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Methods for sampling discontinuity traces on rock mass 3D models: state of the art

G Umili

Department of Earth Sciences, University of Turin, via Valperga Caluso 35,
10125 Turin, Italy

gessica.umili@unito.it

Abstract. Discontinuities are an intrinsic characteristic of rock masses, and they appear at every scale of a technical survey. Issues related to the procedure's duration and the operator's safety during the survey have encouraged the development of non-contact methods: images and digital models serve as representations of the rock mass for surveying the geometric features of discontinuities. In particular, various automatic and semi-automatic trace sampling methods were developed in the last decade, focused on estimating persistence and the degree of fracturing. A review of these methods is presented in this paper, highlighting their strengths and disadvantages.

1. Introduction

Discontinuities are an intrinsic characteristic of rock masses. They appear as traces on rock exposures, such as natural outcrops, tunnel fronts, quarry faces. Natural outcrops can have an infinite variety of shapes and dimensions, but a common characteristic is their non-planar surface, on which traces can be clearly recognized. The surface of tunnel fronts, on the contrary, is affected by the excavation method used. Traces can be masked somehow.

Moreover, elements that do not represent actual traces could be created in the excavation process. Therefore, particular attention should be paid to the detection of traces on tunnel fronts. Quarry faces pose similar issues. On perfectly smooth surfaces like the one in the picture, traces are linear elements that must be distinguished from veins and other textural features.

Trace length plays a role in different parameters used to describe rock mass behavior in a quantitative way. The first and most common one is persistence.

In 1978, the ISRM commission [1] defined persistence as the areal extent or size of a discontinuity within a plane. Persistence can be crudely quantified by observing the trace lengths of discontinuities on exposed surfaces. It is one of the most important rock mass parameters but one of the most difficult to determine, too. Other parameters have been defined to quantify fracture abundance in a rock mass. They are all defined as the ratio between the dimension of the considered feature and the sampling region's size ([2], [3]). In particular, the areal intensity P_{21} is defined as the length of traces per unit sampling area. The volumetric intensity P_{32} is instead the area of fractures per unit volume of rock mass: even if not explicitly mentioned, we will see later that also P_{32} can be inferred based on trace sampling.

Issues related to the procedure's duration and the operator's safety during the trace survey have encouraged the development of non-contact methods: images and digital models serve as representations of the rock mass. In particular, various automatic and semi-automatic trace mapping



and sampling methods were developed in the last decade, focused on estimating persistence and the degree of fracturing. A review of these methods is presented in this paper, highlighting their strengths and drawbacks.

2. Trace survey

Trace survey includes two steps: trace mapping and trace sampling.

Mapping consists of the creation of a sketch of the traces. When we think about a map, we imagine bidimensional support, such as a sheet of paper. But we will see later that also 3D maps of traces can be created. In any case, the best map would be in scale and digital. In scale means that traces can be directly measured on the map. Digital means that the map is a database suitable for being input in algorithms.

Sampling consists of measuring and counting traces, possibly on a map, to avoid direct access to the rock face. A certain degree of automation can be useful to speed up the operation. Trace sampling is far from being an easy task due to the aleatory nature of traces. The relation between discontinuity extension and generated traces is necessarily probabilistic. If discontinuity localization is aleatory, traces will appear aleatory even if the extension is deterministic [4].

Moreover, different kinds of sampling errors can be made [5]. Errors may result from the relative orientation incidence between discontinuity and observation support. We must also keep in mind that joints with large areas have a more significant probability of being sampled than smaller ones.

Similarly, long traces have a more significant likelihood of being sampled than shorter ones. A trace that extends beyond the sampling window has an undetermined length, which causes a censoring effect on the sample. And finally, traces shorter than a minimum length cannot be sampled, which causes a truncation effect on the sample.

How did we get to methods for automatic or semi-automatic trace mapping and sampling on digital rock masses? For answering this question, we will review a bit the history of trace mapping and sampling to better understand and appreciate the development associated with trace surveys.

3. Evolution of trace sampling

The central assumption for trace sampling is that all discontinuities are planes, intersecting the sampling tool as line traces. Traces were originally sampled along a scanline: the operator measured the length of traces intersecting the scanline and calculated the mean value.

Then, the sampling philosophy changed from linear towards areal and, consequently, from deterministic to probabilistic. Many authors adopted methods for sampling traces within finite-size areas on the exposure (usually rectangular or circular windows) ([6], [7], [8], [9]). This procedure is called areal sampling. It reduces biases inherent in the sampling orientation and increases the number of recorded discontinuities.

Parallel to this, the research community proposed estimators for mean trace length and density of traces based on trace count within the sampling window ([10], [11], [12], [13], [14], [15], [16]).

These estimators are particularly simple, and they do not suffer from orientation bias. The procedure is based on the classification of the traces visible on the considered sampling window, following geometrical criteria; the lengths of observed traces and the distribution of trace lengths are not required.

Estimators for mean trace length and density of traces can be used to start the statistical analysis of the measured trace length for inferring the discontinuity size distribution [10]. The discontinuities are assumed to be thin circular discs in 3-D space. At the end of the process, one can calculate the expected discontinuity diameter $E(D)$ and estimate the intensity of rock discontinuities P_{32} .

4. Evolution of trace mapping

The evolution of trace sampling methodologies came first. Then it was followed by the development of trace mapping methods, a fact strictly connected to the availability and affordability of digital supports, such as images and, more recently, three-dimensional models.

In fact, the traditional trace mapping procedure consisted of a manual survey performed by an operator directly on the rock mass. The operator drew a trace map based on what he saw on the rock face. However, there were issues related to the procedure's duration and the operator's safety during the survey. Also, direct access to the entire rock face was difficult to achieve.

4.1. Mapping on images

The limitations previously mentioned led many authors (i.e., [17], [18]) to turn their attention to supports that represent the rock mass, such as digital photographs and orthophotos. If adequately scaled, images can be used to recognize traces, map and measure them.

In a gray-scale image, a discontinuity trace can be visually represented by a linear feature. The methodologies for the automatic trace mapping based on digital images that we find in the literature (i.e., [19], [20], [21], [22]) in general include the following steps (figure 1): acquisition of the digital image, with proper resolution and illumination; pre-processing, to enhance the features to be detected by means of filters; segmentation, to subdivide the image into its constituent parts. This step is the core of the methodology: different algorithms for edge detection can be used, for example, Canny's filter. At the end of segmentation, a binary image is created: black pixels belong to elements of interest, the remaining ones are white. Processing operations on the binary image, using dilation and thinning algorithms, assigns every object in the image the width of one pixel. Neighboring pixels can be connected to form segments. Each segment is then numbered and placed on a list, along with the coordinates of the pixels that constitute this segment.

At this stage, the database contains segments that do not correspond to discontinuity traces and have to be filtered out. Segment linking could be necessary. Also, automated procedures to extend incomplete segments could be implemented. At the end of the process, an expert's interpretation is still required to complete the trace map and avoid gross errors.

Automatic trace mapping based on digital images has several benefits: it is faster than manual mapping, and the resulting map is a stored database suitable for further operations. Also, it is particularly suitable for flat rock faces. Its best potential application could be on flat quarry faces.

However, this method also has several drawbacks. Since trace identification is based on color data contained in the image, it must be considered that the result depends on rock color and texture. Besides, light in an uncontrolled environment can significantly vary, locally and globally, depending on the sun position with respect to the rock mass, weather conditions (for example, presence or absence of cloud cover), rock conditions (for example, wet rock). Therefore, different light conditions could lead to very different results regarding the trace map's completeness and accuracy.

Moreover, these methods suffer from common issues related to the bidimensional nature of the support. Depending on the camera asset and position in relation to the rock mass surface (for example, let us imagine to be at the foot of the rock face), the images would suffer from projective distortion. Finally, a single image can contain occlusions.

Occlusion is defined as a rock mass portion that cannot be seen from the camera shooting point because a rock protrusion hides it. The result is that not the entire rock mass surface represented by the image will be available for trace mapping.

Finally, traces are elements of the 3D space: representing them on a bidimensional map means introducing projective distortion. This concept inspired the development of methods based on 3D models.

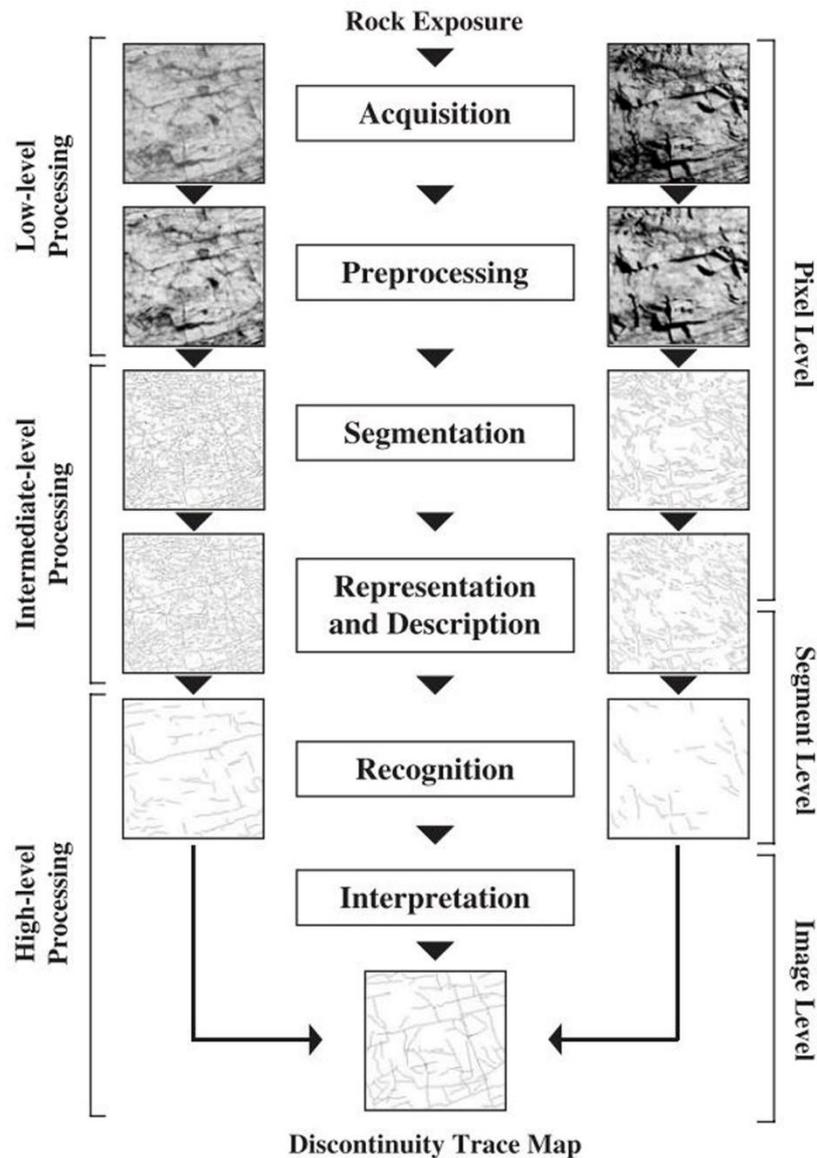


Figure 1. The construction process of a discontinuity trace map based on digital images (from [20])

4.2. Mapping on 3D models

Natural outcrops have an infinite variety of shapes and dimensions, but a common characteristic is their non-planar surface. In fact, generally, the surface has edges, most of them created by the intersections of different discontinuity planes.

It is essential to notice that this consideration is generally valid in natural outcrops. At the same time, on artificially profiled rock faces, the validity could significantly decrease due to the presence of artificial edges mixed with natural edges. Moreover, discontinuity surfaces are irregular in shape, occur at any orientation, and contain variable amounts of small-scale roughness and large-scale undulation. These characteristics make the surface of a rock mass outcrop, and therefore the 3D model created to represent it, a very complex object.

In short, a Digital Surface Model (DSM) consists of a triangulated point cloud that approximates the true surface of an object. The coordinates (X, Y, Z) of each point are known. A high density of points corresponds to a good correspondence between the discretized surface and the actual rock mass surface. A low density instead can produce a smoothed surface. The triangulation generates a

topology: in fact, every point is connected to the adjacent points by the side of a triangle. Therefore, the triangulation defines the spatial relation between the points in the DSM. For each point of the model, its neighbors are known. Moreover, each triangle is a plane. Therefore, its normal is estimated and can be used, for example, to define the orientation of the triangle.

In recent years, many researchers have been working on mapping discontinuity traces on 3D models representing the rock mass's surface. Due to the mapped traces' three-dimensional nature, the most common term used to describe the operation is "extraction" more than mapping. Therefore, in the following, we will talk about "trace extraction", and we will refer to maps containing 3D traces.

Basically, two main strategies have been proposed for automatically extracting traces from a 3D model. The first one is based on the fact that natural outcrops generally have sharp edges created by the intersections of different neighboring planes [23]: therefore, it takes advantage of the segmentation of the surface of the digital model. The surface is automatically divided into planes through specifically developed algorithms ([24], [25], [26], [27]). The traces are identified as the boundaries of the obtained planes. Therefore, we can define this as an indirect method.

For example, the algorithm in [23] is based on the assumption that structural fractures can be geometrically identified as sharp edges of neighboring planes with large angles. The code determines whether a line should be marked as a fracture by comparing the intersecting angle of the two related surfaces with a threshold angle. Discontinuity persistence can be calculated based on the bounding polygon dimensions ([24], [25]).

The second strategy for automatically extracting traces from a 3D model assumes that a trace can be geometrically identified as an edge of the digital model's surface. Traces are detected directly as surface breaklines, namely asperities or depressions of the DSM (figure 2). Therefore, we can define this as a direct method.

The first code developed for this purpose classifies each point of the model surface according to its principal curvature, which is an indicator of non-planarity [27]. 3D principal curvature is characterized by two values, called maximum and minimum principal curvature, respectively. These values are calculated for each point by solving simple equations [28], considering each point's neighborhood.

Thresholds on curvature values are then chosen to select all the significant edges of the surface: only points with curvature values above the thresholds are considered in the further steps. A series of operations are performed automatically on the groups of points identified by the thresholds. The connection of vertices is performed with algorithms that use principal curvature values and directions to create edge paths automatically. The paths are then refined, optimized, and segmented. This process's philosophy is very similar to that implemented in methods for trace mapping on images (i.e. [20], figure 1). The final database contains, for each trace, the ordered list of points, the parameters of the best fitting line, and the estimated length [27].

Another example of a direct method implements the Normal Tensor Voting Theory (NTVT) to extract edges: this method can handle sharp features and show robustness to noisy data [29].

In general, trace extraction methods on digital models have many benefits: the resulting map is a stored database suitable for further operations; they are applicable to almost any rock face. And most importantly, results are independent of rock color, texture, conditions, and illumination. It is evident that the DSM must contain only rock mass surface. Every other element, such as vegetation and artificial objects, must be removed from the model.

Anyway, these methods also have several disadvantages. DSM resolution has a direct influence on results accuracy and completeness. In fact, the amplitude of the distances between points of the DSM influences the quality of the approximation of the real surface. Besides, the resolution's decrease has an effect of smoothing and deterioration of the edges, which reduces the range of principal curvatures, and disrupts or alters the edges' continuity. Thus, the decrease of the resolution reduces both the accuracy and the completeness of the extracted traces with respect to the real traces.

Moreover, the method allows one to detect traces represented by edges: therefore, flat surfaces are not suitable for being processed with this method.

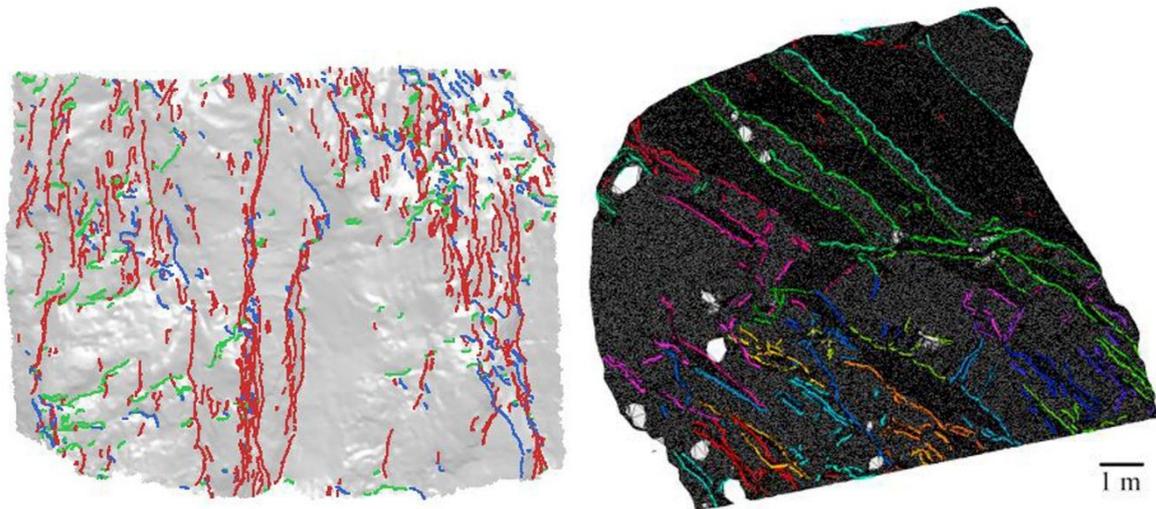


Figure 2. Examples of 3D discontinuity trace map obtained with direct methods: left) based on curvature (from [27]); right) based on NTVT (from [29])

The direct approach is based on threshold values on different geometrical parameters: different thresholds can lead to different results; therefore, the choice of proper values is fundamental.

The indirect approach is instead based on the segmentation of the surface in planes. This approach's results depend on the goodness of the fitting planes and the accuracy of the segmentation. Therefore, in any case, the parameters involved in the processing must be appropriately calibrated. This task is not easy because outcrops are so different from each other, and it is challenging to adapt the algorithms' performance to every possible case.

Finally, it is essential to remark that a field analysis based on geologic experience must always validate the automatically extracted data.

5. Sampling on 3D trace maps

As previously stated, a 3D trace map is a stored database containing geometrical data associated with each trace, and therefore it is suitable for further investigations. First of all, cluster analysis can be made in order to classify traces according to main discontinuity sets, even without assigning the number of sets [27]. Then, statistical analyses considering measured trace lengths can be performed for each set and in different portions of the rock mass in order to assess representative values [30].

Moreover, traces can be orthogonally projected on a plane and automatically sampled in 2D windows/scanlines following the methods listed in Section 3. The automatic procedure allows one to quickly perform sampling on a huge number of windows in different locations and with different radius, by creating a grid of centers of circular windows covering the entire trace map [27].

6. Conclusions

The survey of the geometrical features describing a rock discontinuity is a challenging task. In recent years, thanks to the progress in remote sensing techniques, digital supports, such as images and, more recently, three-dimensional models, became available and affordable.

This fact encouraged the development of automatic and semi-automatic non-contact survey methods. Trace mapping and sampling methods were developed following the evolution of digital supports. Present procedures allow to automatically create 3D trace maps based on digital models and automatically perform trace sampling. However, the automation of these operations is far from being entirely satisfactory. Future research should focus both on improving the results of trace mapping and developing 3D sampling methods.

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