Rock mass characterisation using LIDAR and automated point cloud processing

by John Kemeny, Split Engineering and University of Arizona, Tucson, USA and James Donovan, University of Utah, Salt Lake City, Utah, USA.

Introduction
At the heart of designing structures in rocks is a thorough characterisation of the rock mass prior to excavation (eg Priest, 1983). The results of rock mass characterisation go on to be used in blast and excavation design, determination of support requirements, cost analyses, numerical modelling, and many other aspects of the design process.

At a minimum, rock mass characterisation usually involves borehole logging and sampling, laboratory testing, and field mapping and data collection. Due to access problems, safety and time and cost concerns, there are many uncertainties and hazards associated with the field mapping and data collection aspects of rock characterisation projects.

New geotechnical/surveying technologies are becoming increasingly important. These include GPS, digital methods for field surveying and data collection, still and video digital cameras, and GIS and associated software for data processing and visualisation.

Ground based 3D imaging is a new and emerging technology for rock mass characterisation. This article defines 3D imaging to include ground based LIDAR surveys (also called 3D laser scanning), high resolution digital cameras, and a host of software for data processing, interpretation and visualisation.

Laser scanners work by collecting an array of high resolution laser-based position measurements. Laser scanners are capable of collecting data at rates over 20,000 points per second, with a position accuracy of less than 5mm at distances up to 800m. The output from a laser scanner survey is a "point cloud" consisting of millions of reflection points that represent the 3D surface that was scanned.

After some data cleaning, a triangulated surface can be rendered from the point cloud data, and many subsequent calculations and visualisations can be made using the 3D surface. In addition, a technique called texture mapping or photo draping can be used to overlay high-resolution colour information from digital images on to the 3D surface.

The techniques are being used in a number of engineering applications, including civil and architectural design, modelling, scene reconstruction, damage and condition assessment. An example of a point cloud of a rock face is shown in Figure 1 (taken along a highway south of Ouray, Colorado). This point cloud has about 1.5M points and the scanning took about 15 minutes.

Overview of the Split FX
Split Engineering LLC is developing a software package, Split FX, that uses data from 3D laser scanners to help field mapping, data collection and data processing associated with rock mass characterisation.
As well as being a point cloud viewer and editor, Split FX is capable of automatically extracting valuable information about discontinuities, including 3D orientation, spacing, size, roughness and block size. It can use information from digital images as well as from point clouds and can plot information on stereonets and histograms as well as export data in various formats. Some key features of the program follow.

**Point cloud registration**
The first step in point cloud processing is to orient the point cloud into the real world coordinate system based on field data. Split FX includes several methods for point cloud registration, the most common is to register the point cloud based on three targets of known position. However, for some applications (such as slope stability), only the orientation registration is required. In these instances, simpler methods are possible, such as only measuring the orientation of the scanner without any position surveying.

**Triangulated mesh generation**
The second step in the Split FX point cloud processing is to create a surface mesh from the point cloud data. The mesh generation algorithm in Split FX allows the user to control the amount of data smoothing. It also includes algorithms for filtering erroneous data points. Figure 2 shows a triangulated mesh of part of the point cloud in Figure 1.

**Patch finder**
The most important processing step in Split FX is the delineation of fracture "patches" from the triangulated surface mesh. The term patch is used rather than fracture, because a single large fracture may be delineated into several smaller patches, depending on the flatness and roughness of the fracture.

Fractures are detected by using the basic property that they are flat. Flat surfaces are automatically found in the triangulated mesh by first calculating the normal to each triangle, and then finding groups of adjacent triangles that satisfy a flatness criterion. This criterion has parameters that can be adjusted by the user.

**Figure 3** shows the patches that were found in the point cloud in Figure 1, using the criterion that a patch must be at least five triangles, and neighboring triangles in a patch must not deviate in orientation by more than 10°. The patches are outlined in yellow and holes in patches are outlined in red. Overall this simple criterion results in a good delineation of the major fractures at the site. Patches can also be manually added, deleted and edited.

**Stereonet plotting**
Once the patches have been found, their average orientations can be plotted on a stereonet. Split FX offers a full range of stereonet features, including upper/lower hemisphere, equal area/angle, grouping into sets and statistical parameters for joint sets.

Each patch plots as one point on the stereonet. However the size of the patch can be adjusted based on other parameters such as the patch area or roughness. Research has found that large patches are a good indication of important fractures and fracture sets. Small patches, on the other hand, may not actually be a fracture but only a small portion of the surface that happens to be flat. Thus it is useful to weight the points by area, and plot the smallest fractures as only a small dot.

**Figure 4** is a plot of the patches from Figure 3. In Figure 4a the points have not been weighted and in Figure 4b the points have been weighted by patch area. Figure 4b is much more useful in identifying fracture sets.

Split FX allows interaction between the stereonet and the point cloud. Delineating joint sets from stereonet data is difficult and necessitates professional expertise. Normally the data is taken in the field and the delineation of joint sets is accomplished later. This means that any difficulties with interpretation of the data cannot be resolved without additional fieldwork.

With access to the point cloud, however, additional analysis can be conducted off site. For instance, a group of patches can be selected on the stereonet and then viewed on the point cloud, as in **Figure 5**. This allows the user to go back and forth between the stereonet and the point cloud to determine with a great deal of precision the delineation of important fractures and fracture sets.

**Figure 6** shows the five joint sets that were found this way from the point cloud in Figure 1. Figure 6 also shows the statistical information calculated for each joint set. The total time spent to produce these results, starting from the raw point cloud file, was about one or two hours. The number of laser points that strike a fracture surface will depend on many factors, including the laser resolution, the size of the fracture, the distance from the fracture, and the orientation of the fracture relative to the scanner orientation.

Fractures that are sub-parallel to the direction of scanning may be under-represented on the stereonet because fewer laser points will strike those surfaces. However careful evaluation of the point cloud and the stereonet can reveal those under-represented areas in the stereonet,
and patches can be added accordingly using hand-editing tools in the FX program. The scanner can only detect surfaces in its line of sight, and the portion of the surface not “seen” is referred to as the scanner “shadow zone”. In some circumstances, an entire joint set may be in the shadow zone, and so several scans need to be taken at different angles to the face to adequately represent structural conditions at the site (Donovan et al, 2005b).

Processing digital images

Discontinuities appear in two forms in rock outcrops, as two-dimensional fracture traces and as three-dimensional fracture surfaces. LIDAR does an excellent job of capturing fracture surfaces, and as demonstrated above, LIDAR along with point cloud processing software can be used to reliably extract fracture orientation information.

LIDAR alone, however, will not necessarily give reliable information on other information used in rock mass characterisation, including fracture spacing, fracture size, and block size. This is because fractures may appear as fracture traces and not have a surface expression that can be captured by LIDAR. This is the case in the digital image in Figure 7 taken from a limestone quarry in Belgium.

The spacing of the limestone beds can readily be seen in the image, but the large surfaces that will be picked up by LIDAR do not reflect this spacing (the large surfaces only occur every three to six joint spacings). Similarly, the sizes of the fracture surfaces that would be captured from LIDAR are not representative of the very large extent of the bedding plane visible in the image.

Split FX has some features for processing digital images. The first step is to delineate the fracture traces in a digital image. Figure 8 shows the automatic delineation of fracture traces using an edge detection algorithm in Split FX (automatically extracted traces in red). From the fracture trace information, histograms of fracture orientation, length, spacing and roughness can be calculated and histograms of this information can be plotted.

The information from the point cloud and the digital image can be combined in several ways. For example, the traces as seen in a digital image such as Figure 8 can be compared with traces projected from the 3D fractures in the point cloud.

Figure 9 shows a simple example of this in Split FX. A histogram of the actual trace orientations in the outcrop shown in Figure 9 is compared with projections of the five fracture sets found in the point cloud in Figure 6. It indicates that the trace angles of around 45° are from joint sets two and four, and the trace angles of around 135° are due to the three other sets. The combined image/cloud information can also be used to identify possible missing sets in the point cloud and provide a means of combining the image and point cloud databases.

Sources of error

An important aspect of the use of 3D laserscanners for rock mass characterisation is understanding the errors associated with the instruments, the procedures for scanning in the field, and processing the resulting point clouds.

First, there is a significant range of accuracies associated with different 3D laserscanners. A review of all major 3D laserscanners is given in Pobolne (2005). In terms of scanning accuracy, there are three important parameters: distance accuracy, position accuracy and beam diameter.

All three parameters vary with distance, so either they are usually stated for a given distance or a formula is given for their variation with distance. At a distance of about 50m, the stated distance and position accuracies vary from 4mm to over 10mm (±) between the reviewed scanners. At a distance of about 30m the beam diameters range from 3mm to over 30mm.

Another important difference between scanners is the maximum range, varying from 2m to 2km. The actual maximum range for a particular scan depends on the reflectivity of the material being scanned and generally most rock faces can be scanned at distances over half the stated maximum range.

A parameter that can be varied by the user when scanning is the scan resolution, which is the distance or angle between individual laser rays. The minimum scan increment varies from 0.001° to 0.07° between the reviewed scanners.

For extracting fracture information from point clouds, a key measure of accuracy is the error in the estimation of a fracture’s strike and dip (or dip and dip direction). For a typical scan of a rock face, often over 1,000 laser points will intersect large fracture surfaces, while less than 50 points may intersect smaller surfaces.

It is important to understand how the number of laser points intersecting a fracture surface and the error of the laser impact the accuracy in the estimation of the strike and dip of the plane. For this purpose a Monte-Carlo based computer model has been developed to determine the error in the calculation of strike and dip, based on a laser scanner with given distance and position accuracies and a fracture plane with a given size and distance from the scanner. This model is described in Kemeny et al (2005).

Overall the results are very promising and indicate that errors in the strike and dip less than 0.5° should be able to be attained with fractures containing as little as 20 laser intersections and using almost any of the laser scanners available.

It should be noted that the model does not consider some important conditions, such as roughness of the fracture surfaces, laser reflectsivity and distance between laser points.
sources of possible error, including atmospheric and temperature errors. It also does not include the error associated with registering the point cloud to the real world coordinate system. Depending on the method of registration, errors in the estimation of fracture strike and dip of 2° to 4° may occur (Kemeny et al., 2003).

One way to assess the error in the estimation of strike and dip is to compare orientation measurements extracted from the point cloud with measurements made using manual scanline or cell mapping. Figure 10 shows one such comparison made at a field site in the mountains northeast of Tucson, Arizona. As shown in Figure 11, 50 manual measurements were made and 441 fractures were extracted from the point cloud. The results shown in Figure 11 are typical of the results of these kinds of comparisons.

Overall, there is a good correlation between the measured and extracted orientations. More important however, the extraction of almost ten times as many joint orientations results in a much more accurate assessment of the structural conditions at the site.

Discussion
LIDAR is an exciting new technology for rock mass characterisation, with high quality data obtainable with just a few hours of field time. The point cloud in Figure 1 was obtained without any survey points on the rock face (using the orient by scanner method), eliminating many of the safety hazards associated with field site characterisation.

Automated point cloud processing software such as Split FX allow a large amount of rock characterisation information to be obtained accurately and with only a few hours of processing time. Overall, it is felt that LIDAR surveys, along with automated point cloud processing, is cost effective and can now be used routinely on engineering projects. There are still many issues associated with using LIDAR surveys for rock mass characterisation. Some of these are listed below and will form the basis for future research and development.

1. A number of different LIDAR units are manufactured and commercially available for purchase or hire. The different units have similar, but not identical, capabilities. While manufacturers publish specifications for their units, little guidance has been developed concerning the specifications required (range, resolution, other features) for a particular field application.

2. There are a number of software packages available for processing LIDAR data. Many are created by the scanner manufacturers. Little guidance has been developed concerning suitable software choices for a given application.

3. So far, little attention has been paid to the compatibility of data inputs and outputs between the different software packages.

4. Guidance is needed on specific and appropriate procedures involved to conduct ground-based LIDAR surveys, as well as the appropriate data validation, processing and management procedures. In the field, appropriate procedures must be specified concerning:
    - the suitability of a site for LIDAR surveying
    - the procedures for scanning (number of scans, point spacing, resolution, etc.)
    - establishing surveying control points
    - taking digital images
    - collecting non-digital types of information.

5. After a survey is conducted, data processing and management procedures include the specific steps that should be taken to process the data using various software packages for specific outcomes (ie calculate the slope hazard at a particular site) and the appropriate standards and formats for the various kinds of data from a LIDAR survey, including the raw scanner files, point cloud files, rendered surface files, and calculations and interpretations made on this data.

6. Finally, technical improvements are expected in the future in both LIDAR hardware and point cloud processing software and guidance is needed on the direction and timeliness of these improvements as they pertain to specific field applications.

References
Some references on Split FX and on using LIDAR for rock mass characterisation are given below. A beta version of Split FX, along with tutorials, are available free at www.spliteng.com.


Figure 9: Comparison of actual trace orientations in the outcrop in Figure 8 with the projection of the five fracture sets found from the point cloud in Figure 6.

Figure 10: Field site near Tucson, Arizona where both manual measurements and LIDAR surveys were conducted.

Figure 11: Comparison between field and LIDAR-generated results at the site in Figure 7.