Accuracy issues associated with Lidar scanning for tunnel deformation monitoring

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ABSTRACT
Light detection and ranging (Lidar) is becoming more widely used in the geotechnical community as its number of applications increase. It has been shown to be useful in tunnel for applications such as rockmass characterization and discontinuity measurements. Lidar data can also be used to measure deformation in tunnels, but before a comprehensive methodology can be developed, the accuracy issues associated with scanning must be fully understood.

RÉSUMÉ
Light Detection and Ranging (Lidar) est de plus en plus largement utilisés dans la communauté géotechnique que le nombre de ses applications augmentent. Il a été montré pour être utile dans le tunnel pour des applications telles que la caractérisation masse rocheuse et les mesures de discontinuité. Les données lidar peut aussi être utilisé pour mesurer la déformation dans les tunnels, mais avant une méthodologie complète peut être développée, les questions associées à la précision de numérisation doit être pleinement compris.

1 INTRODUCTION

Light detection and ranging (Lidar) is a method of collecting 3D point cloud data that is becoming widely used for a variety of purposes. It is being adopted in many industries due to its rapid collection speed, high accuracy, and ease of use.

1.1 Geotechnical Lidar applications

Lidar has been proven to have many geotechnical applications including rockmass characterization, discontinuity measurement and landslide monitoring. As Lidar is gaining acceptability in the geotechnical community its number of applications is increasing. There is potential for Lidar to be used to measure both block movements and deformation in tunnels. From Lidar data both the amount of block movement as well as the volume of the moved blocks can be calculated.

Lato et al. (2009) demonstrated the use of Lidar scanning for the evaluation of structural discontinuities in rockmasses. The analysis of structural discontinuities within a rockmass through Lidar surveying rather than traditional surveying methods can reduce the error associated with human bias during the collection of field data such as joints and other structural features.

The need for high accuracy data for the extraction of structural discontinuities is lower than that for deformation monitoring as it is still much more accurate than traditional field investigation methods.

The use of Lidar to determine shotcrete thickness and the amount of overbreak during excavation underground was shown by Fekete et al. (2009). Rockmass characterization based on Lidar tunnel scans is demonstrated in Figure 1. The left hand image shows three successive scans that have been matched together (registered) and the right hand image shows the extracted planes identified by Fekete et al. (2009).

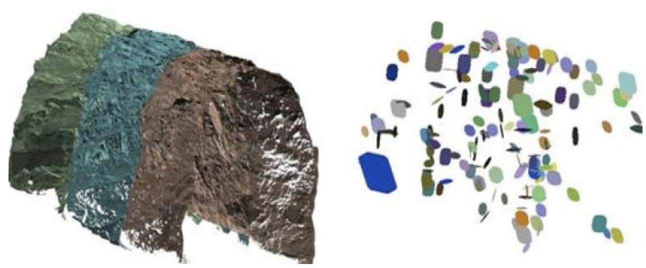

Figure 1: Mapping of joints from linked (registered) Lidar scans of an active tunnel heading (Fekete et al. 2009).

Although Lidar accuracy is very important for the measurement of shotcrete thickness and amount of overbreak, the scale of measurement is still on the order of multiple centimetres, so millimeter differences in accuracy are negligible.

The major issue with using point cloud data for the measurement of deformation that still needs to be addressed is the accuracy and precision of the point cloud data. Deformation measurements are measured on the scale of millimeters, so a complete understanding of the sources of error within the Lidar scanning system and data processing is essential for creating a methodology of measuring tunnel deformation.

1.2 Accuracy and Resolution

It is important to understand the difference between precision and accuracy when referring to Lidar point cloud data. Accuracy refers to how close the measured points are to where the actual points are located in space. Precision on the other hand is a function of the resolution of a scan, and how noisy the data is. Low noise data is important for relative comparisons of scans, whereas when the absolute geometry of the object is of importance, a high degree of accuracy is important. The main contributors to scan resolution are: the scan density, noise, accuracy, spot size and scan referencing.

A complete knowledge of where accuracy errors originate within Lidar data is necessary, so these errors can be minimized. High accuracy point cloud data is very important if the data is to be used for deformation monitoring. This paper will describe sources of error within Lidar point cloud data, current methods for deformation monitoring in tunnels, and how Lidar can be adopted for tunnel deformation monitoring.

2 ERROR IN LIDAR SCANNING

The accuracy of the point cloud data collected by a Lidar instrument can be broken into three different sources of error:

- the error in the range measurement
- the error in the vertical angle measurement
- the error in the horizontal angle measurement

The total error, E, is equal to the square root of the sum of the squares of all the sources of error.

$$E = \sqrt{(\Delta X^2 + \Delta Y^2 + \Delta Z^2)} \qquad [1]$$

where:
ΔX^2 = horizontal angle error
ΔY^2 = range error
ΔZ^2 = vertical angle error

There are also errors associated with field procedures for scanning and the processing of the point cloud data, but this paper will only focus on the areas associated with the collection of data by the Lidar scanner.

2.1 Range error

Range error is affected both by systematic error associated with the Lidar scanner as well as the characteristics of the object being scanned.

2.1.1 Noise

Noise in Lidar scanning refers to the degree of scattering of data around a best fit plane. Lower noise data will have better modelled precision but not necessarily better accuracy. Low noise data is very important for relative comparisons between scans, but accuracy itself is the most important component when absolute geometry is of greatest importance.

It is easy to determine the amount of noise within a scan when there are perfectly flat surfaces within the scan to use as reference planes. In this case a best fit plan is fit to the area of the flat surface within in the scan, and the deviation of the scan points from this surface are used to determine the amount of noise within in scan.

For rough surfaces, such as the wall of a tunnel, the quantification of noise within a scan is more difficult. Noise can be created in phase based scanners by the speed of the scan. A higher rate of point capture causes the scan speed to increase, and the data collected to be noisier. This phenomenon is shown in Figure 2 and 3 which are sections of two successive scans of a tunnel wall at different resolutions.

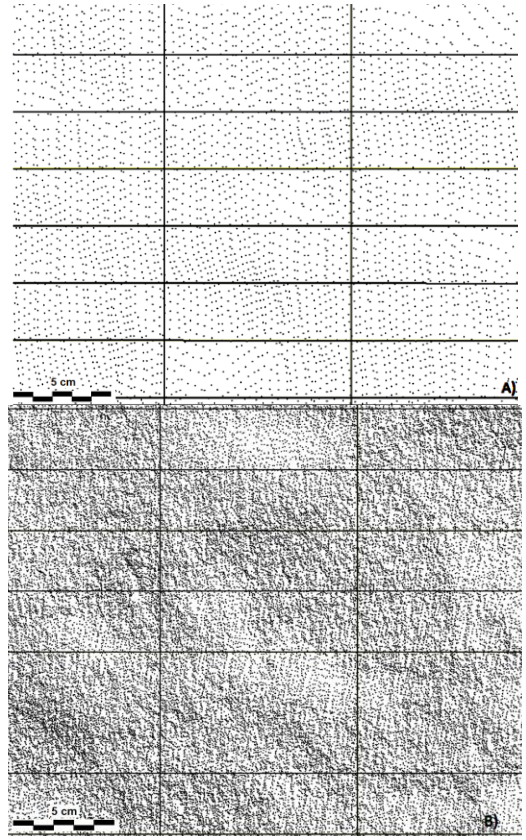

Figure 2. Comparison of medium resolution (A) and super high resolution (B) scan data

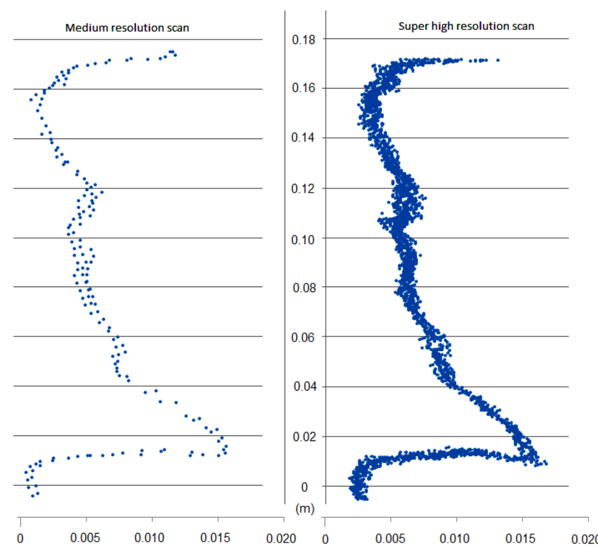

Figure 3. Comparison of medium resolution (A) and super high resolution (B) scan data (line sections from Fig 2).

2.1.2 Beam divergence and spot size

The spot size refers to the diameter of the laser as it strikes the object being surveyed. There are two different methods generally used by industry for measuring spot size (Figure 4). The first is the Gaussian method, where the laser beam is assumed to fall off in accordance to the Gaussian profile. In this measurement method the spot size is measured as the diameter of the beam where:

$$I = \frac{1}{e^2} I_{max} \quad [2]$$

where:

e = mathematical constant

I_{max} = maximum intensity of laser beam

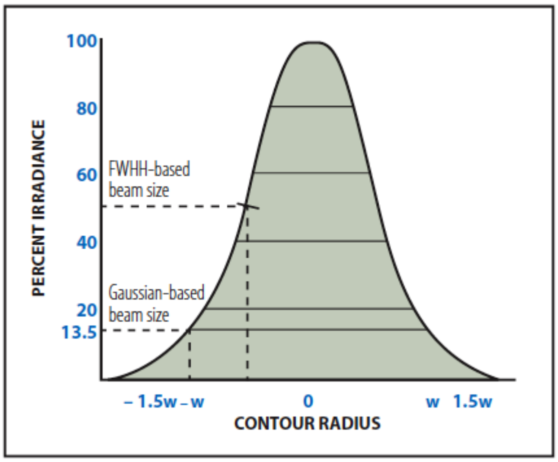

Figure 4. Gaussian profile showing both Gaussian and FWHH beam size measure (Jacobs, 2006)

The other method of spot size measurement is called full-width-half-height (FWHH), where the spot size is equal to the diameter at half the maximum intensity. FWHH can be used for beams that do not have a Gaussian profile. It is important to note that a FWHH measure of spot size will always result in a smaller measure of the spot size than the Gaussian method. Both methods to not measure the entire beam diameter but the spot size they define contains most of the energy of the beam.

The diameter of the laser has a certain diameter when it leaves the scanner, and the diameter of the beam varies as a function of distance from the scanner. It is important to know the spot size of the beam at the location of the scan as the spot size has implication on accuracy. A larger spot size results in less definition and also reduces accuracy. Hence, the further an object is away from the scanner, the less accurate its measurement will be. Smaller spot size also reduces the error created by edge effects, surface curvature effects, abrupt changes in reflectance and oblique angle effects (Jacobs, 2006).

2.1.3 Surface reflectivity

The amount of the laser beam reflected by a surface depends on the colour, roughness, and other material properties such as electric permittivity, magnetic permeability and conductivity (Lichti, 2002). Of main importance to Lidar scanning is the colour of the surface. White surfaces yield a strong reflection of the laser, whereas reflection from black surfaces is weak. White surfaces also produce less noise and less range error than dark surfaces (Jacobs, 2009). The affect a colour surface has on the reflectance of the beam depends on the spectral characteristics of the laser used by the scanner (Boehler, 2003).

2.1.4 Scan density

The scan density for a phase based scanner is based on the frequency of the beam measurement as a phase based scanner sends out a continuous laser source. Scan density can be increased either by sampling more frequently, or, where this is not an option, multiple scans can be done of the same area. In general, a higher scan density results in a higher resolution of the scan.

2.1.5 Angle of incidence

The angle at which the laser hits the object being scanned with affect the accuracy of the scan. At an angle of incidence perpendicular to the scanner, the accuracy of the data collected is greatest. As the angle increase and the scanned surface becomes more oblique to the scanner the measurement of the objects position becomes less accurate.

2.2 Angular error

The angular accuracy of Lidar point cloud data is broken into the horizontal angle accuracy and the vertical angle accuracy. Both of these errors are a function of the scanners measurement of one of its moving parts; the rotating mirror for vertical accuracy and the mechanical rotation for horizontal accuracy. Methods for testing the angular error of a scanner have been developed by Boehler et al. (2003), as ever scanner will have a different angular error.

2.3 Spurious scan points

Spurious scan points are points within a Lidar point cloud that do not represent any real object within the scan. These points should not have been collected by the scanner and must be removed by the user or through a filter before the scan data can be used for deformation monitoring. There are many conditions that can result in spurious points which include but are not limited to atmospheric conditions, interfering radiation, reflective surfaces, edge effects, and the scanners ambiguity interval.

2.3.1 Atmospheric conditions

Atmospheric conditions such as dust or steam in the air can result in unwanted return points. Dust and vapour can scatter the laser, either increasing the noise upon return or returning spurious points.

2.3.2 Interfering radiation
Interfering radiation such as the rays of the sun, which have a similar wavelength to that of the scanner, can be picked up as spurious points.

2.3.3 Reflective surfaces
Reflective surfaces such as mirrors or wet surfaces can reflect the laser beam of the scanner and be returned from different locations. They will be returned from locations other than where the beam initially hit the object.

2.3.4 Edge effects
As the spot size of the laser increases in size the effect of edges is increased. If only part of the laser hits the edge of an object, points will be returned leading away from the edge of the object.

2.3.5 Ambiguity interval
Every phase based laser scanner has a stated ambiguity interval. If points are returned to the laser scanner from a distance farther than the ambiguity interval they will be positioned to close to the scanner. For example, if the ambiguity interval of a scanner is 60 m and a point is returned from 62 m it will be stored as being 2 m away from the scanner.

2.4 Other sources of error

Other sources of error within Lidar scans can be created by the scan method chosen, the calibration of the scanner used, and the georeferencing and aligning of scans.

2.4.1 Scan mode
Depending on the scanner used there are multiple different scanning modes available, such as super high resolution, high resolution, low noise medium resolution. These different scan modes can result in different levels of noise and accuracy, but the degree of accuracy and amount of noise is specific to the scanner.

2.4.2 Calibration of scanner
It is important to ensure that the scanner used for collection of Lidar data is calibrated correctly. If a scanner is not calibrated correctly accuracy of the scan data will be reduced.

2.4.3 Georeferencing and alignment error
Error associated with the georeferencing of a Lidar scan is based on the error in the georeferencing measurements. The less error in the georeferencing measurements used to align the scan, the less error in the scan itself.

Error in a scan can also be created if it is not aligned properly with other scans, or if it is aligned with a scan that is poorly georeferenced.

3 DEFORMATION MONITORING
It is important to monitor deformation in tunnels because it allows for an understanding of the mechanisms of rockmass failure to be gained, and for the prediction of potential stability problems to be made (Lemy, 2006).

3.1 Current deformation monitoring techniques

The most common way to measure deformation in tunnels is to install a number of (usually 5) tacheometric reference points around the perimeter of the tunnel. The points are measured as shown in Figure 5 at a series of epochs to determine the amount of deformation in the tunnel. Although this method is common practice in industry it does present some issues. By only measuring discrete points around the tunnel perimeter, one is unable to gain an overall picture of the deformation that is occurring. Movements between the points, such as twisting, cannot be determined from this method of deformation monitoring (Sternberg, 2006).

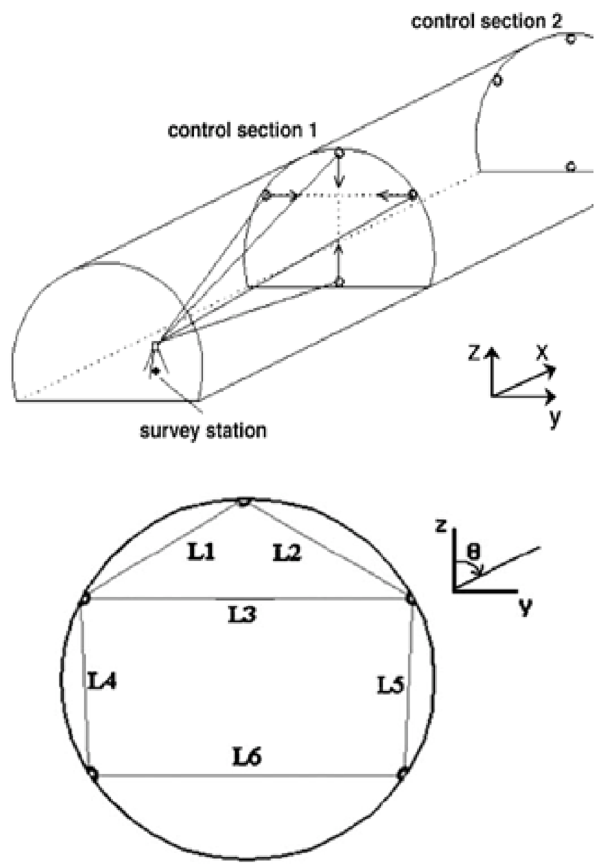

Figure 5. Installation of tacheometric reference points around tunnel perimeter for deformation monitoring (from Kontogianni et al., (2005) and Stiros et al. (2009))

Other measurement methods for tunnel deformation such as broken-ray videometrics (Qifeng, 2009) and GPS measurements (Liu, 2009) have been suggested but are not widely implemented.

3.2 Deformation monitoring with Lidar

Methods of deformation monitoring with Lidar have been proposed by Lemy (2006), van Gosliga (2006), Tsakiri

(2006), Moserrat (2007) and Nuttens (2010). At the very least Lidar can compliment total station measurement of deformation within tunnels (Lindenbergh, 2005).

Lidar provides the ability to get a much more accurate and complete picture of the location(s), mechanism and magnitude of tunnel deformation, as a surface map of the entire surface of the tunnel is being modelled rather than just a set of points.

Tunnel deformation monitoring is normally carried out on final precast concrete liners of circular tunnels. Van Gosliga (2006) has demonstrated a methodology in which a cylinder is fit to the scanned tunnel data and the deviation from this profile is measured. The method of cylinder fitting to scan data is not complicated and this type of deformation measurement works well for tunnels with uniform geometry.

For unlined or only shotcreted, non-circular tunnels or in tunnels where high deformation rates are expected, it is suggested that an ellipse be fit to a cross sectional slice of the tunnel so deformation in 2D can be seen. A small limestone brick lined tunnel was scanned (Figure 6) and a section of the tunnel data was selected for testing of the ellipse fitting methodology.

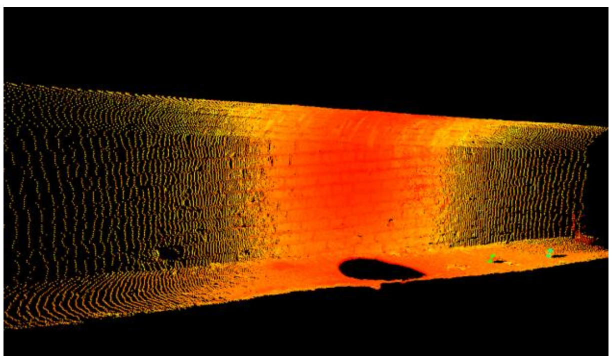

Figure 6. Scan of small limestone brick lined tunnel

The tunnel data was then imported into Matlab, and an ellipse was fit to the data using a direct least squares ellipse fitting algorithm developed by Fitzgibbon et al. (1999) (Figure 7). The tunnel profile can then be unrolled using the centre of the ellipse as a reference point (Figure 8). This allows for multiple profiles of the tunnel to be compared to each other using a moving average of the tunnel profile.

3.2.1 Issues using Lidar for deformation monitoring

Although there are clearly benefits Lidar can provide to deformation monitoring, there are still some issues that must be addressed.

For example, if the point spacing of the scan used for deformation monitoring is larger than the small scale roughness of the surface being measured, deformations that do not actually exist may be measured (Figure 9). If on the first round of scanning all the scan points land on the peaks of the roughness, and on the second scan all the points land in the troughs, a measured deformation approximately equal to the roughness of the surface will be measured that does not represent a real deformation. There is no way to ensure scan points always land in the same place so the only way to avoid this error is to ensure that the scan density is high enough to decrease the error created by surface roughness.

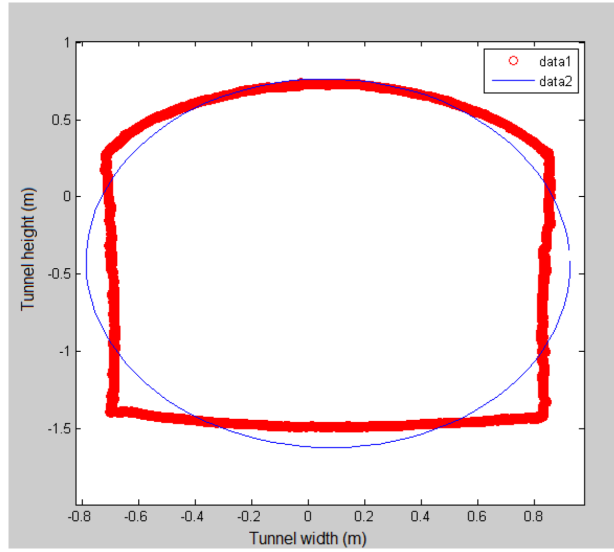

Figure 7. Slice of Lidar scan of tunnel profile fit with ellipse

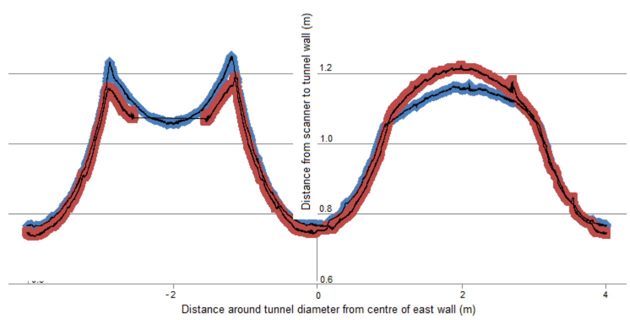

Figure 8. Two different slices of tunnel profile unrolled using ellipse so moving average of profile can be calculated

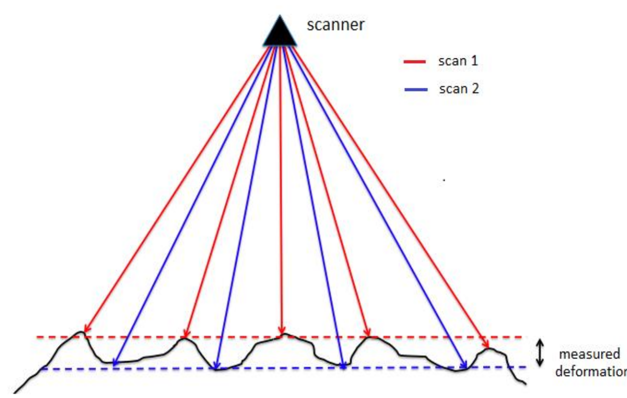

Figure 9. Two scans of a rough surface can result in a measured deformation that does not actually exist

It is also important to ensure the correct parts of the scan are being compared during deformation monitoring. That is to say, one should not be comparing points in the x or y direction of the scan, as then one is just comparing closest points and not actual surface deformation. It can be concluded that the best way to measure deformation is to create a surface from the point cloud data, and then use the normals of this surface to compare one scan to another. In this way the absolute deformation is monitored, rather than any shifts in the scans that are created by points landing at different places on different scans.

5. CONCLUSIONS

Deformation monitoring of tunnels using terrestrial Lidar scanning is useful as it allows for the movement of the entire surface to be characterized. To most effectively use Lidar for deformation monitoring, a complete understanding of all the accuracy issues associated with Lidar scanning is necessary. Once these accuracy issues are fully understood and their effect on scan data can be limited, a methodology for deformation monitoring with Lidar can be developed. For tunnels with non-circular profiles a method of ellipse fitting for profile analysis has been proposed. Future work will consist of refining the ellipse fitting methodology for tunnel profile analysis and measuring deformations in 3D.

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