AN APPROACH TO AUTOMATE DISCONTINUITY MEASUREMENTS OF ROCK FACES USING LASER SCANNING TECHNIQUES

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ABSTRACT

A recent development in the use of lidar remote sensing techniques is ground-based laser scanning. Laser scanning of rock faces yields the spatial relation between all scanned rock surface points, at a very high resolution, basically a dense "point cloud" in three-dimensional space. The subject of this research is to obtain discontinuity information from the point cloud data set, using an approach that can be automated. The first step in this methodology is to interpolate the point cloud data using 3D Delaunay triangulation in order to create a 3D surface. As a 3D triangulated surface, the scanned rock face is represented by a large number of triangles. The orientation of each triangle can subsequently be computed using basic geometrical rules. Analysis of the kernel density stereo plots of the orientation of all triangles, reveal that specific discontinuity sets can be recognised. Obviously, if this approach can be further developed and fully automated, this would give the site engineer or geologist, in real-time, evidence on the internal structure of any discontinuous rock mass. Particularly in areas where access to rock outcrops is poor, application of this technique will be very promising.

1. INTRODUCTION - MOTIVATION OF THE RESEARCH

The idea to obtain discontinuity information from an exposed rock mass through remote sensing is not new. Analogue stereo photogrammetric techniques already allowed the measurement of orientations of individual discontinuities (Rengers, 1967). More recently, applications have been developed that use digital imagery and data processing instead. Basic photogrammetric principles combined with pattern recognition routines allow the user to create 3D models of virtually any object in a cost-effective way (Pollefeys et al. 2000). In the field of rock mechanics applications have been developed that make use of this technique (Fasching et al. 2001, Roberts & Poropat, 2000). These applications do, however, require time-consuming data processing to arrive at the final 3D model and still require manual outlining of discontinuity surfaces in order to calculate orientations. Feng et al. (2001) demonstrated the use of a non-reflector total station to measure fracture orientations. Although good results were obtained, the amount of data points that can be acquired is limited and the manual operation of the total station still requires a large amount of effort on-site.

Laser scanning as a remote sensing technique may provide an attractive alternative approach. It is likely to offer the desired data quality and quantity to arrive at a statistically sound analysis of rock mass discontinuities without elaborate and time consuming data acquisition and data processing. The main advantage over photogrammetry is that laser scanning provides direct co-ordinate measurement and does not rely upon matching approaches to solve the correspondence problem between conjugate feature points within the scene (Baltsavias, 1999). In other words, ground-based laser scanning provides an *instant 3D model* with very high accuracy and data density, which will allow the user to analyse the data in real-time.

The second motivation behind this research is that, considering this large accuracy and high spatial density of laser measurements and the possibilities that modern (3D) data modelling techniques offer, more information can be obtained from the reflected laser signal than merely the geometrical aspects. The principal assumption here is that through statistical evaluation of a 3D surface derived from the cloud of points, it will be possible to differentiate and measure the different discontinuity sets that constitute any scanned discontinuous rock mass. Only this very detailed type of rock mass information could provide the rock mechanics engineer with comprehensive information to characterize and quantify the 3D spatial variation in rock mass properties, which will ultimately enable classification of rock masses, objectively, in terms of homogeneity (Hack, 1998).

2. BACKGROUND ON 3D LASER SCANNING

Ground-based 3D laser scanning is an active remote sensing technique, which yields accurate and detailed 3D information of virtually any object that the laser is able to scan. Computer hard- and software nowadays easily permit the handling of the very large data files inherently associated with this kind of dense data. Different ground-based laser scanning systems are already on the market. The most important commercial systems are: Cyrax (Cyrax, 2002), I-Site (I-site, 2002) and the laser scanners developed by Riegl (Riegl, 2002). The data density typically varies between 25 and 50 mm and the distance from which object can be scanned range between 1.5 to 50 m (for Cyrax) and 2 to 750 m. (for I-site and Riegl).

The location of each point in 3D space is calculated by determining the “time of flight” of the reflected laser beam, which is proportional to the distance from the scanner. Combined with the directional parameters of the scanner (azimuth and angle) this will give the location relative to the scanner’s position. One type of laser scanner, Imager 5003 (Zoller & Fröhlich, 2002), make use of the amplitude modulated continuous wave principle, which uses the phase difference between the emitted and received laser beam to calculate this distance (Mettenleiter & Fröhlich, 2000), which yield a higher spatial accuracy.

Laser scanning of rock outcrops yields the spatial relation between all scanned rock surface points in three-dimensional space. The type of data that is being returned by a laser scanner is basically a dense "cloud" of points in 3D space. The data output of a laser scan survey consists merely of a number of records equal to the number of scanned point where each record consist of an X, Y and Z coordinate (relative to the scanner's position) (see Figure 7). Each point within this cloud represents a single spot on the rock surface. Obviously, the higher the point density the more accurate the rock surface is being represented. An additional attribute given with each point is the reflected intensity (I). At this moment the intensity is not used in the analysis. It could however serve as a useful indicator of for example discontinuity surface roughness.

Current applications of ground-based laser scanning techniques in rock mechanics can be found in areas where excavations of rock masses are involved. The purpose here has been primarily to analyse the geometrical aspects through the computation of excavated volumes or monitoring of the progress of excavation works (I-site, 2002 and Folz, 2000).

3. REPRESENTATION OF THE ROCK SURFACE BY 3D TRIANGULATION

The objective of this research is to describe the geometry of the rock outcrop statistically in terms of orientations of the individual faces that make up the entire surface. Before this can be done the point cloud has to be translated into a continuous 3D surface, through *surface reconstruction*. Surface reconstruction provides a powerful concept for modelling shapes from samples. For point cloud data with only geometric coordinates as input, Delaunay based surface reconstruction algorithms have been shown to be quite effective both in theory and practice (Dey et al. 2001).

Since we are dealing with a rock outcrop scanned at very high detail, generation of a "normal" 2D TIN (Triangulated Irregular Network) will no give the required result. Rock surfaces are often very irregular and consequently vertical as well as horizontal surfaces (i.e. perpendicular surfaces) may be present within the same outcropping rock face. Thus, for similar X and Y values, there may be more than one Z value. To represent such a surface correctly, *3D triangulation* has to be applied, which should result in a genuine 3D TIN.

Most of the available software that can perform 3D triangulation on point clouds actually creates 3D tetrahedrons instead of 3D triangles. Much of the 3D (geologic) modelling industry is interested in modelling of 3D (geologic) bodies. For this research it is essential to reconstruct a 3D surface rather than a 3D body. At least two software packages were found that could carry out a 3D Delaunay surface triangulation: COCONE (Cocone, 2002) and POINTS2POLYS (Paraform, 2002). Although the softwares delivered with the scanner hardware are very advanced and capable of doing 3D surface reconstruction, it was decided to use these platform-independent and freely available softwares., COCONE and POINTS2POLYS.

Both programs give similar results. Where the point cloud is less dense or too scattered (often because of vegetation in the rocks face) both programs yield holes in the surface. For this research this is actually desired, since surface reconstruction is only needed in areas with proper reflection, i.e. where there is a solid rock surface and not where there is disturbance because of vegetation (brushes, trees or grass).

A sample laser scanning data set was made of a rock face along the I-70 service road in Mt. Vernon Canyon in the foothills of the Rocky Mountains (Colorado, USA). The rock outcrop contains well-defined discontinuities (Figure 1) and makes therefore a good test case. The rock mass belongs to the Idaho Springs Formation, which is a Precambrian formation consisting of gneiss, schist and granite with slate filling the spaces between the metamorphic and igneous rock. The scans of the rock face were made with a Cyrax laser scanner from two different locations, parallel to the rock face. Both data sets were subsequently integrated in one larger data set. As a result, portions of the rock face that were obscured in the single scan (see shadows in Figure 3) could be measured during the other scan and thus a truly 3D point cloud data set was generated, without substantial "shadow" areas (Figure 2).

Figure 1. Cyrax 3D laser scanner in front of the surveyed rock face.

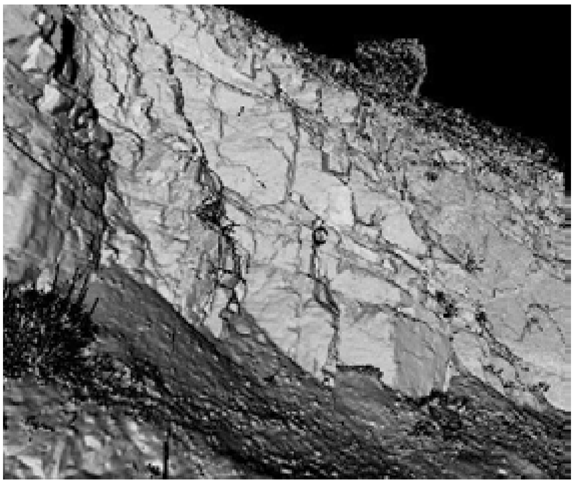


Figure 2. Rendered digital surface of a part of the rock face shown in Figure 1.

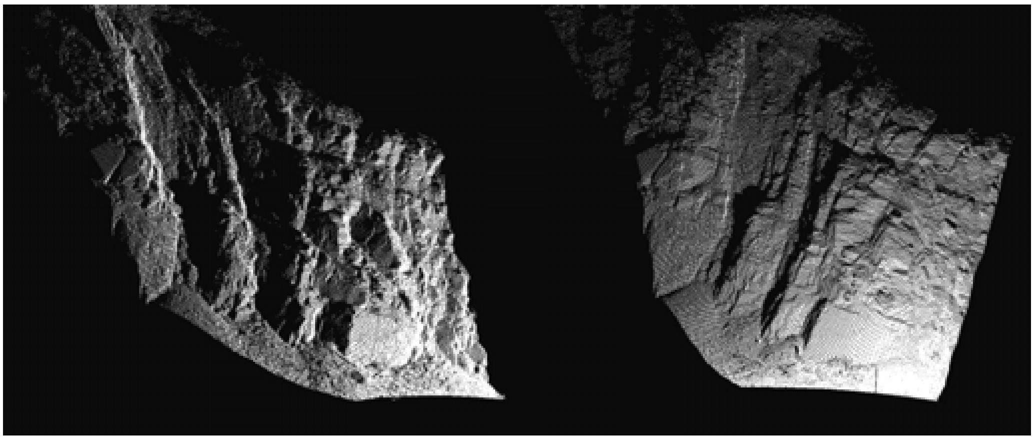


Figure 3. The same exposure from 2 different locations by laserscan.

4. ANALYSIS OF THE 3D TRIANGULATION DATA

The TIN data structure is fairly simple. It merely consists of a number of records (equal to the number of triangles), which list the three nodes that make up each individual triangle (see Figures 7 and 8). Each node number refers back to the record number of the node list, i.e. the point cloud data record table. Since it's X, Y and Z coordinates fix each node in 3D space, it is possible using simple geometrical rules, to determine the orientation of each individual triangle. This is done through the calculation of the normal vector, which is the result of a cross product of any two of the three vectors that represent the sides of each triangle (see Figure 9).

As stated before, each triangle represents a small part of the rock outcrop. We can safely assume that most of the orientations of the facets of a rock outcrop are determined by the internal discontinuity structure of the rock mass. In which case each modelled facet (in the form of a TIN triangle) in fact represents a single orientation measurement, comparable to an individual manual orientation measurement made by compass. Because of the high data density of the laser data, it is possible to have for a single rock outcrop thousands to millions of TIN triangles. Consequently, this allows a similar amount of orientation calculations, which will of course provide a very solid basis to statistically analyse the discontinuity information of any exposed rock mass.

In order to determine whether it is indeed possible to observe (visually) patterns in the data, it was decided to plot the orientation calculation results in an equal area stereonet. Since most of the available stereo plotting programs could not handle such large numbers of orientation data, ArcView GIS was used instead. Through projection of the orientation data to metric coordinates (X,Y) the orientations can be plotted in the GIS as in a stereonet.

Not the entire slope was analysed but as a first test a subset of the data was made, which covers an area with well-defined discontinuities (Figure 4). The selection was also made such that this portion of the outcrop is at the foot of the slope and therefore easily accessed for field-verification purposes (the acquisition of scanline data measurements). The actual 3D virtual rock face model is shown as a rendered image in Figure 5. The rendered 3D TIN model looks very similar to the photograph, to the extent that on the image of the 3D model even a higher amount of structural detail can be observed. After the orientation calculation, the data points were plotted in a stereonet. Kernel density analysis and contouring of the plotted points was done to identify trends in the data (Figure 6). From this result it is apparent that several discontinuity sets can be distinguished.

5. CONCLUSIONS

These first results are encouraging and demonstrate that it is possible to identify discontinuity sets of a rock mass statistically, using 3D laser scan data. The procedure to obtain these results can easily be automated. The 3D laser scanner allows creating "instant 3D models", therefore it will be possible to develop methods to characterise rock masses on the basis of their discontinuity patterns in real-time. Such a system will be useful for operations where rapid analysis of rock mass properties is required, e.g. in tunnelling or mining industry.

Not only will the methodology provide real-time information, it is also expected that the high detail and accuracy of the information that is generated will allow the rock mechanics expert to quantify the variation in rock mass properties. This will ultimately result in an objective approach to characterise and classify discontinuous rock masses in terms of homogeneity.

Figure 4. Photo of the scanned rock face, the area for which the orientation analysis (Figure 6) is done has been outlined.

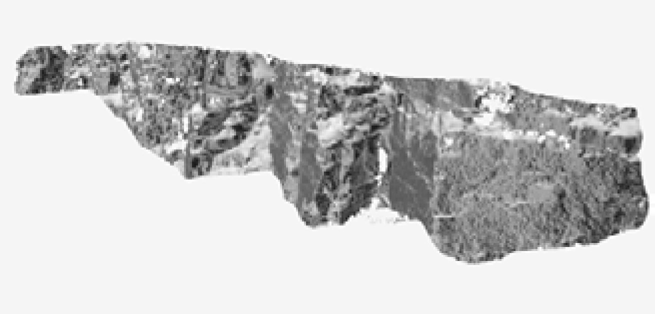


Figure 5. Digitally rendered 3D TIN of the selected rock section as outlined in Figure 4.

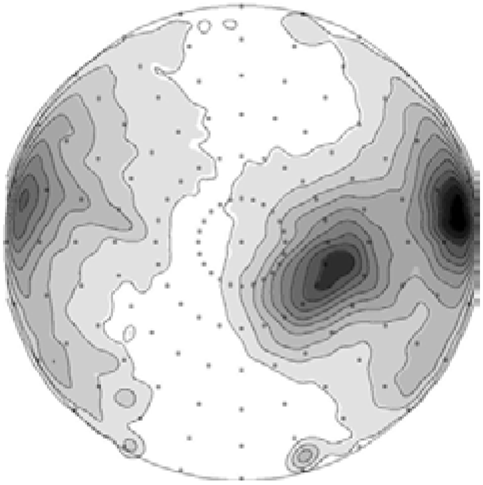


Figure 6. Equal area kernel density stereoplot of the orientations of all triangles within the 3D surface model of the section shown in Figure 5.

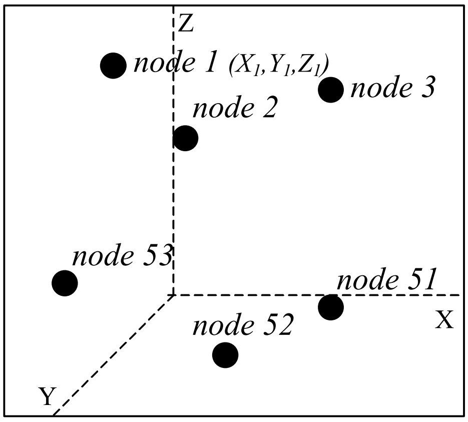


Figure 7. Point cloud data structure

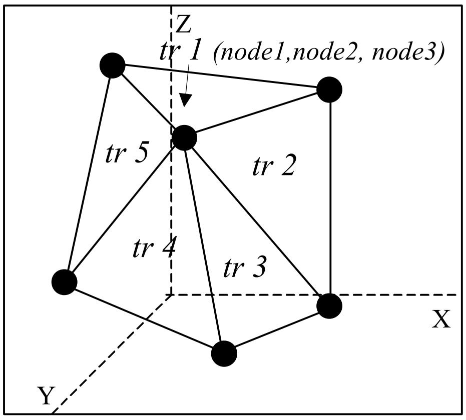
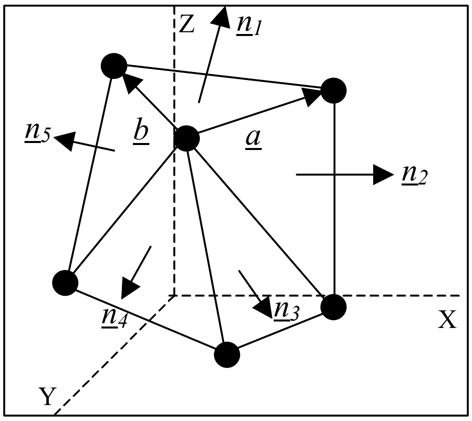


Figure 8. 3D TIN data structure



$$\underline{a} = \begin{pmatrix} X_3 - X_2 \\ Y_3 - Y_2 \\ Z_3 - Z_2 \end{pmatrix}$$

$$\underline{b} = \begin{pmatrix} X_1 - X_2 \\ Y_1 - Y_2 \\ Z_1 - Z_2 \end{pmatrix}$$

$$\underline{n}_1 = \underline{a} \times \underline{b}$$

($\underline{n}_1$ is the vector *cross product* of $\underline{a}$ and $\underline{b}$)

Figure 9. Determination of normal vector of individual triangles using basic geometrical rules. The normal vector is used to calculate the orientation of each triangle (in terms of strike and dip).

6. DIRECTIONS FOR FUTURE RESEARCH

Future research on this subject will focus on the following objectives:

- Development of routines to statistically recognise discontinuity patterns in the 3D data using spherical data distribution analysis and pattern recognition and subsequent determination of the variance within each discontinuity data cluster.
- Development of routines to calculate discontinuity spacing distributions on the basis of the 3D TIN surface model for each identified discontinuity set.
- Use of the reflected intensity data and geometrical information to quantify roughness of individual discontinuity sets. Comparison with detailed laser profiling of single joint surfaces.

- Integration of laserscan data with optical imagery (digital photographs) and comparison of the 3D models with terrestrial photogrammetric analysis.
- Comparison of 3D laser scan data made of a similar rock mass at different resolutions and scales. Comparison with airborne laser scanning data to determine the scale effect within rock masses.

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