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Published in:
ISRM International Symposium - EUROCK 2020

Published: 01/11/2020

Document Version
Peer-reviewed accepted author manuscript, also known as Final accepted manuscript or Post-print

Please cite the original version:
Janiszewski, M., Uotinen, L., Baghbanan, A., & Rinne, M. (2020). Digitisation of hard rock tunnel for remote fracture mapping and virtual training environment. In C. C. Li, H. Ødegaard, A. H. Høien, & J. Macias (Eds.), *ISRM International Symposium - EUROCK 2020: International Society for Rock Mechanics and Rock Engineering Norwegian Group for Rock Mechanics* Norsk Betongforening.

Digitisation of hard rock tunnel for remote fracture mapping and virtual training environment

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Abstract

The knowledge of geometrical properties of discontinuities is of crucial importance in the rock mass characterisation process. Recent advances in photogrammetry allow for an easy digitisation procedure of rock surfaces so that digital 3D models can be used for remote site characterisation.

This paper presents a methodology to digitise tunnel rock surfaces using Structure from Motion digital photogrammetry for remote measurements of discontinuities. The proposed method is applied on a 12 m long and 4 m high tunnel section of an underground research tunnel at Aalto University in Finland, which is scanned using Canon 5Ds R DSLR camera and Canon 14 mm f/2.8 and 35 mm f/1.4 lenses. The photos are then processed in commercially available photogrammetric software – RealityCapture.

As a result, a high-resolution 3D point cloud of the tunnel wall is produced. The point cloud is used for semi-automatic measurements of fracture orientations. In addition, a digital twin of the tunnel section with photorealistic surface texture is created and implemented into virtual reality (VR) system – Virtual Underground Training Environment (VUTE) developed for training of rock mass characterisation. The VUTE system enables remote visual inspection of the rock surface and virtual measurements of the orientation of discontinuities with designated virtual tools. The semi-automatic measurements extracted from the 3D point cloud using a discontinuity extractor software are compared with measurements performed in VR as well as with manual measurements performed in the tunnel. The results demonstrate that all three mapping methods identify three major joint sets with analogous orientations.

The automatic fracture mapping method achieves the highest density of the measurements, allows repeatability, and enables other parameters to be extracted automatically, such as persistence and spacing of the discontinuities. This confirms the advantage of automatic analysis of discontinuities on 3D point clouds of tunnel rock surface digitised using photogrammetry.

Keywords

Digital photogrammetry, Underground tunnel, Rock mass characterisation, 3D point cloud, Virtual reality

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1 Introduction

The discontinuities in the rock mass are one of the most critical factor that governs its geomechanical behaviour. Because of that, the knowledge of the geometrical and mechanical properties of discontinuities is a crucial component in the design of stable underground structures (Hudson & Harrison, 2000). The orientation of discontinuities is typically mapped manually using a geological compass at rock outcrops. However, manual mapping of discontinuities has several limitations. First, the timeframe for the measurements is constrained, especially in underground tunnels due to time pressure of excavation cycles. Second, it is also limited to only the accessible tunnel faces. Most importantly, manual fracture mapping is biased due to human factors, such as previous experience or motivation of the person doing the measurements (Gaich et al. 2003).

Recent developments of remote sensing techniques such as LiDAR and photogrammetry, the fracture plane can be scanned to represent its geometry as a high-resolution 3d point cloud. Particularly the development of the Structure-from-Motion (SfM) photogrammetry allows a cheap and easy method to record rock surface geometry for remote characterisation of discontinuities using off-the-shelf cameras (Uotinen, 2018; García-Luna et al. 2019; Uotinen et al. 2020). Digital models of rock surface combined with new remote mapping approaches, such as the method developed by Riquelme et al. (2014) for semi-automatic measurements of fractures based on 3d point cloud data, provide a straightforward procedure to extract the discontinuity sets and their orientation. Such a remote mapping technique can overcome the limitation of the manual mapping of discontinuities as it allows to map inaccessible rock faces, in a short time frame, and without the human bias.

The SfM photogrammetry can also be used to produce a digital twin of the rock surface, in which the textures are based on high-quality images. Thanks to the recent development of the Extended Reality (XR) technology, which includes Virtual (VR) and Augmented Reality (AR), such photorealistic 3d models can be implemented into a virtual learning environments that can be used for training and education in rock engineering (Jastrzębski, 2017; Onsel et al. 2018, Merkel, 2019), or as a tool for rock mass characterization (Onsel et al. 2019).

The goal of this study is to propose a digitisation methodology of an underground tunnel using the SfM photogrammetry technique. The Aalto Research Tunnel is digitised and the photogrammetric model of the tunnel is then utilized in a twofold manner: (1) to extract from the 3d point cloud of a tunnel wall the discontinuity sets and their geometrical properties using the semi-automatic method by Riquelme et al. (2014), and (2) to implement the high-resolution textured model to a virtual reality learning environment for virtual mapping of the orientation of discontinuities. Finally, the measurements from the semi-automatic method and virtual mapping are compared to manual measurements performed in the tunnel.

2 Digitisation of the Aalto Research Tunnel using SfM photogrammetry

The workflow for the digitisation of a hard rock tunnel for semi-automatic fracture mapping and virtual reality learning environment is presented in Fig. 1 and described in detail in the following subsections. The first part of this study was the photogrammetric digitisation of the tunnel wall. The process was divided into two main steps: image capturing and SfM photogrammetry (see Fig. 1). In this study, the SfM photogrammetry method was used for digitising a 12 m long rock wall section of a 100 m long mapping tunnel in the Aalto Research Tunnel (see Fig. 2). The approximate surface area of the tunnel section was 48 m^2. The tunnel is located in a granitic rock mass, approximately 20 m below the Otaniemi campus of Aalto University in Espoo, Finland.

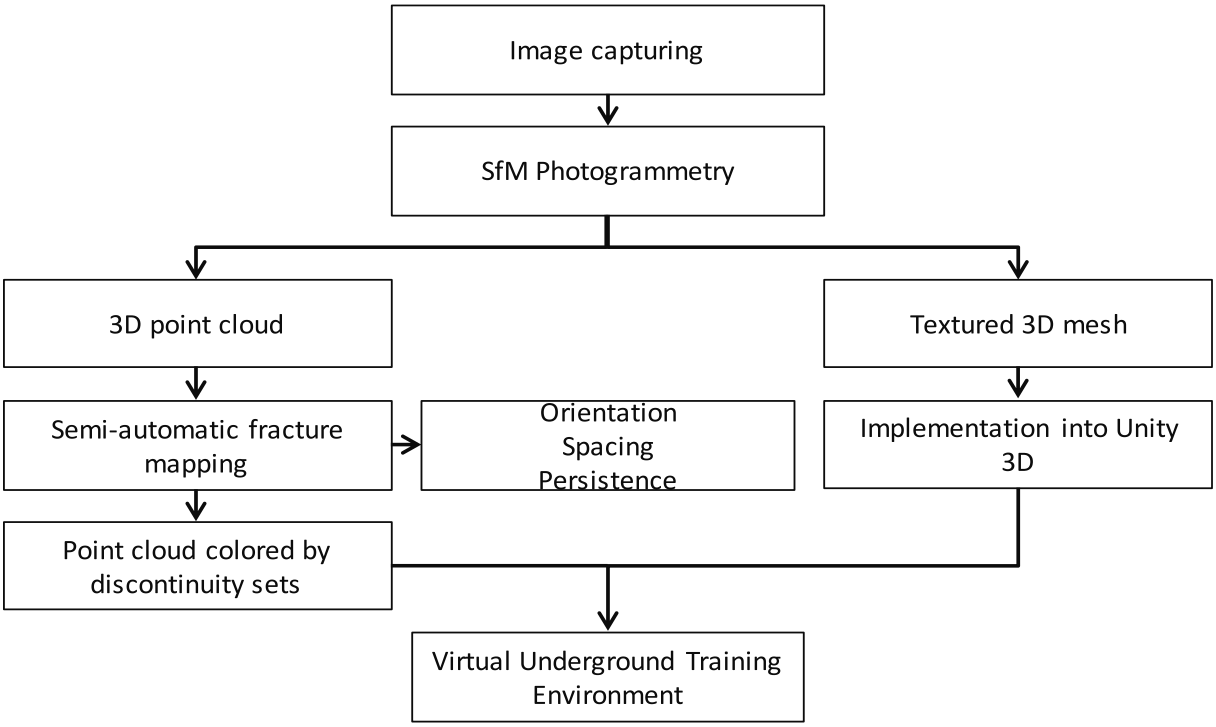

Fig. 1 Workflow for the digitisation of tunnels for semi-automatic fracture mapping and virtual reality learning environment

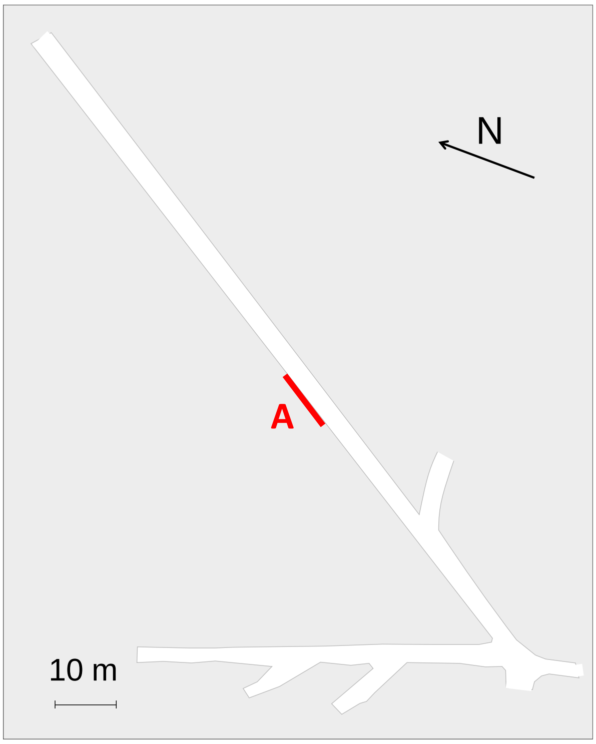

Fig. 2 Map of the Aalto Research tunnel with the marked tunnel section (A) that was digitised in this study. The tunnel is located in a granitic rock mass approximately 20 m below the Otaniemi campus in Espoo, Finland

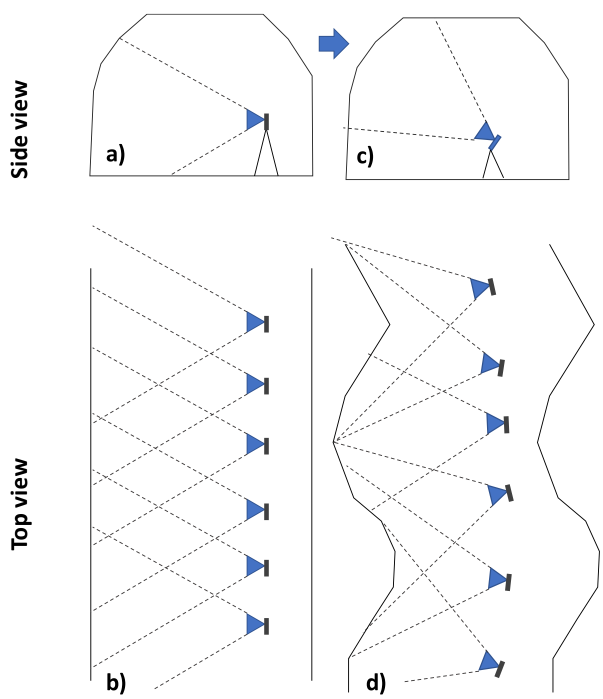

Fig. 3 Sketch depicting the workflow for image capturing of tunnel walls: set up the camera (a), move the camera along the tunnel (b), choose a new position of the camera (c) capture the upper part of the wall and the roof (d)

2.1.1 Image capturing and pre-processing

The images were captured using Canon EOS 5DS R camera (see Fig. 4a) and two lenses: first with Canon 14mm f/2.8 wide-angle lens (Fig. 4b) and next with Canon 35mm f/1.4 lens (Fig. 4c). The camera was set to aperture priority mode with the aperture value of f/8, ISO 100, and RAW image file format. Three Apurture Amaran HR672C (Fig. 4d) and three 2x50W LED panels (Fig. 4e) were used to illuminate the rock surface (see Fig. 5), and the measured illuminance at the tunnel wall was 151 and 292 lux, for the two light types respectively. In between the light panels, the illuminance was 97 lux. The camera was positioned on a tripod, and a shutter release remote was used to prevent blur due to exposure time of 1s required with the given camera settings.

Fig. 4 Camera (a), lenses (b-c) and lights (d-e) used in the study

Fig. 5 An example of the lighting set-up in the tunnel

The following procedure was used to capture 72 images of the tunnel wall with the 14 mm wide-angle lens:

- Position the camera at one side of the tunnel and orient the camera to face the opposing wall (Fig. 3a).
- Capture the first set by moving along the tunnel at regular spatial intervals with at least a 70% overlap between the subsequent photos (Fig. 3b).
- Then change the camera angle/tripod height to capture the upper part of the wall and the roof and repeat the process (Fig. 3c).
- If the tunnel surface is very irregular, follow the tunnel surface so that the camera is oriented parallel to the surface (Fig. 3d).

Next, the 35 mm lens was used, and the camera was positioned closer to the wall, and close-up photos were captured to include the fine details. The same procedure as presented above was used, and 297 images were captured.

In total, 369 RAW images of the tunnel wall were captured using both lenses. The total measured acquisition time amounted to 68 min, out of which the 72 wide-angle photos took 16 min, and the 297 close-up photos 52 min. It has to be noted that the acquisition times were significant due to the slow shutter speed that necessitates the use of a tripod. The speed of image capturing could be increased, for example by using UAVs.

Next, the RAW images were edited in Adobe Lightroom Classic software ver. 9. In the develop mode, the Shadows and Highlights properties were set to +100, and -100 respectively, to even out the lighting of the images. The Texture and Clarity properties were both set to +30 to emphasise texture details. All images were exported as .jpeg with the quality set to 90.

2.1.2 SfM photogrammetry

In this study, the RealityCapture photogrammetric software was used to process the images and reconstruct the 3d models of the tunnel wall. First, all pre-processed images were imported into the software. Next, the photos were aligned at default settings in the image registration process in which the software calculates camera positions, orientations and internal camera states for every input image, and creates a sparse 3d point-cloud of the object. The model was scaled using a measured distance between two distinct points visible on at least four images. In the next step, the software calculated a complete dense 3D model of the object. The final step was to colourise and apply a texture to the model. A detailed description of the workflow for the photogrammetric reconstruction of rock surfaces in the RealityCapture software is given by Merkel (2019).

As a result of the photogrammetric reconstruction, two outputs were produced:

(1) a dense 3d point-cloud consisting of 212 million points with an average surface point density of 0.5 pts/mm^2 (see Fig. 6a), and

(2) a photorealistic textured mesh simplified to 3 million polygons (see Fig. 6b).

Fig. 6 High-resolution point cloud of the tunnel section with camera positions of 369 images (a), and a zoomed section of the textured mesh model (b).

3 Remote fracture mapping

The digitised 3d model of the tunnel wall was used for remote fracture mapping using two methods: (1) semi-automatic method using the Discontinuity Set Extractor (DSE) software, and (2) virtual mapping in the Virtual Underground Tunnel Environment.

3.1 Semi-automatic discontinuity extraction

The semi-automatic fracture mapping was performed using the Discontinuity Set Extractor (DSE) software which is based on the method developed by Riquelme et al. (2014). DSE calculates the normal vectors of each point that is coplanar with its neighbouring points and represents them as poles on a stereonet. Next, the density of the poles is calculated, and the most representative poles are extracted as the discontinuity sets. The point cloud is then classified into separate discontinuity sets. DSE also enables to measure the spacing and persistence of the extracted discontinuity sets (Riquelme et al. 2015, 2018), but this functionality was not explored in this study.

The point cloud of the tunnel wall that was created using the photogrammetric software consisted of 212 million points, which was too large to be processed in the DSE software. Hence, the first step was to simplify the point cloud. For this purpose, the CloudCompare software ver. 2.10.2 was used, and the point cloud was simplified using the Subsample point cloud function. The random subsampling method was chosen, and the output was set to 4 million points. The point cloud was oriented to match the orientation of the actual tunnel using compass measurements of three surfaces. Next, a sampling window corresponding to the zoomed area presented in Fig. 6b was chosen for further analysis. The same sampling window was also used in the manual compass measurements described in section 3.3. The resulting segmented point cloud consisted of 357 135 points.

The subsampled and segmented point cloud was saved as an ASCII file and imported into the DSE software. The principal planes were calculated using the default settings, and the statistical analysis was performed with the minimum angle between the pole vectors set to 35° and the maximum number of principal planes to 5. As a result, three discontinuity sets were extracted (see Table 1), and the point cloud was classified into separate discontinuity sets represented with different colours (see Fig. 7). The principal poles and poles density plots are presented in Fig. 9a and Fig. 9b, respectively.

Table 1 Dip direction, dip and pole density of the tunnel wall discontinuity sets extracted using the semi-automatic method

Discontinuity set	Dip direction [°]	Dip [°]	Pole density [%]
1	332.7	82.9	56.0
2	64.1	85.6	13.0
3	288.7	8.6	4.7

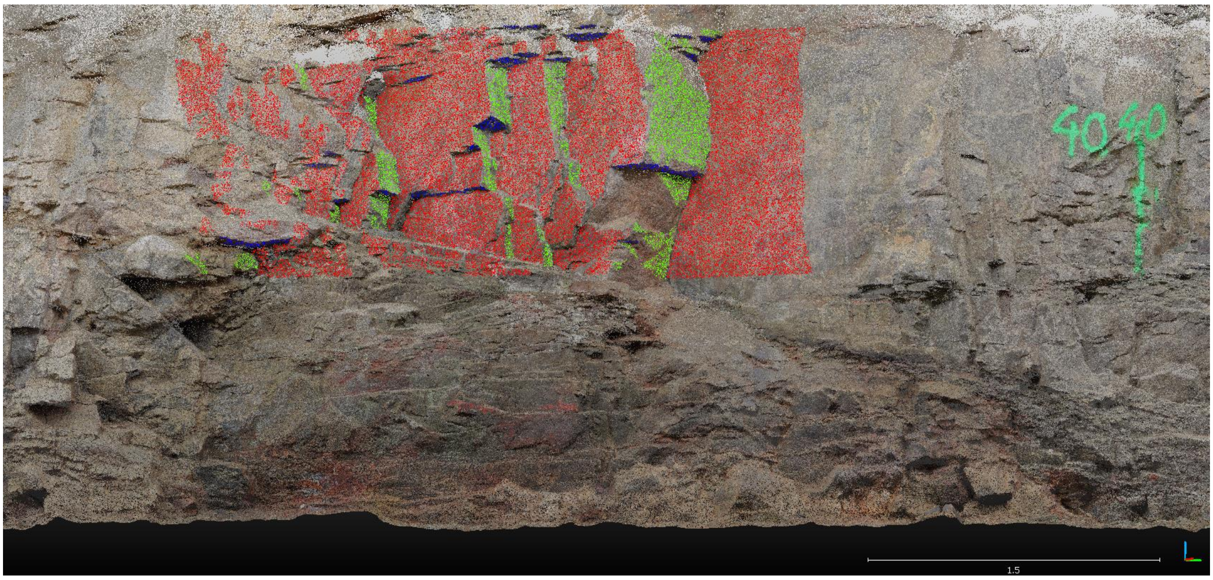

Fig. 7 Simplified point cloud of the tunnel surface and mapping window with the coloured discontinuity sets extracted using the DSE software

3.2 Virtual fracture mapping in the Virtual Underground Training Environment

The Virtual Underground Training Environment (VUTE) is a Virtual Reality (VR) learning environment developed by Jastrzębski (2017) in the Unity game engine for the training of geological mapping on a virtual rock outcrop. The users measure the orientation of discontinuities using digital replicas of mapping tools (see Fig. 8).

The same sampling window, as described in section 3.1 and presented in Fig. 6, was implemented in VUTE and mapped. The procedure of the fracture mapping in VUTE is described in Jastrzębski (2017). In total, 38 measurements of dip and directions were performed in VR by the staff of the Rock Mechanics research group at Aalto University. Also, manual mapping was conducted in the tunnel using an analogue geological compass, and 22 measurements were made.

3.3 Comparison between remote and manual fracture mapping

The results of the semi-automatic, virtual and manual fracture mapping are compared in Fig. 9. Both the semi-automatic method (Fig. 9a-b) and mapping in virtual reality (Fig. 9c) identified the same three discontinuity sets as in the measurements performed with an analogue geological compass in the tunnel (Fig. 9d). The identified discontinuity sets include two sub-vertical sets perpendicular to each other, and one sub-horizontal set. All three measurement methods produce comparable results, which is demonstrated by the pole density plots in Fig. 9.

The semi-automatic method extracted 262 836 principal poles, as compared to only 38 measurements in VR and 22 manual measurements, even though the acquisition times are analogous. It has to be noted that remote mapping of discontinuities can also be performed on the point-cloud manually with a computer-assisted method, such as the Compass plugin for the CloudCompare software (Thiele et al. 2017). However, this does not help to produce repeatable and bias-free measurements. This fact confirms the clear advantage of the semi-automatic methods for fast acquisition of large datasets of discontinuity measurements.

Another important aspect is the influence of model quality on the measurements. García-Luna et al. (2019) indicated that the quality of measurements is directly related to the quality of the photogrammetric model and concluded that only 15 good quality photos are sufficient for an analysis of a tunnel face of 50 m^2. Hence, future studies should further explore and quantify this relationship.

Fig. 8. Virtual measurements of discontinuity orientation in the VUTE virtual reality learning system. Source: https://youtu.be/8Zxtotw_vyg

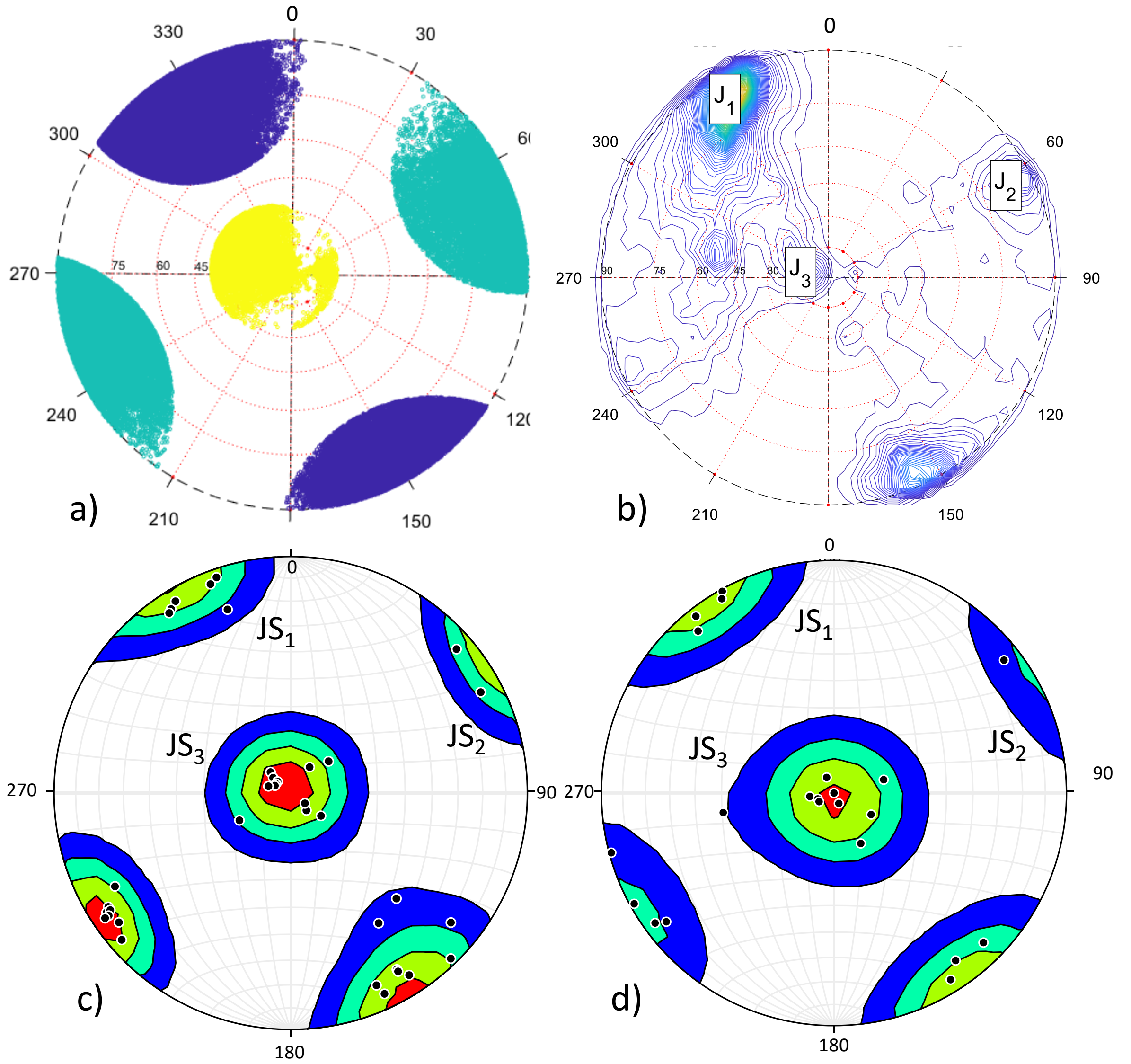

Fig. 9 Results of fracture mapping: principal poles (a) and pole density (b) of three discontinuity sets extracted from the DSE software, c) virtual mapping in the VUTE system, and d) manual mapping performed in the tunnel; c) and d) plotted using the Stereonet software by Allemendiger et al. (2013), and Cardozo and Allemendiger (2013)

4 Conclusion

In this study, the Structure-from-Motion (SfM) photogrammetric method was used for digitising a 12 m by 4 m tunnel section of the Aalto Research Tunnel. It was demonstrated that the SfM method, which uses an off-the-shelf DSLR camera is a viable method to digitise rock surfaces in underground tunnels and allows to produce accurate and detailed 3D models of fracture surfaces. The high-resolution point cloud data of the digitised tunnel section was used for semi-automatic extraction of discontinuities and measurements of their orientations. The photorealistic textured mesh of the tunnel surface was implemented into a virtual reality training system, in which virtual mapping was performed. Both remote mapping methods identified three distinct discontinuity sets and produced results comparable to the manual measurements performed in the tunnel using an analogue geological compass. The results of this study demonstrate that digitisation of rock surfaces using photogrammetry enables accurate, fast, and repeatable remote fracture characterisation method that is free of the human bias. The outlook for the future looks very promising. Due to the recent advances of drones, it is expected that 3D photogrammetric scanning of underground openings, even those inaccessible to humans due to safety reasons, will enable remote rock mass characterisation with automatic methods to be more widespread.

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