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Validation of fracture data recognition in rock masses by automated plane detection in 3D point clouds

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ABSTRACT

This paper presents (1) an automated method to extract planes and their spatial orientation directly from 3D point clouds, followed by (2) extensive validation tests accompanied by thorough statistical analysis, and (3) a fracture intensity calculation on automatically segmented planes. For the plane extraction, a region growing segmentation algorithm controlled by several input parameters is applied to a point cloud of a granite outcrop. Within its complex surface shape, more than 1000 compass measurements were conducted for validation. In addition, digitally handpicked planes in the software Virtual Reality Geological Studio (VRGS) were used for single plane comparison. In a second test site, we performed fracture intensity calculation in Petrel based on results of the segmentation algorithm on mechanical layers of a clastic sedimentary succession. The comparison of automated segmentation results and compass measurements of three different plane sets shows a deviation of 0.70–2.00°, while the mean single plane divergence amounts to 4.97°. Hence, this study presents a fast, precise, and highly adaptable automated plane detection method, which is reproducible, transparent, objective, and provides increased accuracy in outcrops with rough and complex surfaces. Moreover, output formats of spatial orientation and location of planes are designed for simple handling in other workflows and software.

1. Introduction

Various mining and civil engineering projects require extensive investigations of rock masses. To ensure safety and long-term reliability it is essential to characterize their mechanical behavior. While traditional data acquisition requires direct access to the rock face, terrestrial laser scanning (TLS) for generating digital outcrop models (DOMs) overcomes this necessity to some extent and has evolved into a standard method for describing and quantifying reservoir potential and structural characteristics of geological strata.[1–4] To characterize the structural setting of rock masses the fracture pattern is a crucial property and is usually generated by statistical models such as discrete fracture networks (DFNs). The precision of these models is increased the more fracture data is available. Therefore, it is worthwhile to extract the inherent fracture data from TLS point clouds for such outcrop analog studies. Moreover, spatial information of other geological surfaces such as fault or bedding planes are of equal importance for rock mass characterization and can be extracted from 3D point cloud data as well.

At many study sites, manual geological compass measurements and scan line surveys are not feasible or are restricted to small areas because of inaccessibility or rockfall hazard. In addition, manual measurements are time-consuming and error-prone, especially in complex settings. Plane analyses of 3D TLS data provide a tool to overcome all these problems. Another vital aspect is that each single orientation measurement obtained from TLS data can be easily associated with precise spatial information (x-, y-, z-coordinates), which is of great importance for straightforward import into modeling software and further data processing.

Wide accessibility of close-range laser scanning techniques and its increased utilization has recently led to many studies dealing with discontinuity analysis from TLS-derived data.[5–18]

Despite the growing amount of publications, the authors of this study have been the first that focused explicitly on (semi-)automated discontinuity recognition through a 3D region growing segmentation algorithm based on a robust plane fit for normal estimation.[19–21] Much too often a lack of extensive validation tests ("ground truth") with conventional measurement techniques and other software can be observed in existing literature. Furthermore, little value has been attributed to passing on the results for subsequent DFN development in commercial software packages. Published methods regarding estimations of discontinuity spacing often lack the necessary precision for

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significant DFN models and do not include all relevant discontinuities. Hence, these methods may not be sufficient to reflect the true fracture intensity.

The originality of our study lies within several aspects. (1) We present the newest version of a constantly improved algorithm for automated detection of 3D planes, which has multiple advantages. The algorithm needs only a minimum of data preprocessing, if any. It works efficiently and fast without necessity of high processing power; hence, it is applicable on field laptops for in situ analysis. The algorithm is highly adaptable to specific applications or different outcrop conditions. In addition, the extensive output data is optimized for straightforward import into analytical and modeling software for further use. Finally, it delivers very precise and accurate orientation data in a short time. (2) Furthermore, we provide extensive validation tests for statistical significance by comparing our results with two alternative methods, which leads to new insights about ground truth fit and orientation data quality. (3) In addition, a workflow is proposed for precise fracture intensity (or spacing) calculations, which is based on orientation data extracted by the presented algorithm, applicable for fracture network modeling. Moreover, pitfalls of intensity sampling are highlighted.

First, the automated plane detection algorithm is described in detail including data preprocessing steps. The algorithm performs a 3D region growing segmentation of point cloud data controlled by several parameters. To test the automated plane detection, an outcrop with intricately developed planes was chosen. More than 1000 geological compass measurements and orientation data, handpicked digitally with the software VRGS, were used to validate the results. By comparing the manual and digital methods, we reveal the statistical significance of plane set mean orientation calculations. Finally, we present a case study for digital fracture intensity estimation using the commercial modeling software Petrel.[22]

2. State of the art

Several authors used the acquired TLS data for manual plane extraction.[12–14,23,24] However, an automated identification of planes is desirable. Hence others introduced (semi-) automated methods on 3D point cloud derived 3D meshes[10,18,23] and used a fuzzy k-mean clustering algorithm for plane set classification. However, due to their nature, 3D meshes are accompanied by smoothing and might therefore lead to an unwanted alteration of the original data and loss of detail.

Because of the constraints mentioned above, the number of studies regarding the (semi-)automated identification of discontinuities in 3D point clouds has increased.[5–7,9,11,15,17,23,25–27] Some authors proposed the use of least squares adjustment on a subset of points through planar regression[28,29] or through a sampling cube in the point cloud,[9,27] while others[30] applied a procedure based on the Random Sample Consensus (RANSAC)[31] algorithm by setting up an iterative process, in which the inliers of the best plane are removed from the data at each iteration until no more planes are found. The normal vector calculation on 3D point clouds has been widely accepted.[15] Jaboyedoff et al.[32] proposed the application of the principal component analysis (PCA) for the calculation of normal vector orientation of every point and its coplanar neighbors. This concept was adopted by several authors for plane identification in point clouds.[15,23,25,26]

Three recently published studies[5,6,15] utilized normal vector calculation as a basis for subsequent discontinuity set recognition, performed directly on 3D point clouds. For this purpose Assali et al.[5] applied a spherical k-mean algorithm on the normal vectors associated with each point to classify subsets of discontinuities. Riquelme et al.[15] made use of a coplanarity test to remove anomalous points and applied a Kernel Density Estimation (KDE) to identify discontinuity sets. Most recently, Wang et al.[6] published a region growing approach for an automated plane extraction, that is similar to the algorithm used in the present study. On the other hand, García-Sellés et al.[8] performed a planar regression for normal vector estimation and subsequently applied a region growing segmentation algorithm, but their approach is not (semi-) automated. Other studies by[5,27,33] recognized discontinuity spacing in point clouds. These studies apply a virtual scanline perpendicular to identified discontinuities belonging to one set. Gigli and Casagli[9] applied a similar approach, but used an elongated cylinder instead of a scanline to cut the discontinuities.

3. Study sites

3.1. A: Natural outcrop Wilkenfels

This natural outcrop is a rock face in the nature sanctuary Russenstein in Heidelberg (located at UTM zone 32 U 479951E and 5474025N), which consists of biotite granite of Variscan age and is located close to the Upper Rhine Graben main boundary fault. It is intensely fractured with several visible minor faults orientated parallel to the main boundary fault. The most prominent surfaces are parallel quartz mineralized slickensides intersecting the whole outcrop with an average spacing of 1.2 m, partially giving the outcrop a layered appearance. The overall fracture pattern is very complex with several different fracture sets and sometimes irregularly orientated cracks. Blocks or surfaces often show spherical weathering. For this study, the westernmost part of the outcrop was investigated (Fig. 1). It is about 15 m long, 14 m wide and 8 m high.

This site has several specific characteristics that are important for proper ground truth validation tests: (1) it provides full accessibility for compass measurements; (2) the TLS unit can be positioned at different levels around the target to minimize occlusion effects; (3) there are planes developed in almost all possible directions providing an optimal dataset to reveal systematic errors; (4) fractures are not concealed by quarry walls or other secondary surfaces in this natural outcrop; and (5) complex fracturing, rounded or curved planes and rough surfaces provide a challenging test for the segmentation algorithm. However, there

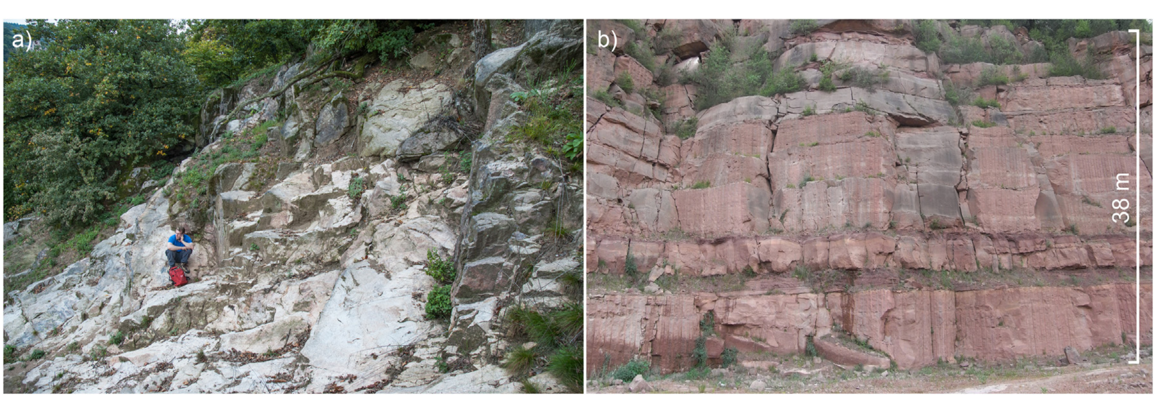

Fig. 1. (a) Upper section of the natural outcrop Wilkenfels. View in SW direction. Meditating geologist for scale. (b) Quarry Rockenau. View in W direction.