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Method to obtain 3D point clouds of tunnels using smartphone LiDAR and comparison to photogrammetry

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Abstract. Remote sensing methods, for example, photogrammetry and laser scanning can be employed to scan rock masses by digitizing underground spaces or slopes. To reconstruct a 3D model by photogrammetry, plenty of photos should be captured. This process is time-consuming and can be dangerous when the rock mass is unstable. Therefore, rapid capturing methods are needed to reduce the acquisition time. This can be achieved with LiDAR scanners that capture a 3D point cloud with a high-speed pulsed laser beam. However, the cost of laser scanners is high, which limits their usability. Apple's iPhone 12 Pro Max smartphone is equipped with a LiDAR sensor and is much cheaper than conventional laser scanners. Several mobile applications for 3D models using the smartphone Lidar have been developed, making the scanning process easy. Therefore, smartphones can be used for rapid scanning of unstable surfaces of tunnels and slopes. In this study, 3D point clouds (3DPC) of a tunnel wall of the Underground Research Laboratory of Aalto University (URLA) are obtained by a high-resolution digital camera and smartphone LiDAR. The models are analyzed and compared. The results show the quality of the smartphone LiDAR sensor is adequate for generating 3D models of underground spaces.

1. Introduction

Characterization of a rock mass is a necessity in rock engineering. To design slopes or underground excavations, several factors should be considered such as geological structure, geometry of slopes and underground excavations, hydraulic and mechanical properties of the rock mass. Rock masses' strength depends on the properties of intact rock and discontinuities. The stability of rock spaces could almost rely on the discontinuities rather than the strength of the intact rock [1].

Physical access to the rock surface is essential with traditional methods. Therefore, access to the site and the environmental condition can limit the collected datasets. Remote sensing techniques have been introduced to several fields, especially rock characterization. There is growing attention in extracting information regarding discontinuities from the remote sensing derived datasets. These techniques could help to characterize discontinuities from close or far ranges of surfaces [2, 3, 4].

Structure from Motion (SfM) and 3D ground-based laser scanner [5, 6, 7] or Terrestrial Laser Scanner (TLS) [8] are among remote sensing techniques which have been employed to scan slopes and underground spaces. TLS uses the Light Detection and Ranging (LiDAR) instrument. TLS is able to scan surfaces with high-speed data acquisition, but the cost may not always be acceptable. The SfM is more appropriate compared to LiDAR among the field's experts [9]. A camera is used in the SfM technique. Discontinuity sets could be extracted and analyzed by 3D point clouds provided by SfM and LiDAR by Discontinuity Set Extractor software (DSE) [4, 10].

Companies are more encouraged now to develop devices with powerful processors and high-resolution cameras since the use of smartphones is growing. In 2020, iPhone 12 Pro Max (later iPhone) with an excellent camera and a LiDAR sensor was launched by Apple Inc. iPhone LiDAR sensor can be used to scan slopes' surfaces or tunnels' sections. There is a number of applications for iPhone which are using the LiDAR sensor to generate 3D meshes or point clouds with a vertical orientation and at a scale ratio of 1:1. The scale ratio of 1:1 means that the obtained 3DPCs by those applications are at actual size. Thereby, iPhone-derived 3DPC can be utilized for characterization of rock slopes or underground spaces. Datasets can be collected effectively by a user.

A tunnel wall of the Underground Research Laboratory of Aalto University was scanned by the Canon EOS 5DS R DSLR (later DSLR) camera (SfM technique) and LiDAR of iPhone 12 Pro Max (TLS technique). The purpose is to compare the quality of the 3DPC obtained by DSLR camera and smartphone. The purpose was also to assess these tools' utility to detect discontinuities on the rock mass surface. The results show the capability and reliability of the LiDAR of iPhone for detecting joint sets as an accessible device.

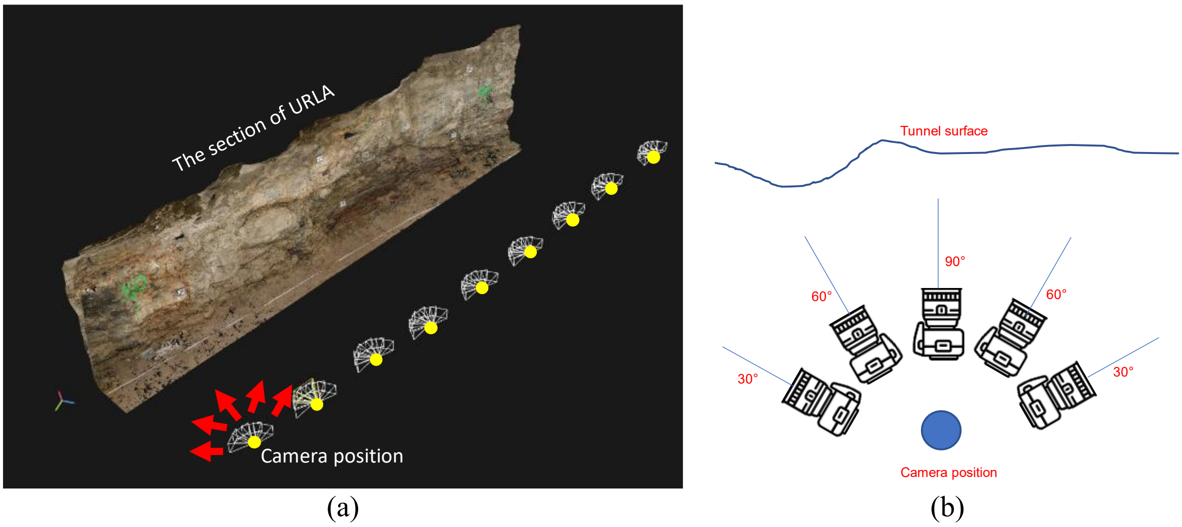
2. Methodology

A 10 m section of URLA was scanned using the DSLR camera as an SfM technique and an iPhone as a Lidar technique. The tunnel was excavated in granite rocks at the depth of 20 meters beneath the Otaniemi campus in Espoo, Finland (Figure 1).

Figure 1. Map of the Aalto Research tunnel with the marked tunnel section with red color.

The DSLR with Canon 35mm f/1.4 lens was used. Images were taken from 9 locations spaced evenly in one row (Figure 2(a)), which resulted in 45 images. The distance between camera positions was 1.5 m and the height of the camera was 1.7 m. In each position, 5 photos were captured in different angles in the horizontal direction (Figure 2(b)). A 3D model was reconstructed by SfM photogrammetry in RealityCapture 1.2 software by Capturing Reality [11]. The DSLR camera model was scaled by markers placed on the tunnel wall. The distances between markers were measured by the tape meter. The marker' type was one ring 20 bit generated by RealityCapture. Circular, single ring, 20-bit is a circular target with a 20-bit data ring. The circle is divided into 20 parts. The whole process of scanning the abovementioned section was presented by [6].

There are several applications to generate a 3DPC model using the LiDAR feature of iPhone. The PloyCam 1.2.7 [12] and EveryPoint [13] applications, among them, were used to scan the section of the tunnel. The pattern used to scan the section by iPhone is shown in Figure 3. This pattern covers the whole section. The distance between the smartphone and the object was 2.5 m.



(a) (b)

Figure 2. (a) shows the SfM model of the scanned section of URLA and the camera positions, (b) the angle of taking photos from the top view.

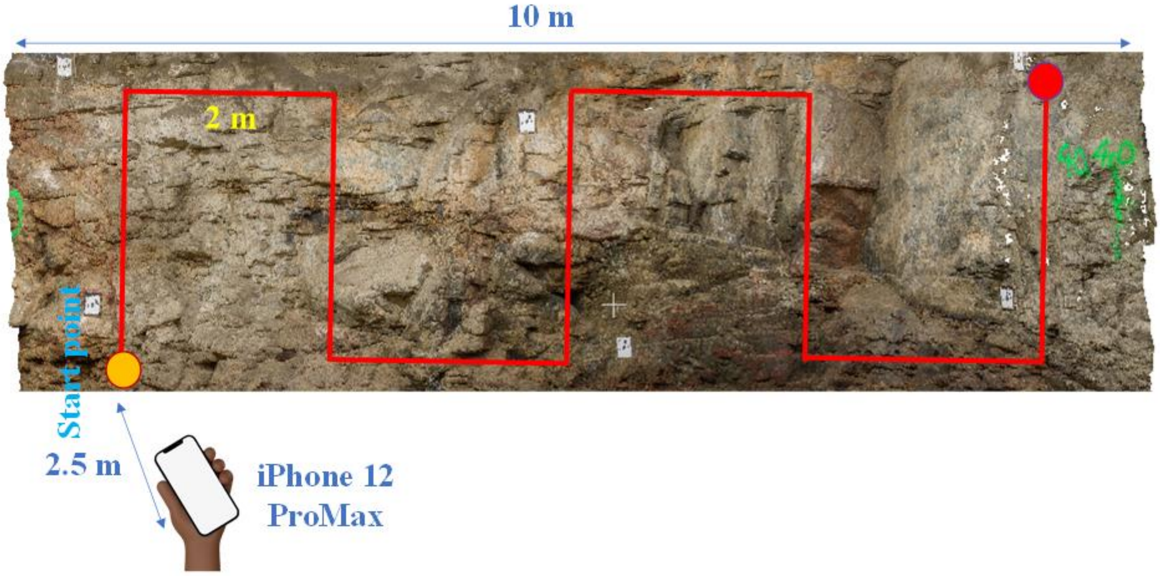


Figure 3. The pattern of scanning the section of the tunnel using iPhone.

Polycam is a postprocessing application. It means the raw data of the section was collected by default setting in the first stage. After that, the collected data was processed in high-quality setting. The custom settings chosen for processing were listed as follows: depth range 5 meters, voxel size 4 mm, and simplification 0%. Depth range represents the distance between the smartphone and the object. Voxel size controls the approximate distance between output polygons and points, with smaller values leading to more polygons or density of points and longer computation time. Simplification is applied to the mesh before texturing, higher values result in lower quality. The processing time in the smartphone was 67 seconds. This application makes a mesh model firstly and then extracts a 3DPC based on that mesh model. In EveryPoint application, the setting should be defined before scanning. The following setting was used for scanning: 3D voxel size 5 mm and maximum scanning depth of 5 meters. The resulting 3DPCs of the applications were scaled automatically.

The DSLR camera was considered as a benchmark for this study. Obtained 3DPCs from the applications were compared to the 3DPC regenerated by DSLR camera photos. The comparison was intended to evaluate the quality and reliability of the smartphone Lidar over those of the SfM technique.

The Surface density function in CloudCompare [14] was used to estimate surface point density. The number of neighboring points with a sampling radius of 1 cm was selected to estimate surface point density of each point cloud.

Discontinuity Set Extractor software (DSE) was used to analyze 3DPCs and to detect joint sets [10]. The default settings were used to calculate the principal planes. The minimum angle between the pole vectors was set to 35° and the maximum number of principal planes to 10 to do the statistical analysis. After establishing the normal vector, the corresponding normal vector pole was calculated and plotted into a stereonet. Ultimately, non-parametric density function of all the poles was computed by applying Density Estimation method. Afterward, the stereonet of each 3DPC was plotted and the assigned principal poles were extracted.

If 3DPCs' sizes are huge, firstly they should be simplified via Subsample point cloud function in CloudCompare. To simplify the 3DPCs, the space subsampling method was chosen with a minimum 5 mm space between points. Then, the subsampled 3DPCs were imported into DSE software.

3. Results and discussion

Figure 4 illustrates the three resulting 3DPCs from the DSLR camera and iPhone applications. In all cases, discontinuities could be observed. Some non-reconstructed surfaces can be seen in Figure 4(c) obtained by EveryPoint.

(a) DSLR camera

(b) Polycam

(c) EveryPoint

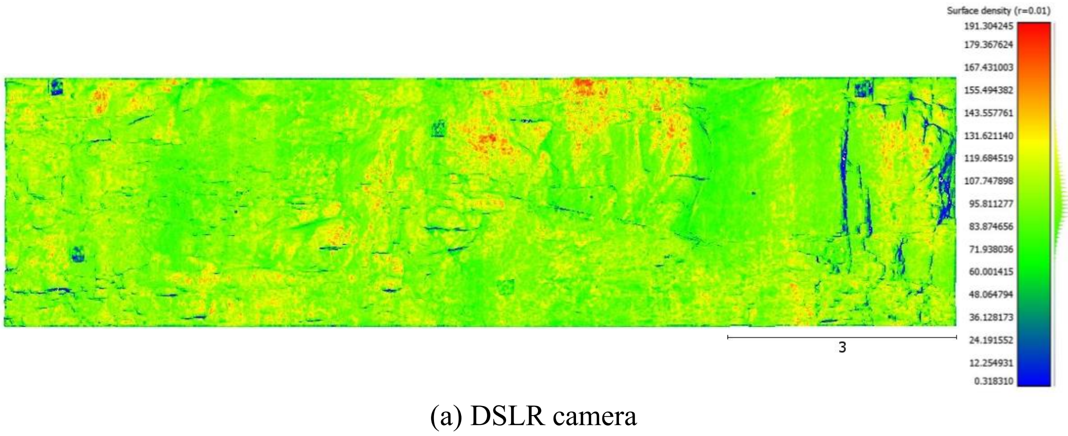
Figure 4. 3D point clouds of the section of the tunnel regenerated from the data obtained by the different methods, (a) SfM, (b), and (c) LiDAR.

The condition in which the data was captured has a major influence on the results. The distance between the device and the surface was about 2.5 m during the scanning. The depth range for iPhone can be considered as a drawback for its usage in this field rather than other methods like SfM. But 1:1 automatic scaling is the advantage of this device. Another advantageous factor is iPhone's low scanning and processing time, about 4 minutes in total.

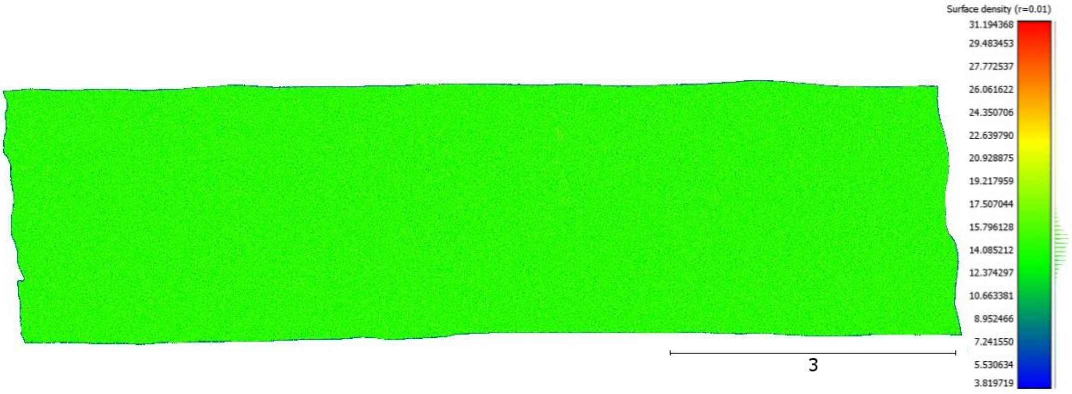
Table 1 shows the surface point density of the scanned section by each method. The largest point density is related to the DSLR and the minimum points produced by EveryPoint application. Figure 5 shows the surface density of each 3DPC and the distribution of points on the surface. The blue color signifies the lowest point density and the red color represents the maximum point density. Green and yellow colors show the smooth distribution of the points. The 3DPC obtained by Polycam has the same distribution because it was created based on the mesh model. The methods could be ranked according to producing points as follows: Canon EOS 5DS R DSLR camera, Polycam application, and EveryPoint application.

Table 1. Mean surface point density of the 3D point clouds of the section of the tunnel.

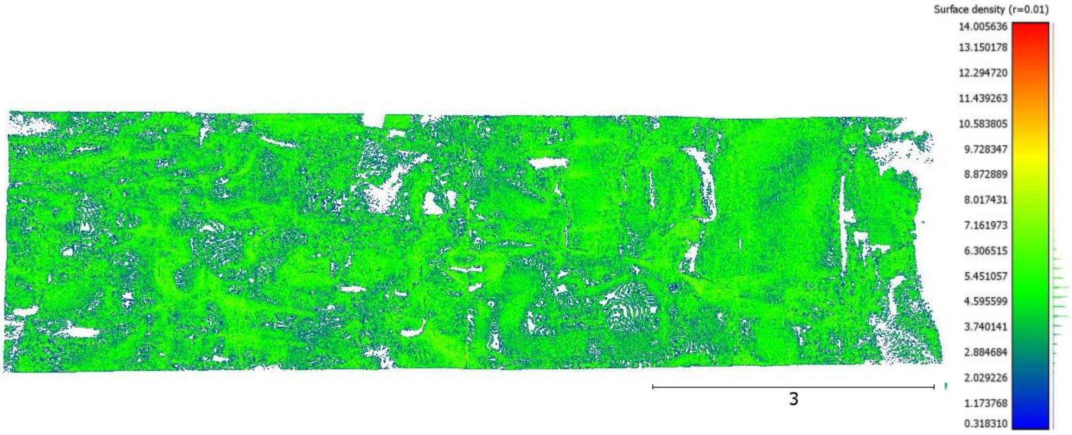
Method	Point count	Mean point density (point/cm^2)	Standard deviation
DSLR camera (SfM)	32,315,112	101.20	18.96
Polycam (LiDAR)	4,259,599	14.48	1.29
EveryPoint (LiDAR)	1,366,428	4.67	1.13



(a) DSLR camera



(b) Polycam



(c) EveryPoint

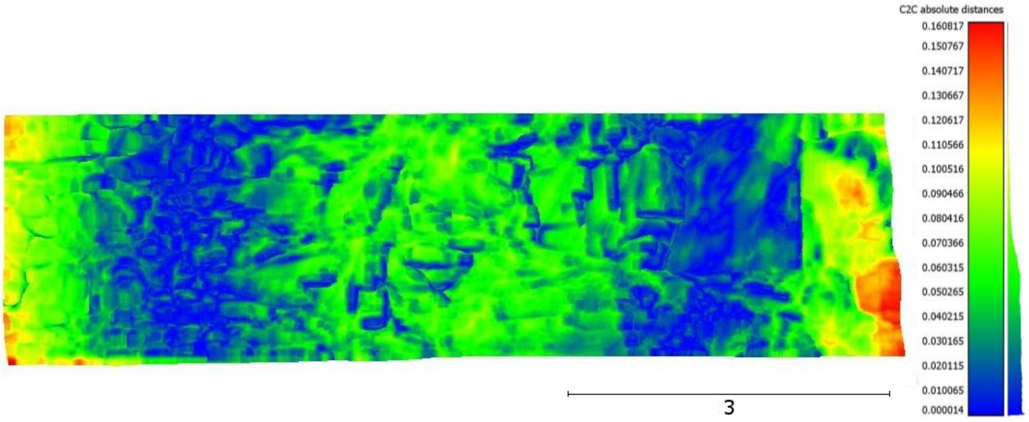
Figure 5. Point density of the section of the tunnel in 3D models obtained by the different methods, (a) SfM, (b, and c) LiDAR.

The cloud-to-cloud distance between models obtained by different applications and the DSLR camera is tabulated in Table 2. The mean, standard deviation (SD), and root mean square error (RMSE) of those distances is calculated. If the mean differences are zero and standard deviation values are close to each other, it means the point clouds are similar. But the lowest RMSE values are obtained from EveryPoint. It means the data obtained with this application is the closest to the SfM models obtained by DSLR camera.

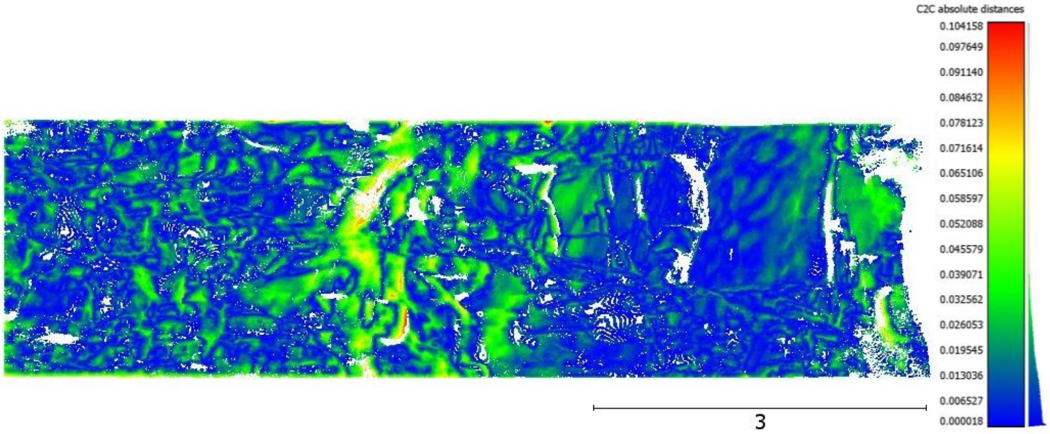
Table 2. Mean surface point density of the 3D point clouds of the section of the tunnel.

Smartphone application	Mean (cm)	Standard deviation (cm)	RMSE (cm)
Polycam	4.05	2.80	4.93
EveryPoint	1.47	1.25	1.92

Figure 6 depicts the cloud-to-cloud distance between each application and DSLR data. Red and blue colors signify the maximum and minimum distances between each 3DPC and the benchmark, respectively. One reason for the difference could be explained by the different methods used by applications to regenerate 3DPCs. But the differences are not big and most areas are colorized with blue and green where the minimum distances were measured. The largest difference for Polycam is 16 cm and for EveryPoint is 10 cm



(a) Polycam



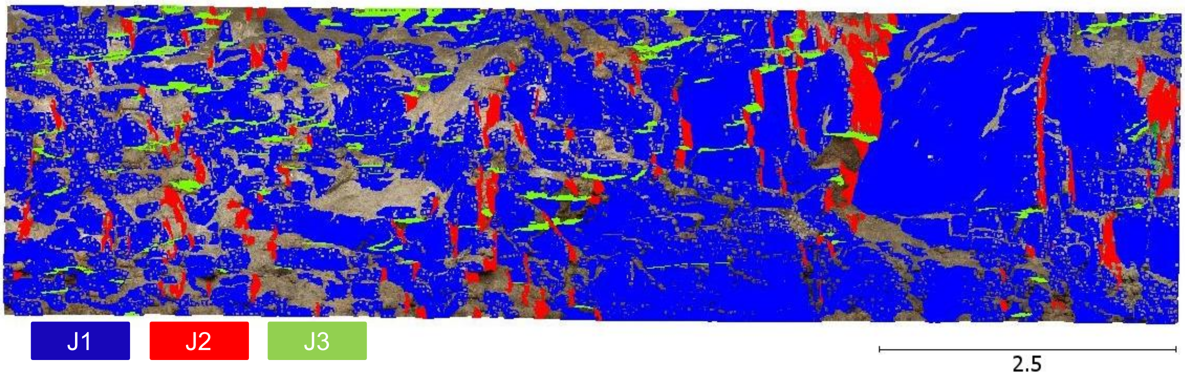
(b) EveryPoint

Figure 6. Comparison of cloud-to-cloud distance of point clouds obtained from iPhone applications to DSLR point cloud.

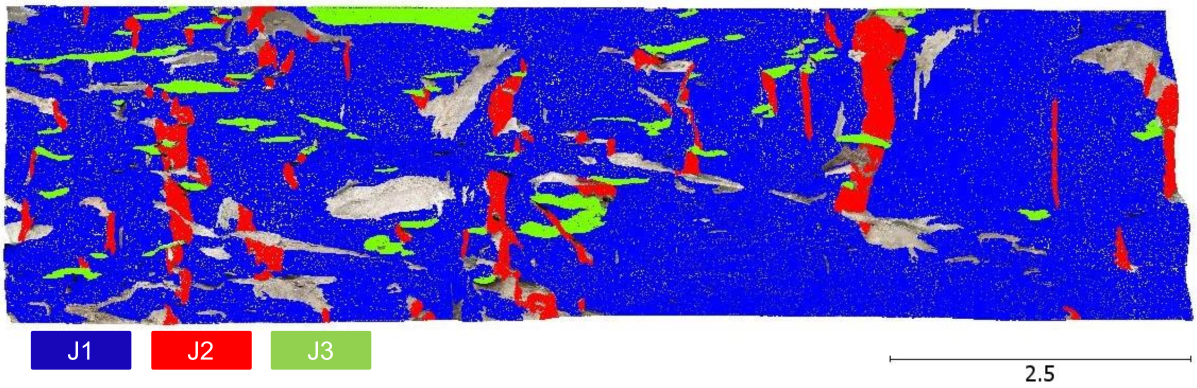
To detect joint sets by DSE software, the 3DPCs were subsampled with 5 mm spacing. As a result, three discontinuity sets were extracted and tabulated in Table 3. Figure 7 shows each 3DPC was classified into separate discontinuity sets with different colors. The principal poles are illustrated in Figure 8. Figure 8(d) shows the principle joint set was measured by an analog compass [6] and drawn by Stereonet software [15].

Table 3. Dip direction and dip of the section of the tunnel extracted by DSE from different 3DPCs.

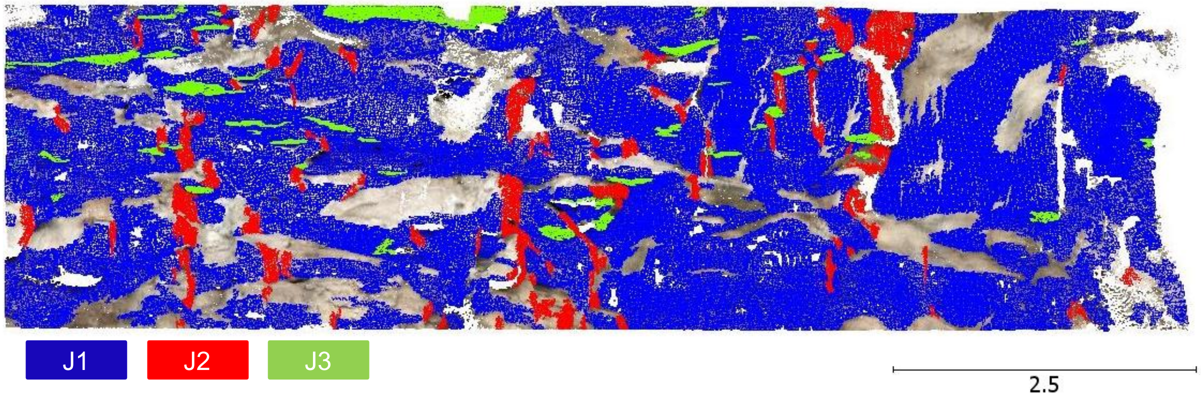
Method	Joint set	Dip direction	Dip
DSLR camera (SfM)	1	317.4	77.93
	2	58.48	81.75
	3	278.22	19.12
Polycam (LiDAR)	1	308.29	82.68
	2	73.55	85.12
	3	302.19	34.41
EveryPoint (LiDAR)	1	307.19	73.55
	2	74.23	87.93
	3	302.56	34.53
Manual compass mapping	1	325.16	89.00
	2	58.90	87.87
	3	311.59	4.74



(a) DSLR camera



(b) Polycam



(c) EveryPoint

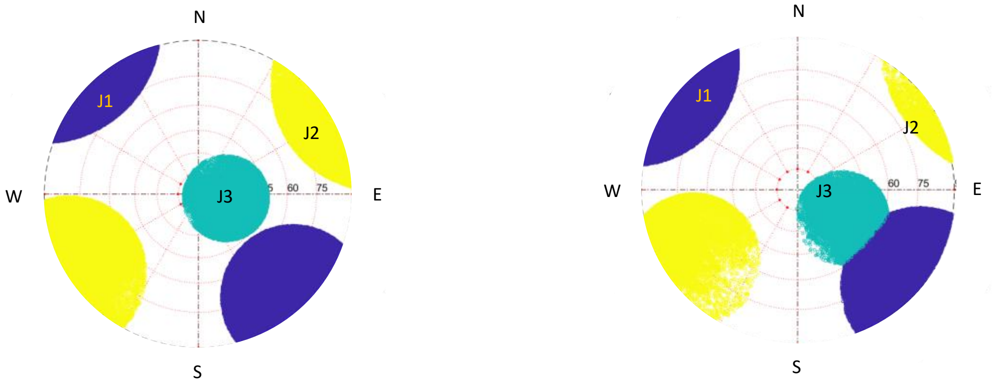
Figure 7. Different 3DPCs of the section of the tunnel surface obtained via photogrammetry (a) and LiDAR (b and c) with the colored discontinuity sets extracted by the DSE software.

Despite the non-reconstructed surfaces of EveryPoint's 3DPC (Figure 7(c)), the number and orientation of the principal poles show good results. The obtained 3DPCs by different methods prove the validity of using iPhone for reconstructing the section of the tunnel as well as obtaining approximate dip and dip direction and number of principal discontinuity sets. This visualization illustrates a perfect fit between the use of DSLR camera and iPhone-derived datasets.

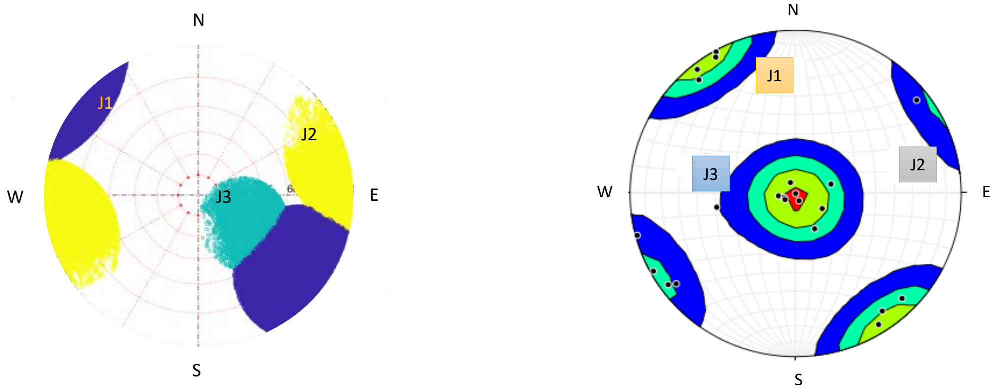
Remarkably, the number of the discontinuity sets, their orientations, obtained by the manual inspection and the classified point clouds show close results. Compared to the manual measurement, the

3DPCs obtained by different methods could be listed as follows: DSLR camera case with a perfect match, Polycam with near match and EveryPoint with acceptable estimation.

Based on the results, despite its shortage in reconstructing some areas by EveryPoint or extracting a 3DPC based on a mesh model by Polycam, scanning with iPhone LiDAR gave acceptable results in comparison to the DSLR camera. This study confirms that the iPhone is a possible alternative to analyze discontinuities.



(a) DSLR camera (b) Polycam



(c) EveryPoint (d) Manual mapping with geological compass

Figure 8. Principal poles of three discontinuity sets extracted from DSE software using 3DPCs obtained via photogrammetry (a) and LiDAR (b and c) and (d) plotted principal poles drawn by Stereonet software.

4. Conclusions

To evaluate the applicability of the iPhone 12 Pro Max LiDAR sensor to generate 3D tunnel models, two commercial software applications (Polycam and EveryPoint) were used. The quality of the processed 3D Point Clouds (3DPC) was compared with the 3DPC reconstructed with the help of a good quality Canon DSLR camera. The 3DPCs were analyzed by Discontinuity Set Extractor software (DSE) to obtain the number of discontinuities sets and their orientations. The principal poles of joints were extracted and compared with manual mapping of the joint sets. The comparison was made between the results and those of SfM and iPhone 12 Pro Max Lidar derived 3DPCs, showing acceptable similarities. According to the manual mapping of joint sets, 3DPCs of DSLR and Polycam application produced more accurate data than EveryPoint application.

This work recommends the ability of iPhone LiDAR to detect joint sets. Keeping aside its range limitation, the fast development of these devices and the applications show a bright horizon where smartphones can be used to analyze and detect geological features such as joint sets. Additionally, smartphones' applications can be further developed and improvised to detect small geometrical features and avoid simplification of data. All in all, it seems this smartphone could be employed by rock mechanic engineers to collect and analyze preliminary data with low-cost rather than expensive and time-consuming approaches.

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