3D Positioning Systems for Underground Construction Robots

Steven Garlinge
Geodata KODA Australia Pty Ltd
steven.garlinge@geodatakoda.com

David Mares
Lend Lease Bouygues Joint Venture
d.mares@bouygues-construction.com

Daniel O'Shaughnessy
Geodata KODA Australia Pty Ltd
daniel.oshaughnessy@geodatakoda.com

ABSTRACT

As Global Navigation Satellite System (GNSS) technology does not work underground, total stations reign as the 3D positioning system of choice in tunnel environments. It follows that there has been limited development of extra-dimension solutions to automation-of-construction tasks. The current trend of mega-projects, and multiple mega-projects running concurrently, has seen the industry reconsider this issue. NorthConnex comprises of approximately 20 km of road tunnels (therefore, 40 km of walls) in which specialist drilling and fixing machines are employed to install permanent fixtures into the excavated and lined tunnels. The use of automated systems for roadheader and bolter positioning during the excavation phase is relatively mature, however the extension of these systems into the tunnel fitout processes is traditionally limited. This paper outlines how Geodata KODA Australia, in partnership with the NorthConnex project, has found opportunities to apply its software and systems to provide significant enhancement to multiple workflows where large, specialist machinery performs drilling and installation work over a huge scale to high accuracy requirements. Two machine types were targeted by the team. The first, ROBY, is a drilling and anchoring system with application to installing anchors into the roof of the tunnel for lighting, cable tray and fire safety systems. ROBY is required to contribute to drilling over 100,000 anchors with a high degree of accuracy. The second, Paneller, is a multi-bit drilling system which is designed with the specialist task of drilling for architectural wall panels. At peak, two paneller machines work towards the drilling of over 40 km of wall panels in NorthConnex. Such paneller machines were used as early as 1999, but only now have automated positioning systems been implemented. Other systems capitalise upon further extension to these techniques by implementing a single-prism positioning system in which certain assumptions and techniques ensure that a fast and accurate machine positioning solution is available to wall-trimming machines.

KEYWORDS: *Tunnelling, robots, automation, navigation, NorthConnex.*

1 INTRODUCTION

NorthConnex comprises of approximately 20 km of road tunnels (therefore, 40 km of walls) in which specialist drilling and fixing machines are employed to install permanent fixtures into the excavated and lined tunnels. The use of automated systems for roadheader and bolter positioning during the excavation phase is relative mature, however the extension of these systems into the tunnel fitout processes is traditionally limited.

Worldwide, the average big construction project takes 20% longer to complete than planned and runs a staggering 80% over budget (Garcia de Soto, 2019). This sobering thought saw the NorthConnex project partner with Geodata KODA Australia to find opportunities to apply software and systems to provide significant enhancement to multiple workflows where large, specialist machinery performs drilling and installation work over a huge scale to high accuracy requirements.

2 GETTING STARTED

It is worth noting that many other underground positioning systems exist, but they are limited by their inability to provide an accurate position that is suitable for placing mounting anchors to survey tolerance. As such, total stations reign as the 3D positioning system of choice.

Historically, there is limited development of extra-dimension solutions to automation of construction tasks. There are many reasons for this, but mainly, it seems to boil down to project-by-project thinking, which limits investment in ideas or initiatives that will take more than one project to be fully realised, and may provide, at best, neutral commercial benefit to the initial project sponsor. The current trend of mega-projects, and multiple mega-projects running concurrently, has seen the industry reconsider this trend.

2.1 Robotics

In 2014, KODA Engineering started integrating a modern robotics modelling concept (Denavit-Hartenberg, see Spong et al., 2004) into its software systems. Initially it was developed for multi-limb roadheader and bolter navigation, but it soon became apparent how useful the system was to be for niche positioning and automation products. Geodata KODA have successfully adopted this platform to several applications throughout 2018-2020.

Worth emphasising is the power of this robotics system overall. The key benefit is that any robotic limb, or machine, or combination of limbs, can be modelled by this system and represented via a simple configuration file. Previously (and currently by many others), machine dynamics parameters are hard-coded or limited to those that were thought of at the time of development. The configuration-based definition of machines makes this a thing of the past.

A good example of the power of the robotics modelling system is from earlier in the NorthConnex project, where bolters were fitted with full navigation systems. During calibration, a residual error was observed between calibrated and calculated models. Soon it was apparent that due to wear and tear and manufacturing tolerances, a degree of ‘slack’ existed in a particular movement joint. The solution to this was to create an additional joint to represent the defect. This required re-mapping sensor values from an existing extension sensor to the unplanned joint movement and then updating the configuration. The residuals from the calibration were immediately reduced from 100 mm to better that 20 mm – more than good enough for drilling for rockbolts – with no coding, no mechanical work and no electrical work.

2.2 Commercial Approach

From an economic perspective, the NorthConnex project was able to realise significant additional value from its fleet of total stations as purchased for the excavation phase. Approximately 13 units of the Leica TS16 1" instrument remain after the excavation process. ROBY and Paneller are finding a new life for at least 6 of these units directly.

Worth noting are the commercial aspects of the engagement of Geodata KODA to the NorthConnex project. A collaborative approach was adopted to great success. Such an approach served to de-risk each organisation in ways that a traditional contractual appointment would not be easily able to. Both companies were able to share purchasing and associated cash-flow challenges. Also, in many cases, Geodata KODA faced challenges caused by interfaces with other parties involved with the solution. By close integration with the principal contractor, all invested parties were rarely confused as to what their objective was: "create success for NorthConnex".

3 THE ROBOTS

3.1 ROBY

3.1.1 General

For NorthConnex, two machine types were enhanced by the team. The first, ROBY, is a drilling and anchoring system with application to installing anchors into the roof of the tunnel for lighting, cable tray and fire safety systems (Figure 1). ROBY is required to contribute to drilling over 100,000 anchors with a high degree of relative and absolute accuracy.

Figure 1: ROBY in use.

In terms of the automatic drilling platform, ROBY itself is a mature product, having been developed in Europe and used before on another tunnelling project in Hong Kong. However, the system was only able to be viable on NorthConnex if a significant improvement to the machine positioning system was realised.

To guarantee such an improvement, two total stations were used to provide real-time positioning for the machines. Two prisms (front and rear of the machine) were each tracked by a single total station each. The two-point, continuous positioning from the total stations is combined with dual-axis level sensors on the machine to provide a solution for all six transformation parameters (scale not necessary) from the ‘machine coordinate system’ to the ‘project coordinate system’.

3.1.2 Performance

In previous implementations, ROBY showed positioning times of several minutes. Now, from a cold start (very few times per day, ideally one), the system has a solution within 21 seconds, and when running, is supplied a position multiple times per second.

The speed and accuracy of the positioning system led to the (unplanned) development of a system to show the real-time position of the machine against all planned and previously drilled anchors while it was being advanced to the next drilling location. In this way, the machine was not moved too far, and anchors missed, nor was it moved too little, and the power of the system was left unrealised.

3.2 Paneller

3.2.1 General

The second, Paneller, is a multi-bit drilling system which is designed with the specialist task of drilling for architectural wall panels in the tunnel environment (Figure 2). During 2019, two paneller machines worked towards the drilling of over 40 km of wall panels in NorthConnex. Such paneller machines were used as early as 1999, but only now have automated positioning systems been implemented.

Figure 2: Paneller in use (NorthConnex tunnels).

Paneller uses the same dual-instrument, tracking-based positioning method as ROBY, but the software is also required to perform full 3D calculations of the position of the drilling machine relative to tunnel stringlines, then provide automation outputs to the machine hydraulics to guide the machine into place.

3.2.2 Performance

Manual positioning of Paneller takes a skilful operator and surveyor over 60 seconds to perform, with many interactions between them. Sometimes it is worse, and rarely better. With the combination of a real-time positioning system, and automation outputs, the machine is positioned in less than 15 seconds with involvement of the machine operator only. Anecdotal evidence also suggests that the positioning result with the automated system is more consistent and accurate overall.

3.3 Tunnel Trimer

3.3.1 General

A third system, Tunnel Trimmer (not used on NorthConnex), showcases an interesting extension to these techniques by implementing a single prism positioning system, in which certain assumptions and techniques are used to ensure that a fast and accurate machine positioning solution is viable in a restricted and fast-moving construction environment (Figure 3).

Figure 3: Tunnel Trimmer in use.

A dual-axis level sensor and single prism are measured continuously. Then, based on the known constraints of the solution (the machine is mounted on rail, tunnel geometry is correlated strongly to the position of the rail, the tool can only cut to the left of the machine, the prism is on the front of the machine, the total station is always in front of the machine, and the tool is held perpendicular to the reference surface (in plan only)), it is possible to generate a second, virtual, prism to supply a two-prism solution for the system to position the milling head in 3D.

This solution requires certain ‘administrative’ controls to work well, i.e. operator training and compliance to those constraints. To date, this has not proved to be an issue based on having motivated and interested operators, custom build hardware and a unique environment in which the reference surface is very well defined.

3.3.2 Performance

The Shaver project has shown that the traditional notions of (1) setout, (2) perform work and (3) check work can be shattered by intelligent automation systems. This familiar cycle features delays on the critical path, but also lagging information, which would be better suited to being displayed in real-time while the construction task is being undertaken.

Particularly demanding construction tolerances needed to be observed: (1) there could be no 'tights' and (2) over-excavation was limited to 20 mm. If over-excavation was observed, then the expensive and time-consuming repairs were penalty enough in themselves.

While this is not a novel concept (as many real-time automation solutions for construction machines exist), an ability to quickly, confidently and economically apply these systems to unique and novel machines is.

4 TECH TALK

4.1 Instruments

Leica TS16 total stations, with specialist software and hardware, and external command interfaces, provide an excellent platform for innovation and optimisation.

4.2 Data Types

Tunnel stringlines are commonplace, but extra value has been extracted from them in the execution of these projects. In simple cases, the tunnel profile in area and known height of the machine give a specific area for the machine to search.

In the case of Paneller, stringline definitions were enhanced to include 'null' elements as there were some areas where a valid wall panel solution was not provided by the design, or not needed. By incorporating null elements, it was possible to keep the wall strings for the entire length of the project as contiguous and well-integrated, without having to resort to multiple string definitions or shortcut fixes. When in the hands of surveyors, complex data types or design interpretation is easily handled, but that is not the audience of ROBY or Paneller. One must think how to simplify and make the available data more robust so that it is valuable to the end user.

Full 3D tunnel Triangulated Irregular Network (TIN) models were developed for the tunnels at NorthConnex. For ROBY, bolt patterns are draped to a final survey model, and then an approximate location for each pin can be determined. By doing this, the project can provide a safe, but accurate position for ROBY's drilling tool to seek before performing fine positioning to find the actual surface of the shotcrete. By providing an accurate and confident model of the actual tunnel rather than the design tunnel, many seconds of slow movement were eliminated per anchor.

4.3 Communications

In the case of ROBY, a two-way User Datagram Protocol (UDP) based JavaScript Object Notation (JSON) data protocol was developed between the positioning system and the robotic drilling platform. The main benefit of this approach was that the protocol could be expanded and enhanced as new ideas or requirements emerged. The main purpose was for exchange of real-time spatial information between the systems. The coordinates of the prisms, stations, time of measurement and estimated precision are transferred continuously to ROBY for it to use.

4.4 Automation Challenges

In the case of Paneller, the underlying positioning system remains very similar to that of ROBY, except that the information is transmitted internally in the software rather than via UDP. Paneller’s special task required the software to provide automation outputs to the hydraulics of the machine based on the observed spatial information.

Again, the importance of communicating the accuracy and currency of the spatial information was critical. Indeed, there were some emergent challenges faced with certain combinations of lights and signals potentially having detrimental effects on the system if wires were broken or bulbs were blown. Some careful time spent risk assessing this saw some significant re-working of the initial solution to the robust solution that was deployed.

5 PERFORMANCE GAINS

The construction industry continues to see an increasing tendency for surveyors to be ‘held captive’ by construction activities, which demand near constant positioning support. This is a symptom of (a) more complicated designs, (b) attitudes of risk minimisation (both to project, and self) and (c) less skilled or spatially aware tradespeople. In the applications presented here there was incredible benefit in moving the surveying task away from the critical path. Specifically, the system runs itself without any need from operators or trades to interact with surveyors on a minute-to-minute basis.

Immediate, direct performance improvements were noted for all machines. As discussed above, the economic benefit of eliminating or minimising the need for spatial positioning to be performed on the critical path cannot be understated. All professions must contribute to the minimising of critical path activities, ensuring that those that do remain are adding essential value that is aligned with schedules and budgets.

It should be noted that such approaches do not necessarily reduce the amount of surveying work required, but reconfigure when, and under what conditions, the work is performed. Support of these systems requires (1) total stations and radios to be moved, configured and prepared, (2) batteries to be changed, (3) data to be configured and (4) control to be extended. The ability to plan and predict work is increased.

6 CONCLUDING REMARKS

By implementing and engaging in innovation today, we are creating a basis for the new ideas of the future. A particularly rewarding trend has been witnessed during this work. In all cases the current (or planned next-generation systems) include emergent ideas, which were not anticipated or conceived during initial scoping. Only during the early days of deployment did the actual power of the solution present itself, and some new ideas emerged. We hope that the recent work in this area provides further inspiration to our clients and the broader industry, and that successful projects like this become more commonplace.

It is worth reinforcing that these robotic and automation techniques are not designed to take away jobs from surveyors, but instead we hope (1) to continue meeting the demand for spatial positioning in the mega-project construction environment, often running 24 hours a day, 7 days a week, and (2) to continue providing positioning solutions in an industry environment where the supply of qualified, or suitably skilled, individuals is at a point of exhaustion. Solutions like these contribute to ensuring that the idea of a surveyor is maintained at high professional standard and not viewed as a para-professional, blue-collar worker, carrying around some expensive equipment.

REFERENCES

Garcia de Soto B. (2019) The construction industry needs a robot revolution, https://www.wired.com/story/the-construction-industry-needs-a-robot-revolution/ (accessed May 2020).

Spong M.W., Hutchinson S. and Vidyasagar M. (2004) *Robot dynamics and control* (2nd edition), Wiley, New Jersey, 303pp.