) and reliable stability when spraying. The Oruga manipulator is operated through electric remote control. It is ideal for slope protection and compact enough to work within a TBM back-up rig.

Meyco Rama

The Rama is a range of manipulators manufactured by MEYCO. Their common features are that they can be mounted on almost any type of carrier vehicle or mounting stage. They are all of robust and simple construction and they vary in that each model has a different maximum spraying range, derived from their physical dimensions. They all have a spraying head with two hydraulic oscillating motors with nutation device transmitting the required wobble movement to the shotcrete spraying nozzle; adjustable speeds allowing optimum nozzle positioning.

Case Study: Mining—Kidd Creek

The Kidd Creek Mine is located in Timmins, ON, Canada, where copper-zinc-silver deposits were discovered in 1963. Owned by Falconbridge Limited, it was put into production in 1965 with an open pit mine, which was excavated from 1965 to 1977. Subsequently, the ore body has been mined through three separate shafts known as the No. 1, No. 2, and No. 3 mines.



For years, Kidd Creek used bolt and screen construction for primary ground support. Dry-mix shotcrete was used as secondary reinforcement and for repair where needed. At the end of the 1990s the company began searching for a better, faster, safer ground support method.

In approaching the search for a new ground support protocol, the challenge was to develop a system that would be safe and economically feasible to apply in a complex and deep mining environment and would be accepted by the mine workers. They needed a viable new ground support method that would reduce exposure to unsafe working conditions and meet stringent government and company regulations.

Early in the process, the workers were focused simply on finding a better, faster way of applying dry-mix shotcrete—they were not considering wet-mix shotcrete. The mine had tried wet-mix shotcrete in the early 1980s and it was not a success, so they were reluctant to explore that alternative. In 1999 the mine explored new technologies to help meet its goals. The workers recommended an innovative steel fiber-reinforced wet-mix shotcrete system (SFRWS) using the latest automatic delivery and spray equipment as a solution that would meet all of the Kidd Creek goals—increased productivity, enhanced safety, and improved structural performance.

In July of 2000 the Falconbridge Board of Directors approved the development of a new mine on the Kidd Creek site. Known as Mine D (Deep), it will extend the mine from a depth of 6800 ft (2070 m) to 10,000 ft (3050 m). When completed, it will be the deepest base metal mine in the world, and it will require a significant infrastructure, including a new internal underground shaft, hoisting facilities, and approximately 9 mi (15 km) of development. Started in 2001, the project is estimated to take 4 years to complete and approximately 130,000 yd^3 (100,000 m^3) of construction concrete and 78,000 yd^3 (60,000 m^3) of shotcrete will be used.

As a result of the success of the SFRWS in field trials and subsequent use, Kidd Creek Mine management decided to use the system in the construction of Mine D. The mine commissioned a state-of-the-art on-site batch plant with capacity to feed two 8 in. (200 mm) diameter cased boreholes to depths of 4600 ft (1400 m) and 4800 ft (1460 m), respectively. Five wet-mix shotcrete spray mobiles and seven transmixers were acquired to meet the needs of the mine.

Tenders were let and the mine chose the MSV shotcrete sprayer as supplied from MBT's Allentown Equipment manufacturer. The MSV was designed especially to handle the underground environment. It features a robust carrier and uses some of the most effective and efficient drive components on the market. It has an overall tramming length of only 24 ft (7.3 m) and a height of 90 in. (2.28 m). The sprayer was not only capable of higher and safer tramming speeds; it was also able to cover numerous headings in one shift.

As of late summer 2003, the Mine D project had reached a level of 8000 ft (2438 m), with more than 18,200 yd^3 (14,000 m^3) of shotcrete applied using the MBT MSV spraying units. An indicator of the improved safety is the fact that since fully implementing SFRWS as primary ground support in early 2002, there has not been one loose related injury.

Case Study: Civil—Bergen Tunnel

Economics based upon productivity vary based upon the tunnel size, mining cycle, and purpose of shotcrete application. A comparison between productivity of mechanized spraying versus hand spraying can be extracted from the Bergen Tunnel Rehabilitation Project, North Bergen, NJ, and the Cameron Run Tunnel Rehabilitation Project, Alexandria, VA.

During rehabilitation of the Cameron Run Tunnel, the contractor, Merco, Inc., hand sprayed wet-mix shotcrete using a Reed B30 concrete pump. The Reed B30 has a theoretical output of 30 yd^3/hr (22.8 m^3/hr). Typical actual volumes applied were 6 yd^3/hr (3.6 m^3 /hr) or 40 yd^3/shift (30.4 m^3/shift).

On the Bergen Tunnel Rehabilitation Project, Merco/Obayashi, JV used a self-contained robotic shotcreting machine known as the Meyco Potenza (described above). The Potenza is equipped with a Suprema shotcrete pump with a theoretical output of 26 yd^3/hr (20 m^3/hr). With the use of the Potenza shotcrete robot, the shotcrete volumes on the Bergen Tunnel project reached an hourly average of 18.2 yd^3/hr (14 m^3), with the best day (two shifts) being 218.4 yd^3 (168 m^3). In addition to the increased output, the shotcrete crew size for robotic spraying was reduced to 3 men versus 5 men for hand spraying. Although specific dollar values were not applied to the cost reduction in comparison, the increased output and shotcrete manpower reduction made some obvious contributions to an in-place cost savings.

The Future

Meyco Logica is a relatively new machine, based on the well known kinematic principles of the Robojet, and has been developed in cooperation with industry and academia. This manipulator with 8 degrees of freedom has a new automatic and human-oriented control system. The new tool enables an operator to manipulate the shotcrete spraying jet in various modes, from purely manual to semi-automatic and fully automatic, within selected underground areas. It is also able to measure the tunnel profile with a laser scanner.

In one of the modes, the operator uses a six directional joystick (Space Joystick). The calculation of the kinematics is done by the control system. A laser scanner sensor measures heading geometry and this information is used to control automatically the standoff distance and the angle of the spraying jet. The aim of this control is not to automate the whole job of spraying but to simplify the task and enable the operator to use the robot as an intelligent tool, and to work in an efficient way with a high level of quality.

With a correct angle of application and constant spraying standoff distance, a remarkable reduction in rebound, and therefore savings in cost, is achieved. Further, if the heading profile is measured after spraying as well, the system will relay information on the thickness of the applied shotcrete layer, which up to today was only possible with core drilling and measurement. If an exact final shape of the heading profile is required, the control system is being developed currently to manage the robot to spray to these defined limits automatically.

The system shows that increased productivity in shotcrete application is doubtlessly possible without increasing danger to personnel or without huge increases in cost.

The Westerschelde Project was an example of a successful project using 2 Logicas to spray a 2 in. (50 mm) lining of passive fire protection mortar with tolerance ±0.16 in. (4 mm). The total tunnel length was 1 x 4 mi (2 x 6 km).

In the Netherlands, Meyco supplied equipment used for the application of fire protection mortar to the Groene Hart tunnel project. To fulfill the standards to spray apply a defined, constant, and homogenous layer of a passive fire protection mortar, preference was given to a job site-tailored solution. All spraying equipment was placed on gantries allowing trucks supplying the TBM to pass underneath. Mechanical engineers designed and built a spraying nozzle mounted on a wagon traveling on a guide rail along the tunnel. The whole construction moves on a ring beam along the tunnel wall. All these movements can be conducted with "teach-in" functions to allow automatic spraying within a defined area. After a 13 ft (4 m) longitudinal length is sprayed, the gantry will be moved and the next spraying phase can be repeated. By the time the whole set-up was commissioned a thickness of 1.4 in. (35 mm) with spraying accuracy of ±0.08 x 1.4 in. (2 x 35 mm) thickness was being achieved!

Conclusion

Sprayed concrete is an economic, efficient, and versatile means of ground support for modern mining and tunneling operations. As we learn more about the benefits that shotcrete technology can bring to our underground industries, its use will proliferate.

Robotic applicators have already proven to be a useful and sometimes indispensable tool in the application of shotcrete. The advances chronicled above have been built on systematically-developed experience, and as each case study is completed and analyzed, further developments and efficiencies will ensue.

The new frontier is automated shotcrete application, with a very high degree of applied thickness control. While the technology is here today, it needs to be employed on a larger scale where its benefits will be brought to bear for tunnel owners and contractors and mine operators across the globe.

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