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Verification of a methodology for structural data acquisition using smartphone-based LiDAR

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Abstract

3D modelling has become a dominant trend for analysis in various fields of science and engineering, enabling users to collect more accurate data in less time compared to other measurement methods. Technologies that provide 3D data, such as terrestrial laser scanners (TLS), are often expensive, encouraging users to seek more affordable alternatives while maintaining the desired accuracy. Terrestrial laser scanning (TLS) and the Structure-from-Motion (SfM) technique both provide 3D point clouds that allow geometric analysis. Since the early 2000s, the scientific community has tested these two techniques, while companies have gradually integrated them into their workflows.

This paper presents a methodology for collecting structural data from the field using a smartphone as a relatively low-cost tool that implements LiDAR technology. The methodology was evaluated through measurements and analysis conducted at three different locations: Milutinci, Farish and Serta.

The initial approximation for data collection was carried out using mobile phones, which are becoming increasingly suitable for 3D modelling. Recordings were conducted at three different locations in three distinct geological environments. The 3D point clouds obtained from these recordings were processed with various software tools and analytical methods, including semi-automatic software for extracting plane sets and calculating the dip and dip direction elements of identified planes. The results of measurements conducted using 3D point clouds showed high agreement when compared with measurements obtained using a geological compass.

Through the synthesis of results, numerous original regression relationships between the analysed parameters were formed and presented for the first time in this format in our region. This also lays the groundwork for further development of the methodology in future scientific analyses.

Keywords

LiDAR, Structural geology, Point cloud, iPhone, DSE.

1 Introduction

The determination of rock mass characteristics represents a fundamental component of geological and engineering geological investigations. Traditionally, this process relies on field mapping, which generally provides a limited amount of data. Over the last decade, however, the development of new data acquisition systems, such as remote sensing techniques and geophysical methods, has enabled the collection of large and diverse datasets. This has led to the recognition that the methodologies used to calculate various parameters can be redefined and improved (Riquelme et al., 2018).

Three-dimensional modelling based on 3D point clouds (3DPC) has become an essential tool for the acquisition, interpretation, and analysis of geological and geotechnical data (Riquelme et al., 2021). The application of 3D technologies reduces the number of personnel required in the field, increases measurement accuracy, and shortens the time needed to perform specific analyses. Moreover, the acquisition of 3D models is non-invasive, safe, and highly precise. These methods generate datasets that can be stored, reprocessed, and reused without the need for repeated visits to the investigated area. In addition, they provide improved opportunities for monitoring terrain changes, evaluating their development over time, and ensuring better quality control.

For the purposes of a more comprehensive analysis of the available hardware and software on 3DPC, multiple surveys were carried out using an iPhone smartphone. These surveys were conducted at three different localities: the Milutinci locality, on schist outcrops (Ivanovski et al., 2023); the Farish locality, on platy and bedded limestone outcrops (Ivanovski et al., 2024); and the Serta locality, in flysch, specifically sandstone outcrops (Ivanovski et al., 2025), all located in the Republic of Macedonia.

The analysis of the obtained results was performed in two ways. The first involved the use of various statistical and other comparative methods through stereonets, Excel tables, and other types of diagrams. The second involved the introduction of a so-called semi-automatic method aimed at obtaining the required data in an almost fully automated manner, which will be presented below.

With regard to the semi-automatic method, and from the perspective of the most recent research related to this topic, important papers have appeared over the last years, generally covering specific segments of semi-automatic and automatic analysis of acquired 3D point clouds. Among these, Wu et al. (2024) stand out for their use of the Sparrow Search Algorithm (SSA) for automatic processing. Lu et al. (2024a) and Kang et al. (2024) employed several different algorithms for automatic processing. Cardia et al. (2023) used several different algorithms for semi-automatic data processing. Panigrahi et al. (2023) focused on comparing the results obtained by the DSE and FACETS methods, which also represents part in this paper. Zhou et al. (2024) tested an automatic method for landslide detection, while Lu et al. (2024) proposed a completely different approach to discontinuity extraction.

It can be stated that, in recent years, the focus in this field has increasingly shifted toward semi-automatic and automatic methods for generating output data. However, the results are still not at a fully satisfactory level, or they do not provide consistently reliable outcomes. Automatic methods for complete discontinuity extraction are based on a range of different ideas, algorithms, and methodologies. Although they produce promising results, their practical applicability and actual positive outcomes vary considerably. They also tend to detect false-positive results associated with non-geological features such as shadows, roads, or vegetation (Vasuki et al., 2014). Therefore, even fully automated methods currently require significant effort to remove non-geological features in order to ensure that the relevant geological structures are properly detected (Thiele et al., 2017).Semi-automatic methods, on the other hand, provide the researcher with a certain degree of control over the entire process and yield highly satisfactory and repeatable results (Riquelme et al., 2014; Guo et al., 2018; Li et al., 2019; Delgado-Reivan et al., 2023).

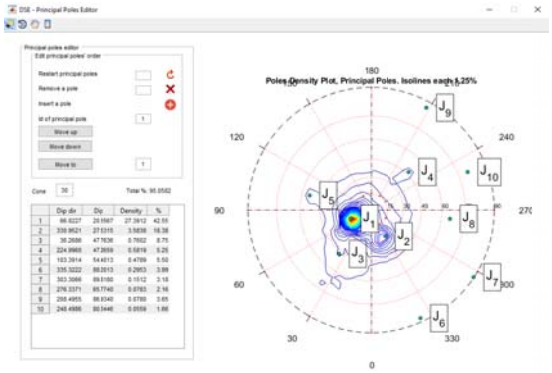
Several software tools are available for the semi-automatic analysis of point clouds and the detection of discontinuities in geological structures. However, a full analysis of the characteristics of all the above-mentioned software packages would represent a very extensive undertaking. Therefore, a study was carried out with the aim of selecting at least two software packages suitable for semi-automatic point cloud analysis in structural geology. For this purpose, and based on data obtained from a large number of published studies (Gigli et al., 2011; Riquelme et al., 2014; Dewez et al., 2016; Riquelme et al., 2015a; Chen et al., 2016; Slob et al., 2005; Wang et al., 2016; Chen et al., 2017; Gomes et al., 2016; Jaboyedoff et al., 2007; Leng et al., 2016; Zhang et al., 2018; Wu et al., 2020; Wu et al., 2021;

Chen et al., 2020; Umili et al., 2013; Li et al., 2016; Ge et al., 2018; Kong et al., 2019; Lato et al., 2012; Guo et al., 2022; Monsalve et al., 2021; Wu et al., 2024; Daghigh, 2022; Riquelme et al., 2015b; Lai et al., 2014; Lu et al., 2024a; Kang et al., 2024; Cardia et al., 2023; Panigrahi et al., 2023; Lu et al., 2024b; Vasuki et al., 2014; Tung et al., 2018; Li et al., 2015), the selected software packages were DSE (Riquelme et al., 2014; Riquelme et al., 2015a; Riquelme et al., 2017) and CloudCompare with its FACETS plugin (Dewez et al., 2016; Tung et al., 2018; Nagendran et al., 2019). The materials obtained from these comparative analyses are extensive, and it can be said that the full potential of these two software packages has still not been exhausted.

The broader study included the use of DSE software, which applies methods such as Principal Pole Extraction and the generation of Pole Density Plots, as well as FACETS, a CloudCompare plug-in. FACETS extracts the planes it identifies, assigns different colors to sets of planes with similar orientations, and generates a tabular overview of the dip and dip direction of the extracted planes. This plug-in provides two fundamentally different algorithms, or approaches, both of which were tested in the broader study: Kd-tree and Fast Marching. Unfortunately, the data extracted using FACETS were not of the same quality as those obtained with DSE. Therefore, due to limitations of time and space, this paper presents only the results obtained using the DSE semi-automatic software for the extraction of geological structures.

2 Milutinci locality

The acquired 3DPC (Ivanovski et al., 2023) were processed using the DSE software (Fig. 1a, 1b).



Planes identified using geological compas

	1	2	3	4	5	6	7	8	9	10	
Dip direction/dip	57/21	329/35	215/46	108/70	336/84	37/67	233/56	255/33	150/89	302/80	total
No of measurements	38	13	5	3	3	4	1	1	1	2	71
% of measurements	53.52	18.31	7.04	4.23	4.23	5.63	1.41	1.41	1.41	2.82	100.00

Planes identified using virtual compas via 3DPC

	1	2	3	4	5	6	7	8	9	10	
Dip direction/dip	61/20	331/33	213/44	108/70	334/87	36/70	231/58	251/37	151/88	308/83	total
No of measurements	38	13	5	3	3	4	1	1	1	2	71
% of measurements	53.52	18.31	7.04	4.23	4.23	5.63	1.41	1.41	1.41	2.82	100.00

Planes identified using DSE via 3DPC

	1	2	3	4	5	6	7	8	9	10	
Dip direction/dip	67/21	331/27	36/48	225/47	103/54	335/88	303/90	276/66	20/87	249/80	total
No of measurements											
% of measurements	42.55	18.38	8.75	5.25	5.50	3.99	3.18	2.16	3.65	1.66	95.07

Fig. 1a.Pole density plot in DSE from 3DPC;Fig. 1b. Identified planes from all methods are marked with similar color.

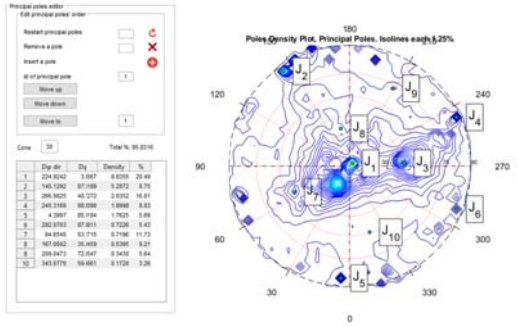
The identified discontinuity sets with the pole density plot (Fig. 1a) show a similar trend to those extracted using geological and virtual compass, as interpreted in (Ivanovski et al., 2023).In this case, the DSE software extracts the planes of the surveyed object with a very high degree of similarity.

If surveys are conducted on “clean” rock surfaces, without the influence of vegetation and other sources of “noise,” even more realistic ratios of the represented planes may be obtained. Attempts were made to clean the 3D point clouds of various unnecessary segments, although this process can always be performed with greater precision. Considering also the fact that the data acquisition itself can always be improved and made more accurate, it can be concluded that this is a process that can be refined many times, thereby further demonstrating the reliability of this method.

The table (Fig. 1b) shows that the most dominant plane set, ranks first across all methods. The percentage obtained by the DSEsoftware is generally lower, mainly because the higher point density leads to the formation of a greater number of smaller planes at the expense of larger ones. As a result, the percentage distribution changes. In addition to the most frequent set, two other plane systems correspond to the measurements obtained using the geological compass and the virtual compass. These three plane sets represent the majority of the planes obtained through the semi-automatic method. Although the remaining planes generally do not coincide with the manually measured ones, they still show a certain trend that partially overlaps.

3 Farish locality

The results obtained in (Ivanovski et al., 2024) are processed with DSE and presented (Fig 2a and 2b):



Planes identified using geological compas

	1	2	3	4	5	6	7	8	9	10	
Dip direction/dip	263/59	40/33	57/55	358/83	229/82	145/84	173/78	258/79	337/84		total
No of measurements	10	6	3	2	2	2	1	1	1		28
% of measurements	35.71	21.43	10.71	7.14	7.14	7.14	3.57	3.57	3.57	0.00	100.00

Planes identified using virtual compas via 3DPC

	1	2	3	4	5	6	7	8	9	10	
Dip direction/dip	264/59	42/33	57/63	4/36	234/79	147/79	173/75	261/79	341/83		total
No of measurements	10	6	3	2	2	2	1	1	1		28
% of measurements	35.71	21.43	10.71	7.14	7.14	7.14	3.57	3.57	3.57	0.00	100.00

Planes identified using DSE via 3DPC

	1	2	3	4	5	6	7	8	9	10	
Dip direction/dip	225/4	145/88	267/49	245/88	4/86	292/87	65/53	167/35	209/73	343/60	total
No of measurements											
% of measurements	20.49	8.75	16.81	8.83	5.69	5.43	11.73	9.21	5.64	3.26	95.84

Fig. 2a Pole density plot in DSE from 3DPC.

Fig. 2b Identified planes from all methods are marked with similar color.

The most dominant set of planes extracted by DSE, unfortunately does not represent a real structural feature of the rock mass, but rather a part of the terrain that has naturally formed in certain areas of the surveyed outcrop. With a total representation of 95.8%, it can be concluded that the analysis covers a large proportion of the orientations present in the terrain, making it relevant and representative of the investigated site.

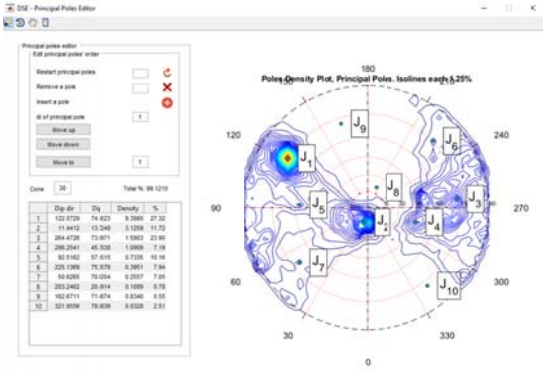
From the table (Fig 2b), it can be concluded that the data obtained using the geological compass and the virtual compass coincide with a high degree of accuracy. However, when these results are compared with those obtained using the semi-automatic method, certain discrepancies become evident, especially when the entire set of plane systems is considered.

The data recorded using the geological compass and the virtual compass refer to planes that were selected for measurement during fieldwork. This selection depended on the field conditions, the exposure of the plane, the curvature or flatness of the plane, as well as the decision made directly on site. In contrast, the semi-automatic method registers all possible planar systems identified through its algorithms. In this case, a successful correlation is obtained if the most dominant plane identified by the semi-automatic method is excluded.

The plane most frequently measured using the previous methods is identified by DSE as the second most dominant plane set. The remaining plane sets show a satisfactory number of overlaps, which suggests that the semi-automatic system was able to recognize real discontinuity systems. Nevertheless, the terrain consists of rock outcrops as well as other areas that are not relevant for structural geology but are still included in the acquired point cloud. The semi-automatic software does not have the capacity to automatically classify these areas as invalid.

4 Serta locality

And for the third locality the obtained 3DPC (Ivanovski et. al, 2025) is analyzed by DSE (Fig 3a, 3b).



Planes identified using geological compas

	1	2	3	4	5	6	7	8	9	10	
Dip direction/dip	115/80	236/79	243/48	29/89	68/88	33/13					total
No of measurements	11	2	1	1	1	1					17
% of measurements	64.71	11.76	5.88	5.88	5.88	5.88	0.00	0.00	0.00	0.00	100.00

Planes identified using virtual compas via 3DPC

	1	2	3	4	5	6	7	8	9	10	
Dip direction/dip	113/78	246/80	242/50	40/81	80/80	37/17					total
No of measurements	11	2	1	1	1	1					17
% of measurements	64.71	11.76	5.88	5.88	5.88	5.88	0.00	0.00	0.00	0.00	100.00

Planes identified using DSE via 3DPC

	1	2	3	4	5	6	7	8	9	10	
Dip direction/dip	122/74	11/14	264/73	286/46	93/57	225/75	51/71	203/20	163/71	322/78	total
No of measurements											
% of measurements	27.32	11.72	23.90	7.19	10.16	7.94	7.05	0.78	0.55	2.51	99.12

Fig. 3a Pole density plot in DSE from 3DPC.

Fig. 3b Identified planes from all methods are marked with similar color.

In this case, the bedding plane of the rock is represented more realistically. Due to the more difficult access to the rock surface for measuring the bedding, this plane was not measured in larger numbers

using the geological compass, and consequently not with the virtual compass either. However, DSE successfully recognized this plane as one of the main planes at this site. The high occurrence of vertical structures indicates the presence of faults or fractures, which is fully consistent with the actual field conditions.

From the table (Fig 3b), it can be concluded that the data obtained using the geological compass and the virtual compass coincide with a very high degree of precision. A relatively high degree of correspondence is also observed for the most frequently measured plane using the geological compass, which in reality represents a fracture that is the most visually exposed. The detection ratio of the other fractures is also at a high level. The bedding plane, which was relatively more difficult to measure, was also detected, one could even say more successfully by DSE, since it identified it as the third most represented plane, which corresponds well to the actual field situation.

5 Analysis

From the perspective of DSE, the differences between these three localities are relatively more pronounced. Based on this comparison, it can be stated that the Serta locality yielded the best processing response from the software. This may be related to the dimensions and complexity of the scanned object, as well as the presence of vegetation and the duration of the scanning process. The greatest discrepancies were obtained at the Farish locality, where the scanning process lasted the longest and where vegetation was most abundant.

The case with Farish locality indicates that the semi-automatic system is not perfect, as it forms planes regardless of the actual connection between the points, meaning that some points may be grouped together even though they do not belong to the same plane set, despite being located close to each other. Therefore, working with such systems requires maximum dedication, focus, and careful interpretation. Since the semi-automatic method provides options for modifying the processing settings, the 3D point cloud can be reprocessed using different plane-forming parameters, which may lead to improved results. In some cases, the terrain itself dictates the need to deviate from the default software settings, which is precisely why such adjustable parameters are available.

It can be said that DSE has a broader processing capacity for this type of data compared with the geological compass and the virtual compass, since a larger number of factors influence its results. DSE provides a wide range of adjustable parameters and available tools for improving the final output, with practically extensive possibilities for optimization. Considering the volume of the obtained data, this method provides speed and efficiency; however, achieving such processing speed also requires a more powerful computer configuration.

6 Conclusions and Recommendations

The DSE method was developed specifically for this type of problem. Therefore, it can be considered highly promising. It provides a high degree of discontinuity recognition, offers a solid number of options for modifying parameters in order to obtain more realistic results, and generates a wide range of useful visual outputs. The large amount of data, the presence of minor issues within the point cloud, and several smaller problems related to certain visualizations indicate that DSE is currently a very promising tool that can provide valuable support to geological practice.

Although the proposed methodology provides a significant improvement in automation, a solid background in structural geology is still required in order to obtain optimal results. The complex methodology and algorithms implemented in this software cannot fully distinguish all useful surfaces that an experienced geologist would recognize as relevant to the investigation. In automated processes, surfaces that are not of primary interest may still influence the generation of plane sets for the investigated area and may therefore lead to misleading interpretations.

In all examples where this software was used, its accuracy in identifying the most dominant planes within the investigated outcrop is evident. However, caution is required when interpreting planes represented by lower percentages, which in any case do not substantially affect the overall structural interpretation.

Despite the high degree of accuracy enabled by modern technological tools, fieldwork remains essential for understanding the characteristics of any terrain and for fully recognizing and characterizing the discontinuities present. Regardless of technological progress, engineers and geologists still need to gain experience directly in the field. A good understanding of the geological setting and field processes, combined with a strong geotechnical background, is crucial for the correct interpretation of results obtained through these modern methodologies.

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