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Automated ground support deformation monitoring: a novel method with new opportunities for geotechnical engineers

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Abstract

One of the regular tasks of geotechnical and mining engineers is the measurement and management of ground deformation in underground excavations. Although other methods have historically been used to do so, light detection and ranging (LiDAR) has emerged as the most suitable technology for this application because it caters for quantitative and omission-free rather than merely qualitative tracking. Regular scanning has shown it to be highly advantageous for mines with swelling or squeezing ground, and those with rapid deformation.

Despite the LiDAR potential for tracking underground mining voids, its adoption has been slow because associated conventional data processing is time consuming and requires training, upskilling, and devotion by geotechnical engineers. This often becomes a bottleneck to bringing this method into use.

Our paper introduces a new solution of fully automated LiDAR point cloud data processing dedicated to void deformation tracking that not only enables geotechnical engineers to avoid having to learn unrelated skills, but also provides immediate output of sophisticated reporting deliverables. This opens up the opportunity to monitor many more excavations at a higher frequency and gain much better insights than is possible with conventional manual processing tools and methodology.

Secondly, this paper presents how this new processing methodology utilises cloud-based data storage and processing infrastructure that allows onsite users to become independent of local IT constraints and to avoid otherwise applicable limitations in storage and viewing of what are very large files. Critically, automatically generated 3D files for localised deformation assessment, as well as automatically generated summary reports presenting key deformation tracking analysis outcomes to decision makers, facilitate the detection and understanding of:

- *In situ support system capacity and capacity degradation.*
- *Ground support behaviour for dynamic conditions and squeezing ground.*
- *Cost efficiency of ground support.*

Keywords: *LiDAR, automation, convergence monitoring, automated point cloud processing, instrumentation and monitoring*

1 Introduction

The introduction of light detection and ranging (LiDAR) technology allows a quantitative assessment across the entire rather than selective excavation volume and its rock surface by collecting a three-dimensional (3D) image of the entirety of an excavation such as an underground drive, decline, or a tunnel. Comparisons between epochs of complete 3D data coverage allows for change detection over time that doesn't feature otherwise typical omissions. The implementation of regular scanning has been shown to be highly advantageous for mines with swelling or squeezing ground, but also at mines with rapid deformation or seismic exposure.

Despite the LiDAR potential, its adoption has been slow. A key reason for that is that working with point clouds is tedious to most geotechnical engineers. Point clouds have long been the realm of surveyors, but to fully adopt their use in geomechanics requires upskilling, and allocated resources which could be already stretched, thus there are often insufficient resources to be applied to bringing the new technology into use.

Jones (2020) summarised that mobile LiDAR mapping techniques took a vast step forward during the 2010s, from research and development to consumer products. The promise of spatially mapping GPS-denied environments opened a world of possibilities. However, the workflow from data acquisition to final interpretation is not currently an automated algorithmic process. Rather, it currently requires a conceptual understanding of the hardware, and various data processing methods to arrive at implementable results. Its advantages include greater spatial coverage, detailed rock mass assessments, and safe access to previously inaccessible areas. The 2020s hold great promise for the technology.

We have further validated Jones' industry observations captured in the previous paragraph by directly querying over a dozen mine site users of this technology for underground geotechnical purposes through a comprehensive questionnaire. The responses overwhelmingly state that these sites have limited or avoided data capture due to lack of time, processing personnel, or processing skills. The time and effort and the expertise and specialist software it takes to process point cloud data into meaningful reports are prohibitive for typical geotechnical engineering teams. These and other findings were published by Franke & Gonzalez (2022) and led the authors to commit to the development of automated processing, analysis and reporting software that would address these shortcomings and therefore fully unlock the potential of using LiDAR for geotechnical tracking purposes.

An academic solution of automating geotechnical data processing was first implemented in a limited desktop functionality prototype by Singh (2022) as described in his PhD thesis completed at the University of New South Wales. We detail our own approach in the following section of this paper. It enables geotechnical engineers to avoid having to learn unrelated skills by allowing for deformation monitoring without associated training or expertise and provides instant reporting results, as well as a sophisticated database with features not available elsewhere. All data processing time and effort is completely replaced by an automated process which, at the same time, opens up the opportunity to monitor many more excavation volumes at a higher frequency than is possible with conventional tools and methodology.

The implementation of a fully automated, LiDAR-based, geotechnical tracking tool was completed by experienced software engineers and included both the development of cloud-based, back-end processing and a cloud-based, front-end reporting functionality. This required automated extraction – also called classification in image processing terms – of the following ground support features from 3D point clouds collected by LiDAR scanners:

- Heads of rockbolts installed in underground mining drives and tunnels protruding from the drive or tunnel wall.
- Overlapping steel mesh installed as a surface support, held together by rockbolts.
- Shotcrete surface support.

Rockbolts come in a variety of types, lengths, and importantly with plates of varying shapes and sizes, as per Figure 1. This is relevant to consider for effective and consistent automated extraction of their position from 3D point clouds. As for the bolts themselves, there is considerable variety, as shown in the size and shape of the plate, as well as the bolt head which is the visible portion in LiDAR scans and hence forms the basis for bolt detection. Note also that some bolts as the one shown in the centre (Figure 1) can have a portion of it – its tail – protrude through the plate, thereby exposing a section of the bolt itself.

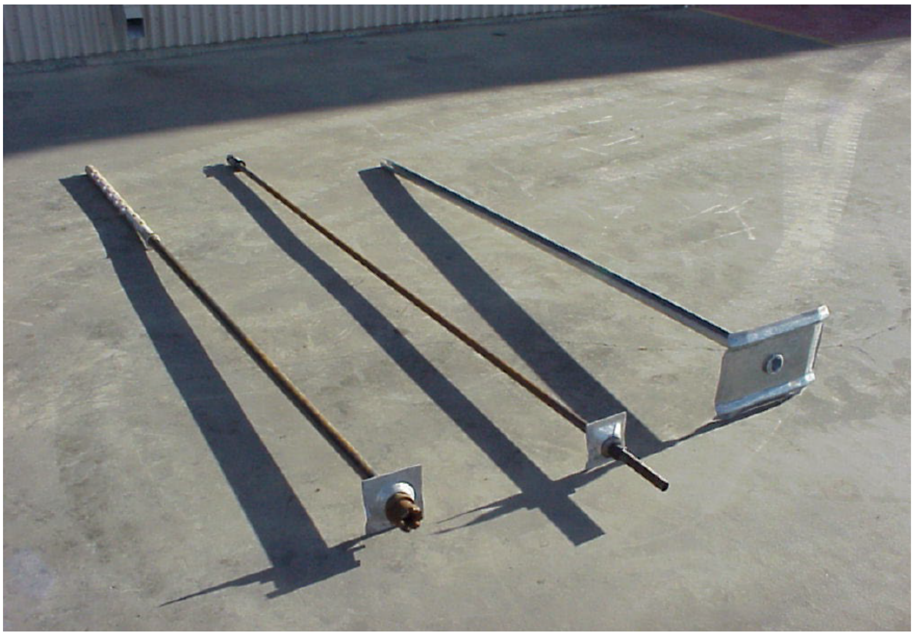


Figure 1 Three different rockbolt types illustrating the variety of anchoring methods within the rock which is invisible, and their heads and plates which are visible to LiDAR scans (Australian Centre for Geomechanics [ACG] 2022)

2 Deformation and ground support tracking methodology

Detecting rockbolts, their compliance to installation requirements, and any changes to their features over time that may compromise protective capabilities is the most important aspect of ground support tracking, because if rockbolts fail, then all surface support comprised of steel mesh and shotcrete will also fail.

There are multiple ways a rockbolt can fail which needs to be accounted for when trying to detect rockbolt failure in scan clouds, including being pulled or pushed out by squeezing ground with plates still attached, as is illustrated in Figure 2. A plate being forced off the bolt renders the bolt ineffective or failed and changes bolt appearance to only showing bolt ends with the plate itself missing, as also illustrated in Figure 2. If the bolt is still inserted in the wall but its plate is no longer in situ, then the bolt will likely not be detectable in a scan cloud because of its small size and inherent noise in scan data. Ideally, an automated rockbolt classification technique aiming to report on ground support health needs to account for these considerations so as to minimise under- or over-reporting of ground support deterioration.

Automatically classifying rockbolts from a 3D point cloud is achieved through cloud descriptors. A variety of cloud descriptors have been developed for different purposes, in particular for classifying natural or general mapping data collected with LiDAR scanners. A good overview of available cloud descriptors is provided by Han et al. (2018). All cloud descriptors suitable for identifying rockbolts at a useful success rate exploit the three-dimensional spatial characteristics of point cloud data to classify elements within it. Modern LiDAR scanners, including mobile LiDAR, used to collect point cloud data in underground mine drives can detect the intensity value recorded for each point, which represents the reflectivity of a particular object at the wavelength of the laser in use. Whilst on its own it is unsuitable to classify rockbolts at sufficient reliability, intensity values can be used to strengthen ground support classification success rates of 3D classifiers. Figure 3 shows an intensity value example for features visible in the raw scan cloud used for automated ground support tracking. The image illustrates what the software algorithm uses as a starting point to extract ground support features fully automatically.

Figure 2 Examples of failed rockbolts due to squeezing ground. Red circles indicate rockbolts that have been pulled out of the wall with their plates still attached but because of their detachment from the wall, they are no longer effective. Note how the plate orientation has been twisted from the original position flush to the wall. The white circle shows a plate that has been detached and has fallen to the ground (ACG 2022)

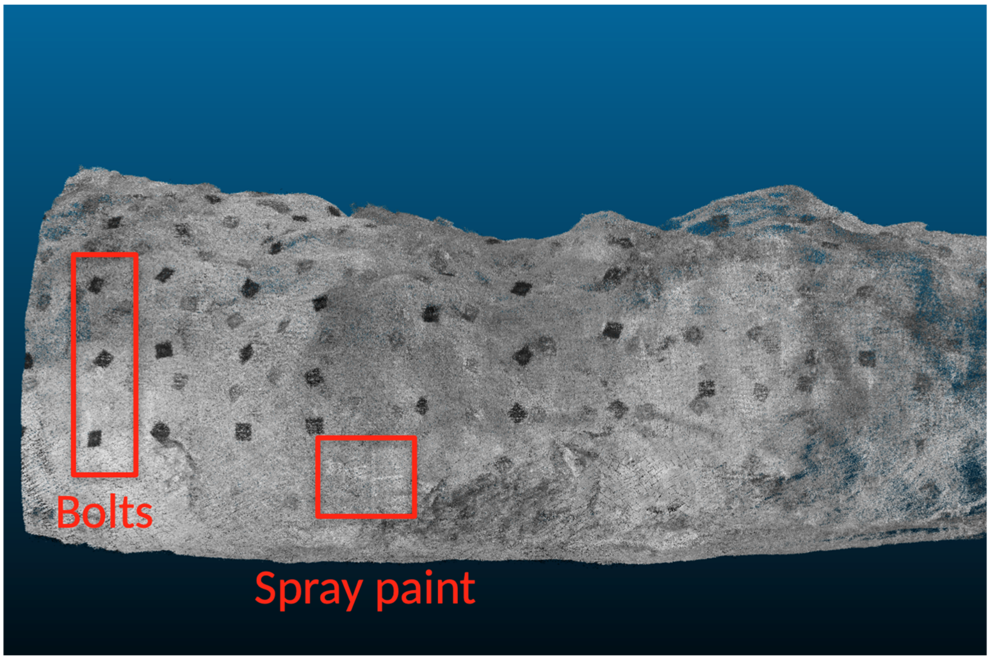


Figure 3 Example of a LiDAR point cloud displayed using its reflective index commonly called intensity values produced by a standard mobile LiDAR scanner

2.1 Drive/void sectioning

Mobile LiDAR is the most suitable type of LiDAR for tracking elongated geographic features, such as underground drives or tunnels, because it produces regular point density and resolution all along the feature, yields sufficient accuracy for the purpose, is faster, and minimises operator exposure. Data collection requires the selection of a spatial area that can be covered within a reasonable amount of time and that stays within the drift precision requirements of simultaneous localisation and mapping specifications in use for mobile LiDAR. Whilst drift precision specifications vary for different equipment and vendors, this generally means that fit-for-purpose point clouds covering up to several hundreds of metres of voids can be collected at any given time. It would not only be non-compliant but also simply impractical to collect LiDAR data for an entire mine site in one go, not least because access restrictions to underground mine sections often apply.

Therefore, users of the automated tracking system need to collect point cloud data for sensible sections of their underground mine network of drives and other voids rather than a very long single dataset covering extensive areas. The most practical approach is to adopt tracking existing drive sections, for example between intersections or as defined in some other existing way of up to hundreds of metres, and to adopt their existing names for tracking over time.

When choosing a drive or void section for LiDAR data collection, it is important to ensure that this section can easily be scanned the same way again for subsequent surveys to track its deformation. The team in charge of data collection needs to consistently adhere to the same sectioning when completing data collections for any series of tracking surveys such that temporal tracking over time is easily traceable and to get the best outcomes from fully automated data processing and reporting.

2.2 Baseline surveys for tracking

The best possible baseline to use for drive tracking is the scan collected immediately after a drive or void was excavated because this provides tracking information over its entire lifecycle. Even for sites that don’t experience much or any regular deformation, because they are not located in any squeezing ground conditions, it can be very worthwhile to collect such baseline data if they are exposed to any seismic events. The effect of seismic events on the integrity of excavations and their ground support can only be evaluated if such baseline data was collected such that the drive scanned after the event can be compared to its undamaged state. Accordingly scan cloud data collection should ideally include two stages:

- After excavation but before ground support is installed, i.e. the scan captures bare ground for the purpose of detecting and reporting on underbreak and overbreak, on excavation design compliance, and on shotcrete thickness design compliance if shotcrete is in use. This scan serves as the thickness baseline for the latter.
- After excavation and immediately after installation of ground support for the purpose of reporting on shotcrete thickness design compliance if shotcrete is in use, and for the purpose of unbiased and accurate rockbolt and steel mesh tracking. This stage provides the optimum rockbolt and steel mesh baseline whereas any baseline collected sometime later may already contain deformations that can no longer be extracted.

New underground mining excavations typically only progress a limited distance of several metres per cut which means such surveys can only cover this limited extent at a time. These short sections can, however, easily be combined to a total desired baseline scan cloud length of up to several hundred metres for subsequent ongoing tracking if appropriate georeferencing practices are adhered to.

One of the most important geotechnical engineering criteria for sites to stay in control of is installed ground support capacity. A rock or cable bolt has a finite capacity associated with its possible elongation under deformation, as is approximated through pull or drop tests. Once this inherent capacity is exhausted through deformation, the bolt fails. If rock or cable bolt baseline scan clouds, as described, have been collected, the automated tracking system can be used to determine remaining bolt capacity every time a new scan epoch is uploaded to the system by using the input parameters of automatically measured and tracked deformation, and manufacturer supplied or a mine site’s in-house capacity values of bolts are in use. If such baseline scans have not been collected, then there is no absolute certainty on whether a baseline collected later may or may not already contain deformation that has reduced installed bolt capacity.

3 LiDAR data collection

Aside from sectioning drives or voids into sensible extents, as described earlier, site data collection personnel should also make sure that point cloud coverage within each of these sections is as continuous and of as good quality as it can be to maximise tracking reliability. This includes avoiding any large gaps in coverage of the drive or void surface in the point cloud because of obstructions by unrelated objects such as conveyor belts, vehicles, fixed or mobile equipment, ventilation bags or other personnel. One of mobile LiDAR's usage strengths is its ease of filling in such data coverage gaps simply by moving to the other side of any line-of-sight obstructions during data collection.

If personnel in addition to the data collector must attend scanning because, for example, an escort is required, then such personnel should stay in the scanner blind spot as much as possible to avoid being captured in the scan and therefore potentially obstructing parts of the drive or void surface. The automated data processing pipeline described later in the paper does include a data clean-up step that automatically deletes such erroneous data from the scans but any associated gaps in the coverage on the drive or tunnel wall as the actual feature of interest cannot be brought back.

General convergence mapping and tracking can be completed with moderate to low resolution scan clouds which provide ample coverage for the task. For ground support tracking purposes, however, the resolution of scans needs to be reasonably high such that rockbolts and their plates and steel mesh are captured at a sufficiently high resolution in them because scan cloud points capturing ground support features need to be dense enough for automated feature extraction to work. This requires at least several tens of scan cloud points to represent the bolt and bolt head shape as the smallest feature to be classified and is comfortably achievable with modern mobile LiDAR equipment because it can collect high resolution scan clouds at normal to fast walking speeds or even at slow driving speeds if the scanner is mounted on a vehicle.

3.1 Georeferencing

There are three methods for registering or georeferencing point clouds collected at different dates in any sections of underground drives or voids to cater for deformation tracking:

1. Stop-and-go georeferencing using control points.
2. Target registration.
3. Cloud-to-cloud registration.

Cloud-to-cloud registration uses overlapping features in separate scan clouds to align the coordinate systems of two or more of them. Whilst this works well for many applications, it is not the preferred option for deformation tracking purposes because the deformations themselves can cause the alignment to contain an error. In simple terms, any deformation distorts the alignment and in turn introduces an error to the intended deformation tracking. Cloud-to-cloud referencing can only be done reliably if completely undeformed areas at appropriate locations within the underground drive can be identified in both scans to be aligned. Naturally, no neighbouring scan cloud coverage can be brought into a common coordinate system using cloud-to-cloud registration which means that all location context of deformation is lost.

Registration using targets placed in the field for alignment of multiple scans has historically been in use primarily for stationary rather than mobile LiDAR data collection. As soon as a target is moved, it no longer serves a purpose for underground drive deformation tracking so using targets in this context is impractical.

Whilst it is possible for the automated deformation tracking system presented in this paper to report on underground drives and voids in isolation by using the random local coordinate system for each drive or void segment, if cloud-to-cloud or target registration methods have been used, it is much more preferable to track all sections in the mine's global coordinate system because that unlocks knowledge on all spatial correlation of tracked deformations across the entire underground drive network. This allows for notably better interpretation of deformation trends and how to address them. Therefore, stop-and-go georeferencing using control points is the superior method for this purpose.

Older generation LiDAR instruments and their workflows have not made it easy for operators to complete georeferencing using control points. In the past, the authors have observed at a number of underground mining operations using mobile LiDAR that whilst surveyors have been comfortable with the less streamlined older processes, geotechnical engineers were typically not sufficiently trained in them. However, this issue has now been overcome with the arrival of latest generation mobile LiDAR (Caroni Geospatial 2023) which make the data collection process simple, with no specific training required. Figure 4 shows how stop-and-go georeferencing is done by holding the mobile LiDAR scanner's dedicated reference base with its notch stationary on top of the control point marker at any orientation for 10 seconds before moving on to continue scanning. The control point mark can be located on the drive floor, wall or ceiling. A minimum of four control points need to be surveyed in this way for fast georeferencing of any scan cloud completed for ground deformation purposes.

Figure 4 **Stop-and-go georeferencing by setting up the scanner on top of a control point mark with known survey coordinates in the mine's coordinate system**

In summary, the use of control points is easy to do in the field, minimises the georeferencing post-processing workload and effort, and importantly it also minimises registration error. The latter is particularly important if smaller deformation magnitudes are to be tracked for moderately squeezing ground conditions, otherwise the georeferencing error can become larger than the deformations to be tracked.

4 Automated LiDAR data processing and deliverables

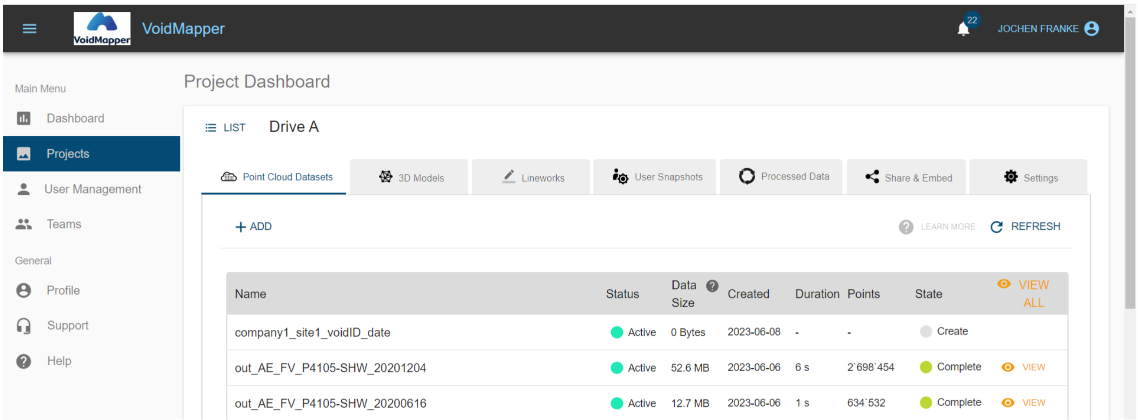
The core of the system presented in this paper is its automated data processing pipeline that overcomes the issues of excessive data processing effort and time, the specialist training and expertise, as well as the third party software it takes to manually process raw scan cloud data into meaningful reports and deliverables for geotechnical engineers.

Using VoidMapper (Franke & Gonzalez 2023), once a user has uploaded a geocoded scan cloud to the system's cloud-based online portal, all subsequent data processing and reporting occurs fully automatically.

The steps that are completed in the background no longer require any manual intervention – which is the downside of standard manual data processing – and these include:

1. Automated data clean-up removing any unwanted elements such as vehicles, ventilation bags, loose hoses, conveyor belts, stationary equipment, people, or random scanner noise from the data so that deformation or damage tracking of drive or void surfaces is not affected by them.
2. Automated short-term comparison (STC) between the current uploaded scan survey of the drive section covered and its previous survey.
3. Automated long-term comparison (LTC) between the current uploaded scan survey of the drive section covered and its oldest available survey which ideally should be the baseline survey of the newly excavated drive or void.
4. Automated comparison between the current uploaded scan survey of the drive section covered and its drive design, in other words its design compliance (DC).
5. Automated generation of a summary report containing information on the automatically detected worst deforming areas for the STC, LTC, and DC, and other key tracking indicators.
6. Ground support specific tracking output and reporting.

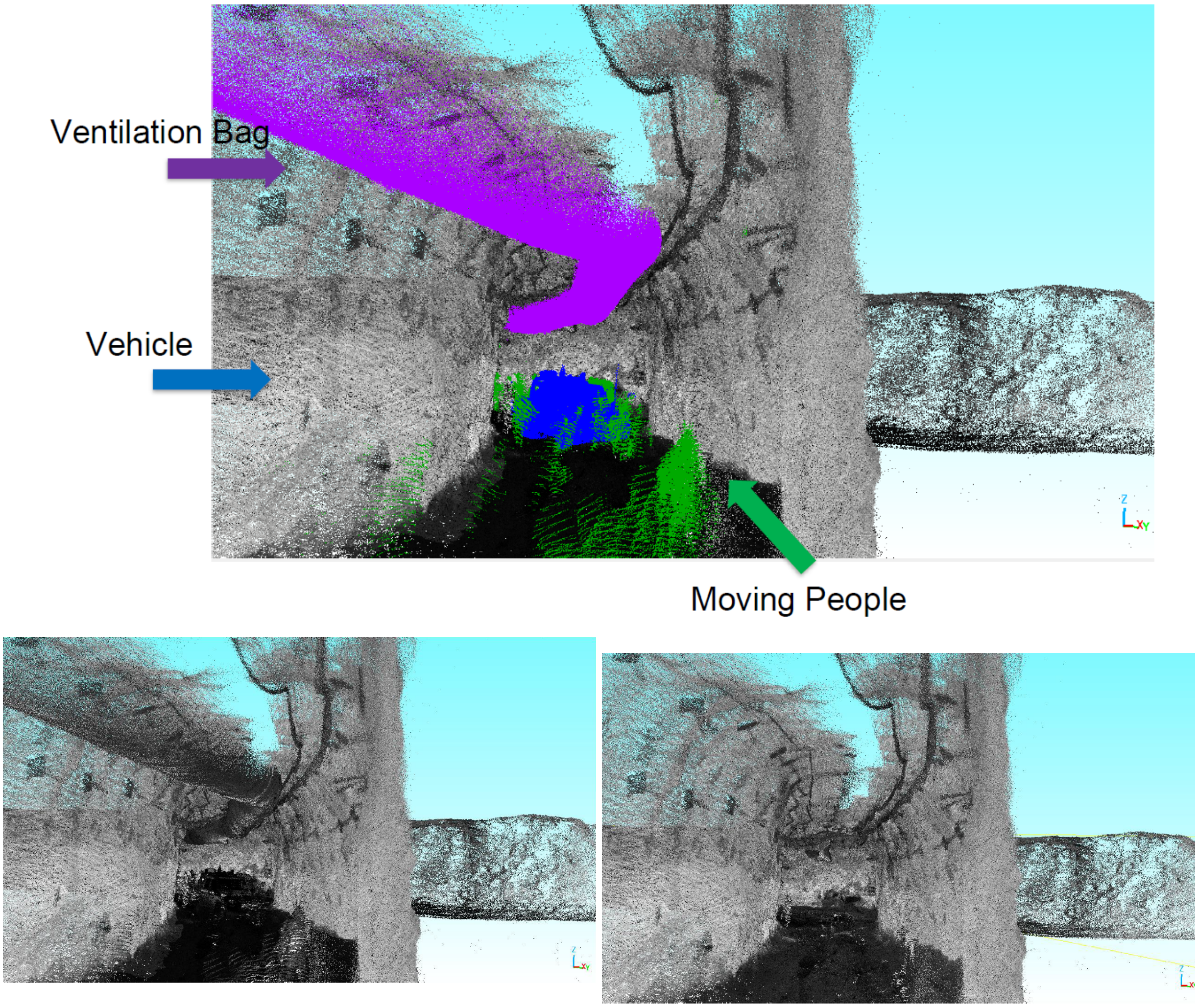
Uploaded and processed files are listed under a project, as shown in Figure 5, and can be selected for 3D viewing and analysis.



Name	Status	Data Size	Created	Duration	Points	State	VIEW ALL
company1_site1_voidID_date	● Active	0 Bytes	2023-06-08	-	-	● Create	
out_AE_FV_P4105-SHW_20201204	● Active	52.6 MB	2023-06-06	6 s	2'698'454	● Complete	VIEW
out_AE_FV_P4105-SHW_20200616	● Active	12.7 MB	2023-06-06	1 s	634'532	● Complete	VIEW

Figure 5 Automated cloud-based system project dashboard listing all scan cloud files contained in a project and their characteristics

The first step of automated processing listed earlier has to identify and then remove unwanted elements from the scan cloud so that they don't cause deformation tracking to generate false positive results. If, say, a person walking through the scene during scan data collection in a drive is not removed, it may end up being the biggest deformation recorded, albeit not a real one. This step of data clean-up is tedious and time consuming if done manually using third party cloud editing software. The repetitive nature of having to identify unwanted elements in the scan cloud representations of what is an enclosed 3D space is typically also fairly demanding for a human operator and is one of the key reasons why this technology had not been taken up by geotechnical engineers in the past. What used to take a person many hours of laborious work is now completed by an algorithm within minutes at a much higher success rate. An example for why this is so is provided in Figure 6.



Original scan

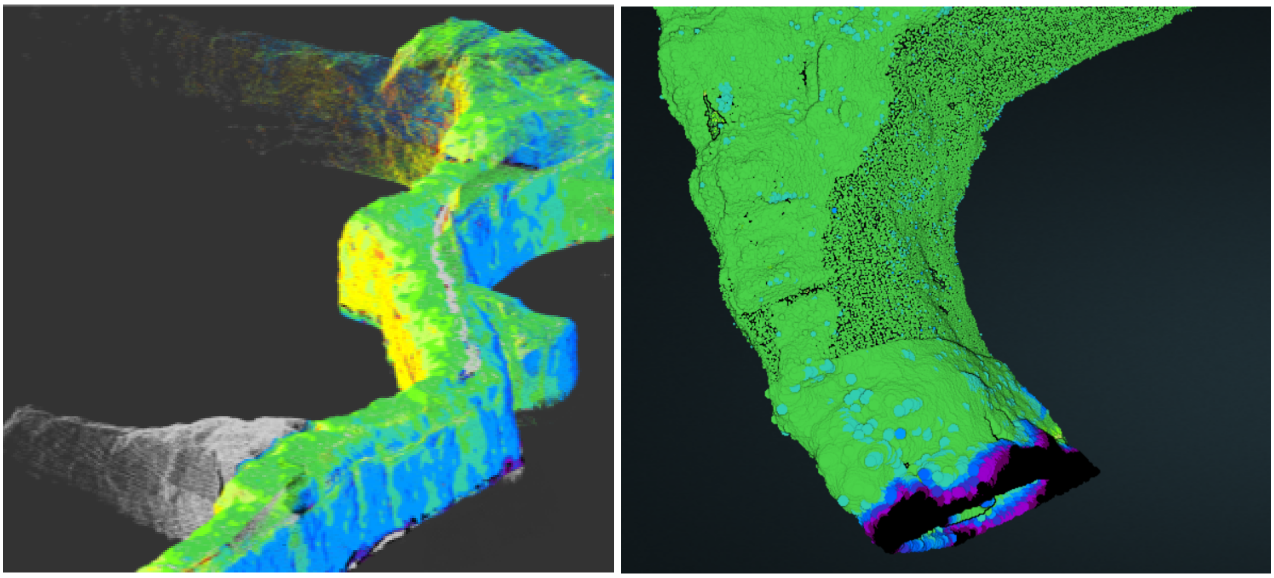
Objects removed

Figure 6 **Example of difficulty for a human operator to identify unwanted elements in a 3D scan cloud as shown in the screen shot labelled 'original scan' in the bottom left. The image at the top shows that this scene contains a vehicle (blue), a ventilation bag (purple), and moving people (green) which appear as ghosted figures without well-defined outlines which makes their manual selection and deletion difficult. The bottom right screen shot labelled 'objects removed' shows the automatically cleaned scene fit for error-free drive deformation tracking**

The implementation of short-term and long-term comparisons to track associated deformation trends in the automated system uses a dedicated algorithm that accounts for mismatches in scan cloud coverage which was detrimental to early attempts to complete such comparisons using either simple cloud-to-cloud or cloud-to-mesh methods that are based on a minimum distance calculation between closest points in the two surveys to be compared. If one of the two point clouds has a data gap caused by an obstruction, for example, because a vehicle was parked in the way one time, or both data sets have corresponding data gaps at different locations because, for example, ventilation bags or suspended hoses moved between scan dates, then a minimum distance calculation between the two scan clouds results in an artificially exaggerated deformation. The reason for that is that, to find a corresponding point, the algorithm has to look beyond the data gap in the second point cloud which makes that distance longer than it should be.

In contrast to the above minimum distance method, the automated system discussed in this paper utilises a dedicated neighbourhood search algorithm to first check at multiple scales whether there is a valid corresponding point in the second scan cloud to be compared before calculating the deformation distance for it. If no such valid point can be found within a suitable neighbourhood search space then it classes this point's deformation as indeterminate, meaning it does not calculate a deformation for it. This means that exaggerated deformation calculations are avoided and do not distort tracking results. This effect is visually obvious in 3D viewer files by representing all indeterminate deformation points in grey, as shown in Figure 7.

In Figure 7a, the example of a 3D viewer file automatically generated by the authors' system shows deformations in colour whereas areas with insufficient data to calculate valid deformations are shown as grey. A newly excavated drive section on the left is coloured entirely grey because this new drive portion was not yet excavated when the older scan was collected and hence there is no valid data for comparison. Simpler minimum distance comparison algorithms used in other systems would have calculated large deformations for this newly excavated drive. Similarly, there is an elongated grey area where there are obstruction gaps in the data behind the ventilation bag mounted on the drive ceiling, which is also coloured grey. Minimum distance algorithms would have calculated a large but false deformation instead. Figure 7b was created with a minimum distance algorithm not used in the authors' system because it can calculate erroneous deformation particularly at the ends of surveyed drive sections since there is often slightly mismatching data coverage between surveys collected at different dates, resulting in what is shown as large blue to black deformations that are not actually real.



(a) (b)

Figure 7 (a) Comparison of the authors' dedicated algorithm to correctly deal with mismatching data in two point clouds to be compared; (b) A standard point to point minimum distance algorithm containing erroneous deformation results at the tunnel end

Automatically generated summary reports, as per step five of the automated processing pipeline described earlier, contain the key indicator of worst deforming area to put decision makers in a position to quickly judge whether or not the latest survey picked up anomalies. The extraction of the worst deforming area is completed by the algorithm when conventionally this determination has to be done by a person manually. As for all other manual steps, this is time consuming and potentially subject to human error. It's easy for a data processor to visually miss a worst deforming area potentially resulting in a safety risk, whereas the automated algorithm quantifies every qualifiable anomaly based upon the set range.

4.1 3D viewer data and functionality

Whilst the summary report containing all key tracking information on STC, LTC, and DC serves as the first port of call to determine the status and any potential need for remediation of convergence as well as ground support deformation, the automated tracking system also provides tracking data and deliverables in a cloud-based 3D viewer. This allows users to dig deeper and analyse root causes or identify trends for any issues that might have been identified in a summary report. Figure 8 shows an example for such a 3D file containing significant deformations for a site located in heavily squeezing ground.

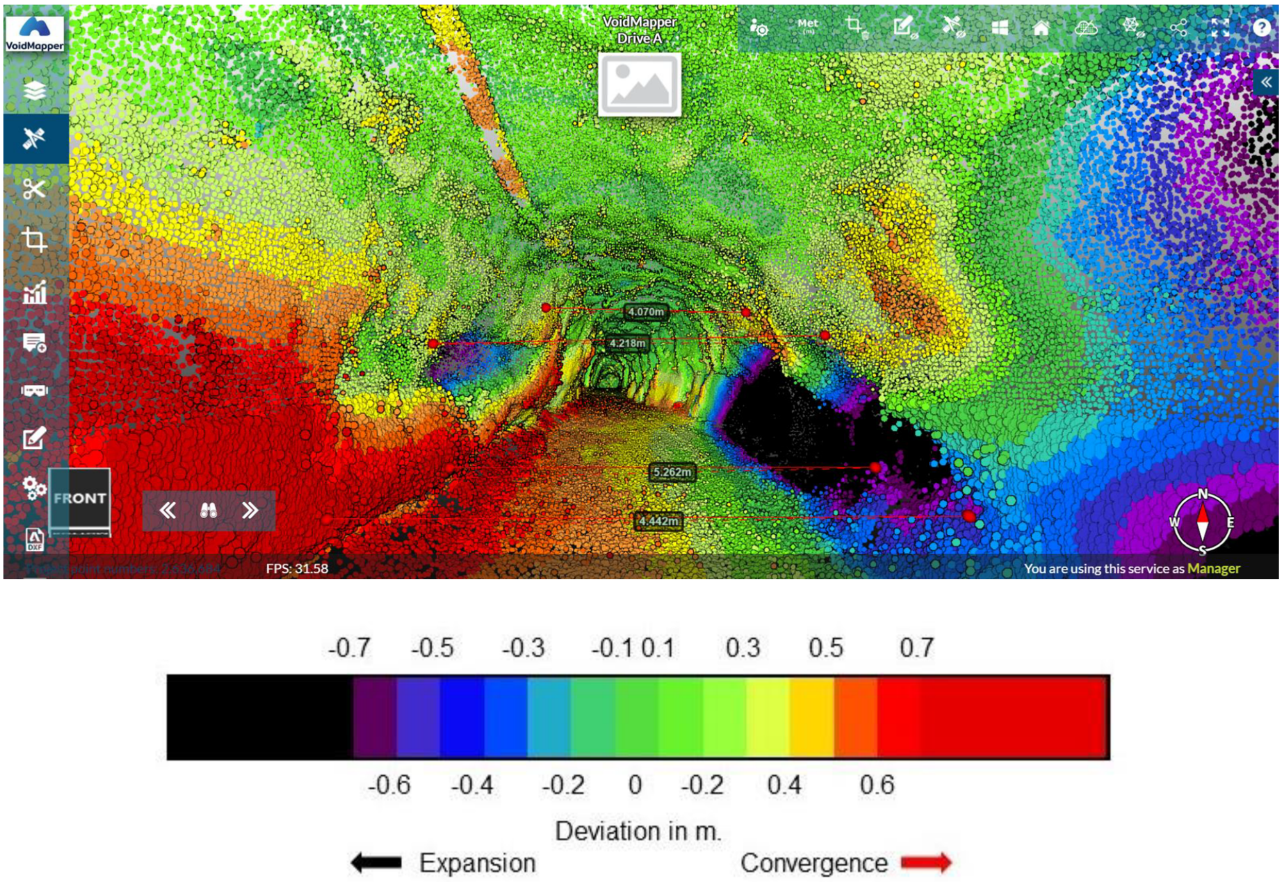


Figure 8 Screenshot of a 3D view of a data file selected from the project dashboard of the cloud-based tracking system portal. This example is a long-term comparison for highly squeezing ground showing a convergence bulge in red on the left and an expansion section in black on the right-hand sides, respectively. Distance measurements taken in the 3D viewer, as shown, highlight deviations of drive width impeding mobile equipment transition

4.2 Ground support reporting

Aside from spatial convergence and expansion reporting detailed in the preceding section of this paper, the automated system also provides tracking of specific ground support elements. The fundamental and basic rock or cable bolt reporting starting point is to extract the following for all of them:

1. 3D position in the mine coordinate system.
2. Ring spacing between bolts for each cross-section of installed bolts.
3. Longitudinal bolt spacing in-between rings.
4. Average bolt density per square metre for each tracked drive section.

Other derived reporting information is based on this fundamental data automatically extracted for each scan survey. These fundamental bolt parameters are, however, not really useful per se to geotechnical engineers, as these data sets need to be presented in a more meaningful way or else all effort to get to this point is wasted. The authors have, to date, not seen any publicly available industry efforts or offerings that have done that in an effective, repeatable, and automated way such that it can become a regular geotechnical decision-making workflow, which the system presented in this paper intends to address.

One of the key deformation parameters that determines the health of the entire ground support system is remaining bolt capacity. The automated tracking system covered in this paper determines a proxy for this parameter by reporting on the deformation of bolt heads and plates. This does not represent remaining bolt capacity as such, as it does not consider what has occurred to the bolt itself embedded in the rock, which is not detectable by LiDAR data. Nevertheless, it stands to reason that if a bolt head or plate is displaced by geotechnical deformation from its original position when newly installed by a magnitude of distance comparable to the capacity of the bolt in use, as determined by separate means, then this is a valid quantified way of estimating how much more deformation a bolt can take before it will fail.

Since the capacity of rock and cable bolts related to deformation elongation before failure is typically in the order of up to 20–40 cm, as reported on extensively by industry research and associated publications including a broad overview published by the Australian Centre for Geomechanics in Chapter 7 (Potvin & Hadjigeorgiou 2020), it is important to clearly define and then be consistent about what exact position of the visible rock or cable bolt portion is extracted from a scan cloud and reported on. Inconsistencies of multiple centimetres could equate to up to a quarter or more of bolt capacity for different surveys or individual bolts to creep in that affect the precision of bolt deformation tracking. It is important to accurately extract and track identical positions on the bolt for each bolt and each survey or tracking will likely be unreliable.

Therefore, 3D bolt positions in the given coordinate system of the scan cloud, as per item 1 listed, need to consistently refer to one of the locations on the bolt, as shown in Figure 9. Arrows on the images indicate where bolt positions should be extracted because these points represent the plate to centre of bolt contact transferring loads. Since these load transferring points are not visible in scan clouds, they need to be extracted by a secondary process of feature extraction. Another option for a bolt position is its end point marked with red crosses for the examples shown in Figure 9, which is visible in the scan cloud if that has been collected at a suitably high resolution with fit-for-purpose LiDAR instruments.

When both the positions of the invisible bolt to plate load transfer point and the positions of the bolt end point are extracted, it enables the system to provide additional tracking information on the length of the bolt tail and with it the installed critical embedment length (CEL) that can mobilise the capacity of the steel through the actual length of coupled grout, resin, or friction bolt. CEL is calculated by subtracting measured bolt tail distance from total bolt length; the latter being supplied as predefined input by bolt vendor specification data sheets. For the automated system to be able to report on this, users need to provide *a priori* information about key bolt specifications including bolt length.

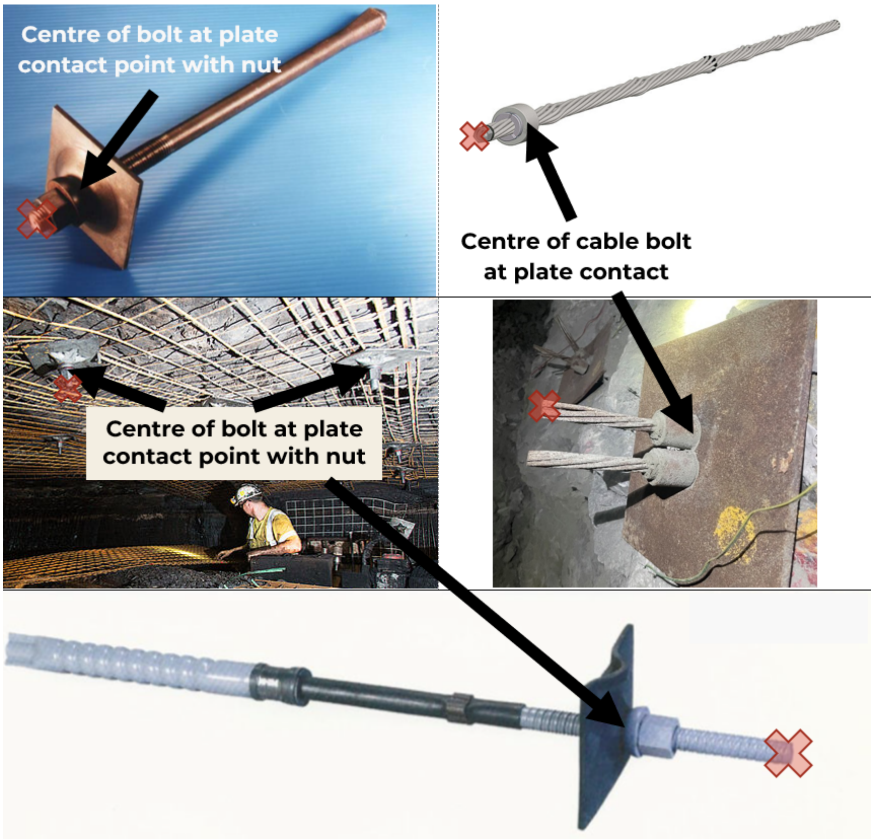


Figure 9 Examples (ACG 2022) of different rock and cable bolt designs and their plates to illustrate the different bolt feature options for bolt position extraction. Whether plate to bolt contact (black arrow tips) or bolt ends (red crosses) are selected to represent bolt positions, this choice must remain consistent such that tracking is reliable and accurate

5 Benefits, competitive advantages and conclusions

In broad terms the biggest competitive advantage of the automated system presented in this paper is that it unlocks the full potential of LiDAR-based underground drive and ground support deformation tracking because tedious, time consuming, and onerous manual data processing by trained specialists is replaced by an algorithm and software. Where in the past this meant that mine sites had to limit what they tracked and how frequently they tracked it, this is now no longer limited because no work hours have to be dedicated towards scan cloud data processing and analysis reporting anymore. The algorithm doesn't mind or take materially longer to produce reporting output on five or 50 scan surveys.

Any such additional tracking provides better insights into deformation behaviour of a site than was possible to gauge with manual data processing, which in turn provides better data to base good decisions on. From the perspective of, and using insights available to, a mine manager, Mercier-Langevin (2019) reports that ground support in a mine, depending on the prevailing ground conditions, can make up a sizeable portion of its operating budget and that for marginal projects, proper ground support design can mean the difference between being profitable or not. Therefore, a more reliable method to track ground support health and to time any rehabilitation appropriately can lead to material cost savings. Kamp (2022) provided a good case study on the use of LiDAR convergence monitoring to develop an effective and comprehensive ground control rehabilitation strategy for a mine experiencing significant deformations. An automated system for data processing, as presented in this paper, is ideally suited for such a scenario and can provide the means to effectively and economically continue the application of optimally timed rehabilitation for such cases to minimise overall ground support costs on an ongoing basis.

Conversely, if safety risks stemming from ground support deterioration can reliably be identified in a timely fashion, then this may prevent incidents or accidents through rockfall that still regularly occur in underground mining. The Government of Western Australia (2020) released new regulations relevant to professional liability for adhering to geotechnical best practice that have been brought in line with other Australian states and have become a personal obligation for senior Australian geotechnical engineers, as discussed in-depth by geotechnical peers of the Western Australian Ground Control Group (2023). This makes using best available and easily usable technology and methods for risk reduction even more important.

There are wider benefits, in addition to the those described in previous paragraphs, stemming from the system's architecture and design, as well as the sophistication of reporting as further described below.

5.1 Cloud-based software and data storage

Point clouds often contain a large number of points and have a large data file size that can be challenging to deal with for even latest generation high-end desktop computers when data processing and for lag-free display of associated 3D data. The system presented in this paper avoids these issues by moving all back-end data processing and front-end user interface features into the cloud, accessible through a web browser-based portal. This also makes data storage for even the largest mine sites with many tens of kilometres of frequently tracked underground drives unproblematic because storage space is virtually unlimited.

Other associated benefits include meaningful results that are delivered in a matter of minutes because powerful cloud-based server systems are deployed rather than waiting weeks for in-house personnel or external service providers to deliver manually produced reports. There is also no need for local installation of software on desktop machines which can be a hurdle at mine sites where constraints to managing such processes may hinder geotechnical engineers.

Having a cloud-based central data repository of tracking data also allows different stakeholders at different locations to simultaneously access the automatically generated output data, thereby enabling better collaboration and visibility of the status of underground drive and ground support deformation. This could, for example, allow principal geotechnical engineers or remote operations centres located potentially thousands of kilometres away from the mine to access and utilise this information that was previously typically accessible to only a few people on often only one local desktop computer.

5.2 Geotechnical reporting

As detailed throughout this paper, the sophistication of reporting by the automated system goes beyond simply stating basic measurement parameters which by themselves are not really useful to geotechnical engineers for their task of ensuring safety and economic ground support management. Whilst already available and released system features go well beyond other deformation tracking descriptions published elsewhere, the authors are currently pursuing the implementation of additional functionality that should further increase the system's usefulness.

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