Approaches for the digital measurement of rock mass discontinuities

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Abstract. Rock mass characterization plays an essential role in rock engineering activities. Presently several approaches for digitally measuring rock mass discontinuities are available. This study summarizes some of the main technological approaches, together with comparative quantitative evaluations of discontinuity measurements. For the steeply inclined Engelswand outcrop in Tyrol, Austria, an Unmanned Aerial Vehicle was used to acquire a series of photographic images in order to generate a true color georeferenced point cloud and derivative 3D models. Discontinuity orientations were measured by manual, assisted and automated digital approaches. Orientations of individual discontinuity planes and the statistics of the overall discontinuity structure were evaluated. The manual and assisted measurement methods provide compatible results and are considered highly relevant in the context of rock engineering. While automated measurement methods are able to provide an overall indication of the dominating discontinuity pattern, discrimination of individual discontinuity sets is not feasible. While this is a major limiting factor in terms of extracting useful data for rock engineering practice, a dual digital measurement approach is considered prudent when large data sets are being evaluated. This involves conducting rapid automated measurements to obtain an overall representation of the rock mass structure, followed by supplementary manual or assisted measurements to more precisely extract pertinent structural data.

1. Introduction
Characterizing rock mass discontinuity properties such as orientation, spacing, persistence, wall strength, infillings, roughness and aperture is a fundamental task in rock engineering practice [1]. To an ever-increasing extent, classical analog methods for characterizing these properties are being superseded or supplemented with remote digital measurement techniques. The digital methods tend to increase objectivity and repeatability, and are particularly attractive when accessing the rock mass entails safety risk for field personnel. However, there are a number of different approaches and techniques for performing digital measurements, the intricacies of which should be well understood by the rock engineering practitioner.

The purpose of this study is to make a quantitative comparison of discontinuity orientations obtained using different digital measurement methods. Specifically, an Unmanned Aerial Vehicle (UAV) was deployed to capture photographic imagery of the Engelswand outcrop in Tyrol, Austria. The imagery was combined to generate true color high resolution 3D point clouds using the Structure-from-motion (SfM) method [2]. As enumerated herein, the discontinuity orientations were then extracted from the point cloud using different manual, assisted and automated techniques. The discontinuity measurement
approaches investigated include: (i) manual methods (RiSCAN PRO v 2.1.2 [3]), (ii) semi-automated / assisted methods (open-source CloudCompare v 2.11.3 – Compass Plugin [4], ShapeMetriX UAV (SMX) v 4.0.5 [5], 3DM Analyst v 2.6.2 [6]) and (iii) automated methods (open-source CloudCompare v 2.11.3 – Facets Plugin [4], 3DM Analyst v 2.6.2 [6]). Prior studies have shown strong correlations between digital point cloud measurement results and traditional measurements made with a geologic compass [7][8][9]). Considering that safe access to the Engelswand impedes traditional analog measurements, the intent of this study is to focus on digital methods only.

2. Study site

As depicted in figure 1, the Engelswand is located near the village Tumpen in the approximately N-S striking Ötztal (Tyrol, Austria). The Ötztal is a U-shaped valley formed by glacial erosion and it separates the Ötztaler Alps in the west from the Stubaier Alps in the east. The Engelswand consists of granodiorite-gneiss [10] and is situated within the Ötztal-Bundschuh nappe system within the Upper Austroalpine basement nappes [11]. These nappes were thrusted over the Penninic nappes during Eocene-Oligocene times.

An overview of the approximately 160 m high by 120 m wide Engelswand outcrop is depicted in figure 2. The rock mass has discontinuities with trace lengths of several tens of meters (figure 2), whereas the dominant discontinuities in general dip steeply into western (D1), eastern (D2) and southern (D3) directions. As enumerated below, additional and less prominent discontinuities also occur.

Figure 1. Location of the Engelswand outcrop (basemap from tirisMaps, Amt der Tiroler Landesregierung)

Figure 2. Engelswand outcrop (dash-dotted line) on the left and the inset outcrop area selected for detailed measurements (dotted line) enlarged on the right.
3. Methods

3.1. Photogrammetric survey and processing
The Unmanned Aerial Vehicle (UAV) DJI Mavic Pro was used to acquire photographic images of the Engelswand outcrop. The camera resolution and focal length are 4000 x 3000 pixels and 4.7 mm, respectively. Eight Ground Control Points (GCP) were installed for georeferencing and measured with a Leica GS 15 GNSS real time kinematic rover.

Agisoft Metashape v 1.5.3 and 1.6.4 [12] was used to generate 3D point clouds for analyses performed with CloudCompare and RiSCAN PRO. The camera alignment was specified with high accuracy and generic preselection. Dense point clouds were produced with medium quality parameters for the entire Engelswand and for the selected inset outcrop area, with high quality parameters. The 3D textured surface models for the ShapeMetriX UAV and 3DM Analyst studies were generated within the respective software.

3.2. Digital measurement of discontinuities
Digital measurements of discontinuity dip and dip directions were performed with the open-source CloudCompare plugins Facets and Compass and with the commercial software RiSCAN Pro, ShapeMetriX UAV and 3DM Analyst.

RiSCAN Pro is developed for the application of RIEGL Terrestrial 3D Laser Scanner Systems and offers manual measuring orientations of defined polygons within the point cloud. The function calculates a plane from the coordinates of the selected area using the least-squares fit algorithm [13]. The CloudCompare plugin Compass enables manual measuring of orientations within point clouds and was also developed to rapidly extract and measure structural traces, lineations and true thicknesses [8]. Planes are measured by fitting points selected by a circle tool using the least squares algorithm. Traces are determined by deriving the least cost path between user defined points, subsequently a plane is fitted to each trace by using least squares to estimate a structure orientation [14]. Analyzing a point cloud using Compass can be improved by transforming the data with the CloudCompare plugin HoughNormals [15]. Subsequent conversion to dip and dip directions, HSV colored visualization and query options facilitate the distinguishing of structures.

ShapeMetriX applications are developed for the contact-free acquisition and assessment of geometric rock mass features by 3D images [16]. Mean orientations of discontinuities selected by areas or traces are computed. Discontinuities are measured directly on the textured model and can easily be grouped in sets. Stereographic projections of the data can be received in seconds.

3DM Analyst is a digital photogrammetric system developed for mapping, surveying, mining and engineering tasks, whereas one of the most popular uses is the generation of 3D images for geotechnical analysis [17]. The orientation of discontinuities, is determined by finding a best fit plane to a set of points digitized on the surface of the textured model [18]. Availability of stereographic projections provides a quick assessment of the data. Besides the capability of manual measuring 3DM Analyst also contains an algorithm automatic detection of planes.

Facets is a CloudCompare plugin developed for the automated extraction of planar structures from 3D point clouds [9]. The software provides the two algorithms Kd-tree (KD) and Fast marching (FM) to divide a point cloud into clusters of adjacent points, both using a least square fitting method. The procedures result in polygons which are colored with respect to their dip direction and can be further grouped into plane families. Data can be visualized in stereograms.

3.2.1. Individual discontinuity planes. To compare the results of the different approaches for digital measurements ten specified discontinuity planes (figure 3) were selected. The CloudCompare plugin Compass enables direct measurement of individual planes by a circle selection tool. Measurements were taken with constant radius to cover the entire area of every selected individual plane and the mean dip and dip direction was calculated. In RiSCAN Pro, ShapeMetriX UAV and 3DM Analyst individual discontinuities can be framed by polygons and no further processing is required. Before applying the
automated algorithms of the CloudCompare Facets plugin, the individual discontinuities were extracted from the point cloud. Since both algorithms result in several facets per individual plane, the mean dip and dip direction was used for comparison to manual and assisted measurements.

![Image](image.png)

**Figure 3.** Image on the left indicates ten individual discontinuity planes. Detailed views for plane 1 and plane 2, measured by using different techniques, on the right.

### 3.2.2. Overall discontinuity structure
In addition to comparing individual measurement results, the orientation statistics for the overall rock mass were evaluated. This involved the manual, assisted and automated measurements of the defined inset area of the Engelswand using the same methods described above. For the automated measurements both CloudCompare (Facets) and 3DM Analyst were tested.

### 4. Results

#### 4.1. Individual discontinuity planes
For the 10 discontinuities evaluated the maximum difference and maximum standard deviation (σ) in dip direction are 7 and 2.53 degrees, respectively. For dip magnitude these maximum values are 4 and 1.63 degrees, respectively. The results of individual discontinuity measurements are summarized in table 1.

**Table 1.** Orientations of ten individual discontinuity planes (dip direction/dip) as measured by different digital methods.

| Plane | RiSCAN PRO | CloudCompare Compass | ShapeMetryx UAV | 3DM Analyst | CloudCompare Facets FM | CloudCompare Facets KD | σ Dip dir | σ Dip |
|-------|------------|----------------------|-----------------|-------------|------------------------|------------------------|----------|-------|
| Plane 1 | 195/84     | 194/83               | 194/83          | 190/84      | 195/81                 | 193/83                 | 1.87     | 1.10  |
| Plane 2 | 184/84     | 183/85               | 182/85          | 183/85      | 183/84                 | 185/84                 | 1.03     | 0.55  |
| Plane 3 | 255/83     | 256/83               | 255/82          | 255/82      | 254/83                 | 249/83                 | 2.53     | 0.52  |
| Plane 4 | 240/70     | 240/70               | 240/69          | 240/69      | 240/71                 | 240/72                 | 0        | 1.17  |
| Plane 5 | 099/59     | 097/59               | 099/58          | 097/58      | 094/61                 | 094/61                 | 2.25     | 1.37  |
| Plane 6 | 051/61     | 050/60               | 050/62          | 049/60      | 049/60                 | 050/62                 | 0.75     | 0.98  |
| Plane 7 | 082/85     | 083/85               | 083/87          | 082/84      | 081/85                 | 083/86                 | 0.82     | 1.03  |
| Plane 8 | 201/63     | 201/67               | 201/63          | 202/65      | 207/64                 | 205/66                 | 2.56     | 1.63  |
| Plane 9 | 084/86     | 085/86               | 084/86          | 084/84      | 085/85                 | 083/85                 | 0.75     | 0.82  |
| Plane 10| 243/76     | 243/75               | 244/76          | 245/78      | 244/76                 | 243/76                 | 0.82     | 0.98  |
4.2. Overall discontinuity structure

4.2.1. Manual and Assisted measurement methods. Of the methods evaluated only RiSCAN PRO is considered to embody the principles of manual digital measurements, wherein the user must decide on each detail of measurement area and location. This is analogous to how manual measurements are made in the field: a high degree of interaction is required to decide where to execute the measurements. Assisted measurements are exemplified by the software packages CloudCompare (Compass plugin), ShapeMetriX UAV and 3DM Analyst. While a significant level of user interaction is still required, a variety of digital mapping tools greatly facilitates measurements, particularly when large datasets are involved. As an example, the time required to measure 202 discontinuities using RiScan Pro is 260 minutes. The times required to measure 279, 247 and 233 discontinuities with CloudCompare (Compass plugin), ShapeMetriX UAV and 3DM Analyst are 190, 180 and 100 minutes, respectively. These measurements were made within the inset area of the Engelswand and are shown in figure 4. Each of these methods resulted in the identification of four discontinuity sets along with a small number of outlier discontinuities. The mean orientations for each discontinuity set along with measurement statistics are summarized in table 2.

Figure 4. Lower hemisphere equal angle stereographic projections of manual and assisted discontinuity measurements: a) RiSCAN PRO; b) CloudCompare Compass; c) ShapeMetriX UAV; d) 3DM Analyst.
Table 2. Mean discontinuity set orientations and measurement statistics according to manual and assisted methods.

| Set | Software        | Mean Dip dir/dip | No. measurements | Fisher’s K | Variability limit (68.26%) | Confidence limit (68.26%) | σ Mean Dip dir | σ Mean Dip |
|-----|-----------------|------------------|------------------|------------|-----------------------------|---------------------------|----------------|------------|
| D1  | RiSCAN PRO      | 262/85           | 92               | 17.73      | 20.73                        | 2.21                      | 1.29           | 0.57       |
| D1  | CC Compass      | 265/84           | 118              | 20.74      | 19.15                        | 1.80                      |                |            |
| D1  | ShapeMetriX     | 263/84           | 120              | 22.15      | 18.52                        | 1.72                      |                |            |
| D1  | 3DM Analyst     | 264/85           | 109              | 18.03      | 20.55                        | 2.01                      |                |            |
| D2  | RiSCAN PRO      | 097/63           | 42               | 45.04      | 12.96                        | 2.02                      |                |            |
| D2  | CC Compass      | 093/65           | 68               | 50.28      | 12.26                        | 1.50                      |                |            |
| D2  | ShapeMetriX     | 094/66           | 54               | 55.72      | 11.65                        | 1.60                      |                |            |
| D2  | 3DM Analyst     | 100/60           | 50               | 51.01      | 12.28                        | 1.75                      |                |            |
| D3  | RiSCAN PRO      | 196/83           | 40               | 29.83      | 15.95                        | 2.56                      |                |            |
| D3  | CC Compass      | 198/85           | 56               | 27.02      | 16.76                        | 2.27                      |                |            |
| D3  | ShapeMetriX     | 199/84           | 41               | 25.68      | 17.19                        | 2.73                      |                |            |
| D3  | 3DM Analyst     | 191/84           | 45               | 24.88      | 17.47                        | 2.65                      |                |            |
| D4  | RiSCAN PRO      | 278/43           | 17               | 37.41      | 14.23                        | 3.49                      |                |            |
| D4  | CC Compass      | 277/45           | 25               | 45.01      | 12.97                        | 2.62                      |                |            |
| D4  | ShapeMetriX     | 277/48           | 16               | 34.58      | 14.80                        | 3.74                      |                |            |
| D4  | 3DM Analyst     | 283/44           | 19               | 36.95      | 14.32                        | 3.32                      |                |            |

4.3. 4.2.2 Automated Measurement Methods. For the entire Engelswand outcrop, CloudCompare Facets produces 6102 and 7454 facets using the FM and KD algorithms, respectively. Pre-filtering of vegetated areas and post-filtering of erroneous facets reduced the respective number of facets to 5456 and 6579. Results of the automated approach by 3DM Analyst can be visualized in a stereographic projection within the software, data export is not possible and a number of measurements is not given.

As depicted in figures 5, 6 and 7, all of the automated measurement methods indicate an overall discontinuity structure that dips moderately to very steeply to the west to southwest and east-to-northeast. While this structure is generally consistent with the overall structure identified with the manual and assisted measurement methods, further discrimination of the four discontinuity sets from the automated results is not possible. Though the most distinct result is obtained within the inset outcrop area using point clouds generated with high quality parameters.

Figure 5. Lower hemisphere equal angle stereographic projections of automated discontinuity measurements made with the CloudCompare Facets FM algorithm (Octree level: 8, Max distance @ 99 %: 0.15 m, Min points per facet: 100, Max edge length: 1.5 m): a) entire Engelswand outcrop; b) inset outcrop area (medium quality); c) inset outcrop area (high quality).
5. Discussion and Conclusion

In this study, manual, assisted and automated methods for measuring discontinuity orientations were evaluated. Specifically, measurements of select individual discontinuity planes and the overall rock mass structure were compared.

The manual and assisted measurement methods provide compatible results and are considered to truly reflect key attributes of the discontinuity structure. For practical applications, the information derived from these different methods can be considered essentially equivalent and highly relevant in the context of rock engineering. The assisted methods thus have the main advantage of measurement efficiency, which can be an important consideration when making a large number of measurements.

The automated measurement methods are able to provide a clue regarding the dominating discontinuity pattern; however, discrimination of individual discontinuity sets is not feasible. While this is a major limiting factor in terms of extracting useful data for rock engineering practice, there is potential value in terms of efficiency. If great care is taken to pre-and-post filter the results, an overall structural pattern is quickly revealed using automated algorithms.

On the basis of these studies a dual digital measurement approach is considered prudent when large data sets are being evaluated. This involves conducting rapid automated measurements to obtain an overall representation of the rock mass structure, followed by supplementary manual or assisted measurements to more precisely extract pertinent structural data.
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