

3-D Discontinuity orientations using combined optical Imaging and LiDAR techniques

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ABSTRACT: The importance of the collection and analysis of data on discontinuities cannot be overemphasized. Problems which include sampling difficulties, risks, limited access to rock faces and exposures, and the delay in data collection has led to a high need for data collection tools and analysis techniques that can overcome these problems. Great developments have been made towards automated measurements using both optical imaging and LiDAR scanning methods but there is still more room for improvement. Discontinuities manifest themselves as ‘facets’ that can be measured by LiDAR or fracture ‘traces’ that can be measured from optical imaging methods. LiDAR scanning alone cannot measure ‘traces’ neither can optical imaging methods measure ‘facets’. This is complicated by the fact that both ‘facets’ and ‘traces’ are often present in the same rock cut, making the selection of an appropriate measuring tool very difficult if not impossible. In this paper, we present our research on the development of robust software to determine 3-D discontinuity orientations from combined LiDAR and optical imaging techniques.

1. INTRODUCTION

There are breaks or cracks in every rock mass [1]. Discontinuity is the most general term which suggests a break in the continuity of a rock fabric with no implied genetic origin (Fig. 1a). Discontinuity can be defined as a significant mechanical break or fracture of negligible tensile strength, it has a low shear strength and high fluid conductivity when compared to the rock itself [2]. Discontinuity influences all the engineering properties and behavior of rock [3]. When dealing with discontinuous rock masses, the properties of the discontinuities become a prime importance since that determines to a large extent the mechanical behavior of the rock mass [4]. The presence of discontinuities in a rock mass can affect engineering designs and projects, which include the stability of slopes in a rock mass, the stability and behavior of excavations in a rock mass and the behavior of foundations in a rock mass. The presence of discontinuities also affects rock properties such as the strength of the rock and the hydraulic conductivity of the rock which is responsible for the transportation of groundwater and contaminants [5]. Thus, the importance of the analysis of discontinuities in of a rock mass cannot be overemphasized.

1.1. Rock Falls on Highways

Highways that traverse through rocky terrains often require that artificial vertical slopes be cut by blasting techniques to facilitate the highway construction. A constant danger to the motoring public is for large blocks of rock to fall or slide down, at worst killing and injuring members of the motoring public, and at best blocking the highway and impeding traffic flow. Many of these failures result because of release along planar cracks or discontinuities in rock mass. Whether or not failure occurs will depend on the orientation of the cracks, individually or in combinations (Figure 1.1).

1.2. Prediction and Mitigation of Rock Falls

The cracks or discontinuities tend to cluster in terms of their orientations, into typically three or more sets, which tend to be mutually orthogonal, or roughly at 90 degree to each other (Figure 1.2). Knowing the orientations of the discontinuities can lead to stability prediction based on well established analytical tools as described by Hoek and Bray [6]. Figure 1.3 shows the time honored stereonet projection method [7] where each data point, consisting of a normal vector to an individual

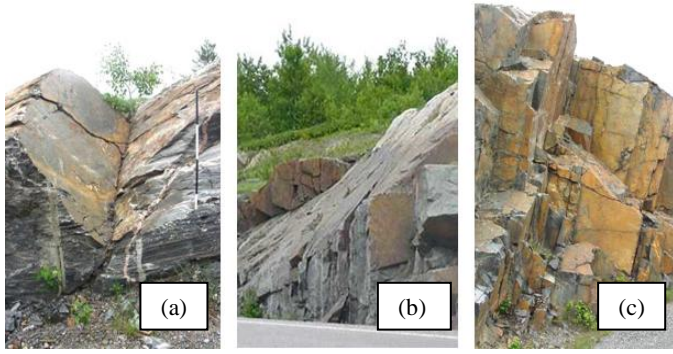


Figure 1.1. (a) Example of wedge , (b) planar , and (c) toppling failures along road cuts.

discontinuity plane, is assigned to a discontinuity set by using cluster analysis. Cluster analysis techniques are described in detail by Maerz and Zhou [5, 8, 9, 10,11].

The orientations can be and have been traditionally measured using manual compass and clinometer methods. These methods are however slow, tedious and cumbersome, and in some cases dangerous because of potential falling rock, and are often limited to easily accessible locations like the base of the slope.



Figure 1.2: Orthogonal nature of joint sets. Measurements of the “cracks” or discontinuities are displayed in Figure 1.3

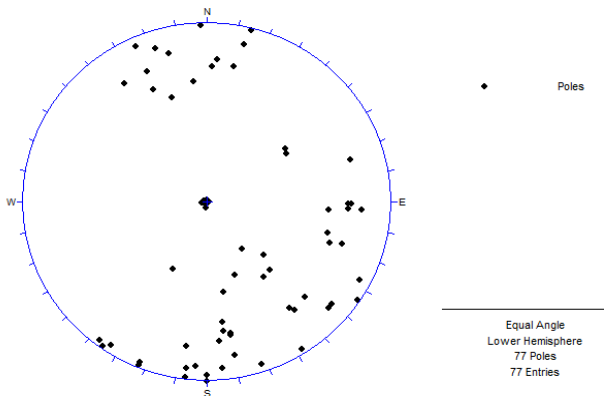


Figure 1.3: Projections of vectors normal to discontinuity plane on a unit lower hemisphere, clustered into three sets.

Once having identified the graphical or computational techniques can be used to determine the kinematic feasibility of failure (Figure 1.4) and standard modeling techniques such as limiting equilibrium analysis can be used to determine if failure will indeed take place (Figure 1.5).

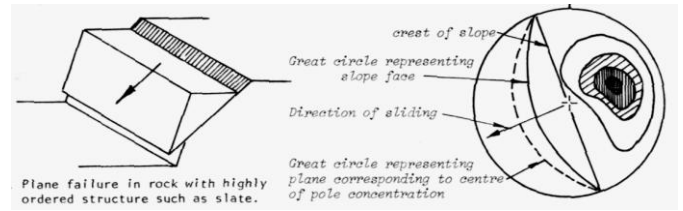


Figure 1.4: Planar failure geometry (left) and graphical method of determining if slide failure is kinematically possible [6].

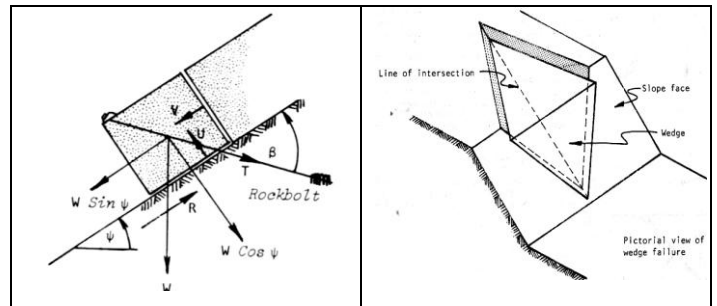


Figure 1.5: Limiting equilibriums analysis applied to planar features (left) and wedge features (right) [6].

1.3. Surface Expressions of Discontinuities

The discontinuities or cracks in the rock mass, when exposed in an outcrop or cut manifest themselves in one of two ways, often in both ways on the same exposure:

1. On flat planar rock cuts, the intersection of the plane of the discontinuity and the planar rock cut results in a visible line (**fracture trace**) that lies on both planes (Figure 1.6).
2. On rock cuts that are irregular, the actual faces of the discontinuities are exposed. These **fracture surfaces** can be considered to be like “**facets**” on a cut precious stone (Figure 1.6).

There are emerging techniques to measure joint orientations for each of these situations, however, two completely different techniques are required for the two types of discontinuity expressions. What is worse is that, in at least one of the methods, the mere presence of the opposite type of fracture expression makes the technique unusable. Even though often both expressions are present, there is to date no legitimate way to combine the two techniques.

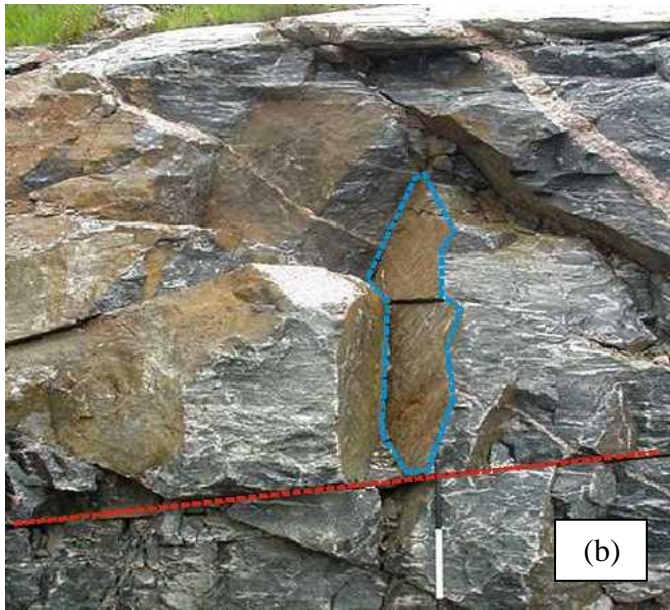
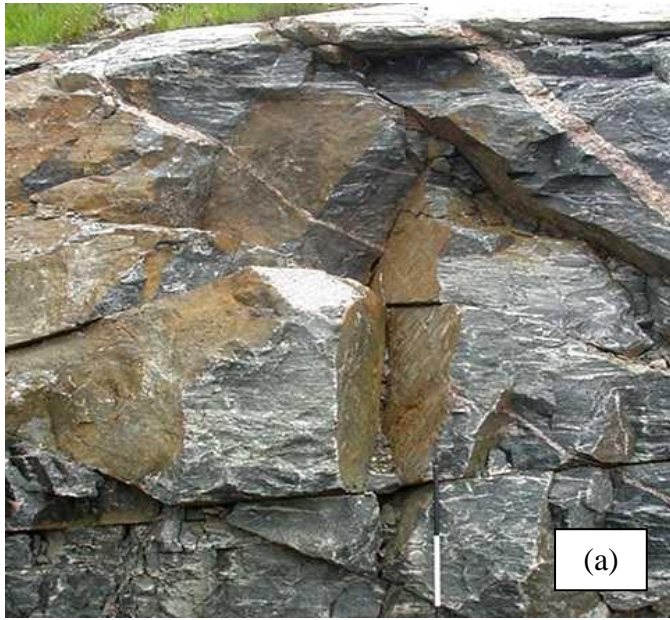


Figure 1.6: (a) A rock cut. (b) The same rock cut showing both fracture traces (red line) and facets (cyan polygon).

1.4. Optical Image Processing

The assemblage of fracture traces can be optically imaged and their (2-D) orientation can be measured by optically imaging the rock cut, using appropriate image processing filters like the canny edge detector to isolate the lines of intersection, and measuring their orientation (Figure 1.7) [6,13].

One shortcoming of this method is that optical images are noisy under realistic field conditions, and false traces are often measured (Figure. 7). In many cases images are so noisy that identified traces are almost unrecognizable [12] and practitioners simply abandon

automated methods and resort to drawing by hand the joint traces [13], thus defeating the purpose of automating the images.

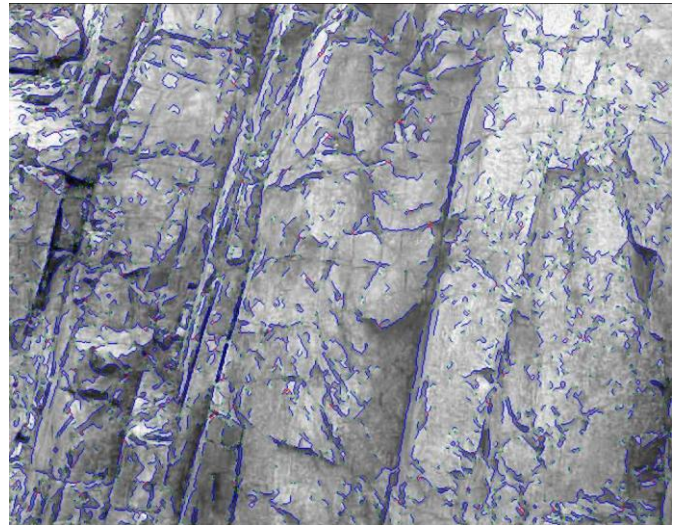


Figure 1.7: Delineated traces of intersections of discontinuities with the excavation plane using canny detector, using WipJoint™ software, of an ignimbrite rock cut in SE Missouri.

The second shortcoming of this approach is that the orientation measurement is in only two dimensions not the required three. Kemeny and Post [12] developed theoretical relationships between 2-D traces and 3-D orientations, but require in addition to the optical image some a-prior knowledge of the possible 3-D orientations such as from non-parallel faces or field mapping. They suggest in their conclusions an approach as proposed herein.

1.5. LIDAR 3-D Scanning

In the last few years, the LiDAR (Light Detection and Ranging) 3-D technology is becoming increasingly useful in geology and engineering. LiDAR was used by Mikos et al to study rock slope stability [14]. Lim et al used photogrammetry and laser scanning to monitor processes active in hard rock coastal cliffs [15]. High resolution LiDAR data was used by Sagy et al to quantitatively study fault surface geometry [16]. Enge et al. illustrated the use of LiDAR to study petroleum reservoir analogues [17]. Using a combination of LiDAR and aerial photographs, Labourdette and Jones studied elements of fluid depositional sequences using LiDAR [18].

The assemblage of facets in a rock mass can be detected using LiDAR techniques. Missouri S&T has recent acquired a LIDAR unit (Figure 1.8). LiDAR data can be used to generate 3-D orientations on Stereonets [19, 20, 21, 22]. A version of the software is even commercially available [23]. The point cloud produced by the laser scanner is searched for a region of co-planar points, and

using any three non-linear points from this region one can determine the orientation solving the classic 3 point problem. Not all published methods give comparisons to manual measurements, and those that do show that the techniques could clearly be improved.

The shortcoming of this approach is that it does not work with flat vertical showing discontinuity traces, where no facets are available, and will in some cases map the flat vertical cut as a series of discontinuities

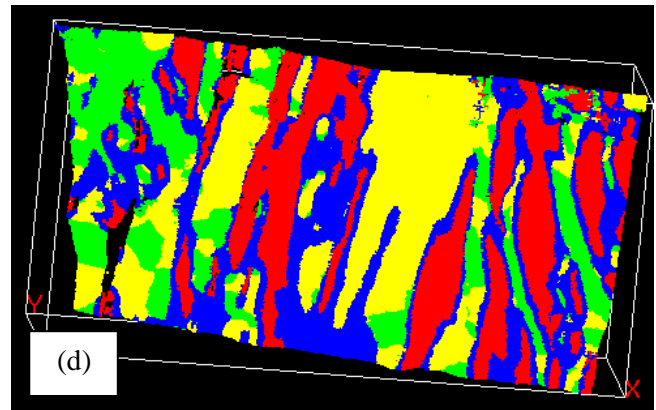
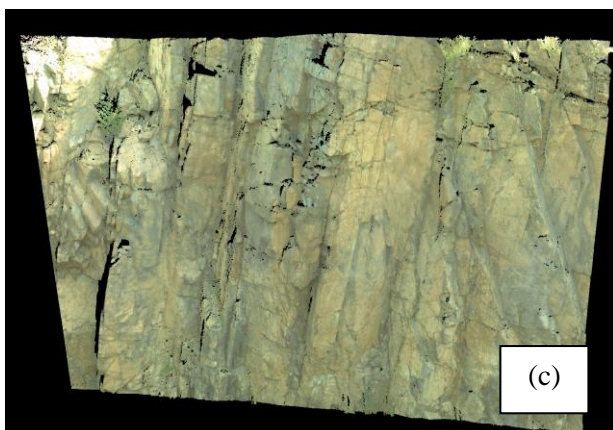
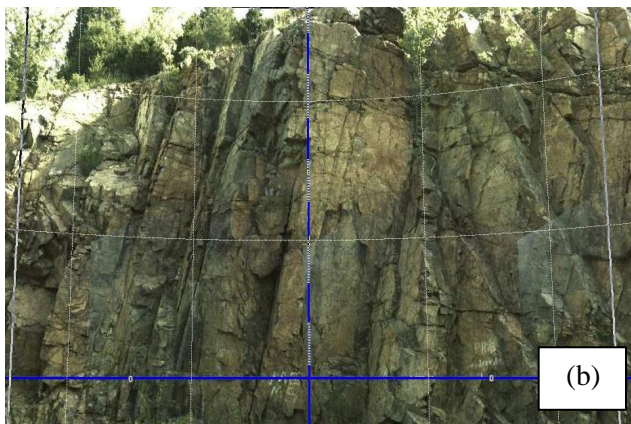


Figure 1.8: (a) The Missouri S&T LiDAR unit. (b) LiDAR unit measuring raveling of a rock face. (c) Resulting point cloud. (d) Identification of discontinuity orientations. The different colors represent common orientations. Blue is the absence of measurable structure.

1.6. Combining the Optical and LIDAR Imaging Techniques

Because rock cuts in practice are typically in places planar and in others irregular, there is a hybrid approach where 3-D LIDAR measurements are geometrically and statistically related to 2-D optical measurement for a combined analysis. In some parts of the image/scan the optical analysis will return good measurements of the traces, while in others the 3-D scanning technology will yield good measurements of the facets. The key however is that there is a geometric relationship between the facets and traces. Given that there are a limited number of joint sets with unique orientations (typically 3 to 5) within variability constraints, there will be three orientations of facets and three orientations of traces. Within a single joint set, the linear trace will fall uniquely on the planar facet. Having sorted out which group traces belong to which set of facets, we can use the 3-D orientations measured on the facets and assign the identified traces where facets are not available for measurement. In addition the traces that do not correspond to facets can be removed from the measurement pool, because they represent noise from something other than discontinuity intersections with rock faces.

1.7 Methodology

The methodology for the research involved 6 major steps;

- Selection of the research sites
- Acquisition of 3-D LiDAR and digital images and data treatment
- Conducting of field manual measurement
- Preparation of manual facets and traces map
- Development of algorithms
- Validation of results

Rock cuts with well defined facets and traces were preferred over others. Stability, accessibility, and safety were all considered in the site selection process. In all, six sites were selected in Missouri (Figure 1.9) and ranked in order of preference. Digital images of the selected rock cuts were taken using the inbuilt optical camera of the LiDAR unit and an external digital camera. Point cloud data of the rock cut were also collected. Collected data were then cleaned and cropped to a desired area. Facets and traces identified on the optical images and point cloud data were located in the field on the selected rock cuts and measurements of the dip and strike were taken using the Brunton compass. Manual facets and trace maps were created based on the field measurements. Algorithms were developed from the LiDAR data and then the results were compared with the field measurements.

2. STUDY SITES

Our study sites are located in Rolla and Ironton, Missouri (Figure 1.9). The sites consist of sandstone and ignimbrite rock cuts along roads. LIDAR scans were conducted using a Leica ScanStation II. The scans were made at 90° and also at about 45° to the cuts (Figure 1.10). Optical images were also obtained using the ScanStation II's inbuilt optical camera and also with an external digital camera.

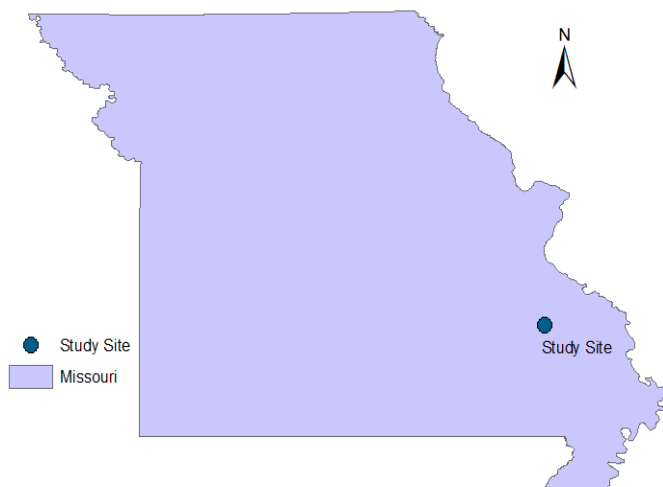


Figure 1.9: Location map of study site (not to scale).

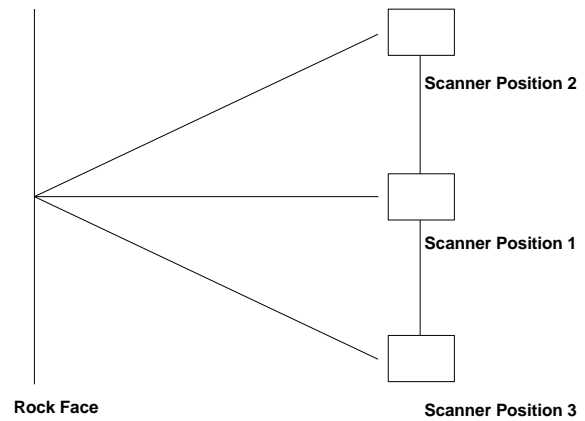


Figure 1.10: Rock face and LiDAR scanner positions

2.1. Discontinuity Facet Measurements The Rolla case

Optical images and point cloud data were collected using the LiDAR unit. Manual measurements of the orientation (dip/dip direction) of exposed discontinuity facets on the rock face were made in the field. Manual discontinuity maps were prepared for the rock cut (Figure 2.0). Algorithms were developed to estimate the orientations of the facets from the point cloud data (Figure 2.0). Measurements of the discontinuity facets were then compared (Table 1).

Dip and dip direction obtained from when the algorithm was run on the LiDAR data were compared to those obtained from the field (manually), results were found to be almost the same as those obtained from the field (Table 1, Figure 2.1).



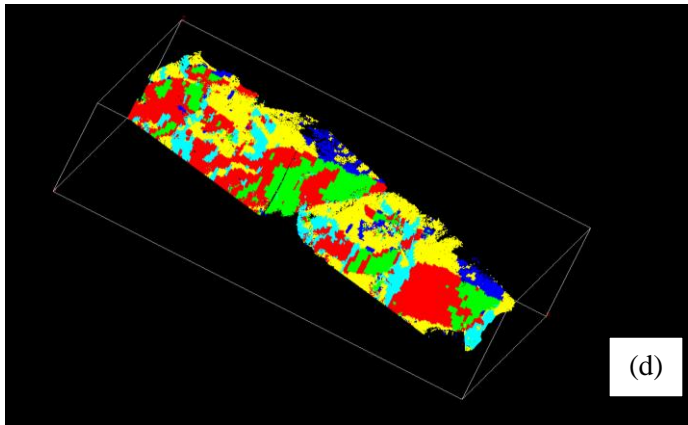
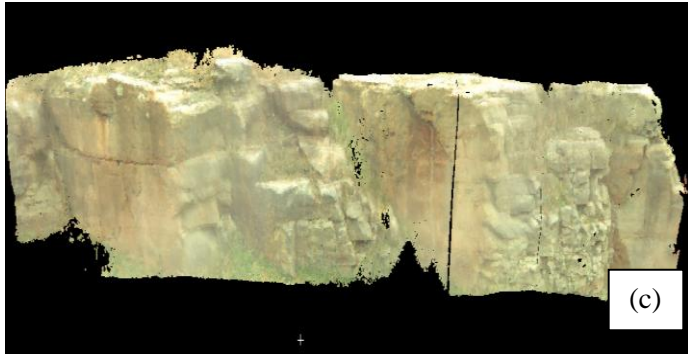
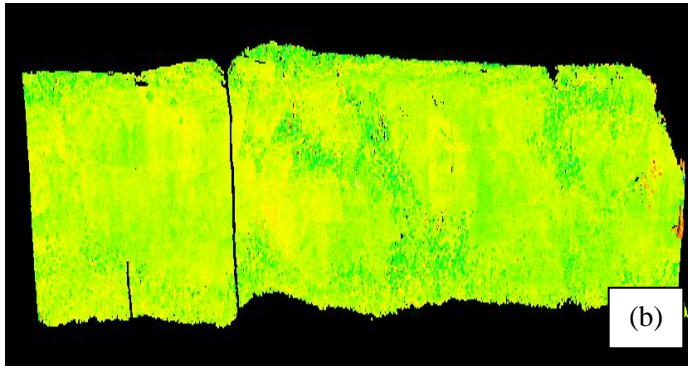


Table 1: Dip direction and dip of facets from manual (field) and LiDAR data

Facet	Dip Dir		Dip	
	Field	LiDAR	Field	LiDAR
1	314	309	86	88
2	332	329	70	67
8	22	22	88	87
10	310	314	83	84
11	333	339	80	78
12	322	328	75	71
18	35	31	87	89
19	298	302	86	80
20	355	358	1	1
21	177	172	85	82
22	174	182	78	78
30	274	274	1	2
32	26	23	45	45
35	182	188	74	73
37	191	191	75	79
56	355	355	76	76
58	353	359	72	75
60	350	353	70	67
73	35	37	89	88
77	3	8	89	83

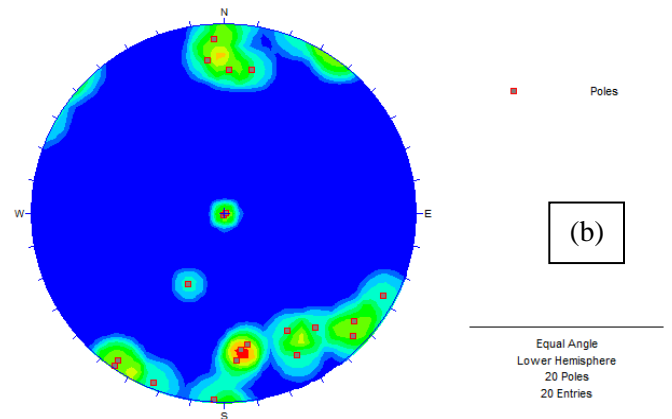
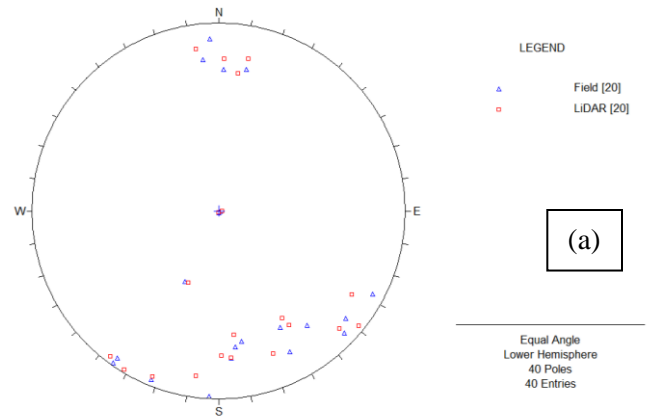


Figure 2.0: (a) Manual discontinuity map of the rock face (red lines represent traces and blue lines represent facets), (b) corresponding LiDAR point cloud data of the rock face, (c) Point cloud data of the rock face with scanner colors. (d). Clustered facets of the same rock face.

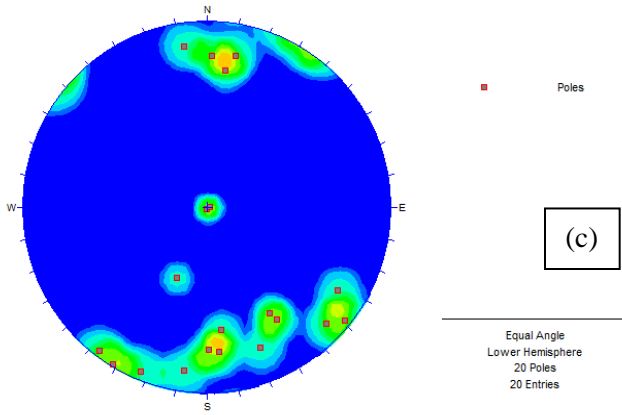


Figure 2.1: (a) Poles of both field and LiDAR data (b) Clustered poles of field data (c) Clustered poles of LiDAR data.

2.2 Discontinuity Trace Measurements from the Optical Image The Ironton case

2D linear traces can be found from optical images. First, canny edge detection [24] was applied to extract the linear traces components. After the components are extracted, all the co-linear trace components were reconciled by iterative line fitting [25]. The linear traces were then clustered together based on their direction using the K-means algorithm [23]. Figure 2.2 shows the process of discontinuity trace measurements from the optical image. Table 4 lists all the detected line traces with their orientations and the cluster numbers it belongs to.

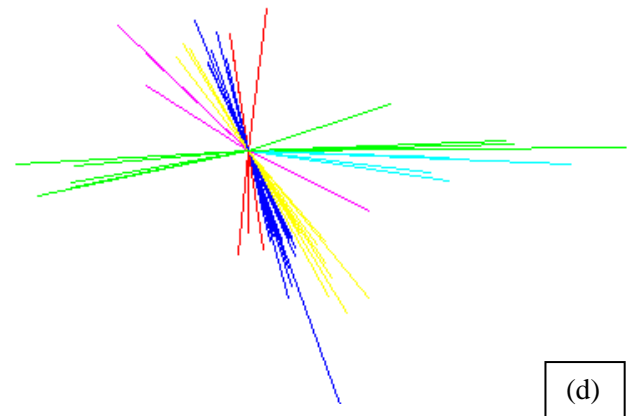
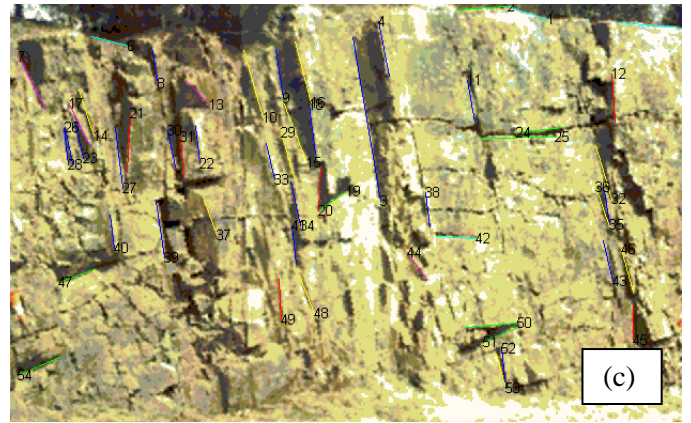


Figure 14: Discontinuity Trace Measurements from the Optical Image. (a) Original optical image; (b) linear trace components detected by canny edge detector; (c) reconciled co-linear trace components by using line fitting. Traces are clustered based on their direction. Six clusters of linear traces, traces of the same cluster are displayed using the same color; (d) directions of the six clusters of the linear traces. Each cluster is shown in one color.

Table 4: Clustered linear traces mean orientations from the optical image

Cluster (color)	Angle (degree)
red	56.9725
green	165.6622222
blue	80.5552381
yellow	10.2625
cyan	72.26818182
magenta	89

3. SUMMARY AND CONCLUSIONS

Obtaining measurements of fracture orientations is critical for analysis of discontinuous rock masses. The time honored method of manual measurements with Brunton compasses is both time consuming and often inconvenient given issues such as restricted access to measurement areas. Great strides have been made towards automated measurements using both optical imaging methods and LIDAR scanning methods. The difficulty is that discontinuities manifest themselves in rock cuts in two different ways; as facets that can be measured by LIDAR or fracture traces that could be measured, at least in 2-D, by optical imaging methods. Facets are defined as the actual discontinuity surfaces that are exposed in the rock cut (most commonly observed in rough irregular rock cuts); while fracture traces are the linear features that are the intersection between the discontinuity and the rock cut (most commonly observed in smooth planar rock cuts). Unfortunately LIDAR scanning cannot measure traces nor can optical imaging measure facets. This is complicated by the fact that both facets and traces are often present in the same rock cut, so selecting the measuring tool to fit the type of exposure is not possible.

This paper presents the initial results of research into combining the optical and LIDAR imaging techniques. The method makes use of a Leica ScanStation II scanner that provides both optical and LIDAR images. LIDAR point clouds are used to map all the facets and measure their orientations. The optical images are used to identify all the traces on the images and measure their 2-D orientations.

Because both of the optical and LIDAR data sets are generated from the same scanner, the two data sets are automatically registered to each other. Facet orientations are calculated by identifying planar regions

within the point cloud and measuring their orientations. Traces are identified from the optical image using Canny edge detection and RANSAC-based iterative line fitting. Trace measurements are reconciled with facet orientations, and 3-D extracted edges are used to validate the 2-D linear traces.

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