Comparison between manual and automated determination of discontinuity orientations in different rock mass types

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ABSTRACT: In this study, the use of automated discontinuity orientation analysis is evaluated as a potential addition to manual data collection. Point clouds of outcrops of three different rock masses in Germany with distinct structural characteristics are analysed using Open-Source Software Cloud Compare and the plug-in Facets. The accuracy of the automated analysis data is compared to manually collected data. The findings of this study confirm that the discontinuity orientation from automated analysis corresponds to the manually generated data regardless of the geological setting but shows differences caused by exposed area of the discontinuity surfaces and undetected discontinuities due to minimal apertures. Further there remain differences between the results of the methods caused by complex morphology, especially in the context of human bias. The automated approach allows for the investigation of areas that are inaccessible by manual methods, and can also reduce human bias through careful interpretation of the results.

Keywords: Automated discontinuity analysis, UAV, DOM, photogrammetry.

1 INTRODUCTION

Automated discontinuity analysis can provide interpretation of 3D geological data and complement manual surveys when outcrops are not fully accessible, e.g., due to vegetation, stability problems or steep and high slopes. Also, automated data collection may provide a quick, yet comprehensive alternative when access to the region of interest is temporally limited, e.g., during tunnelling. During the past two decades Digital Outcrop Models (DOMs) have mainly been created using LiDAR or laser scanning technology (Thiele et al. 2017; Herrero et al. 2022). An alternative approach is the use of unmanned arial vehicles (UAVs) due to low costs, user-friendliness and applicability (Dewez et al. 2016; Jordá Bordehore et al. 2017), especially for generating DOMs of smaller areas (Herrero et al. 2022). According to previous studies, the automated analysis of discontinuity orientations largely agree with manual data (Herrero et al. 2022; Dewez et al. 2016; Monsalve et al. 2021), but inaccuracies have been reported: a) The absolute number of measured values per joint set scales with the area of discontinuities represented in the 3D model, thus statistical analyses in stereographic projections can be misleading due to the larger amount of data at the -apparently- largest discontinuity plane (Dewez et al. 2016). b) Discontinuities may not be exposed well enough for automatic determination, especially when apertures are small. Thus, entire joint sets may remain unidentified (Herrero et al. 2022).

This study focuses on the analysis of photogrammetrically generated point clouds from four outcrops in three different study areas. The primary objective is to examine the influence of geological features such as tectonics and mineralogical composition on the automated discontinuity analysis. Furthermore, the study aims to evaluate the accuracy of the automated results for accessible areas to assess the potential of using automated methods for investigating remote discontinuities of inaccessible areas. We focus on three questions: 1) Is the automated data analysis able to reflect the manual data in terms of the orientation regardless of the geological setting? 2) Do the results of this study reflect the same uncertainties (biased ratios of joint sets and the undetected joint sets if discontinuity planes are not fully exposed but show a minimal aperture) as already found in other studies on automated discontinuity analysis? 3) Are there other differences between automated and manual data that have not yet been considered?

2 STUDY AREAS

Outcrop RMDev1 represents a folded, Devonian, metasedimentary, sandy clay schist that is exposed at a bank slope of the Ahr river in Rhineland-Palatinate, and features slightly folded, slope-forming bedding planes with dip angles ranging from 20° to 55°. A second outcrop of internally unfolded Devonian metasediments with conjugate shear faults (RMDev2) was investigated in the Ahr valley. The outcrop consists of a near vertical slope of horizontal stratified benches with sheared material along the bedding joints. These two outcrop sections are a few hundred meters apart and show different structural geology characteristics due to the folding. Vegetation limits accessibility in some areas of both sections, and undulating discontinuities result from tectonic stress, particularly at the meter scale. The aperture of the bedding planes and other discontinuities is minimal.

The second rock mass (RMCarb) is a Carboniferous claystone with conjugate discontinuities in the Harz Mountains in Germany. The outcrop consists of nearly vertical bedding planes intersected by conjugate shear fractures. The discontinuities are exposed, accessible and have a low roughness. Vegetation is sparse, accessibility is limited mostly due to the height of the outcrop wall.

The third rock mass (RMJur) is a Jurassic limestone with dominantly orthogonal discontinuity systems located in Bavaria, Germany. Bedding planes show minimal apertures and are barely exposed. Due to the outcrop location in an active quarry, mining activities have resulted in broken rock mass and debris cones. Vegetation is not present, but the accessibility of sections may be limited due to artificial surfaces resulting from mining and thus the absence of natural discontinuities at body level in some places. As a result, at least two discontinuity sets, one of them being the bedding, cannot be surveyed manually.

3 METHODOLOGY

The study uses automated photogrammetric analysis and manual surveying to investigate the orientations of discontinuities of four outcrops in three different geological settings. A geological compass is used to manually survey the discontinuities, i.e., orientation of bedding planes, joints and faults by non-systematical measurements in a section of 15 to 30 m in length and up to about 2 m height. Measurements are taken with three different compasses of the same manufacturer and by three different persons on different days. For both outcrops in the Devonian metasediment discontinuity information along a scanline and microstructural data are additionally collected.

A UAV equipped with a camera (resolution 20 MPx) is used to capture the entire height of the four outcrop sections of up to 15 m. Our 3D models of the outcrop walls are created from photogrammetry using the software *Agisoft Metashape Professional Edition*. Point clouds with a density of 50,000 data points per square meter are generated on the basis of the models within the software *CloudCompare*. The models are manually cleared of vegetation (e.g. a branch of a tree that was recognised by the software as a discontinuity) and debris by visual operator inspection to avoid false positives. Subsequently, the discontinuities are generated automatically using the plug-in *Facets* and the KD-tree algorithm within the software *CloudCompare* (Dewez et al. 2016; Woosley, J.C. 2020). An example of a processed data set is shown in Figure 1. The settings for automated data generation are chosen to orient the generated polygons as close to the model as possible, thus keeping the deviation to a minimum. Since each polygon created in this way corresponds to a discontinuity orientation, the amount of data increases accordingly.

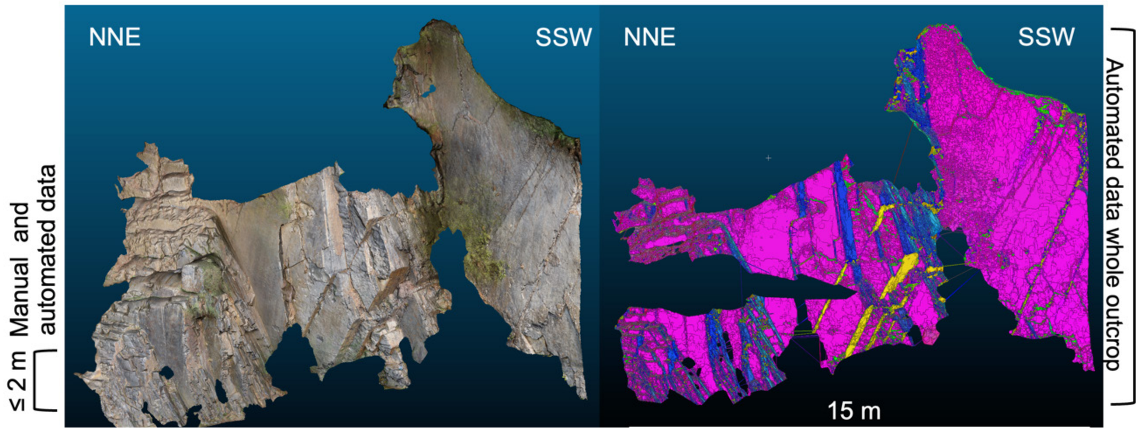

Figure 1. 3D model of the outcrop from the Harz Mountains (left) and the result of the automated discontinuity analysis within *Cloud Compare* (right).

Manual discontinuity orientations are compared to the automated data in the same area and, in addition, to automated data generated for the entire outcrop. The results are presented in box plots and stereographic projections. The box plots show the statistics of orientation data as quartiles, with the central box representing the interquartile range (IQR) and the median. The whiskers extend to the minimum and maximum values (1.5 x box width), with outliers plotted as individual points. The stereographic projections show poles as well as contour plots. The stereonets with pole points and colour contour plot with density clusters are plotted using *Dips* by *Rocscience.*

4 RESULTS

The dimensions of the outcrops (A) and the number of measurements achieved per data acquisition method (n) are summarised in Table 1.

Table 1. Outcrop area A with length l and height h and the number of measurements per approach.

Outcrop	RMDev1		RMDev2		RMCarb		RMJur	
A [m^2] = l [m] x h [m] / n [-]	A	n	A	n	A	n	A	n
Manual (≤ 2 m)	30 x 2	498	30 x 2	112	15 x 2	59	30 x 2	85
Automated (≤ 2 m)	30 x 2	20,809	30 x 2	30,587	15 x 2	23,554	30 x 2	33,055
Automated (complete A)	30 x 10	45,466	30 x 10	57,138	15 x 8	227,231	30 x 15	70,589

The orientation resulting from the automated discontinuity analysis agrees well with the manual discontinuity data, regardless of rock type. The automated data in the range ≤ 2 m and across the entire outcrop are similar for RMDev1, RMDev2 and RMCarb (Figure 2 to 4). The manual data exhibits a higher level of cluster dispersion, with numerous clusters characterized by low density. In contrast, the automated data reveals a greater dispersion of individual data points across the stereonet. RMDev1, RMDev2 and RMCarb (Figure 2 to 4) have fewer clusters in the automated data, which is also reflected in the corresponding box plots with a tendency towards a lower IQR for the automated data.

This can be explained by the larger amount of data and the observation previously made by Dewez et al. (2016) that the number of values depends on the exposed area. Moreover, the slope-forming discontinuities, e.g. the pink ones in Figure 1 (RMCarb), contribute to a larger proportion of the total area compared to other sets of discontinuities, leading to an increased number of polygons and thus individual data points. The area fraction-dependent representation of discontinuity sets in the automated data leads to dense clusters in the stereonets for certain sets while making discontinuity sets with smaller exposed areas less distinguishable. The discontinuity sets less represented in the stereonets may thus remain undetected in an interpretation solely based on automated data.

In RMJur (Figure 5), the discontinuity set of the horizontal bedding and a nearly vertical discontinuity set can be recognized in the stereonet with the automated data for the entire outcrop, but do not show in automated ≤ 2 m nor manual data. The two discontinuity sets were recognized during the manual survey. However, they could not be measured by the automated (≤ 2 m) nor manual method because of the low aperture in the area ≤ 2 m, as Herrero et al. (2022), has already noted. Only in higher parts of the outcrop (> 2 m), the discontinuity surfaces are exposed, which allows them to be detected by the program. In summary, neither method could fully capture all discontinuity sets. However, the orientations of the discontinuities represented in all three data sets are similar among the different approaches. The different approaches result in varying ratios of discontinuities per set, leading to different formations of clusters and box plots.

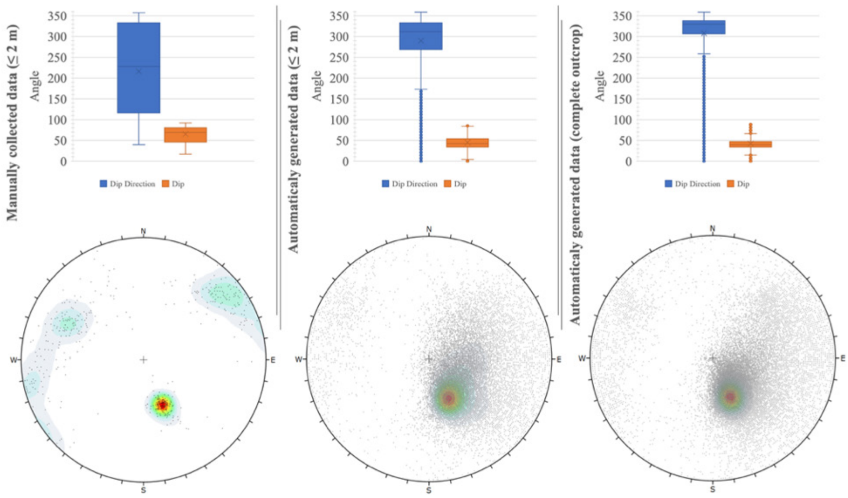

Figure 2. Box plots and stereographic projections of the Devonian metasediment RMDev1.

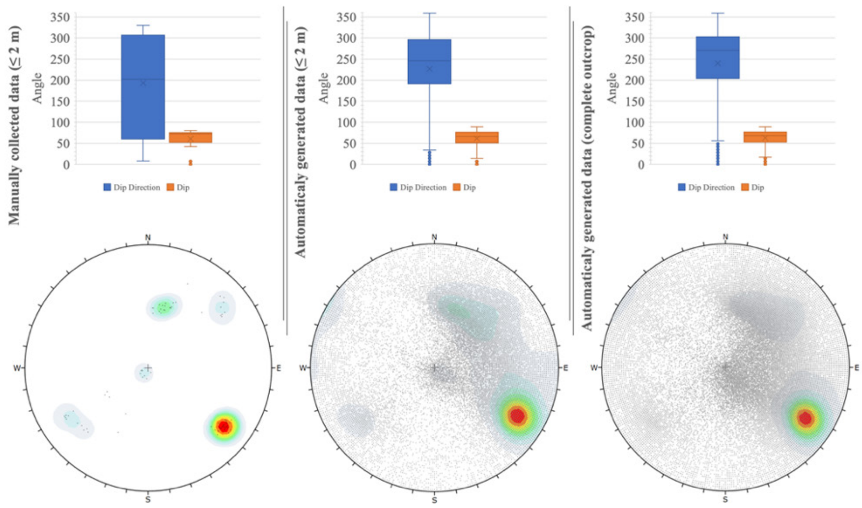

Figure 3. Box plots and stereographic projections of the Devonian metasediment RMDev2.

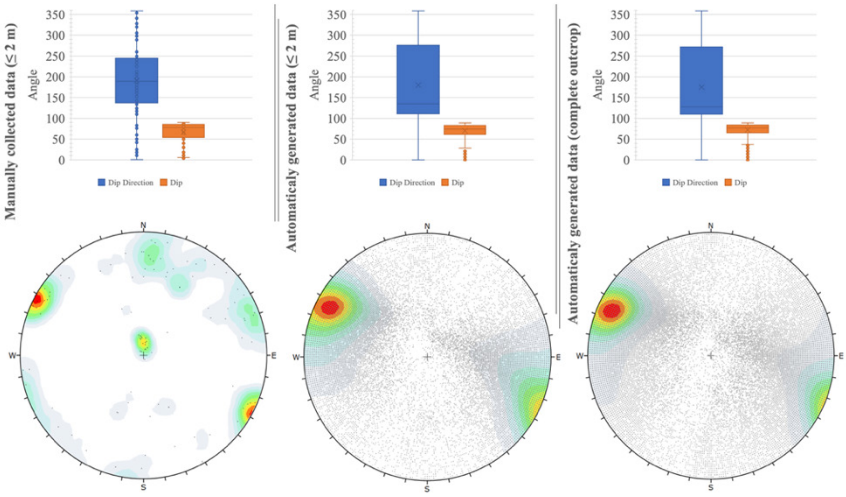

Figure 4. Box plots and stereographic projections of the Carboniferous claystone RMCarb.

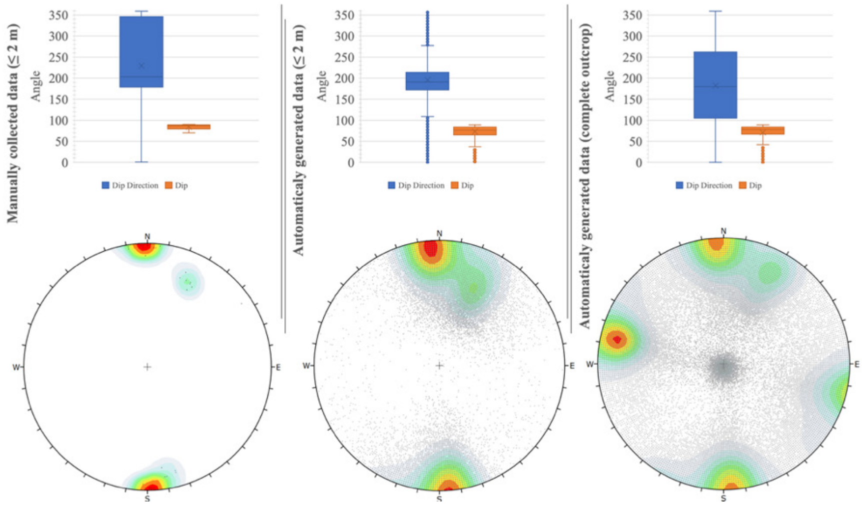

Figure 5. Box plots and stereographic projections of the Jurassic limestone RMJur.

5 DISCUSSION

The results of the automated discontinuity analysis align with the manual data, regardless of rock type. Remaining discrepancies are largely attributed to the effect of exposed area and the presence of discontinuities with small apertures. Further inaccuracies are associated with complex morphology, especially in the context of human bias, which the automated data seems to compensate to some extent. Removal of vegetation and debris is necessary to avoid generating false positives, but can also lead to the loss of discontinuity sets (e.g., horizontal discontinuity in RMCarb).

There is a large scatter in the automated data compared to the manual data owing to algorithm-induced noise or false positives, e.g., in regions with sheared material, vegetation or debris. To minimise data scatter and avoid false positives, efforts were made to remove debris and vegetation from the models, but small patches were not completely eliminated. RMDev2 exhibits more sheared regions and more discontinuity sets in general than RMDev1, which may account for the comparatively high dispersion observed in the automaticed data of RMDev2.

In Figure 2 (RMDev1) and Figure 4 (RMCarb), the clusters identified during the manual survey are hardly or not to be found in the automated data. The exposed area and the morphology can lead to a changed representation of densities in the clusters. Both outcrops show complex morphologies due to their tectonic setting, which has probably led to human bias in the measurement process and inaccuracies in the automated analysis. In Figure 4 the cluster at an angle of inclination of about 0° does not appear in the stereonets based on the automated data. This discontinuity can only be measured in an area of about one eighth of the outcrop, and was probably measured relatively often due to its good accessibility (easy to climb, smooth flat surfaces). Additionally, this area was overgrown with vegetation and therefore cut out of the 3D model. Thus, these data points are completely missing in the automated data. In both Figure 2 and 4 a gradual progression can be seen in the automated data, which is not visible in the manual data. This difference is likely attributed to the complex morphology and the resulting limited ability of humans to perceive gradual changes, indicating a potential human bias. Scanline methods can be used to reduce human bias depending on technical feasibility, i.e., RMDev1 was analysed using scanlines in the x- and y-axis, not the z-axis.

6 CONCLUSIONS

Automated discontinuity analysis yields mostly accurate data and a larger dataset than manual measurement, encompassing inaccessible areas. It enables more precise representation of gradual progressions in discontinuity orientations. However, limitations of automated data arise in cases of discontinuities with small apertures and potential bias due to exposed area. While automated procedures simplify discontinuity measurements, data interpretation still requires effort to clean 3D models and validate the analysis. If feasible, scanline analysis can be used to mitigate human bias and provide valuable information, i.e., strength and fracture fillings. This information facilitates significant conclusions regarding the stability of rock mass. Our findings indicate that the optimal quality of discontinuity analysis is achieved through a combination of automated and manual data analysis.

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