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The use of three-dimensional laser scanning for deformation monitoring in underground mines.

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ABSTRACT

The measurement and management of deformation in underground excavations is a key responsibility of geotechnical and mining engineers. A critical aspect of these roles is to ensure ground support is ensuring there is sufficient capacity for the expected demand.

Current methodologies for monitoring deformation and ground support serviceability limits require measuring displacement at distinct points, or using visual observations. These current methods limit the assessment to a qualitative interpretation of deformation across the entire excavation.

Recent advancements of Light Detection and Ranging (LiDar) technology is introducing a new method for monitoring deformation. These allow a full three-dimensional image of extended sections of an excavation to be precisely scanned and subsequent scans to be compared. The results can provide valuable information on the magnitude, direction and extent of regions exceeding the ground support serviceability limits. This new method provides a quantitative assessment across the entire excavation being monitored.

The implementation of regular scanning has shown to be highly advantageous for mines with swelling or squeezing ground, but also at mines with rapid deformation. The use of LiDar technology as a routine deformation measurement tool for geotechnical and mining engineers and further applications are discussed in more detail in this paper.

INTRODUCTION

A significant hazards in underground mining is a fall of ground. In the event of a fall of ground there are significant costs to rehabilitate the excavation returning it to a sufficient standard.

Throughout the excavation design process consideration for ground control focuses on understanding and minimising deformation of the rock mass. Several methods are used, these include:

- Kinematic analysis, relies on structural mapping and wedge identification. From this analysis, a ground support design is engineered to support the wedge and minimise deformation.
- Empirical methods, based on generalized rock mass parameters and is subjective.
- Numerical methods, best accounts for known influencing factors such as stress, adjacent faults and excavations.

All of these methods require validation, this can only be achieved through measurements and monitoring. Current options for measuring and monitoring deformation include:

- Instrumented ground support
- Extensometers
- Tape extensometers

These methods provide discrete point-to-point measurements and are not representative of the deformation of the entire excavation. In very rare cases the use of a survey total station may be used in areas such as intersections to monitor convergence, however this technique is time consuming and impractical to apply mine wide.

Mine wide monitoring usually occurs through routine damage mapping, or the compiling of previous rehabilitation plans. This provides an estimate of the rock mass response to mining activities. Both of these methods are subjective to the engineer’s observations.

In more recent years, the mining industry has benefitted from the introduction of LiDAR based devices. This overcomes the limitation of the methods described above. Surface mining methods have adopted these techniques since LiDAR and GPS have been coupled to provide high accuracy measurements. LiDAR combined with GPS and unmanned aerial vehicles (UAV) have allowed for wide scale scanning of pits and stockpiles. Recent developments in robotics and software engineering have more recently combined LiDAR with either Inertia Measurement Units (IMU) and/or Simultaneous Localisation and Mapping (SLAM) algorithms to develop mobile laser scanners that can work in GPS deprived environments such as underground mines. The advantage of using mobile scanners over conventional survey stations is that they have the capability to provide spatially continuous coverage over extended distances without the necessity of stitching multiple scans together.

COMMERCIALLY AVAILABLE DEVICES FOR POINT CLOUD GENERATION

Commercially available mobile laser scanners first came to the market in 2014 with the introduction of the GeoSLAM Zeb-1. In the years following, numerous scanners have been introduced, including the Mine Vision System (MVS), uGPS Rapid Mapper, V-Scan3D, Zeb-REVO and PX-80.

The available scanners all have some similarities in the mechanisms for generating 3-dimensional point clouds, that is they all use LiDAR and a SLAM algorithm. Differences in the scanners are the secondary means of device location and point cloud alignment. Secondary methods include the use of inertia measurement units (IMU), stereo cameras, a second laser and radio frequency identification devices (RFID). **Error! Reference source not found.** provides a brief summary of some commercially available mobile laser scanners for underground applications.

Table 1 - Summary commercially available mobile laser scanning devices

Device Name	**Zeb-1**	**Zeb-Revo**	**MVS**	**uGPS Rapid Mapper**	**V-SCAN3D**	**PX-80**
Manufacturer	GeoSLAM	GeoSLAM	Mine Vision Systems	Peck Teck Consulting	Clickmox	Paracosm
Scanning method	Handheld	Handheld / Vehicle mounted	Vehicle Mounted	Vehicle Mounted	Handheld / Vehicle mounted	Handheld
Secondary alignment method	IMU	IMU	Stereo-camera	Dual laser, IMU, WiFi, RFID	-	IMU
Point Cloud Capture Rate (points/sec)	43,200	43,200	~ 40,000	-	-	~ 300,000
Claimed Absolute Accuracy	30-300mm	30-300mm	20-30mm	2% accumulated error per unit distance travelled	-	20-30 mm
Point cloud colourisation	No	Coupled camera	Stereo camera image	Grey scale intensity	-	RGB
Weight	600g	600g	-	-	<970g	2.2kg

The advantages and disadvantages of each device is beyond the scope of the paper and should be researched in further detail by the reader. The correct device will be determine on the specific application sought by the mine.

Data acquisition is a simple task of either walking or driving slowly with the device as outlined by the manufacturer. The remaining part of this paper examines the applications for the data.

APPLICATIONS

The laser scanning data in underground mines can be used by surveyors, geologists, geotechnical and mining engineers. These applications are summarized in the flowchart presented in Figure 1. This paper discusses some of the requirements and interpretations associated with using mobile laser scanners for the purpose of convergence monitoring.

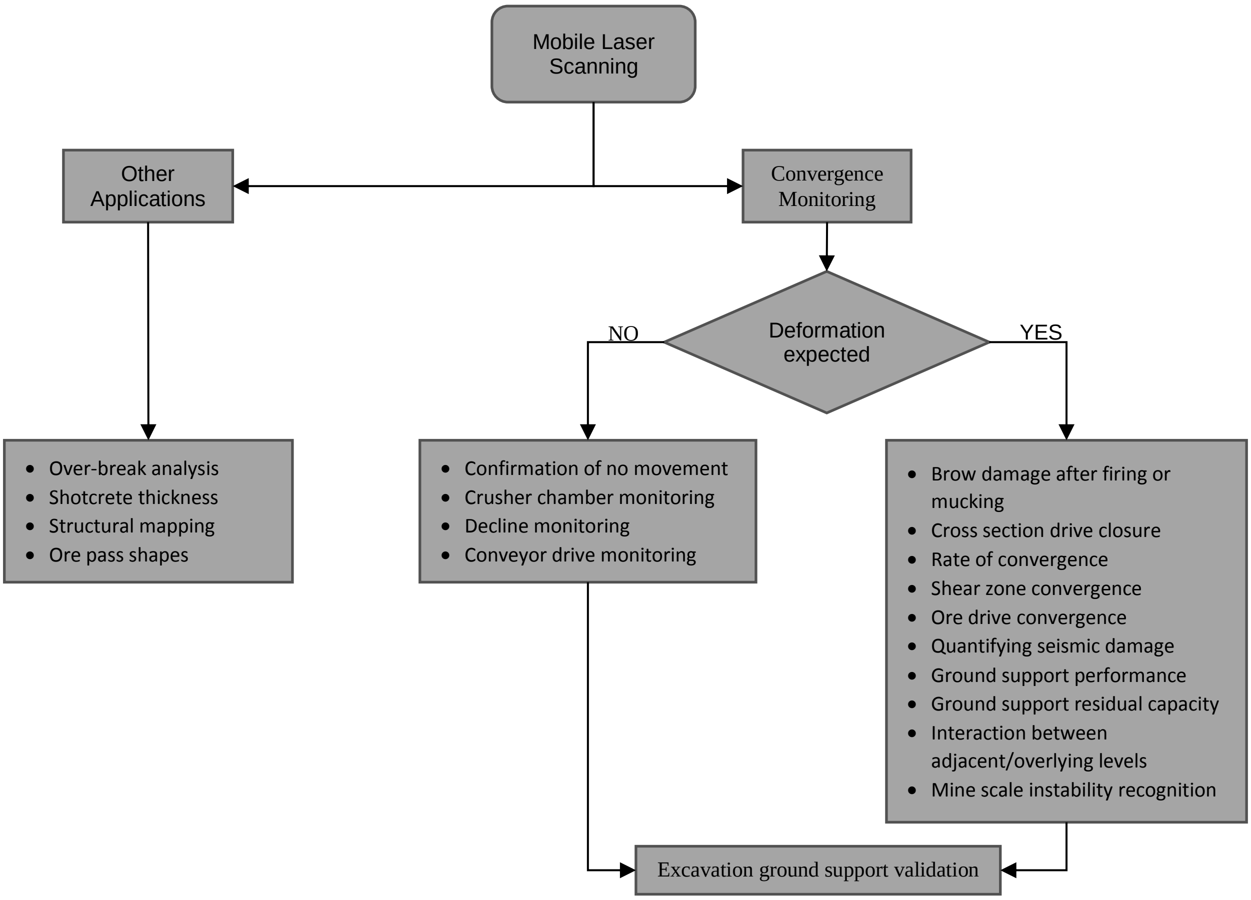

Figure 1 – Flowchart of the application for mobile laser scanning in underground mines

Convergence Monitoring

Convergence monitoring is a broad term that relates to quantifying spatial changes in the excavation geometry over time. Although this concept seems simple, the excavation geometry either remains stable, converges or diverges with time, as shown in Figure 2. It is a necessity that any analysis shows the magnitude of movement and distinguishes between convergence and divergence. This is required to ensure that the alignment between the primary and secondary scans are sufficiently accurate and the final results are representative of the movement that has occurred in the excavation.

The calculation of distance between the primary and secondary scan can be undertaken using various commercially available algorithms. It has been found that using a point-to-point calculation technique provides a quick appreciation for movement. However, more complex algorithms calculate an average local surface of the primary scan and then calculates the vector displacement to the average local surface of the secondary scan. These more complex algorithms have been found to yield more accurate results.

The visualisation of the output file is best done in three-dimensions, shown in Figure 3, such that location and displacement magnitude can be appreciated along with whether convergence or divergence is occurring. This type of visualisation also allows for the recognition of any alignment errors that may require amending.

An alternative method is to plot the distribution of deformation at distances from a particular location, such as a stope brow. This method is presented in the graph in Figure 4. There are three key observations can be made from this graph:

- Significant displacement (>125mm) extends for more than 100m back from the brow. In this case, it is likely this displacement is generated from the retreating of stopes on the levels above.
- The two peaks in data represent the stockpiles at ~50m and ~165m from the brow.
- The increase in convergence at the 190 – 225m from the brow can be attributed to a cross cutting shear zone.

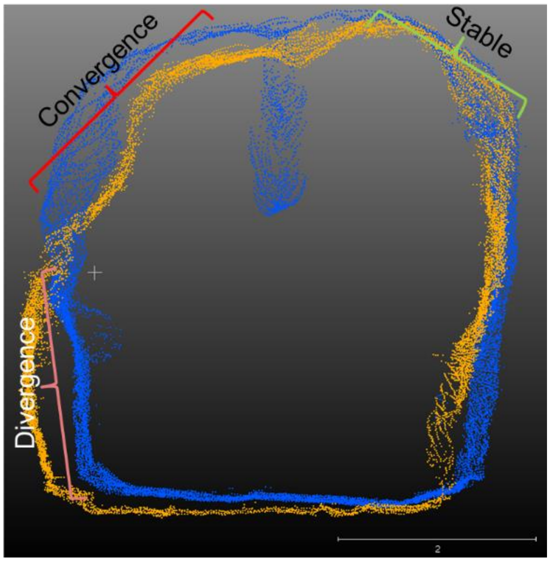

Figure 2 – A cross section of a deformed drive showing different directions of movement that must be appreciated in interpreting scans

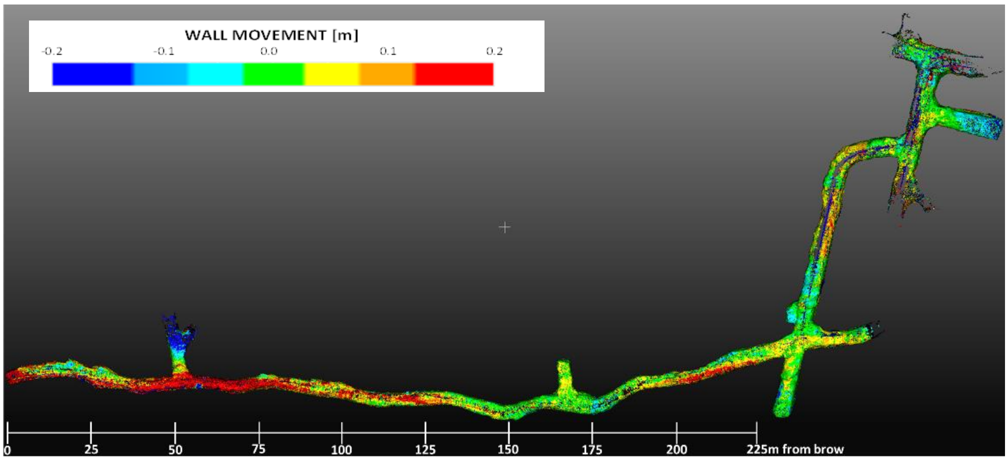

Figure 3 – An example of the heat map showing drive displacements after a period of time

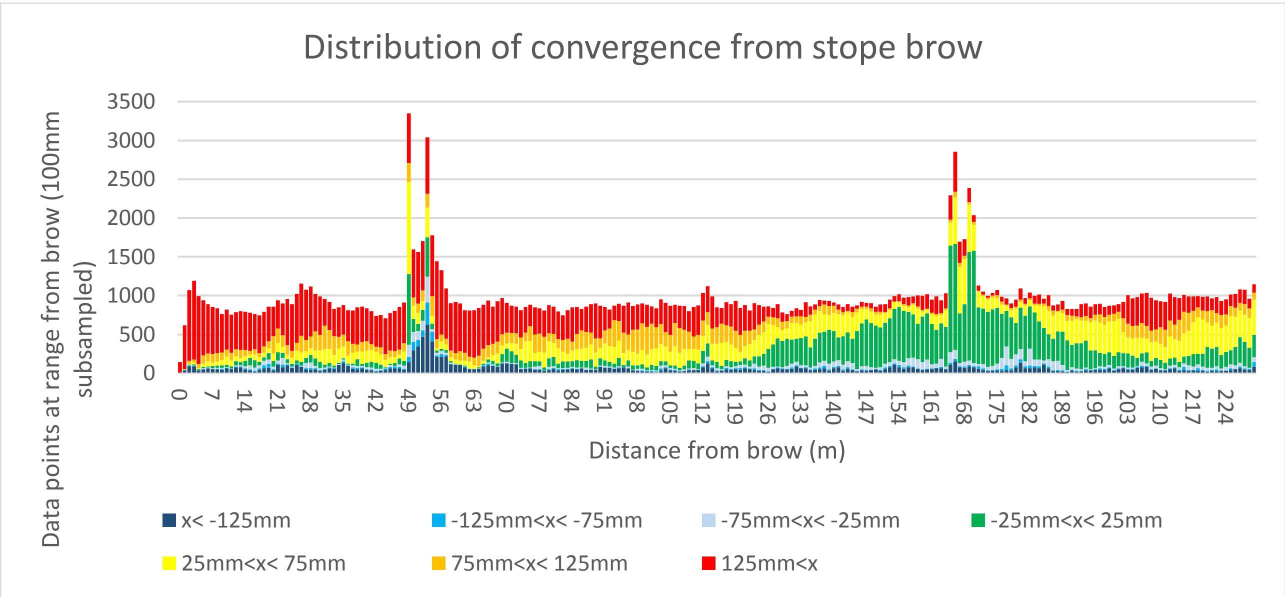

Figure 4 – The distribution of displacements along the ore drive shown in Figure 2.

Convergence Rates

Another application of mobile laser scanners is the analysis of convergence rates. Several applications are proposed, including:

- Assessing the effectiveness of ground support designs.
- Assessing the rock mass response of different geotechnical domains.
- The scheduling of rehabilitation so access restrictions can be planned for in advance.
- As a warning for an excavation failure. The inverse velocity method is commonly used in open pit mining to assess the stability of a benches and pit walls. Conceptually a similar method can now be applied to underground mining by assessing the convergence rate.

The cross sections shown in Figure 5 are of an ore drive at various time periods. It can be seen that in the first seven months of monitoring there is only minor deformation. In the following three months convergence increases with up to 400mm occurring prior to rehabilitation.

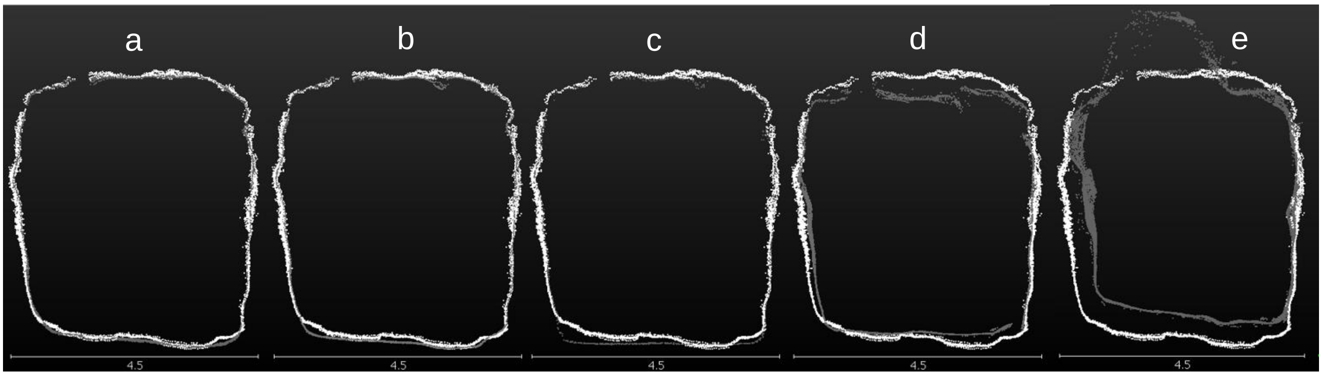

Figure 5 – An example of convergence rates of a development cross section showing the emergence of an instability at a) 2.5 months b) 5 months c) 7 months d) 10 months and e) 14 months

Ground Support Residual Capacity

The concept that a rock mass will apply a demand on the ground support which has a finite capacity is well understood. In a controlled laboratory environment, Drover and Villaescusa (2016) have undertaken testing for a range of commonly used rock bolt and mesh combinations examining the relationship between energy dissipation and displacement (Figure 6). However, this concept is difficult to measure and quantify in a mining environment due to the quantity of support elements involved. Mobile laser scanning data provides spatially continuous measurements of the in-situ displacement of the rock mass. This can be used to infer the residual capacity of the support elements and to identify areas where the support is near its capacity.

The application of this concept requires additional considerations including:

- Loading mechanism.
- Creep, this information can assist in determining a time period at which the support will reach an ultimate capacity and require rehabilitation.
- Seismic loading, energy dissipation is critical over a much shorter period meaning rehabilitation may be required at an earlier period to always ensure capacity exceeds the potential demand.

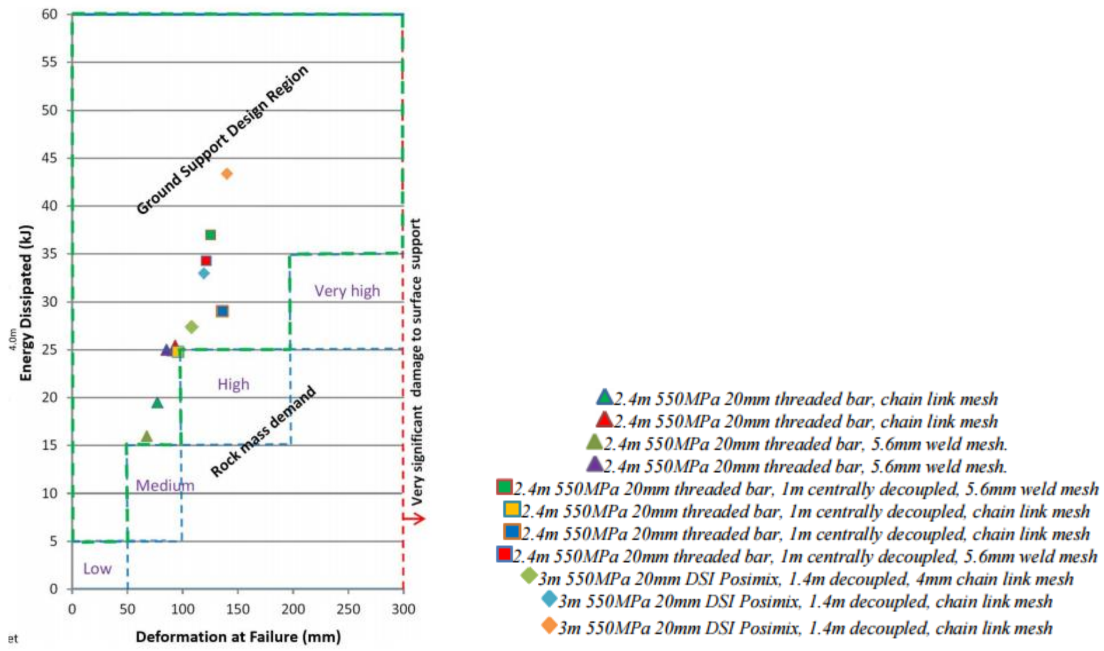

Figure 6 – Energy dissipated versus deformation at failure for combined schemes of rock bolts and mesh tested as WASM. From Drover and Villaescusa (2016)

CONCLUSIONS

Mobile laser scanners are an emerging technology providing surveyors, geologists, geotechnical and mining engineers an insight into the rock mass response to mining. Although these devices have been commercially available for a number of years now, their applications and uptake with in the mining industry are still in their infancy. As the manufactures continue to improve the accuracy and efficiency of the devices, and the mining industry further their ability to work with the data we will continue see new applications, an improved understanding of geomechanics and increased safety in underground mines.

There are many applications in underground mining for the data acquired by these devices, of which three convergence monitoring applications have been presented.

The spatially continuous data provides engineers with measurements for the interpretation convergence rates with respect to location, geological domain and structures. This knowledge can be applied to improving ground support designs, scheduling rehabilitation and identifying potential fall of grounds.

Although the convergence monitoring results provide a valuable insight, this data is not a replacement for more conventional techniques of monitoring displacements such as extensometers. Rather, mobile laser scanning data should be used in conjunction with more traditional measurements techniques.

REFERENCES

Drover, C. and Villaescusa, E. 2016. Dynamic load demand on a ground support scheme – a case study, *Mining Technology*, ***125**, 4, 191-204.*