Janiszewski, Mateusz; Prittinen, Markus; Uotinen, Lauri; Torkan, Masoud; Rinne, Mikael

Rapid photogrammetric method for rock mass characterization in underground excavations

Published in:
The IV Nordic Symposium on Rock Mechanics and Rock Engineering

DOI:
10.33112/nrock2023.20

Published: 24/05/2023

Document Version
Publisher's PDF, also known as Version of record

Please cite the original version:
Janiszewski, M., Prittinen, M., Uotinen, L., Torkan, M., & Rinne, M. (2023). Rapid photogrammetric method for rock mass characterization in underground excavations. In H. Sigursteinsson, & A. K. Ingimarsson (Eds.), *The IV Nordic Symposium on Rock Mechanics and Rock Engineering: Proceedings of the NROCK 2023* (pp. 213-221). Jarðtæknifélag Íslands. https://doi.org/10.33112/nrock2023.20

Proceedings of the NROCK 2023
The IV Nordic Symposium on
Rock Mechanics and Rock Engineering
ISBN 978-9935-9436-2-0
DOI 10.33112/nrock2023.20

Rapid photogrammetric method for rock mass characterization in underground excavations

Mateusz Janiszewski (mateusz.janiszewski@aalto.fi)

Mateusz Janiszewski
Aalto University, Espoo, Finland
Markus Prittinen, Lauri Uotinen, Masoud Torkan, Mikael Rinne
Aalto University, Espoo, Finland

ABSTRACT

Underground excavation mapping and rock mass characterization are critical for ensuring the safety, proper design, and maintenance of underground infrastructure. Traditional mapping methods typically involve manual inspections and measurements that require contact with the tunnel surface, which can be time-consuming, expensive, and pose safety risks to personnel. In recent years, photogrammetry has emerged as an alternative method for generating high-resolution digital 3D models of tunnels, enabling rapid and remote rock mass measurements. In this paper, we present a method for tunnel and stope scanning using photogrammetry and remote rock mass mapping from 3D models. Two case studies are presented to demonstrate the effectiveness of the proposed method. In the first case, a multi-camera rig consisting of action cameras is used for video-based photogrammetric reconstruction of underground tunnel excavation. The rock mass data is then extracted from the model and visualized. In the second case, a drone workflow is used to map out rock mass features in stopes. Images taken with the drone are processed to create a 3D point cloud of the stope, which is then used to extract discontinuities from the rock mass surfaces. The orientation and spacing of these discontinuities are measured and visualized on top of the photorealistic 3D mesh of the stope for inspection. The proposed method significantly reduces the data capture process. The advancements in camera and software technologies have made it possible to acquire rapid and accurate 3D models of underground excavations that can be used as a source of rock mass data. Our results demonstrate that photogrammetry is a robust approach for underground rock mass inspection and remote mapping.

KEYWORDS

Rock mass characterization; fracture mapping; photogrammetry; underground; tunnel

1. INTRODUCTION

Understanding the behavior of rock mass in underground excavations is crucial for ensuring safe and efficient mining operations. Discontinuities in the rock mass, such as joints and fractures, play a significant role in governing its behavior. Mapping these discontinuities is essential for predicting and managing rock mass behavior, designing support systems, and planning mining activities. Traditionally, discontinuity mapping was done manually, which was a slow and time-consuming process that was prone to bias. In some cases, mapping was not even possible due to limited access to the area or safety concerns.

Recent advances in photogrammetry and in particular the Structure-from-motion Multi-view Stereo (SfM-MVS) photogrammetric method has shown great potential for digitizing the rock mass surface and extracting discontinuities using computer-assisted mapping methods (García-Luna et al. 2019). However, using photogrammetry in underground excavations poses many challenges, such as limited access, safety concerns, and the need for rapid and accurate data acquisition (Janiszewski et al. 2022).

In this study, we demonstrate a method for remote rock mass characterization in underground excavations using photogrammetry. Specifically, we show how a multi-camera rig can be used for quick data acquisition in underground tunnels, and a drone workflow can be used to digitize stopes. We then demonstrate how 3D point cloud data can be used for the digital mapping of joint planes using the 3D models of the rock mass surface. Our goal is to provide a comprehensive and practical solution to remote rock mass characterization that addresses the challenges posed by underground excavation environments.

2. RAPID TUNNEL PHOTOGRAMMETRY WITH A MULTI-CAMERA RIG

In this section, we describe the proposed tunnel photogrammetry method for rock mass characterization using a multi-camera rig. Traditional photogrammetry methods for tunnel mapping require capturing a large number of images from various positions and angles, which can be time-consuming and difficult to perform in narrow, unstable underground spaces.

2.1. Multi-camera rig

A multi-camera rig was constructed consisting of four GoPro Hero 8 cameras mounted on a PVC pipe frame (Figure 1) (Prittinen, 2021). The positioning of the cameras is optimized to capture the maximum area of the tunnel with sufficient overlap between images. The cameras are mounted horizontally with the top camera facing downwards and the bottom camera facing upwards, while the left side camera is slightly angled towards the right and the right camera is angled towards the left. This configuration allows for the rapid collection of data by taking four images at the same time and covering all tunnel surfaces.

An automatic shutter release GoPro smart remote is used to synchronize the start and end of recording across all four cameras. Optional battery-powered LED lights can be mounted on the frame to improve image quality in low-light conditions, but in this study, more powerful 360 lights and LED panels were used to illuminate the tunnel surface. The frame can also be mounted on a tripod and capture still images, but this was not done as the priority was to increase the acquisition speed as much as possible.

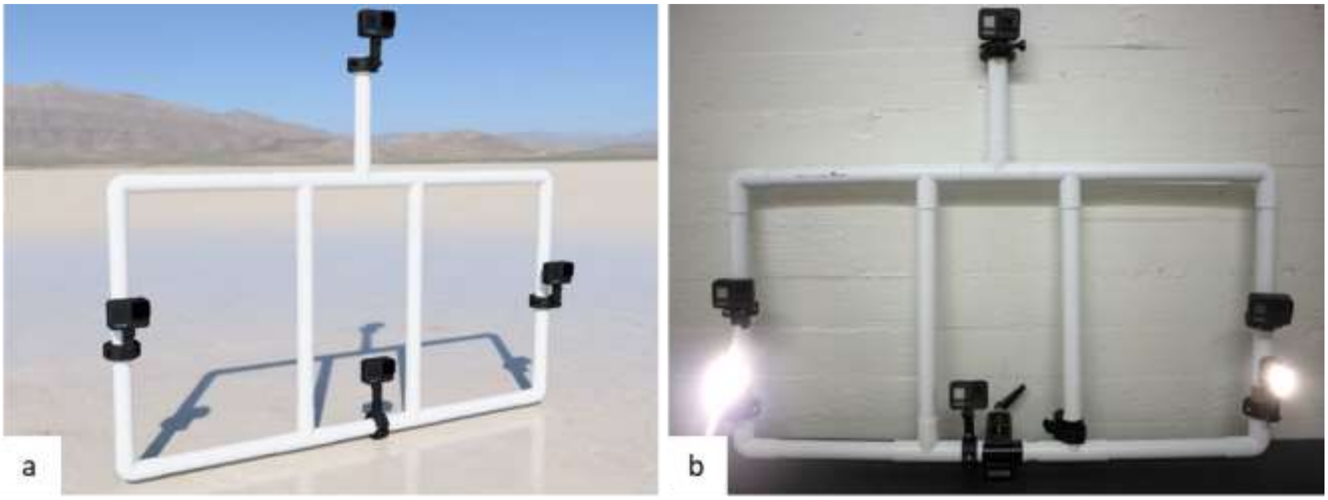

Figure 1. Multi-camera rig for rapid photogrammetric data acquisition in tunnels (modified after Prittinen, 2021).

2.2. Test site

To demonstrate the effectiveness of this method, a tunnel face of the Underground research laboratory of Aalto University (URLA) was scanned. Both walls of the tunnel are unsupported, and the area is used for engineering geology exercises to train fracture mapping. A tunnel drift measuring 4.4 × 2.9 × 4 meters was digitized using the proposed multi-camera rig (Figure 2a).

To illuminate the tunnel face evenly, the lighting setup included two DeWalt DCL074 360 lights and two Aputure Amaran Tri-8s LED light panels, which were positioned inside the tunnel drift (Figure 2b).

To orient and scale the model, an alignment board was designed according to Garcia-Luna et al. (2019), with five control points and known distances. The board is positioned horizontally, and the azimuth of one edge is measured so that the model can be oriented correctly (Figure 2c). In addition, to control the accuracy of the photogrammetric reconstruction, ten control points were mounted on the tunnel walls. Each control point consisted of a 20-bit circular marker generated with RealityCapture software that is automatically detected by the software from images, printed and laminated, and attached to a wooden platform that was attached to the wall.

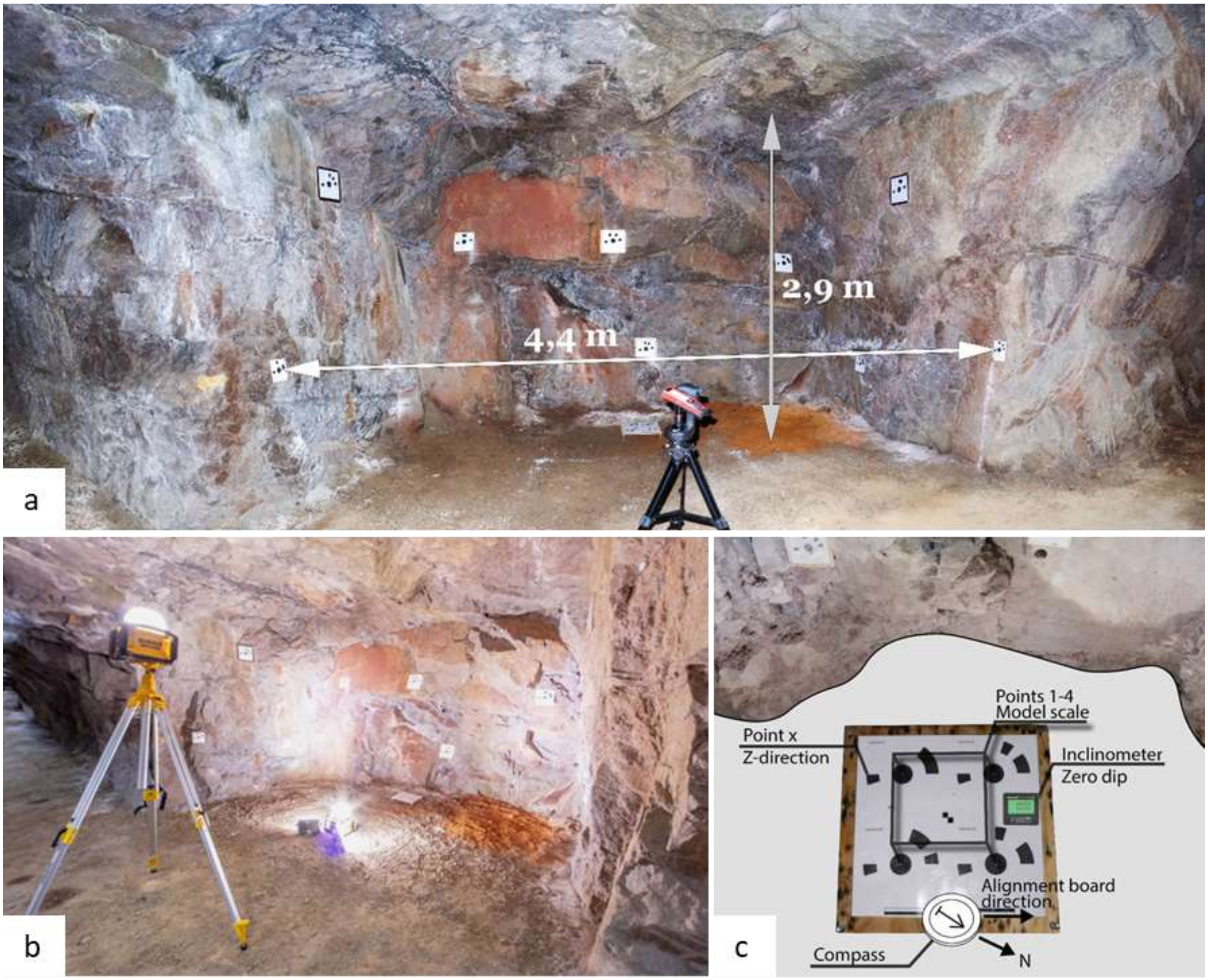

*Figure 2. Tunnel drift dimensions (a), the portable lighting setup (b), and the alignment board with control points and known control distances used to scale and orientate the 3D model (c) (*modified after Prittinen, 2021*).*

2.3. Data acquisition and processing

Each camera recorded a 4K video with a frame size of 4000 × 3000 pixels. Due to low light conditions, a compromise between fast shutter speed and ISO was necessary. A shutter speed of 1/96 s and ISO of 800 were used. Frames were extracted from the videos at 1-second intervals using RealityCapture software, resulting in 480 frames (Figure 3a). The total time to capture all data was 172 seconds.

The extracted frames were processed using RealityCapture v.1.0.3 photogrammetric software, reconstructing the 3D model on Normal detail settings. The processing was done on a PC equipped with an AMD 3990x 64-core 2.9 GHz processor, 256 GB RAM, and 2 x GTX 1080 TI graphics cards. A total of 472 frames were aligned, and a mesh with 23.7M polygons and a point cloud with 11.9M points were produced. The processing times were as follows: alignment (4 min 33s), reconstruction (19 min 27s), and texturing (3 min 49s), totaling 27 min 49s. The point cloud was cropped and cleaned, leaving 9.1M total points with a mean point density of 14.8 pts/cm² (Figure 3b).

Reference distance measurements were taken using a Leica S901 laser distance measurement tool, comparing 13 distances measured between the control points mounted on the wall. The mean error was 3.7 mm, and the maximum error was 8.6 mm.

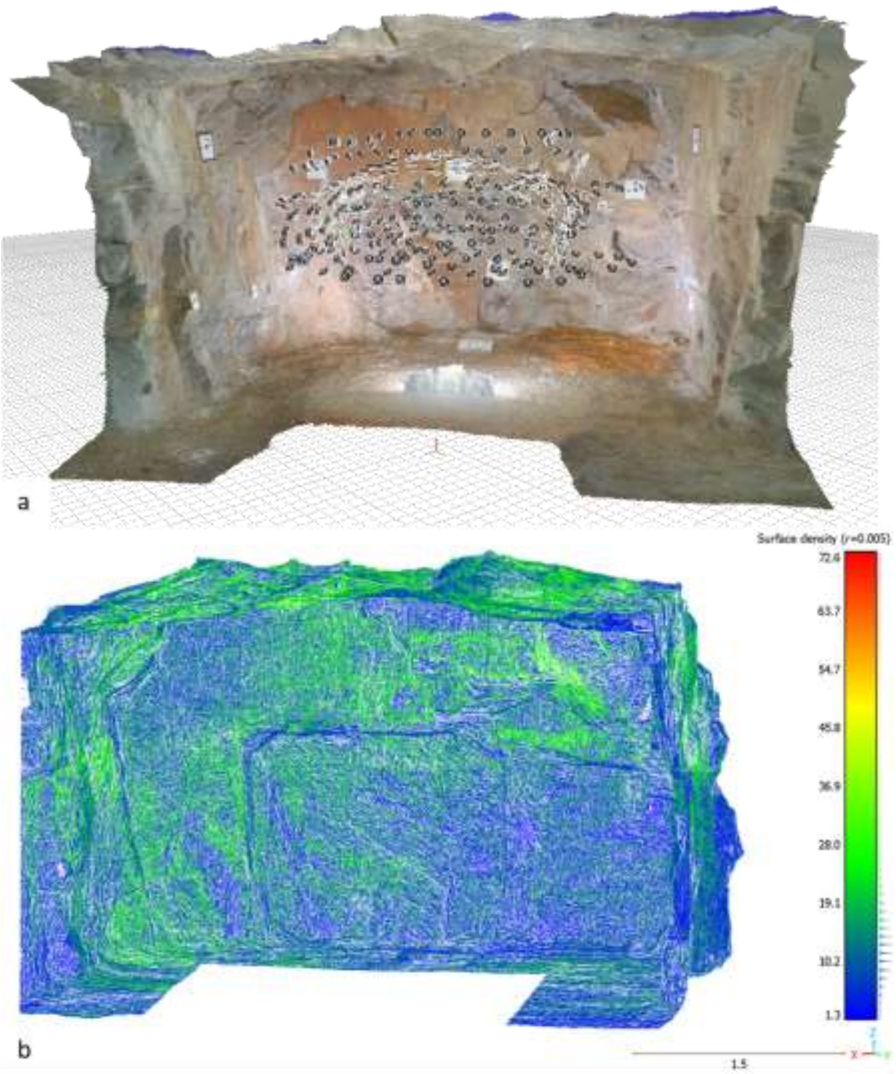

Figure 3. Photogrammetric model of the tunnel drift (a) and the cleaned point cloud colored by point density in pts/cm^2 (b).

2.4. Rock mass data measurement

The resulting 3D point cloud was then processed to extract the discontinuities in the rock mass surfaces. First, reference fracture orientation measurements were conducted manually using a geological compass, measuring seven planar and smooth discontinuity planes. Next, the orientation of the same fracture planes was measured digitally on the point cloud using the Compass plugin in CloudCompare software (Thiele et al. 2017). The mapping comparison against manual compass measurements showed a mean difference of 8.3 degrees for dip direction and 2.4 degrees for dip (Figure 4b).

The point cloud was then processed using a semi-automatic method in Discontinuity Extractor (DSE) software, which clusters the point cloud into discontinuity planes and extracts the mean orientation of discontinuity sets (Riquelme et al. 2014). Four discontinuity sets were identified, and their mean orientation was extracted (Figure 4a). The mapping comparison against manual compass measurements showed a mean difference of 10.4 degrees for dip direction and 3.6 degrees for dip. Thus, the orientation of discontinuity sets measured from the point cloud can be considered comparable to reality.

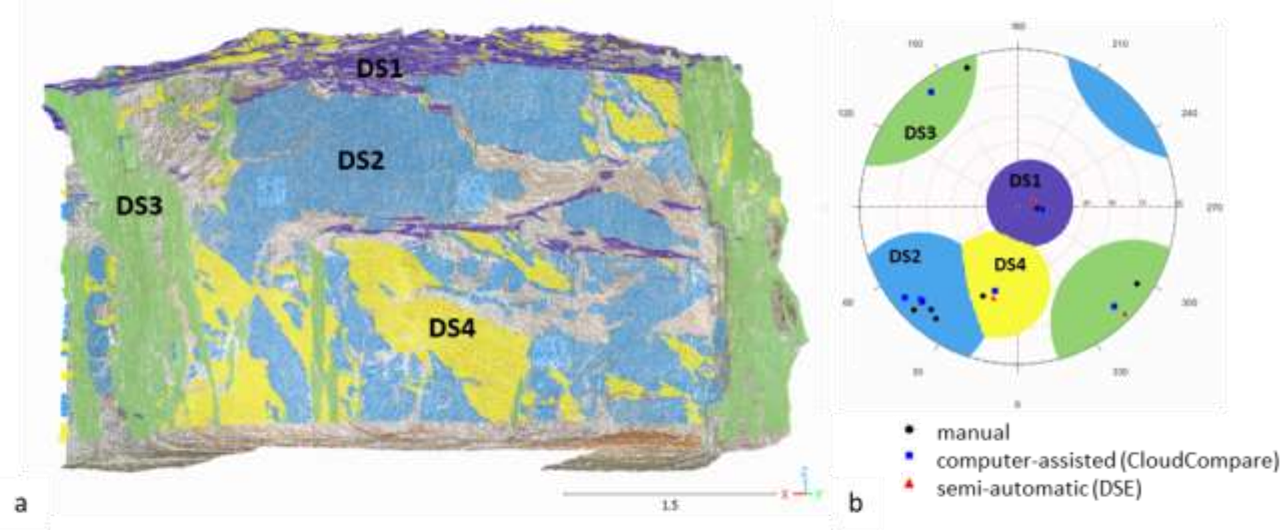

Figure 4. Discontinuity orientation results: visualization of the discontinuity sets extracted from the point cloud using the semi-automatic method in Discontinuity Set Extractor software (a), and comparison between the reference manual discontinuity measurements and digital measurements (b).

2.5. Discussion

The proposed multi-camera photogrammetric method for rock mass mapping in underground excavations demonstrates several advantages over traditional mapping methods. One of the primary benefits is the significant reduction in data capture time. In our case, the time to capture the entire drift was 172 seconds. This rapid acquisition enables efficient workflow, reducing the need for time-consuming manual inspections and minimizing safety risks to personnel. Another benefit of the proposed system is its low cost, with the total costs lower than a single high-resolution camera and lens combination.

In addition to its time and cost efficiency, the proposed method also yields accurate digital rock mass measurements. The reference distance measurements showed a mean error of 3.7 mm and a maximum error of 8.6 mm. The orientation of discontinuities measured from the 3D point cloud was comparable to reality, with a mean difference of 8.3 degrees for dip direction and 2.4 degrees for dip when using the Compass plugin in CloudCompare software. When utilizing the semi-automatic method in DSE, the mean difference for dip direction was 10.4 degrees, and for dip, it was 3.6 degrees. These results indicate that the accuracy of digital rock mass measurements obtained through the proposed method is within a reasonable range for engineering applications.

However, there are some limitations to the proposed method. Firstly, the proposed method requires a portable lighting setup to illuminate the tunnel surface. In consequence, setting up the lights reduces the acquisition speed. Such lighting is not necessary for scanning the tunnel face with a LiDAR, which can produce a grayscale point cloud in dark conditions. Secondly, there was no dust present at the test site, unlike active tunnels where construction activity generates fine dust particles that could interfere with photogrammetry. However, this problem would also affect laser scanning. Next, in operational tunnels or mines, photos may have to be taken from a larger distance due to safety precautions for working under unsupported roofs. This would reduce the point density, as pixels would represent a larger area on the tunnel surface. Finally, the point density of the resulting 3D model is lower compared to a model captured with a high-resolution camera. However, the resulting point cloud is still sufficient for accurate rock mass measurements and is significantly faster when comparing the time to capture the photos.

3. STOPE MAPPING WITH A UAV

Another rapid photogrammetry approach for underground excavations is to use an Unmanned Aerial Vehicle (UAV), which enables remote image capturing from a large area in a short amount of time. However, due to the confined space, low light conditions, and a lack of GPS signal underground, only special UAVs can perform photogrammetric missions successfully. This is especially difficult in underground spaces with restricted access, for example, open stopes, where mine personnel is prohibited from entering due to safety reasons. One example of a UAV that is capable of such missions in open stopes is Elios 2 from Flyability. The drone is equipped with a protective cage and a lighting system that enables photography of remote and hard-to-reach areas.

For the purpose of this study, an open dataset consisting of images taken inside a stope was downloaded from the drone manufacturer's website (Flyability, 2022). A stope in the Golden Sunlight Mine in Montana, USA, was scanned using the Elios 2 drone to explore the potential for stope photogrammetry in an active mine. The upper part of the stope with dimensions 10 × 30 × 100 m was scanned in 4 flights (~35 min total flight time) using the Elios 2 UAV. The drone was recording videos in 4K ultra high definition, which were then processed and 2105 frames with a size of 3840 × 2160 pixels were extracted. In this study, the dataset was reprocessed to test the remote rock mass mapping workflow to measure the orientation and spacing of discontinuities from a photogrammetric 3D model of an underground stope.

3.1. Data processing

The images were processed in Reality Capture photogrammetric software to reconstruct a 3D model of the stope. In total, 1755 images were aligned, and the processing times were as follows: alignment (14 min 08s), reconstruction (6 h 32 min), and texturing (3 min 42s), totaling 6 h 54 min. The resulting point cloud had 289.7 million points and a point density of 33.1 points per cm^2. However, to enable faster processing and ease of handling, the point cloud was cleaned and simplified to 11 million points with a point density of 1.6 pts/cm^2. In addition, a textured 3D mesh was also exported from the software for visualization (Figure 5).

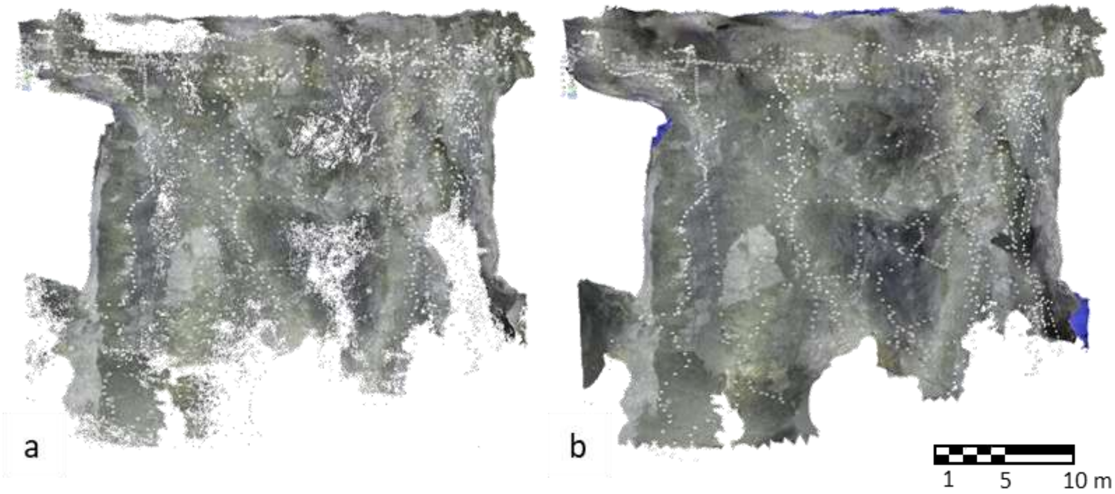

Figure 5. Stope 3D point cloud (left) and textured mesh (right).

3.2. Discontinuity mapping

Next, the goal was to identify the rock discontinuities inside the stope and measure their orientation using the semi-automatic method in the Discontinuity Set Extractor (DSE) software. The point cloud was further simplified to 1 million points. Four discontinuity sets were extracted and visualized on top of the stope 3D model, and their mean orientation was calculated (see Figure 6). Next, the spacing for each discontinuity set was calculated using the built-in function in the DSE software (Riquelme et al. 2015). The resulting histograms of spacing are presented in Figure 7.

The results confirmed the possibility of using drone photogrammetry for semi-automatic fracture mapping in stopes. The next step would be to filter out the data, compute the final measurements and visualize the 3D point cloud of the extracted discontinuities on top of the photorealistic 3D mesh, for example with the use of virtual reality as demonstrated in Janiszewski et al. 2020.

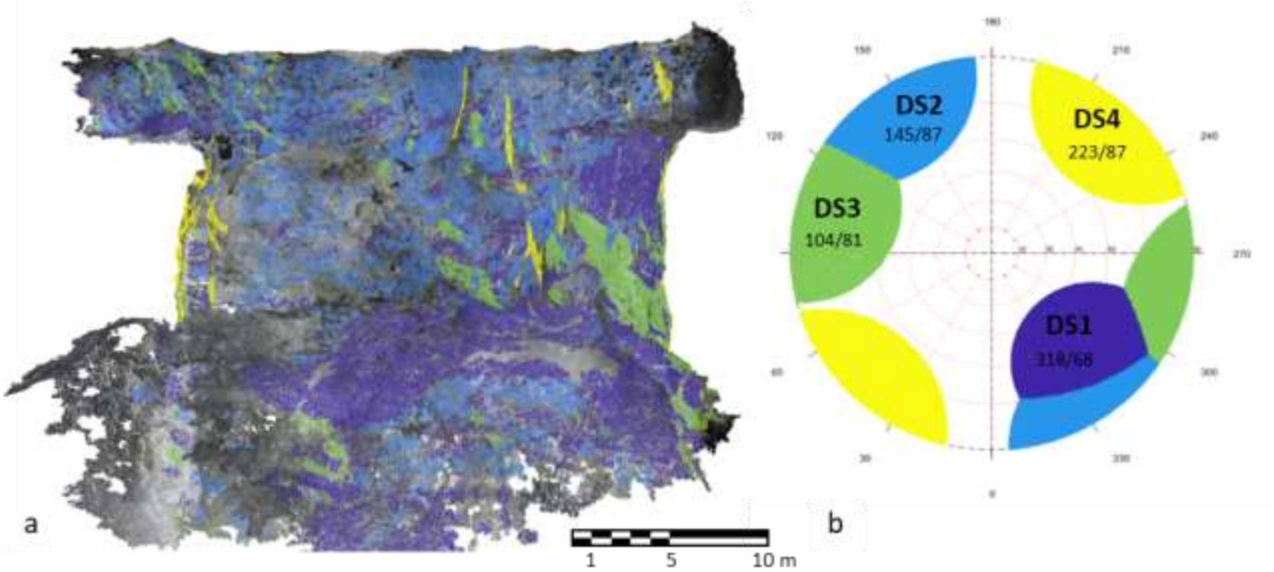

Figure 6. Discontinuity sets extracted from the stope 3D point cloud (left) and their mean orientation (right).

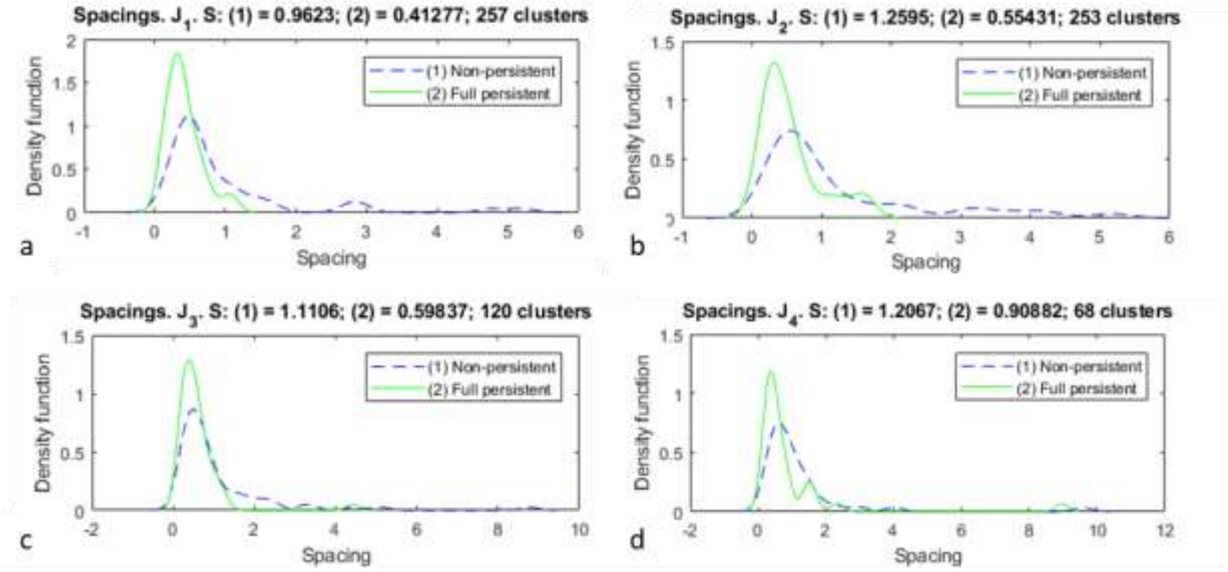

Figure 7. Normal spacing distributions of the four discontinuity sets extracted from the stope 3D model.

3.3. Discussion

The use of drone photogrammetry for stope mapping, as demonstrated in this study, offers several significant benefits for underground excavations. One primary advantage is the ability to remotely map rock mass features in open stopes, which was previously not possible due to access restrictions. This remote mapping capability not only reduces the time required for data acquisition but also opens up the possibility for automation, which can lead to further efficiency improvements. Furthermore, the use of a UAV for rock mass characterization reduces the risk of injury to personnel, as they do not need to enter potentially hazardous areas.

However, there are also limitations to this approach. The high cost of specialized UAVs, such as the Elios 2 drone used in this study, can be a barrier to widespread adoption. Additionally, the short battery life of drones poses a challenge, particularly for extensive underground excavations, as it may require multiple flights and battery changes to cover the entire area of interest.

Despite these limitations, there is significant future potential for UAV-based photogrammetry in underground excavations. The development of multi-camera UAV systems could increase acquisition speed and improve the quality of data, further enhancing the effectiveness of this method. Moreover, advancements in drone technology, including longer battery life and improved navigation capabilities, could further expand the applications of drone photogrammetry in underground excavations and other challenging environments. Ultimately, the combination of these advancements with the inherent benefits of remote mapping, automation potential, and reduced risk for injury positions UAV-based photogrammetry as a promising method for rock mass characterization in underground excavations.

4. CONCLUSIONS

The rapid photogrammetric method for rock mass characterization in underground excavations presented in this study offers an efficient, accurate, and remote alternative to conventional data acquisition techniques. This method not only reduces the time and costs associated with traditional mapping techniques but also provides reliable data for effective underground infrastructure design, maintenance, and safety assessments. Two case studies demonstrated the use of photogrammetry to rapidly acquire spatial data from the rock mass surfaces in underground tunnels and stopes. The photogrammetric 3D models allow for remote mapping of discontinuities to identify the number of joint sets and to measure their orientation and spacing for further analysis. By demonstrating this approach, we hope to enable more efficient and accurate mapping of underground excavations for rock mass characterization.

5. ACKNOWLEDGEMENTS

This research was funded by the Academy of Finland under grant no. 319798. The authors greatly appreciate the financial support.

REFERENCES

Flyability (2022). Photogrammetry dataset. https://info.flyability.com/photogrammetry-dataset (Accessed on 14 December 2022).

García-Luna, R., Senent, S., Jurado-Piña, R., Jimenez, R. (2019). Structure from Motion photogrammetry to characterize underground rock masses: Experiences from two real tunnels. *Tunnelling and Underground Space Technology 83* (2019) 262-273. https://doi.org/10.1016/j.tust.2018.09.026

Janiszewski, M., Uotinen, L., Baghbanan, A., Rinne, M. (2020). Digitisation of hard rock tunnel for remote fracture mapping and virtual training environment. in CC Li, H Ødegaard, AH Høien & J Macias (eds), *ISRM International Symposium - EUROCK 2020*, Trondheim, Norway, 14/06/2020.

Janiszewski, M., Torkan, M., Uotinen, L., Rinne, M., (2022). Rapid Photogrammetry with a 360-Degree Camera for Tunnel Mapping. *Remote Sensing* 14(21), 5494. https://doi.org/10.3390/rs14215494

Prittinen, M. (2021). Comparison of camera equipment for photogrammetric digitization of hard rock tunnel faces. Master’s thesis. Aalto University, Finland. http://urn.fi/URN:NBN:fi:aalto-202105236935

Riquelme, A.J., Abellán, A., Tomás, R., Jaboyedoff, M. (2014). A new approach for semi-automatic rock mass joints recognition from 3D point clouds. *Computers & Geosciences* 68, 38–52, https://doi.org/10.1016/j.cageo.2014.03.014

Riquelme, A.J., Abellán, A., Tomás, R. (2015) Discontinuity spacing analysis in rock masses using 3D point clouds. *Engineering Geology* 195, 185-195, https://doi.org/10.1016/j.enggeo.2015.06.009

Thiele, S.T., Grose, L., Samsu, A., Micketwaite, S., Vollgger, S.A., Cruden, A.R. (2017). Rapid, semi-automatic fracture and contact mapping for point clouds, images and geophysical data. *Solid Earth* 8, 1241–1253. https://doi.org/10.5194/se-8-1241-2017