A method for automated discontinuity analysis of rock slopes with 3D laser scanning.

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Abstract. This paper describes the interim results of a study to characterize discontinuous rock masses using 3D laser scanning data. One of the main advantages of this method is that now an unbiased, rapid and accurate discontinuity analysis can be done. With 3D laser scanning it is now also possible to measure rock faces whose access is restricted or rock slopes along highways or railway lines where working conditions are hazardous. It is also shown that the proposed method will also be cheaper than traditional manual survey and analysis methods. Laser scanning is a relative new surveying technique, which yields a so-called ‘point cloud’ set of data, where every single point represents a point in 3D space of the scanned rock surface. Since the density of the point cloud can be high (in the order of 5 mm to 1 cm), it allows for an accurate re-construction of the original rock surface in the form of a 3D interpolated and meshed surface, using different interpolation techniques. Through geometric analysis of this 3D mesh and plotting of the facet orientations in a polar plot, it is possible to observe clusters, which represent different rock mass discontinuity sets. With fuzzy k-means clustering algorithms individual discontinuity sets can be outlined automatically and the mean orientations of these identified sets can be computed. Assuming a Fisher’s distribution it is subsequently demonstrated that the facet outliers can be removed. Finally, it is shown that discontinuity set spacings can be calculated as well.

INTRODUCTION

3D laser scanning versus traditional field survey techniques

In rock mass characterization, the analysis of discontinuity properties are very important because this will determine, to a large extent, the mechanical behavior of the rock mass [1]. Therefore, most civil and mining engineering works that deal with rock masses, require a good understanding of the discontinuities (joints bedding planes and fractures) in the rock mass. Properties such as orientations, roughness and spacing of the different discontinuity sets are therefore important to determine.

Discontinuity properties of a rock mass can be measured in the field using standardized methods, such as scan line surveys or cell mapping [22], [23]. Both systems have their respective advantages and disadvantages, but all manual field survey methods have several disadvantages in common [16]:

- Erroneous data are introduced due to sampling difficulties, e.g. choice of sampling method, human bias, instrument error, etc.
- Safety risks are often considerable. Often field measurements are carried out at the base of existing slopes or during quarry, tunneling or mining operations or along busy highways.
- Direct access to rock faces is often difficult or impossible.
- Apart from these practical problems, manual field survey methods are also time-consuming, labor-intensive and therefore costly.

Laser scanning in combination with an automated discontinuity analysis, has several advantages over the traditional manual field survey methods:

- In this paper it is demonstrated that laser scanning can be used as a cheaper, more objective and more precise and accurate method to determine discontinuity orientations.
- Laser scan surveys can be carried out rapidly (in minutes) and at some distance (from 4 up to 800 meters) away from the actual site in a controlled environment, so that safety risks are minimized. Some laser scanners can even be operated by remote control via an infrared or wireless ethernet link.
- Laser scanning can reach rock faces up to several hundreds of meters away from the operator, so that discontinuity properties of inaccessible spots can be obtained, which was previously impossible to do.

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 [24]. 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 [21]. In the field of rock mechanics, applications have already been developed that make use of this technique [8] [26]. 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. With photogrammetric techniques it is also necessary to measure in several control points within the scene to arrive at a proper 3D model. It was demonstrated by Feng et al. [9] that it is also possible to use 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 time and effort on-site. A few recent publications demonstrate the possibility to determine discontinuity orientations from single digital images on the basis of fracture traces and advocate the combined used of laser scan data with digital imagery [16] [17].

3D terrestrial laser scanning on the other hand, is a relatively new, but already revolutionary, surveying technique. The main advantage over photogrammetric techniques is that a 3D data model is generated in real-time. Different laser scanning systems exist, but the technique used outdoors for geodetic surveying or for measuring large civil engineering structures is usually the ‘time-of-flight’ or ‘laser range finding technique. The time-of-flight or ranging scanners have a laser diode that sends a pulsed laser beam to the scanned object [27]. The pulsed laser beam moves trough a rapidly changing elevation and azimuth angle of a rotating or oscillating mirror inside the instrument. The pulse is diffusely reflected by the surface of the object it hits and part of the light is being returned to the receiver. The time that light needs to travel from the laser diode to the object surface and return is very precisely measured. Knowing the speed of light, the distance from the scanner to the object can be computed. With the azimuth and angle of the beam, the position of each point where the beam is reflected can subsequently be calculated.

The laser scan survey yields a digital data set, which is essentially a dense ‘point cloud’, where each point is represented by a coordinate in 3D space (X, Y and Z, relative to the scanner’s position) and the reflected intensity (I) of the laser beam. With this data, the 3D shape of any object or environment can be determined and analyzed. A new generation of ranging laser scanners also yields (using co-registration of digital imagery) for each point the passive color (i.e.: red, green, and blue reflection values). Very large and complex objects can also be scanned from different positions. Most software used to capture the survey data allow to merge the different surveys into a single point cloud. In this way, the ‘shadow’ areas of surveys can be complemented with scans where the previously hidden areas can be ‘seen’ by the laser beam.

The most important advantage of the laser scanning method is that a very high point density can be achieved, up to 5 mm resolution or larger. Therefore, the shape of the surveyed object or scene can be modeled with a very high resolution, precision and accuracy, in three dimensions. Laser scanning can measure objects and scenes up to a distance of nearly 800 meters under ideal conditions. In real-world situations however, distances in the order of 50-100 meters are more usual. The method is also fast: a full 360° scan can be carried out with the latest models in less than 4 minutes. Most laser scanners fit on a regular surveying tripod and can have a laptop or palmtop attached to operate the scanner and to store the survey data. It should be noted, however, that the developments in laser scanning technology go very fast and some of the specifications given here may already be outdated the moment this paper is published.

Data quality issues

Currently, a number of 3D laser scanning devices are on the market from different manufacturers that use the ranging principle (E.g. Leica-Cyrax, Riegl, Trimble-Mensi and Optech-Ilris). The underlying principles of the different laser scanners are essentially the same, but the quality of the generated data may vary between manufacturers and models. The most important quality parameters are:

- Resolution: the minimum distance between measured points (mostly in the order of 5 mm to 1 cm), depending on the range to the object and size of the object (see laser beam divergence). It determines what level of detail can be recognized from the scanned scene or object.
- Accuracy and precision: This determines how well the data represents the actual geometry of the scanned scene of object. As mentioned before, the laser scanner measures 'time of flight' of the laser beam. Since the time differences are so small, there is a limit to the precision with which this can be measured. This basically results in an error of the range measurement, which can be in the order of 25 to 10 mm for a single shot or 15 to 5 mm for averaged multiple shot measurements [25]. Range precision is independent of the distance to the object. There is also a limit in the precision with which the angle and azimuth of the beam can be measured, which obviously should results in a positional error as well. Compared with the error in range, this seems to be disregarded as a major concern by the laser manufacturers.
- Scanning speed: This has drastically improved over the years with improved hardware and improved data storage techniques. Depending on the scanner type, resolution, size of the object or scene, scanning speeds can range between a few minutes to half an hour.
- Laser beam divergence: A laser beam is never perfectly parallel, but always has a certain amount of divergence. For example, a laser beam that is the size of a small dot (15 mm) at around 20 meters, may be the size of a large dish (30 cm) at 100 meters distance (3 mrad). Obviously, this results in an averaging of the measurement over a larger area. It also decreases the amount of reflected energy and thus limits the range at which objects or scenes can be scanned. Recent laser scanners however, improved drastically in beam divergence, which may now be down to 0.25 mrad (25 mm per 100 m) [25].

DATA PROCESSING

Geometric correction of the data

The laser data is in principle georeferenced to its own coordinate system, relative to the scanner's position (often the scanner's position is defined as the origin: [0,0,0]). If it is needed to integrate the data into existing databases in CAD or GIS for example, then the data has to be referenced to a regional or a local grid system. Most laser scanning systems allow real-time or posterior georeferencing of the point cloud data using reflectors that have pre-measured coordinates. These can be measured in with for example with a total station with reference to existing benchmarks or with Differential GPS.

However, for the application of using laser scan data to measure discontinuity properties, it is not strictly necessary to georeference the entire data set to a local or regional grid or coordinate system. For the measurement of discontinuity orientations, it is only required to re-orient the data relative to the true North and to make sure that the data is level. In other words, the (X,Y,Z) coordinates should be referenced such that for example the Y-axis represents the true North-South direction and the X-axis represents true East-West direction and Z represents the actual elevation. For a slope stability analysis for example, it is merely needed to know the relative orientation of joints and bedding planes compared to the actual slope orientation and geometry. The same applies to quarry and tunnel operations, where the block size and block stability is of key importance, which does not require an absolute georeferencing.

Most of the time, the direction in which the scan is being made (where the laser beam has angle 0 and azimuth 0) is considered the Y direction (or false North) and X and Z the (false) Easting and (false) elevation, respectively. If the scanner (on a tripod) is leveled perfectly horizontal and the bearing (true north) of the scanner can be measured, it is possible to apply a simple rotation to the data set to make it orient to the true North. Of course, it is a crude way of re-orienting, which depends entirely on the precision with which the bearing of the scanner can be measured and the accuracy with which the scanner can be leveled. However, the relative accuracy remains intact. It can be expected that laser scanners in the future will be equipped with a build-in leveling device, an electronic compass and DGPS, so that instant relative or even absolute georeferencing can be achieved. For a very accurate georeferencing to a global or local grid, additional geodetic measurements will still be needed.

In some cases, the laser scanner cannot be oriented horizontally, for instance, when a scan has to be made at an angle in order to capture the top of a steep and high rock face. It this case the point cloud data set cannot merely be rotated, but has to undergo a more complex transformation. For this it is required to have in the scanned scene some reference information. It is for example possible to place in the scan or on the rock face two flat boards (in the case-study described further in this paper, these were two 60x60 cm white plywood boards – see Figure 2). The orientation of these boards can be measured with a regular geological field compass (mostly only up to 1 degree precision). Since the boards appear in the data set, the orientation according to the scanner's coordinate system can be calculated and these can subsequently be compared with the true orientation. On the basis of this, transformation parameters can be computed to re-orient the entire data set. It should be emphasized that even though the accuracy of the transformation may not be very high with this rather crude method, the precision of the data remains intact.

Surface reconstruction

Just on the basis of the point cloud data it is not possible to derive valuable information. Point cloud data can only be visualized, which does give the user a very good visual impression of the scanned object (see Figure 3). However, in order to analyze the surface of the object it represents, the point cloud data has to be interpolated and reconstructed as a 3D surface model.

3D surface reconstruction algorithms can roughly be divided into Polygonal and Parametric. An example of polygonal techniques is 3D Delaunay triangulation, which creates irregular, triangular patches based on simple linear interpolation between the points in 3D space. Examples of applications that use 3D Delaunay surface triangulation on point clouds are: Cocone [7] [5] and Points2Polys [20]. Examples of parametric techniques and applications are NURBS (Non-Uniform Rational B-Splines) or Radial Basis Functions (RBF's) [3] [4], which use parametric functions to define surface patches. Parametric techniques create more "natural-looking" surfaces and more accurate representations and interpolates in areas with missing data. Parametric techniques however, require more computing power than polygonal interpolation techniques.

Polygonal interpolation techniques were used in a first attempt to reconstruct the scanned rock faces. It works well on laser scan data sets where the spatial resolution is relatively small compared to the laser's range error. The technique that was initially used was based on 3D Delaunay triangulation. This technique resulted in a seemingly visually correct reconstructed surface. The surfaces have holes in areas with noisy data where the method could not create a proper interpolation (e.g. in areas on the rock face with vegetation, trees or bushes). In fact this is advantageous, since our rock face analysis should exclude areas covered with vegetation. If however, the data density of the point cloud is relatively high compared to the error, the Delaunay interpolation gives poor results. If for instance an object is scanned with a resolution of 5 mm, while the position error is in the order of 10 mm, the Delaunay routine interpolates linearly between neighboring points. It is not difficult to imagine that the interpolated surface is then more influenced by the error than by the overall trend. This problem can be overcome by under-sampling the point cloud data or to decrease the scanner's resolution.

The RBF parametric technique for example overcomes this problem. It uses polyharmonic RBF's to reconstruct smooth, manifold surfaces from (noisy) point cloud data and it can repair incomplete meshes. An object's surface is defined implicitly as the zero set of an RBF fitted to the given surface data [4]. This technique allows fast reconstruction of surfaces, even on the basis of millions of points, something that was not possible before. At present, a good desktop PC with a minimum of 500 Mb Ram can already compute surfaces of laser scan data in minutes, rather than hours.

Polyharmonic spline functions result in very smooth interpolations. The technique is scale-independent and therefore well suited to reconstruct surfaces from non-uniformly sampled data. If there are missing data or "holes' these are filled and the surfaces are smoothly extrapolated. In some instances this is unwanted, for example if there is vegetation present. Vegetation on a slope result creates fuzzy points before the slope. If no removal takes place beforehand, these points area being interpolated as well and can be seen as 'blobs' in the reconstructed surface. An advantage of this RBF method is that it can handle noisy laser scan data very well. Noise from the surfaces can be smoothed out, using different techniques, which is demonstrated in Carr et al. [3]. The functional representation of an RBF is in effect a solid model, which means that gradients and surface normals can be determined analytically. This allows the user to create uniform meshes that has advantages for mesh simplification and re-meshing applications [4].

DATA ANALYSIS

Stereo or polar plotting of individual facets of the reconstructed rock surface

After the surface reconstruction, the geometry of the rock face is now represented by hundreds of thousands to millions of triangles or facets. Each individual facet has three (3) nodes or points that are defined in 3D (X,Y,Z) space. In case of a surface reconstructed using polygonal techniques (such as Delaunay triangulation), each node is the actual original laser scan point, since a linear interpolation is used. In case of a surface reconstruction using parametric techniques, each node is part of the computed polynomial meshed surface, thus not representing anymore an original laser scan point (compare Figure 6 with Figure 7).

Since the 3D coordinates of each node are known, it is possible, through the application of basic geometric rules, to determine the orientation for each facet or the normal of each facet [28] [29]. The assumption is that most surfaces in a discontinuous rock outcrop are actually formed by the internal discontinuity structure of the rock mass. In this case each facet represents in fact a single orientation measurement, comparable to an individual manual orientation measurement made for each discontinuity set in a traditional way with a geological field compass.

In many cases this assumption may not be valid. If, for instance, surfaces in the outcrop are formed by fractures through intact rock, or if the surfaces have been affected by weathering, these surfaces are not characteristic for a specific discontinuity. If much rubble, scree or soil is present in the rock outcrop, this will of course also affect the outcome of the analysis. This all will ‘pollute’ the data and introduces ‘noise’. However, the underlying hypothesis of this research remains, which is that if discontinuity sets are clearly visible in the rock outcrop, it will also be possible to observe trends in the data. If trends can be observed in the data it should then also be possible to statistically define them, even if the data contains noise.

By plotting the orientations of all individual facets in a stereo or polar plot, the trends in the data can be visualized and recognized in the form of clusters [29]. Following the hypothesis, each cluster therefore represents a different discontinuity set. Because of the high density of the laser data, it is possible to have for a single rock outcrop hundreds of thousands to millions of facets. Consequently, this will provide a solid basis for statistic analyses (clustering techniques) to obtain the discontinuity information contained in the laser scan data of the exposed rock mass. In the following paragraph this clustering technique is explained. It was decided to apply automated clustering in order to eliminate as much as possible the human bias from the entire procedure.

Identification of joint sets using clustering techniques

For the automatic clustering of discontinuity sets, the adjusted fuzzy k-means clustering method is used, suggested by Hammah and Curran [14]. The disadvantage of this method is that an initial guess of the number of clusters has to be made which introduces again the human bias. However, the number of sets closest to reality can be determined with the aid of validity indices, like those proposed by Xie and Beni [31] and Gath and Geva [12]. One major advantage is that this algorithm can be improved through the use of quantifiable discontinuity properties, such as spacing, or joint roughness [32].

The clustering algorithm is based on a “soft” classification scheme, i.e.: it includes all facet orientations. This means that cluster outliers are not removed. To reduce the presence of this noise and to allow for a better rock surface analysis, a rejection criterion, like that proposed by [18] for the delineation of discontinuity sets needs to be found. The mean orientation of each cluster will play a key-role in the approach of a cluster distribution and should therefore be known with great accuracy. This can be achieved by an appropriate clustering in combination with a weighting or by simplifying the data set. Simplification of the mesh can for instance be done using the fastRBF surface reconstruction method. Adjoining triangles with similar orientations can be grouped and made into larger facets. The larger a facet will become after the simplification, the more it will be representing of an actual discontinuity plane. This information can be used to improve and speed up the clustering process.

All approaches that can lead to a proper delineation of each cluster boundary are based on the assumption that the distribution pattern is that of a so-called ‘Fisher distribution’ [11], i.e.: a circular concentration around the mean. Fisher distributions have been observed in many of the stereo plots from the laser scan data and it seems therefore a justified theory. In this study Fisher’s k-value is used in an iterative process of increasing sub-cluster size. Since a higher Fisher’s k or concentration parameter κ corresponds to relatively dense distribution, the highest value found for any subset should mark the boundary of the entire cluster. The difference in variance of the mean orientation between two subsequent subsets produces a comparable result. This (simple form of) F-test [2] [6] is being used as a first pragmatic approach to delimit the cluster boundaries (see Figure 11).

Fisher's model as a probability density function further allows for the determination of the frequency of orientations on a unit sphere [10] [2] [23]. It also indicates the variance of the mean orientation. Both parameters can serve as a factor to delimit the different clusters by using critical cone angles or frequencies as a threshold value. Another approach is to test for equivalence between two subsets originating from one cluster, determined by a pooled F-test statistic [6].

Determination of discontinuity spacing distributions

Another very important aspect in rock mass characterization is the determination of discontinuity set spacing and spacing distribution. Together with the orientation of the discontinuity sets, this determines the variation in size and shape of the blocks that make up the fabric of the rock mass. For most engineering applications dealing with rock masses, this is crucial information. By separating the individual discontinuity sets and surfaces from the entire data set, it becomes possible to analyze these surfaces in 3D space and subsequently derive the distances (spacings) between them.

IMPLEMENTATION OF THE DATA ANALYSIS

In order to carry out the data processing and data analysis steps described in the previous paragraphs, a number of computer scripts have been written using Matlab as a programming platform. The advantage of using Matlab is that it is well suited to process large amounts of data and it provides good visualization routines, which do not require extensive programming experience. An additional advantage is that the FastRBF routines to re-construct surfaces are available as Matlab toolboxes so that all routines can be integrated in a single script. The processing and analysis steps are listed below and are illustrated at the end of this paper. Another software is currently under development by Split Engineering [30] that make use of generally the same concepts as described in this paper.

For demonstration purposes a small part of rock slope has been singled out, which has well-developed discontinuities (see Figure 2 and Figure 4). This data set was processed and analyzed using the described method. This rock slope was scanned with Optech's ILRIS-3D Intelligent Laser Ranging and Imaging System [15]. The location of the slope is in Spain, along road TP7101 between Falset and Bellmunt, Priorat district, Catalan Province. The rock consists of Slates of Carboniferous age.

The data processing steps are:

1. Raw (x,y,z) point cloud data import (see Figure 3)
2. Cropping of data if desired (see Figure 5 and Figure 6)
3. Re-orientation of data using rotation or transformation
4. Parametric surface reconstruction (using the FastRBF toolbox) (see Figure 7)
5. Visualization of the meshed surface in Matlab
6. Surface export to generic OBJ (Wavefront) or VRML (Virtual Reality Modeling Language) data formats for visualization and exchange purposes

The data analysis steps are:

7. Calculation of orientation of facets
8. Plotting of all facet orientations in a stereo net
9. Cluster analysis using the fuzzy k-means method (for results please refer to Table 1)
10. Visualization of different clusters in a stereo net through coloring of the different cluster regions (see Figure 9)
11. Applying the colors of the different cluster regions to the 3D meshed surface in order to verify visually whether the automated clustering result is as expected (see Figure 10)
12. Remove cluster outliers, re-calculate mean set orientation (see Table 1) and visualize results in a stereo net (see Figure 11)
13. Re-applying the colors of the different cluster regions to the 3D meshed surface in order to verify visually whether the delineated clusters really outline the 'real' discontinuity sets (see Figure 12)
14. Model each individual joint plane and visualize them (see Figure 13
15. Calculate discontinuity spacings within each set (see Table 1)

COST/BENEFIT ANALYSIS

An example is given below that illustrate the advantages in time and costs of discontinuity analysis based on laser scan survey data over a traditional analysis. The data are from an actual case study described by Monte [19]. This study was on a section of roadway of US Highway 93, which is a major commercial route between Phoenix, Arizona and Las Vegas, Nevada. The Arizona Department of Transportation contracted URS Corporation (URS) in 2003 to complete a geotechnical investigation for widening of a 5.6 km stretch of US-93. This section of roadway, located between Wickenburg, Arizona and Interstate 40, traverses through granite and basin fill and floodplain deposits.

The traditional survey and analysis required:

- Cell mapping, 350 joint orientation measurements, 2 people for 2 days
- Processing and making graphs of the data, 1 person for 2 days
- Total 6 man days (with overhead, assume $1000 per day)
- Share of equipment and software costs $250 (1/10th of actual cost of Brunton, stereonet software, etc.)

Total cost: about $6250 (mostly manpower)

A laser scan survey with automatic software analysis would require:

- Field scanning (six scans) and digital imaging, 1 person for 1 day
- Data processing: 0.5 to 1 day
- Scanner rental: $1500
- Share of other field equipment (camera, etc.), $200
- Share of software costs, $1500 (assume 1/10th of actual cost of $15000 for data processing software)

Total cost - $4700 - $5200 (1/3 manpower, 2/3 equipment and software)

The conclusion that can be drawn from this comparative study is that laser scan-based survey and automated analysis can be considerably faster, less labor-intensive and therefore cheaper than traditional survey and analysis. If the laser scan equipment and software is also used on a more routine-like basis, rental and share costs will likely become even lower.

Developments of this new technique, like all other new ICT techniques, are very rapid. The capabilities of current laser scanners are greatly improved compared to the first generation, but the price of a system has remained the same or is even becoming less, since larger numbers are being produced and sold.

CONCLUSIONS

In this paper it is demonstrated that 3D laser scanning data can be used as a tool to:

- Model rock slopes at high detail and with high accuracy in three dimensions with parametric surface reconstruction techniques.
- Determine the orientations of discontinuity sets in an outcropping discontinuous rock mass from this modeled rock surface without physical access to the slope.
- Automate the cluster analysis using fuzzy k-means clustering.
- Remove cluster outliers assuming Fisher's distribution.
- Visualize the results in stereo- or polar plots.
- Visualize the results in the 3D surface model.

The advantages of the method described in this paper are that:

- No physical access is needed to or near the rock surface to measure discontinuity orientations, which has obvious advantages in terms of safety.
- Inaccessible rock faces can now be analyzed, particularly for slope stability and block size analysis this has obvious advantages.
- The human bias in determining rock mass discontinuities is mostly removed.

- More discontinuity data can be gathered than using traditional (manual) techniques, which allows proper application of statistical tools.
- Higher accuracy of the orientation measurements can be achieved: There are three parts to accuracy:
  1. Accuracy of measurement of strike and dip
  2. Much better statistical sampling therefore more accurate joint sets and properties of each set
  3. The fact that you are measuring the average orientation of a fracture rather than the specific location where the Brunton compass is placed.
- Laser scanning can also assist other aspects of a geotechnical project. An important example is that an accurate survey of the geometry of a slope is realized, which can be integrated with other geometric elements, such as drainage ditches, road surface in a CAD or GIS system.
- It is faster, less labor-intensive and therefore cheaper than traditional surveying

DIRECTIONS FOR FURTHER STUDY

The method described in this paper require still extensive verification and comparison with manual and traditional survey techniques in order to confirm that this method can really replace the traditional and accepted techniques. Comparison will be done using scan line surveys and the SSPC rock mass classification system [13]. Some key aspects that need further research are listed below.

Determination of surface roughness

Another hypothesis, which is not mentioned in the paper yet, is that it will also be possible to derive roughness characteristics for each discontinuity plane and set, from the laser scan data. Large-scale roughness is clearly visible in the 3D point cloud and 3D surface models. Since the different discontinuity sets can be recognized and separated at this moment, it should also be possible to statistically analyze in detail the surfaces of individual discontinuity sets or individual discontinuity surfaces. Because of the positioning error, which is now in the order of 1 cm, it will probably not be feasible to recognize small-scale roughness, which is in the same order of magnitude or smaller. However, the developments in laser scanning technology go very fast and it will be likely that in the future these positioning errors can be reduced.

Use of intensity

The intensity of the reflected laser beam, which has not been included in any of the analyses yet, may also be of use in the determination of surface roughness. The rougher a surface is, the more diffusely the laser beam will be reflected. However, the relationship between roughness and intensity may be very complex, since parameters such as angle of inclination, moisture and mineralogy also influence the intensity level.

Different joint sets and rock units may also be recognized on the basis of differences in and intensity. An experienced (engineering) geologist can, merely by looking at an image of pointcloud data (for instance Figure 3), intuitively interpret this image and classify the rock mass in different units. The question is how to capture the “experience” in formalized rules and apply this to the laser scan data to achieve similar (or better) results.

Integration with image analysis methods

In some instances, where the discontinuities are not-well developed and exposed, for example on very smoothly blasted or excavated rock faces, the proposed method may not generate satisfactory results. However, if joint and bedding traces can still be observed in the rock face, the combined use with image analysis such as proposed by Kemeny [16] & [17] will likely provide good results. The latest laser scanner model of Riegl [25], for example, already integrates digital imagery into the laser scan data, by coloring the pointclouds with the photo information.

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Figure 1. Typical field set-up of a laser scanner (Optech 3D Ilris scanner [15]) . The umbrella is to keep the scanner cool and to be able to read the display. Persons in picture: John Kemeny (left) and Bart van Knapen (right). Location: Along road T710 between Toroja and Vilella Baixa, Priorat district, Catalan Province, Spain.

Figure 2. Carboniferous slates with well-developed discontinuities. Part of this slope (outline with the square) is used in this paper to demonstrate the methodology. Note the two boards in the pictures, which were used to reference the laser scan data set. Along road TP7101 between Falset and Bellmunt, Priorat district, Catalan Province, Spain.

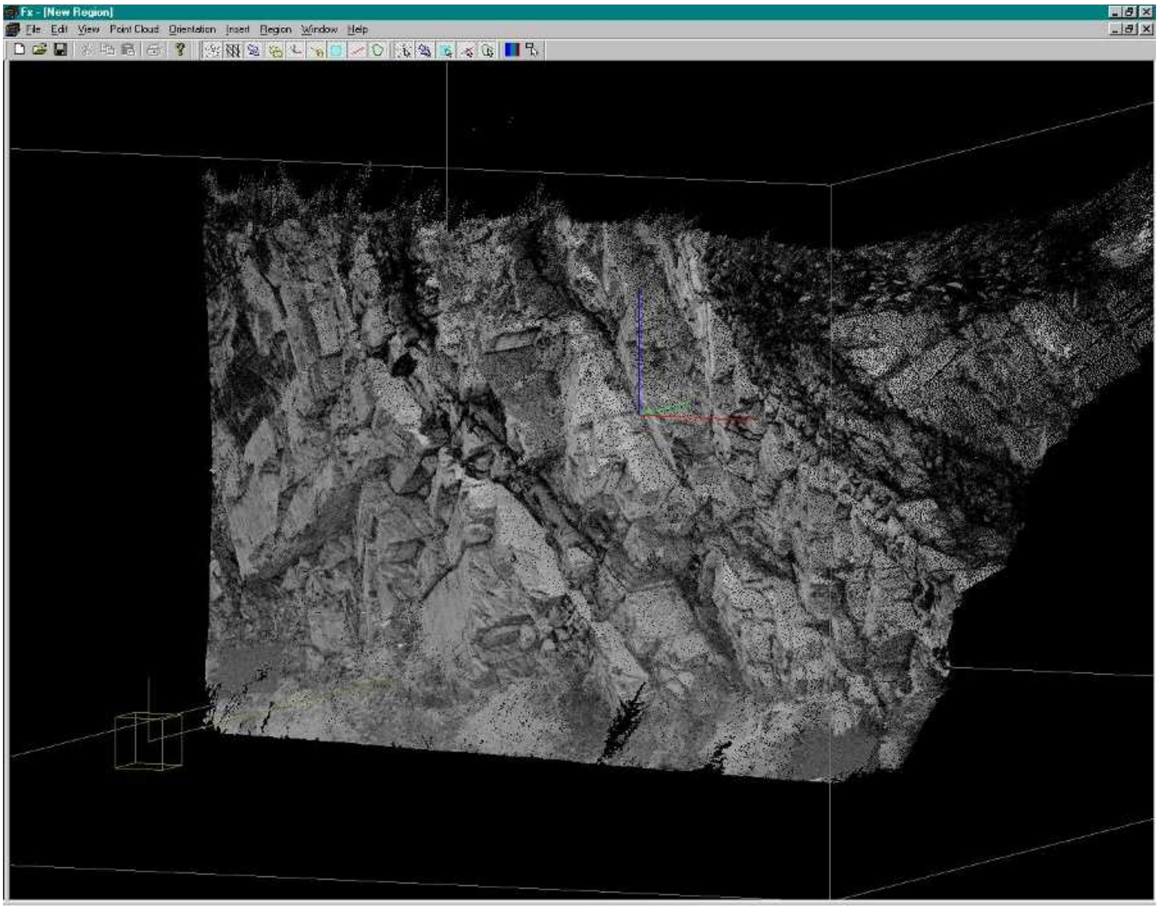

Figure 3. 3D visualization of the entire point cloud (with the software Fx, beta version 1.0 from Split Engineering [30]) of the scan made of the slope in Figure 2. The reflected laser intensities are shown in greyscale (i.e. white is high reflection and black is low reflection).

Figure 4. Detail of the rock face area that is used to demonstrate the method. Refer to Figure 2 for the position. The dimension of the area is about 1.5 x 2.0 meters.

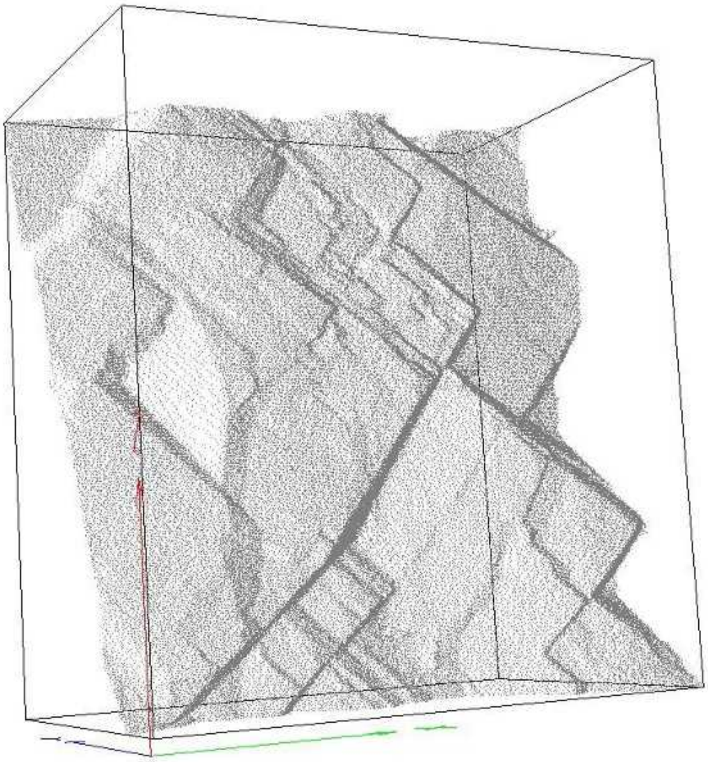

Figure 5. 3D visualization of the original point cloud, of the cropped area, illustrated in Figure 2 and Figure 4. Notice the clear discontinuity sets

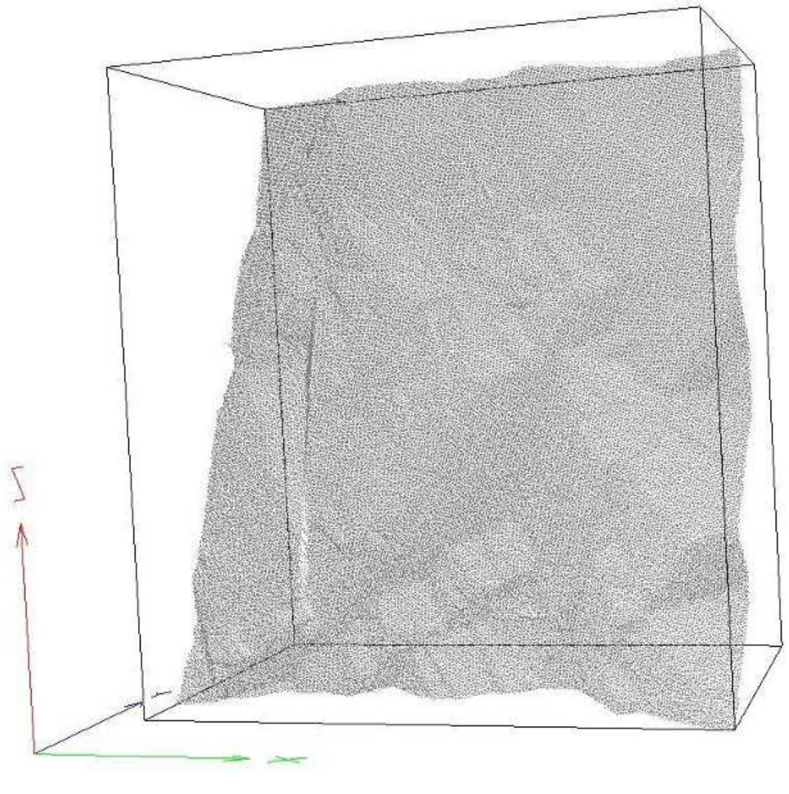

Figure 6. 3D visualization of the original point cloud. This view shows the high density of the data (5 mm resolution) and also shows the 'fuzzy' character of the original data that is caused by the influence of positioning error (+/- 1 cm).

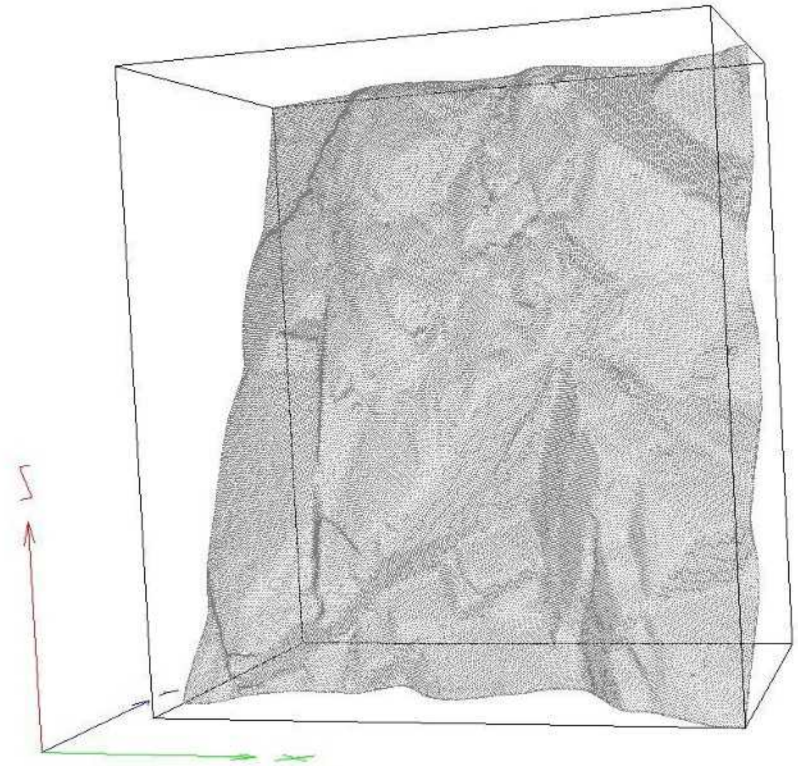

Figure 7. 3D visualization of the points of the facets that have been meshed using the parametric FastRBF method. If compared with the original data set (Figure 6) it is evident that the fuzzy character is removed and that actually more detail can be observed.

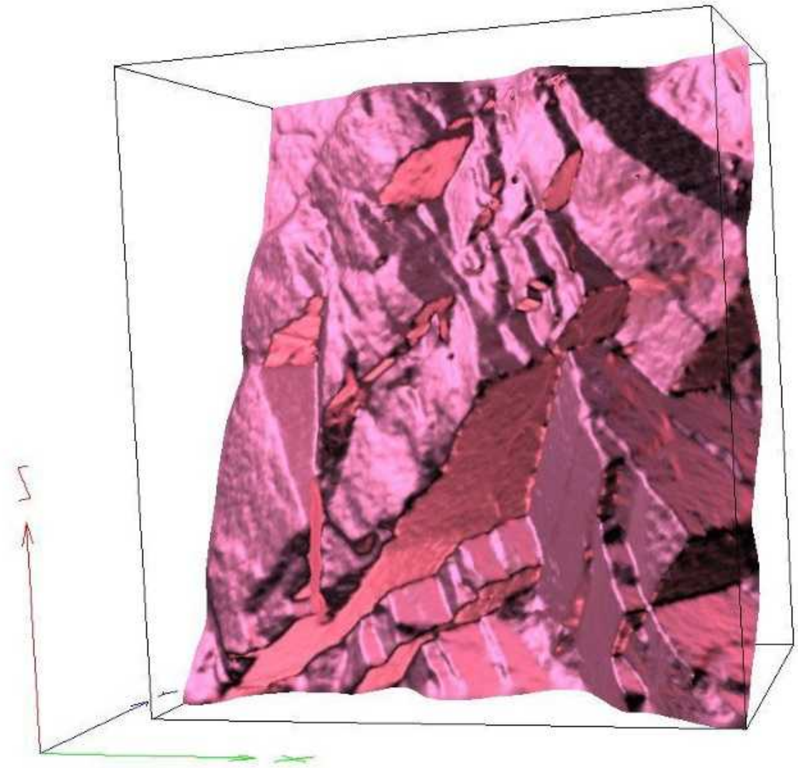

Figure 8. 3D rendering of the reconstructed rock surface using the FastRBF method. Artificial lighting has been used to emphasize the visible structures and the amount of detail.

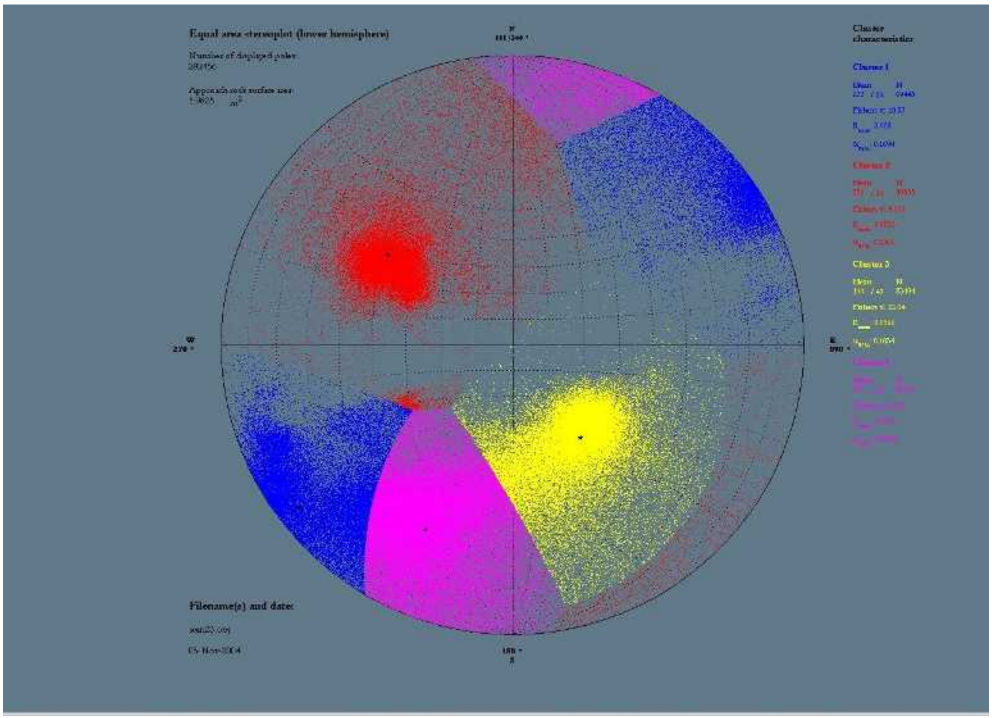

Figure 9. Polar plot of all the orientations of the individual facets in the 3D surface model. Clusters and cluster centers are identified with the fuzzy k-means method. Facets belonging to different discontinuity sets receive a different color. Note that all facets are classified, also the obvious outliers in the cluster, which may belong to non-discontinuity surfaces. Please refer to Table 1 for a legend to the statistics.

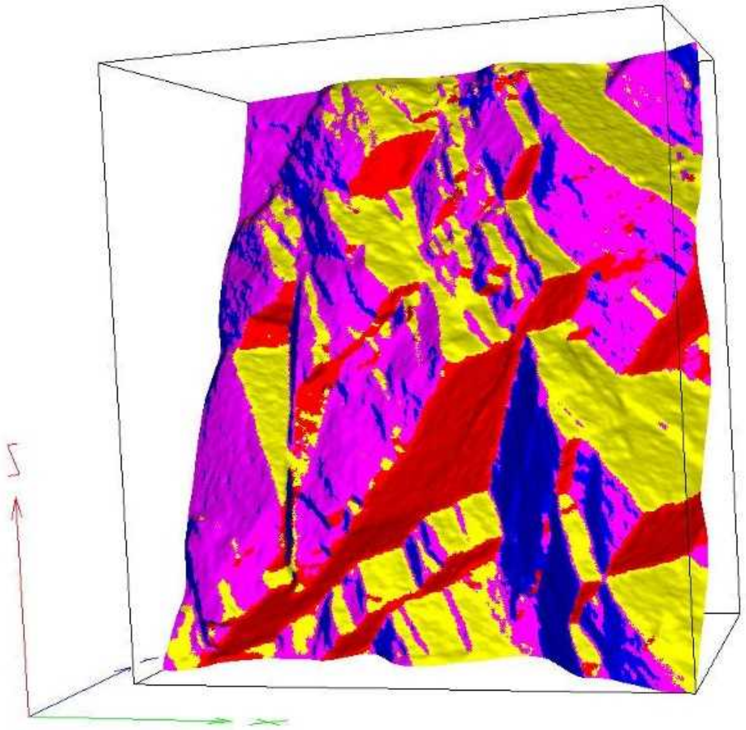

Figure 10. Re-coloring of the 3D surface model with the color assigned to the different discontinuity clusters in Figure 9. Note that all surfaces are being classified, also surfaces which are clearly non-discontinuity surfaces. Apparent are the clear outlining of the bedding (in yellow) and the orthogonal ("red) joint set.

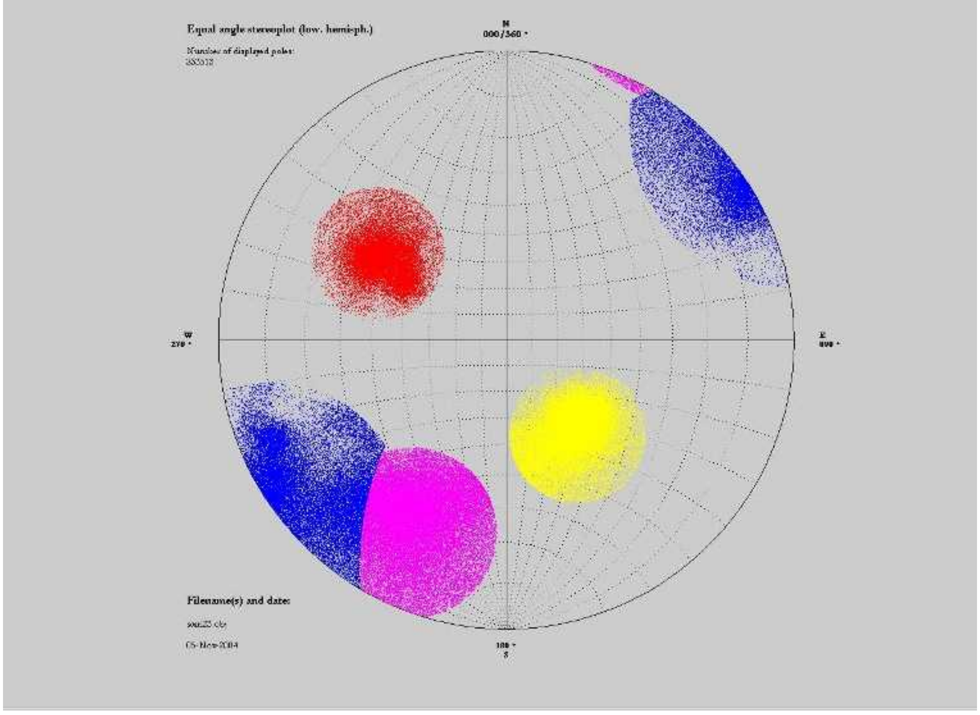

Figure 11. Polar plot of all facets that fulfill (a simple type of) F-test [2] [6]. This is being used as a first pragmatic approach to delimit the cluster boundaries. All outliers have been removed. Compare with Figure 9. Please refer to Table 1 for a legend to the statistics.

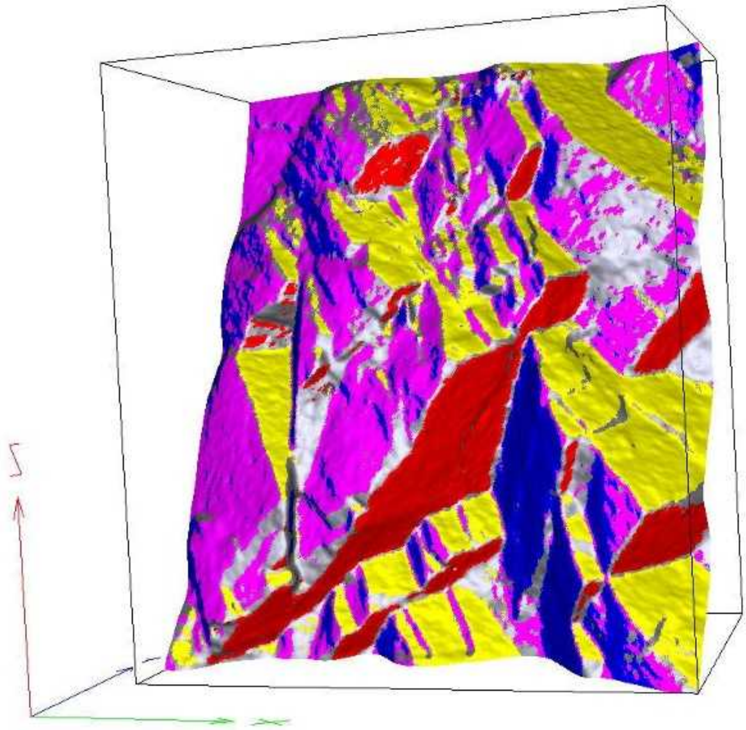

Figure 12. Re-coloring of the 3D surface model with the color assigned to the different discontinuity clusters in Figure 9. All facets that do nut fulfill the F-test (see Figure 11) have not been colored and are shown in grey. It is evident that only 'real' discontinuity surfaces have now been classified and colored. Compare with Figure 10.

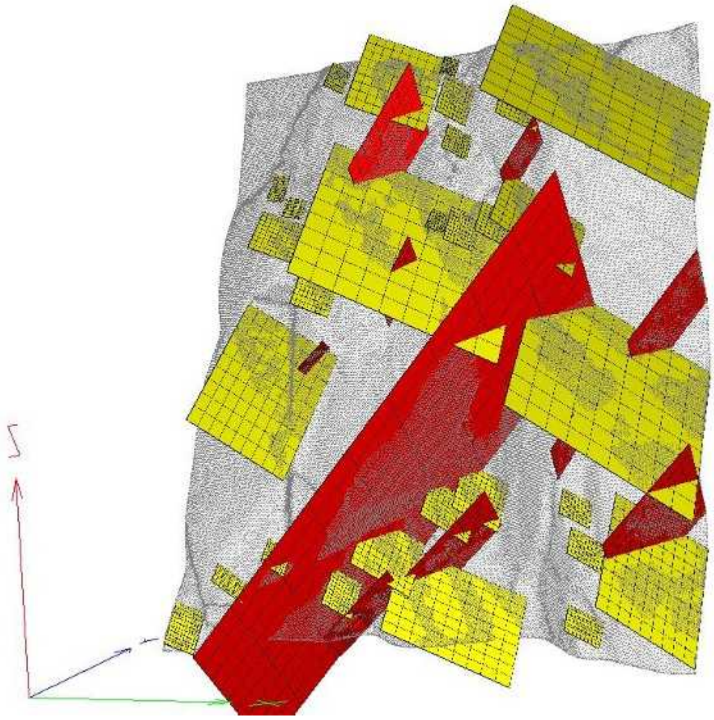

Figure 13. Here the individual discontinuity planes are visualized of sets 2 (red) and set 3 (yellow), modeled as linear trend surfaces. By calculating the distances between the individual surfaces, joint set spacing can be computed.

Table 1. Summary statistics

	Before outlier removal			After outlier removal			Set spacing statistics	
Discontinuity set number	Number of facets	Mean orientation	Fisher's K-value	Number of facets	Mean orientation	Fisher's K-value	Mean normal set spacing	Dimension of set ⊥. to orientation
Set 1 'blue'	69445	233/04	10.87	62684	233/05	16.37	8.20 cm	147.59 cm
Set 2 'red'	50855	306/34	8.56	34081	304/36	60.33	20.29 cm	162.28 cm
Set 3 'yellow'	83494	144/47	23.04	67336	304/36	50.27	7.03 cm	161.65 cm
Set 4 'purple'	88662	205/20	23.33	69855	206/20	42.04	4.13 cm	58.10 cm
The data file contains 292456 facets originating from 147425 points								

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