

Fracture mapping using 3D laser scanning techniques

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ABSTRACT: 3D terrestrial laser scanning is nowadays the technique for 3D mapping and documentation of rock faces and tunnels that shows most potential. In this paper two state-of-the-art methods are described to map rock mass fractures on the basis of 3D laser scan data: a semi-automatic method and a fully automated approach. Both methods give good results and have both their advantages and disadvantages in terms of practical implementation. Both methods make use of the very high level of detail and precision that the 3D laser scan data provide. This, together with the rapid method and simple way of data acquisition makes 3D lasers scanning the most promising fracture mapping tool in the future.

1 INTRODUCTION

In a rock engineering project, fracture mapping is one of the important steps, which provides the input data for further rock mechanics analysis, rock engineering design and numerical modeling. Currently, fracture mapping at rock faces is well-known performed by using compass and inclinometer, and documentation by recording information on a notebook and photographing with a camera. Although these so-called traditional methods are now still used in most of the rock engineering projects, the quality and quantity of the data are sometimes unable to meet the requirement in rock engineering projects.

The most well-known drawback for traditional methods is that too much personal work are involving in the in-situ data acquisition procedure, which is time-consuming, not accurate enough, sometimes difficult and dangerous to reach the rock faces physically. In addition, the way of data recording and storing can not make the full use of modern IT and computer technology to speed up the data processing, and then provide the input data in a required format for further analysis and designing.

Therefore, it has been recently realized that applying a new method for in-situ data acquisition is the key point to solve the bottleneck problem for improving the rock face mapping data with both quality and quantity. In recent years, the efforts of developing new techniques for in-situ data collection at rock faces are in progress. Techniques, such as photogrammetry (e.g. Harrison, 1993; Coe, 1995), image processing (e.g. Post and Kemeny, 2001), total station (Bulut and Tudes, 1996; Feng, 1999) and laser scanning (Feng 2001, Slob et al., 2002, 2004), have been tested for measuring of different joint parameters and documentation of rock faces. The presented method has applied a newly-developed 3D visual laser scanning technique to characterization and documentation of joint and jointed rock masses at rock faces.

A 3D terrestrial laser scanner can quickly record a great amount of digital 3D information of an object. Each scan takes just few minutes with a high-speed sampling rate up to

hundreds of thousands of points per second, and covers up to hundreds of square meters with the optimal scanning resolution in the order of mm's. Each scanning point can be recorded by 4 parameters, i.e. the 3D co-ordinates (X, Y, Z) and the reflected intensity (I). Some laser scanners can in addition provide colour information (R,G,B) through the concurrent use of digital photography.

Therefore, the geometry of rock faces can be quickly recorded in three dimensions with the 3D digital model and a grey-scale or even colour image (3D gray-scale image or 3D colour information). By measuring a few reference points for each scan, the rock face can be transformed into a geo-referenced co-ordinate system, which enables the user to locate any parts of a rock face in real 3D space. Therefore, 3D measurement and documentation of a rock face can be more quickly recorded in a 3D visual and digital format.

The largest problem so far has been to handle the data output. It is not very difficult to carry out a 3D laser scan survey, but it has been quite hard to convert the data to useful information that can directly be used in rock engineering practice. In this paper two different methods are discussed to handle the large amount of point data that a typical 3D terrestrial laser scanning survey yield.

The first method discusses a semi-automatic approach, which makes use of the expert knowledge of the user to identify important rock fractures in the scene. In this way, very quickly, even in real-time, detailed measurements can be made of the key fractures in the scanned face or tunnel wall.

The second method is based on a fully automated approach, which identifies and measures every individual fracture that can be detected. This method is more time-consuming, but can be used to generate large amounts of fracture data, which, in turn, can be used as input for statistical analysis (e.g. calculation of block size distribution) or can be used as input to numerical modeling tools (e.g. 3DEC).

2 SEMI-AUTOMATED PROCESSING OF LASERSCAN DATA FOR MAPPING FRACTURES

By using the semi-automatic method, orientation of a fracture plane (e.g. dip and strike) can be determined interactively or semi-automatically from the 3D laser scanning data. The presented method aims to not only make use of the advantage of modern computer techniques, but also enable the operators to utilize their geological background knowledge to control the mapping results. A typical mapping procedure of this method is not only taken by a computer software as virtual mapping platform, but also interactively performed between the computer and the operator: 1) select a part of rock surface from the whole 3D scanning model by the operator; 2) choose a fracture exposed on the scanned rock surface, and mark the exposed fracture surface interactively by the operator; 3) Automatically calculate the best-fit fracture plane by the computer program, and then calculate the fracture orientation. Figure 1 shows an example for fracture mapping based on 3D laser scanning data from an exposed rock face. Once selecting an interesting area from an exposed rock surface (Fig. 1a), a fracture can be interactively selected by a software based on the user's geological background from the 3D digital model, which is important in the authors' opinion, so non-geological linear features can be avoided to be mapped. Afterwards, a best-fit fracture plane can be created by the computer (Fig. 1b), and then automatically calculate the fracture orientation (dip angle and dip direction). Therefore, orientation of fracture planes can be semi-automatically determined, which means that the geologists select the representative fracture planes in 3D laser image, and the computer technology is employed to make the mapping procedure automatically.

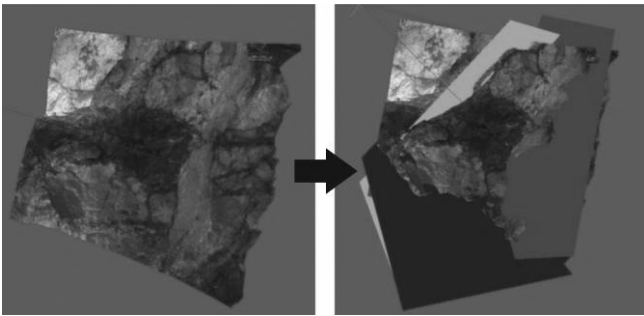


Figure 1. Fracture mapping based on 3D laser scanning data: (a) Scanned exposed rock face; (b) a best-fit fracture plane created from scanning data to determine fracture orientation

By using this method, fracture mapping can be interactively performed in 3D virtual model created by high-resolution scanning data. Although taking a little while to select a fracture interactively, it is important to guarantee that a correct fracture is chosen for mapping. In addition, by the help of computer technology, such as growing a plane from a seed point, rotation and moving a plane with accurate steps, a fracture plane can be accurately and quickly selected, and then calculation of fracture orientation and displaying of fractures in a 3D digital model become automatic and easy to handle, and can directly input to further analysis and modeling.

3 AUTOMATED PROCESSING OF LASERSCAN DATA FOR MAPPING FRACTURES

3.1 Automated processing through surface reconstruction

The first method of automated processing of laserscan data is based on the creation of structure in the pointcloud data through 3D surface reconstruction. This method is documented and published in detail by Slob et al. (2005) and Van Knapen et al. (2006). In short, the basic idea behind this method was that the reconstructed virtual computer-based 3D surface, which consists of a mesh of triangular facets, contains all the discontinuity information. Each meshed triangular facet has in fact an orientation. By plotting of all the facet orientations in a stereonet it is possible to detect trends in the data. The trends then represent the discontinuity sets. Through fuzzy k-means clustering these sets can automatically be recognised and thus the mean orientation of each set can be determined.

3.2 Automated processing through direct segmentation

The other method is based on a direct segmentation approach for processing of the point cloud data. The direct segmentation approach makes use of the raw point cloud data and the advantage is that it does not require prior surface reconstruction, which is the case for the previous method. The spatial structure of the point cloud data is provided through a (kd) tree-based structure. The purpose of the tree structure is to speed up the spatial search in the point cloud, which is important to the efficiency of the direct segmentation approach.

The basic principle behind the segmentation method is relatively simple: it starts with the selection of a seed point around which the nearest neighboring points are selected within a specified search distance. If it can be mathematically verified that most of the neighboring points lie close to the same flat plane, they are all labeled with a (similar) label. From these labeled points, their neighboring points are selected and it is again determined whether most of these points are positioned close to the same mathematical definition of a plane that is found before. This process is repeated unless no new points are found, which demarcates the extent of the discontinuity plane. Then a new random (unlabelled) seed point is selected and the process is repeated until all points in the data set are classified. All points that have the same class are thus part of the same discontinuity planes. Consequently, a single mathematical expression in the form of the plane equation can be determined for each discontinuity. Therefore, the poles or normals to those planes can also be plotted as orientations in a stereo plot. The next step is to identify and demarcate the discontinuity sets. The poles of the planes that are part of the same Fuzzy or Fisher cluster can be re-classified as belonging to the same discontinuity set. In this way the entire dataset can finally be simplified as a number of sets with average orientations. Since the plane equation of each plane in a set is known, the calculation of discontinuity set spacing becomes possible as well.

In this paper only one method is demonstrated for the mathematical recognition of planes in the point data, namely: Principal Component Analysis (PCA). Another method that could successfully be used is a Hough

transformation (Vosselman, 2005). The segmentation approach based on PCA is implemented in a Matlab-based computer code. Both procedures yield a segmented or classified point cloud which is subsequently processed with Matlab to derive the individual plane equations, to find the discontinuity sets and compute the set spacings. Both methods are applied to data of two different rock faces and the results are compared with manual field measurements.

Below the illustrations clearly demonstrate the results and possibilities of using the direction segmentation approach to derived discontinuity orientations data from a large part of a rock exposure. The various illustrations speak for themselves and demonstrate the various analysis and data processing steps in the method. Although at this moment the various steps require some interference of the user in terms of data import and export to various software, the entire process can in principle be fully automated so that in the future the results can be analyzed and displayed in real time, in the field.



Figure 2. Rock exposure with well-developed discontinuity sets along a secondary road in Spain, from the towns of Falset to Bellmunt in Baix-Camp, Catalonia. The rock mass consist of Carboniferous Meta-Siltstone and Slates. According to BS: 5930:1999 the rock mass can be described as: dark-grey to black, silt-clay size, small tabular, slightly weathered META-SILTSTONES and SLATES. The dimensions of the white boards are 60x60 cm. The size of the outlined area that is used for the laser scan analysis is 4x4 meters (see Figures 3 to 5).

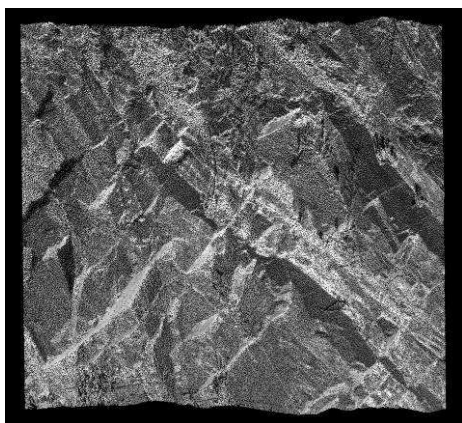


Figure 3. This is a visualization of the laserscan pointcloud of the part of the rock exposure that is outlined in Figure 2. The grey-

scaled value is the laser's reflected intensity value. This pointcloud consist of 616300 points, that are defined by their x,y and z coordinate values. The pointcloud is georeferenced, i.e. oriented with the positive y-axis towards the North and the entire set is level, i.e. the positive z-axis points straight upwards.

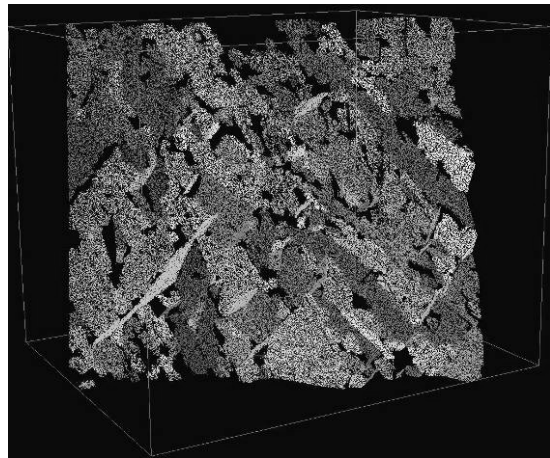


Figure 4. This illustration is the same pointcloud, show in Figure 3, but now each point is classified ('segmented') to individual discontinuity planes. The various classes (planes) are show with different colours. In this case a total of 285 individual planes were recognised

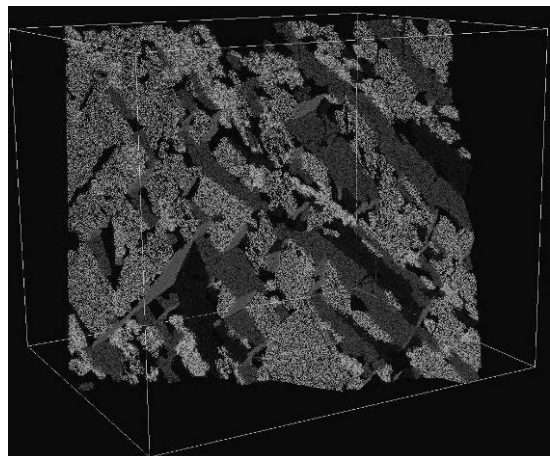


Figure 5. This illustration shows the segmented point, but now classified according to the 5 discontinuity sets that are identified in the stereoplot of all the 285 planes (please refer to Figure 6.)

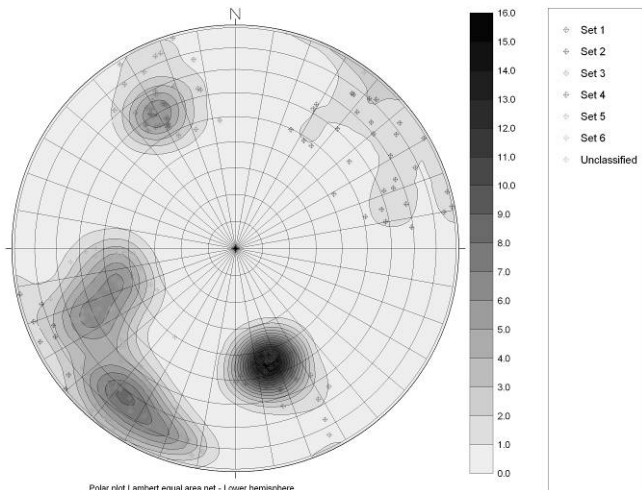


Figure 6. The orientations of the 285 individual planes that were recognised after the pointcloud segmentation are plotted in this stereo (polar) plot. Visually, 5 discontinuity sets are recognised. The various poles of the planes are clustered with Fuzzy k-means clustering. The only user input is the number of joint sets. The colour of the poles in the various sets correspond with the coloured pointcloud in Figure 5, i.e. the 'red' set (1) is the bedding, which is the same as the slaty cleavage in this case.

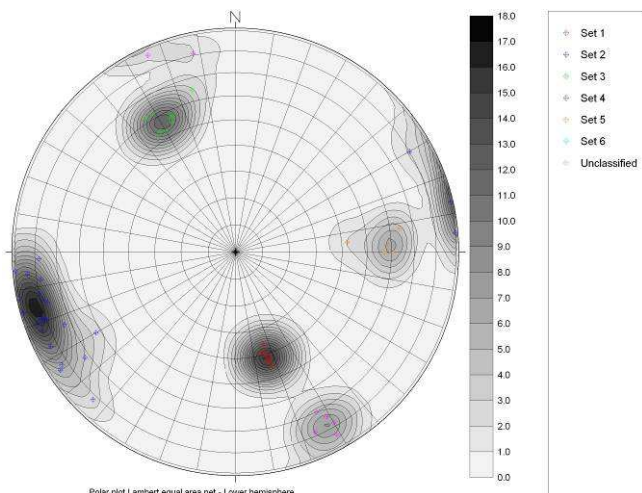


Figure 7. This is the stereoplot of manual (scanline) orientation measurements. It is hard to compare both stereoplots. Only two of the discontinuity sets clearly correspond, while the other sets show little correlation.

4 CONCLUSIONS

In this paper, the new 3D terrestrial laser scanning is introduced for 3D mapping and documentation of rock faces, which enables one to capture 3D data of rock faces with high sampling speed and good resolution, especially 3D laser image can help geologists to perform rock face mapping in a 3D digital model, and speed up the data processing procedure.

Two methods, semi-automatic and full-automatic, are presented to apply 3D terrestrial laser scanning data for fracture mapping, which show both their advantages and disadvantages regarding to the practical applications. With a semi-automatic method, one can surely select a fracture

for mapping with the background knowledge, and then speed up the mapping procedure by the computer capacity. The full-automatic method enables one to capture a large amount of data for statistic analysis, and provide enough data for further analysis and numerical modeling.

In addition, the high-resolution scanning data with both visual and special information can be not only used for fracture mapping, but also has a great potential application to solving different problems in rock engineering.

REFERENCES

- Bulut, F. and S. Tüdes. 1996. Determination of discontinuity traces on inaccessible rock slopes using electronic tacheometer: an example from the İkizdere (Rize) Region, Turkey. *Engineering Geology* 44, pp. 229-233.
- BS 5930:1999. Code of practice for site investigations. British Standard. British Standard Institution, London. BSI 10-1999. 192 pp.
- Coe, J. A. 1995. Close-range photogrammetric geological mapping and structural analysis, Master thesis, *Colorado School of Mines, USA*.
- Feng Q. 1999. Geodetic total station for measuring geometry of discontinuities at exposed rock faces. Licentiate thesis. *Royal Institute of Technology, Sweden*.
- Feng Q., B. Anders and Stephansson O., 2001. Fracture mapping at exposed rock faces by using close-range digital photogrammetry and geodetic total station. Proceedings of The 38th U.S. Rock Mechanics Symposium, Washington D.C. July 7-10. 2001.
- Feng Q. 2001. Novel methods for 3-D semi-automatic mapping of fracture geometry at exposed rock faces. Ph.D. Thesis, Division of engineering geology, *Royal Institute of Technology (KTH)*, Stockholm. ISBN 91-7283-113-8.
- Harrison, J.P. 1993. Improved analysis of rock mass geometry using mathematical and photogrammetric methods. Ph.D. Thesis, *Imperial College, London, U.K.*
- Knapen, B. van. and Slob, S. 2006. Identification and characterisation of rock mass discontinuity sets using 3D laser scanning. In: IAEG 2006 : Pre-proceedings 10th international congress International Association of Engineering Geology : Engineering geology for tomorrow's cities : 6-10 September, Nottingham, United Kingdom CD-ROM / London : Geological Society of London, 2006. paper 438. 11 p.
- Slob, S., Hack, H.R.G.K., van Knapen, B., Turner, K. and Kemeny, J. 2005. A method for automated discontinuity analysis of rock slopes with three - dimensional laser scanning. In: Transportation research record : journal of the transportation research board, (2005) 1913, pp. 187-194.
- Slob, S., Hack, H.R.G.K. & Turner, K. 2002. An approach to automatic discontinuity measurements of rock faces using laser scanning techniques. In Proceedings of ISRM EUROCK 2002: Funchal, Portugal, 25-28, November 2002/ed. By C. Dinid da Gama and L. Riberia e Sousa. Lisboa, Sociedade Portuguesa de Geotecnia, 2002. pp. 87-94.
- Slob, S. & Hack, H.R.G.K. 2004. 3D terrestrial laser scanning as a new field measurement and monitoring technique. In: Engineering Geology for Infrastructure Planning in Europe. A European Perspective. Eds: Robert Hack, Rafiq Azzam and Robert Charlier. Berlin, Springer Verlag, 2004. pp. 179-190.
- Vosselman, G., Gorte, B.G.H., Sithole, G. and Rabbani, T. 2005. Recognising structure in laser scanner point clouds. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences. ISPRS WG III/4, V/3 Workshop "Laser scanning 2005", Enschede, The Netherlands, September 12-14, 2005.