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Proof-of-concept pipeline for digital rockmass analysis using an inexpensive 360° camera

M. Janiszewski[1], M. Torkan[1], S. L. Vidanage[1], P. Oikkonen[2], A. Riquelme[3], J. Liukko[4] & L. Uotinen[1]

[1] *Aalto University, Finland*
[2] *Normet Group, Finland*
[3] *University of Alicante, Spain*
[4] *YIT, Finland*
mateusz.janiszewski@aalto.fi

0000-0002-7365-2777

Abstract

Rock mass characterisation, specifically characterising fracture distribution, density, and orientation, is crucial for a better understanding of stability and hydraulic properties. There are several methods for characterising fracture networks, such as manual mapping and remote sensing.

This paper presents a proof-of-concept workflow for digital rock-mass analysis using a 360° imaging system photogrammetry combined with a three-dimensional Gaussian Splatting (3DGS). The method was tested ona tunnel drift (Site 1) and a 20-meter wall section (Site 2) in the Underground Research Laboratory of Aalto University (URLA). A compact 360° camera was used to acquire continuous panoramic image sequences of two sites in the tunnel. These images were processed into a 3D representation via photogrammetry combined with 3DGS, providing both accurate surface geometry and highly efficient and hyper-realistic real-time rendering. Fractures and discontinuity sets were extracted from the reconstructed surfaces using established methods such as 3D point cloud processing and semi-automatic clustering of fracture planes, allowing 3D fracture orientation measurements.

The resulting orientations of discontinuity sets measured digitally from the 360° camera-based 3D point cloud differ 3.4° on average compared to previous measurements obtained from laser scanning and photogrammetry data. The 3D point cloud coloured by discontinuity sets was imported into Blender and visualised on the 3DGS. This enabled users to inspect the tunnel digitally, visualise structural features, and review spatial data in high resolution.

The study demonstrates that a functional end-to-end digital rock-mass sensing pipeline can be assembled using an inexpensive 360° camera and existing software tools, offering a practical foundation for advancing automated rock-mass intelligence in future mining and tunnelling applications.

Keywords

Fracture orientation, Photogrammetry, Tunnel, 360 camera, 3D Gaussian Splatting.

1 Introduction

Rock masses are inherently characterised by discontinuities, which influence their mechanical and hydraulic behaviours. Therefore, a thorough and precise mapping of these discontinuities is crucial for evaluating rock mass behaviour in engineering applications, such as tunnelling and mining. Rock mass characterisation utilising digital tools is rapidly becoming a standard across the industry.

Recent years have witnessed significant advancements in geomatic methods for digitising rock mass surfaces into three-dimensional (3D) models, particularly using terrestrial laser scanning (TLS) and Structure-from-Motion Multi-View Stereo (SfM-MVS) photogrammetry. These methods facilitate a semi-automated approach to mapping rock discontinuities, offering numerous benefits including rapid data acquisition, high repeatability, reduced human bias, and the capacity for remote analysis. The deployment of fast, large-scale photogrammetry within underground construction environments is proving highly effective for modern mapping workflows (Evins et al. 2025). Despite their proven advantages, traditional digital mapping methods are not without limitations. Laser scanning, while providing exceptional accuracy, often requires expensive, fragile, and specialised hardware. Conventional photogrammetry offers a more cost-effective alternative, but it necessitates a meticulously planned camera network to ensure sufficient image overlap, which can be challenging and time-consuming in active, underground environments. To address these challenges, previous research explored the use of 360° cameras for rapid SfM-MVS tunnel mapping (Janiszewski et al. 2022). While these studies successfully demonstrated the viability of 360° imaging, the hardware utilised was often expensive, heavy, and difficult to deploy routinely.

Recently, inexpensive and highly compact 360° cameras have become widely available on the market, presenting new opportunities for rapid data collection and enabling easy data collection for new spatial reconstruction methods such as 3D Gaussian Splatting (3DGS). Therefore, the primary goal of this study is to test the feasibility of utilising a small, low-cost 360° camera for SfM reconstruction and structural rock mass characterisation within an underground hard rock tunnel setting. This paper presents a proof-of-concept processing pipeline that integrates 360° panoramic image capture, traditional SfM-MVS point cloud and mesh generation, automated discontinuity set extraction, and 3DGS visualisation, evaluating its potential use for underground rock engineering.

2 Methodology

2.1 Data collection

The data collection for this study was conducted in the Underground Research Laboratory of Aalto University (URLA), Finland. The site is located 10-20 meters below ground. The rock mass is predominantly composed of granite and granodiorite and is characterised as moderately fractured and mostly dry. The fully exposed rock mass makes it an ideal testing ground for photogrammetric mapping. To evaluate the methodology under different spatial constraints, two separate areas within one tunnel were selected. Site 1 was a tunnel drift that was previously used for videogrammetry tests by Janiszewski et al. (2024), though the original control points were no longer present. Site 2 consisted of a larger, continuous 20-meter-long tunnel section near the drift (see Fig. 1).

2.2 360-degree image acquisition

Image data was acquired utilising a compact DJI Osmo 360° camera (see inset in Fig. 1a). The device features two lenses with a 2 mm focal length (8 mm full-frame equivalent). The camera internally stitches the dual-lens output to generate equirectangular images with a resolution of 15520 × 7760 pixels (20 MP) in JPG format.

At Site 1, to minimise shadows and produce even lighting, the drift was illuminated by a single, battery-powered DeWALT DCL074-XJ LED work light, which provided around 5000-lumen luminous flux with 360° coverage (Fig. 1a,c). The 360° camera was mounted on a stationary tripod. To capture the entire geometry, images were taken at three distinct elevations (high, mid, and low) on both sides of the drift, resulting in 17 total camera positions (Fig. 1b). The camera parameters were manually set to ISO 200, an aperture of f/1.9, and a shutter speed of 1/2 s to ensure optimal exposure in the static environment.

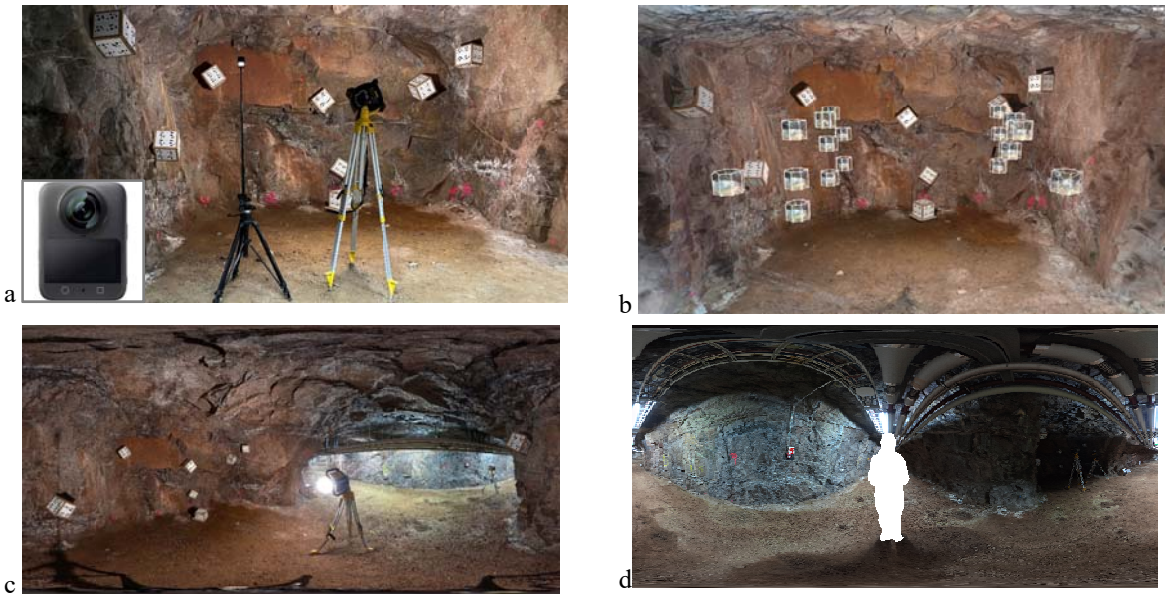


Fig. 1 Data capture set up at Site 1 (a), camera network (b), example panoramic equirectangular image from Site 1 (c), example masked equirectangular image captured handheld from Site 2 (d).

For the extended mapping of Site 2, illumination was provided by the existing fluorescent lights installed along the tunnel roof. To facilitate rapid data collection, the 360° camera was mounted on a dedicated handheld stick. The operator walked along the 20-meter tunnel section, stopping briefly at regular intervals to capture photos. Image sequences were captured at high, mid, and low elevations. To reduce motion blur from the handheld operation, the camera's ISO was increased to 3200, maintaining an aperture of f/1.9, and the shutter speed was increased to 1/60 s. Because the operator was visible in the handheld panoramic shots, a post-processing step was required; Adobe Photoshop was used to manually mask the person out of the images (Fig 1d).

2.3 Data processing – Photogrammetric and 3DGS processing pipeline

Before generating the 3D models, the equirectangular images were converted into standard 2D perspective images using the 360 Image split tool in Meshroom software v.2021.1.0 (Meshroom, 2026). The images were processed into 8 splits with a resolution of 3880 × 3880 pixels. This resulted in a total of 136 images for Site 1 and 448 images for Site 2.

The split images were imported into RealityScan v.2.1 software (RealityScan, 2026). Coded markers mounted on the tunnel walls were automatically detected to establish reference points. The models were scaled and oriented to a local coordinate system using an orientation cube, achieved by setting the top four control points of the cube to the "Ground Control Point" type and assigning their corresponding XYZ coordinates. The images were aligned using default settings, except for 'Image overlap' set to Low, and the 'Max feature reprojection error' was iteratively refined from 2 pixels down to 1 pixel for the final alignment. For Site 1, 136 images were aligned, generating a sparse cloud of 245,848 points with a median reprojection error of 0.41 pixels. For Site 2, all 448 images were aligned, generating a sparse cloud of 1,506,249 points with a median reprojection error of 0.26 pixels.

From the alignment phase, the processing pipeline was divided to serve two parallel visualisation and analysis goals. To enable real-time, hyper-realistic visualisation, the distortion model was set to 'Division', and the alignment data was exported in COLMAP text format for 3D Gaussian Splatting (3DGS) processing within LichtFeld Studio (LichtFeld Studio, 2026). Concurrently, for conventional rock mass analysis, a dense reconstruction was performed in RealityScan on the aligned components. The resulting dense point cloud and mesh were textured, decimated, texture-reprojected, and exported as an .fbx file. The dense point cloud was cropped to the fracture sampling area and exported in .txt format for further processing.

2.4 Data processing – Point cloud analysis and discontinuity extraction

The cropped dense point clouds were imported into CloudCompare v.2.13.2 (CloudCompare, 2026) for pre-processing. To optimise processing, the clouds were subsampled using the spatial method with a minimum spacing of 0.01 m between points. Normal vectors for each point were subsequently computed using the Hough Normals Computation plugin at default settings, and the cleaned data were exported in .ply format.

The semi-automatic extraction of discontinuity orientations was performed using the Discontinuity Set Extractor (DSE) software v.4.00 (Riquelme et al. 2014). The normal vector densities were calculated, and the probability density function (PDF) of the normals' poles was computed using a minimum angle of 30° and 6 bins. A maximum of 5 discontinuity sets was initially allowed (Nmax = 5), which were visually inspected and manually edited. Based on a visual assessment, anomalous sets were subsequently removed. Individual points were classified and assigned to a specific Discontinuity Set (DS) if their normal vector fell within a 30° cone angle of the principal pole. This preliminary classification (XYZ_Js) was exported to CloudCompare for visual validation against the textured mesh. Finally, spatial clustering of each DS was conducted using the DBSCAN algorithm to isolate individual fracture planes. Clusters containing fewer than 100 points were filtered out, and coplanar clusters were merged according to a standard coplanarity test.

Final rendering was done in Blender v.5.0.1 software (Blender, 2026). The clustered point cloud from DSE was imported as .ply, and a shader material was added to display the point cloud coloured by discontinuity sets. The point cloud was overlaid on top of the 3D Gaussian splat (3DGS) imported into Blender using the 3DGS Render by KIRI Engine plugin v. 4.1.5.

3 Results and discussion

3.1 3D reconstruction and visualization

The photogrammetric processing pipeline successfully generated dense point clouds and textured meshes for both test environments, capturing full 360° geometry. For Site 1, the stationary setup yielded a detailed geometric representation of the drift (Fig. 2a). For Site 2, the methodology utilising the handheld 360° camera successfully reconstructed the entire 20-meter tunnel section continuously, proving the viability of the rapid, walking-capture method for larger underground spans (Fig. 2b).

a  b 

Fig. 2 Resulting 3D textured mesh from Site 1 (a) and Site 2 (b).

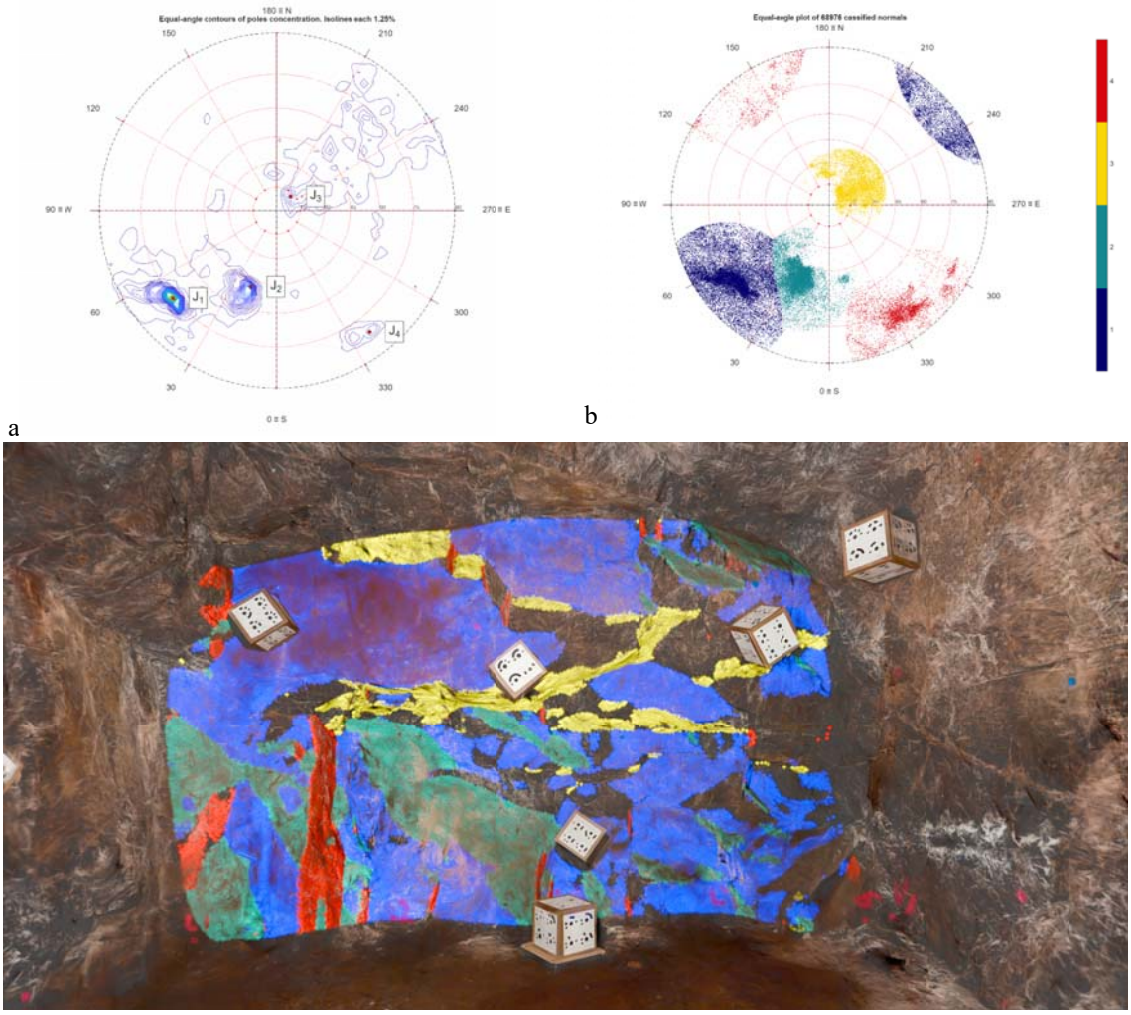
The parallel 3DGS pipeline branch demonstrated the capability for real-time visualisation (Figs. 3–4). Even though 3DGS was only tested for final rendering and not for geometric measurements, as demonstrated by Okutu-Ayiku (2025) for Rock Quality Designation (RQD) measurements, its integration highlights significant potential for future comprehensive digital rock mass characterisation systems. By combining 360° images, 3D point clouds, textured meshes, and 3DGS, a complete multi-data visualisation system can be realised. It has to be noted that the 3DGS from Site 2 suffered from a lack of detail on the floor and roof parallel to the tunnel axis, mainly due to masking of the operator.

3.2 Discontinuity set orientation

At Site 1, four distinct discontinuity sets (DS1–DS4) were extracted from the reconstructed point cloud using the DSE software (Fig. 3). Table 1 compares the mean dip direction (°) and dip (°) values obtained using the compact 360° camera with reference data from previous studies at the same location, which utilised high-resolution Terrestrial Laser Scanning (TLS) and mobile photogrammetry. The orientations derived from the inexpensive 360° camera demonstrate strong alignment with the reference data, particularly for the steeply dipping sets (DS1, DS2, and DS4).

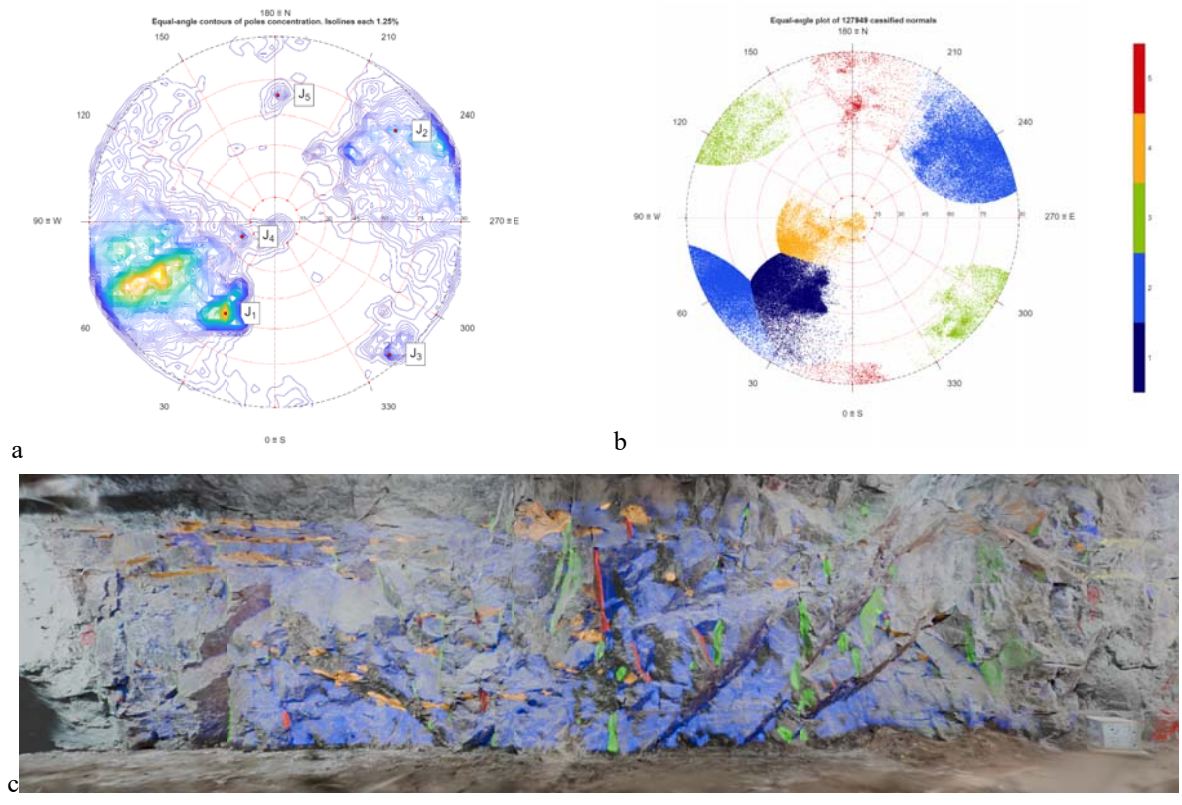
Table 1. Mean discontinuity set orientations (dip direction° / dip°) for Site 1 compared to reference data. The resulting mean and median orientation errors were 3.4° and 2.2°, respectively.

Model	DS1 (Dip dir° / Dip°)	DS2	DS3	DS4
Compact 360° camera (this study)	50.0 / 74.9	18.4 / 48.6	225.0 / 12.8	322.5 / 81.4
TLS reference (Janiszewski et al. 2024)	50.1 / 75.5	20.3 / 51.1	250.0 / 8.7	319.4 / 80.1
Mobile SfM (Janiszewski et al. 2024)	47.5 / 77.6	20.3 / 51.1	224.3 / 11.6	319.4 / 80.0



a b c

Fig. 3 Discontinuity orientation results for Site 1: pole density plot (a), poles with assigned discontinuity set (b), classified discontinuity sets overlaid on the 3DGS of the tunnel face (c).



a b c

Fig. 4 Discontinuity orientation results for Site 2: pole density plot (a), poles with assigned discontinuity set (b), classified discontinuity sets overlaid on the 3DGS of the tunnel wall (c).

Fracture orientation measurements from the compact 360° camera-derived point cloud are comparable to previous studies, but slight deviations exist. This is mainly attributed to the simplified orientation control method employed in the absence of surveyed targets. To resolve this, a permanent control point network with fixed, known coordinates is currently under development at URLA. This will facilitate rigorous benchmarking of the 360° pipeline against standardised TLS data in future tests.

For the extended mapping at Site 2, five discontinuity sets were identified (Fig. 4). Visual assessment confirmed that these sets aligned with previous manual measurements. However, precise values for Site 2 are not reported here. The primary objective for Site 2 was to validate the feasibility of continuous 3D reconstruction over a larger area, which the methodology accomplished.

3.3 Methodological limitations and future work

The utilisation of 360° camera with a smaller sensor inherently results in a reduction of visual quality compared to high-end DSLR cameras. Nevertheless, the geometric quality of the resulting point clouds remains sufficient for extracting reliable rock mass measurements. Lighting strategies present another challenge in underground settings. The use of a stationary 360° work light can cast complex, distinct shadows across the rock face, which may obscure fine structural details. Alternatively, relying on ambient fluorescent lighting by using high ISO settings (as demonstrated at Site 2) proved functional but introduced noise into the source images. Future tests will investigate the effectiveness of dedicated, camera-mounted 360° lighting rigs to provide uniform, shadow-free illumination during mobile capture. Finally, this proof-of-concept was conducted in a controlled underground laboratory, which is largely free of dust and high humidity. For the proposed pipeline to become a robust tool for daily tunnelling and mining operations, future research must validate its performance in active production headings, where dust and humidity may interfere with image capture and the SfM process.

The proposed combined SfM-MVS and 3DGS method provides a framework for visual as-built documentation and for future process automation in underground construction. Integrating this digital pipeline into daily operations could facilitate continuous rock mass classification, driving data-informed decisions for optimised tunnel design and dynamic rock support selection.

4 Conclusions

This study successfully implemented a digital rock-mass analysis pipeline using a lightweight, inexpensive 360° camera in an underground hard rock environment. The workflow reliably produced dense 3D reconstructions and enabled fracture orientation measurements with satisfactory precision. By combining a 360° camera-based photogrammetric model and 3DGS with semi-automatic discontinuity extraction, the proposed method provides an accessible, low-cost framework for rapid rock mass intelligence and visualisation.

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