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LiDAR and optical imaging for 3-D fracture orientations

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Abstract: Data on discontinuities are always necessary for design, characterization and analysis of rock structures. The time honored method of manual measurements with Brunton compass is both time consuming and often inconvenient given issues such as restricted access to measurement areas, introduction of erroneous data due to sampling difficulties and human bias, considerable safety risks since measurements are sometimes carried at the base of existing slopes or during quarrying, tunneling or mining operations or along busy highways and difficulty to have direct access to rock faces. Discontinuities manifest themselves in rock cuts as 'facets' that can be measured by LIDAR or fracture 'traces' that can be measured, at least in 2-D by optical imaging methods. Unfortunately LiDAR scanning cannot measure 'traces' nor can optical imaging measure 'facets'. To overcome all these problems, the need to combine both LiDAR data and optical imaging is necessary.

1.0 Introduction: Naturally 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.

Discontinuity properties can be grouped as geometric or non-geometric. Geometric properties include position, orientation, persistence and open size. Non-geometric properties include wall strength, roughness, filling and water conductivity. The most important discontinuity property is orientation. Orientation influences the potential of the rock mass to move, the direction of movement and the volume of material to be moved [6]. Orientation is so important that it is ultimately used in every kind of analysis, either numerical or non numerical modeling.

Fig. 1.0a: A rock cut showing discontinuities

Discontinuities in rocks manifest themselves in two different ways; as facets or fracture traces. Facets are defined as the actual discontinuity surfaces that are exposed in the rock cut while fracture traces are the linear features that are the intersection between the discontinuity and the rock cut (Fig. 1b).

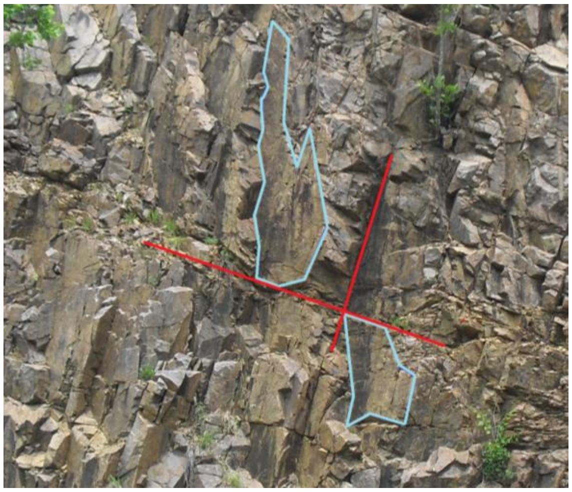


Fig. 1.0b: A rock cut showing both fracture traces (red lines) and facets (cyan polygons).

Methods of obtaining discontinuity data in a rock mass include [6, 3, 7, 8]:

- Cell mapping
- Scan-line mapping,
- Fracture set mapping
- Oriented core

Cell mapping involves dividing the rock face or outcrop into cells and measuring the properties of the discontinuities, scan-line mapping involves stretching a measuring tape along a face or outcrop and measuring the properties of the discontinuities and their points of intersection with the tape line, fracture set mapping involves identifying and measuring the properties of the discontinuities during geological mapping, oriented core is similar to scan-line mapping but used when the rock types of interest are not exposed [6]. The above mentioned methods are manual and have common disadvantages [9] which include:

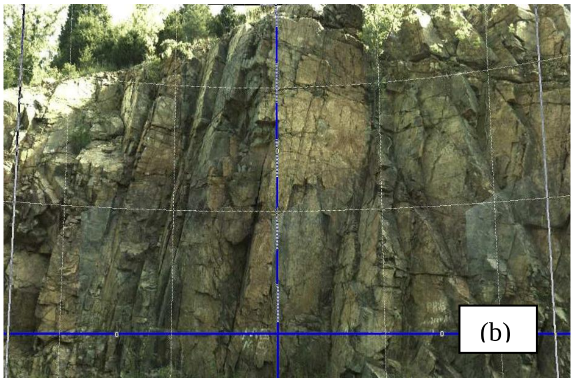
- Introduction of erroneous data due to sampling difficulties and human bias.
- Considerable safety risks since measurements are sometimes carried at the base of existing slopes or during quarrying, tunneling or mining operations or along busy highways.
- Difficult or impossible to have direct access to rock faces.
- Time consuming and labor intensive which make them costly.

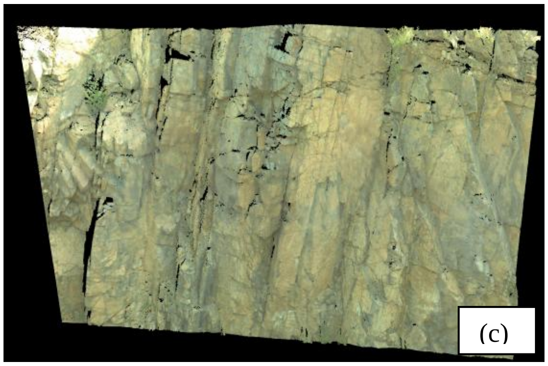
To overcome these problems, the use of laser scanners and digital images is on the increase. Laser scanning and digital images can be used as cheaper, more objective and more precise and accurate methods to determine discontinuity orientations [10, 11]. 3D LiDAR scanning and digital photography are the two dominating imaging technologies [10]. Unfortunately, LiDAR alone can not measure both facets and fracture traces neither can digital imaging alone measure both facets and fracture traces.

Facet orientations can be measured from LiDAR data and fracture trace orientations can be measured at least from 2-D optical imaging methods. This paper presents the results of research aimed at combining optical and LIDAR imaging techniques to analyze discontinuities in rocks.

1.1 3-D LiDAR Scanning and Digital Photography: The LiDAR (Light Detection and Ranging or Light RADar) uses a time of flight light pulses to generate a 3-D image of a surface. It involves the emission of light pulse from a source to a surface, the surface reflects the light pulse off, the reflected light pulse returns to the source which then receives and measures it [10]. A high precision counter measures the travel time and intensity of the returned pulse. The pulse source also measures the angle at which the light pulse is emitted and received, these enables the spatial location of a point on a surface to be calculated [10]. The result is a million of points reflected from the surface. The points are represented by xyz coordinates, these xyz coordinates and their associated intensity values are known as a “Point cloud”. Missouri University of Science and Technology’s LiDAR unit (Fig. 1.1) was used for this research. The LiDAR 3-D technology is becoming increasingly useful in many fields. In forestory, LiDAR data together with fused active hyperspectral reflectance was used to classify tree species [12]. In agriculture, LiDAR based estimates proved reliable and non-invasive to livestock in grazing and herbage studies [13]. In civil engineering, LiDAR has been used in bridge health monitoring [14]. In geological sciences and engineering LiDAR was used by Mikos et al to study rock slope stability [15]. Lim et al used photogrammetry and laser scanning to monitor processes active in hard rock coastal cliffs [16]. High resolution LiDAR data was used by Sagy et al to quantitatively study fault surface geometry [17]. Enge et al. illustrated the use of LiDAR to study petroleum reservoir analogues [18]. Using a combination of LiDAR and aerial photographs, Labourdette and Jones studied elements of fluid depositional sequences [19].

Digital photography on the other hand makes images using a digital technology. The image produced is 2-D. Digital images are excellent for observing traces on smooth rock faces [10]. Digital images contain a great deal of information and their application in the field such as rock engineering that depends heavily on visual data and analysis cannot be underestimated [8]. Digital images can be processed and scaled to suit one's need using different image processing techniques, providing information on trace lengths, spacing and roughness [10; 20]. Handy and others argue that there are other features in digital images of rocks in addition to the presence of fractures that can provide rock characterization information [8]. Color which is a very common characteristic of digital images can be used to extract additional rock information such as fracture fill and changes in rock types. Texture can also be used to obtain information on the weathering of the intact rock, the condition of the fractures, to differentiate rocks from other materials and to classify different types of rocks [21, 22). Kemeny and others have showed a good correlation between Digital Rock Mass Rating (from digital images) method and actual Geologic Strength Index and Rock Mass Rating measurements made in the field [23].





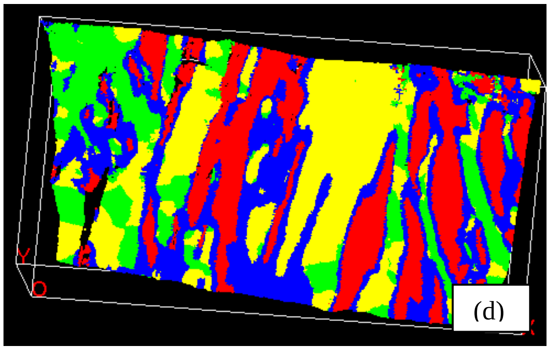


Fig. 1.1: (a) Missouri S&T's LiDAR unit (Leica ScanStation II, tripod stand, a laptop, and a generator set), (b) LiDAR unit measuring raveling of a rock face (c) Resulting point cloud (d) Identification of discontinuity orientations. The different colors represent common orientations. Blue is the absence of measurable structure.

1.2 Study Area: The study area (Fig. 1.2) for this research was located in southeastern Missouri. The study area consists of several ignimbrite rock cuts along a highway. The area was selected because the facets and traces in its rock cuts are exposed and defined.

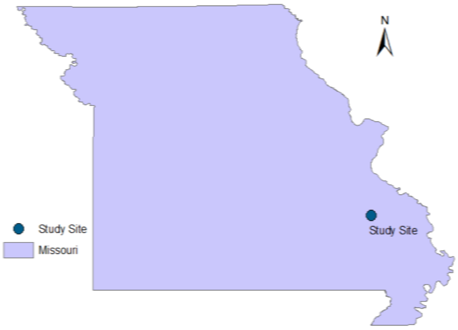


Figure 1.2: Location map of study site (not to scale).

2.0 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 and ranked in other 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 was also collected. Collected data was 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.

3.0 Manual Measurements and Maps: Clearly defined discontinuities (facets and traces) on the digital image were outlined to create a discontinuity map (Fig. 3.0). Numbers were allocated to the outlined discontinuities and then the orientations of their corresponding discontinuities were manually measured in the field using the Brunton compass.

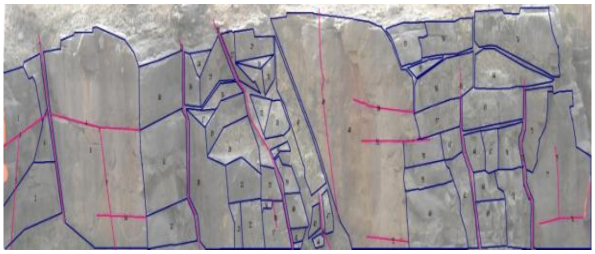


Figure 3.0: Discontinuity map of a rock face. Red lines represent linear traces and blue blocks represent planar facets

3.1 Discontinuity Facet Measurements from the LiDAR point clouds: Normal vectors were computed at each point of the point cloud based on the principal component algorithm. Local neighborhood of the surface points was then determined, noting the k-nearest neighbors of the sample. Using eigen analysis, the local surface properties of the point cloud was estimated. The eigen vectors form orthogonal frames which corresponds to the principal of a point set. Points with similar normal vectors are then clustered based on the k-means algorithm [25]. The results is a discontinuity facet measurement (Fig. 3.1) and mean orientation of each cluster (Table 1).

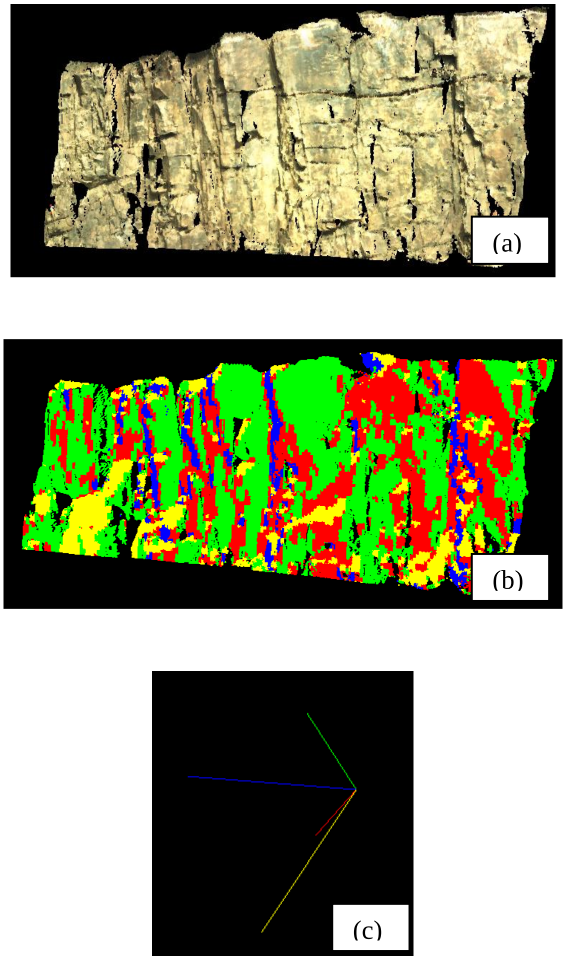


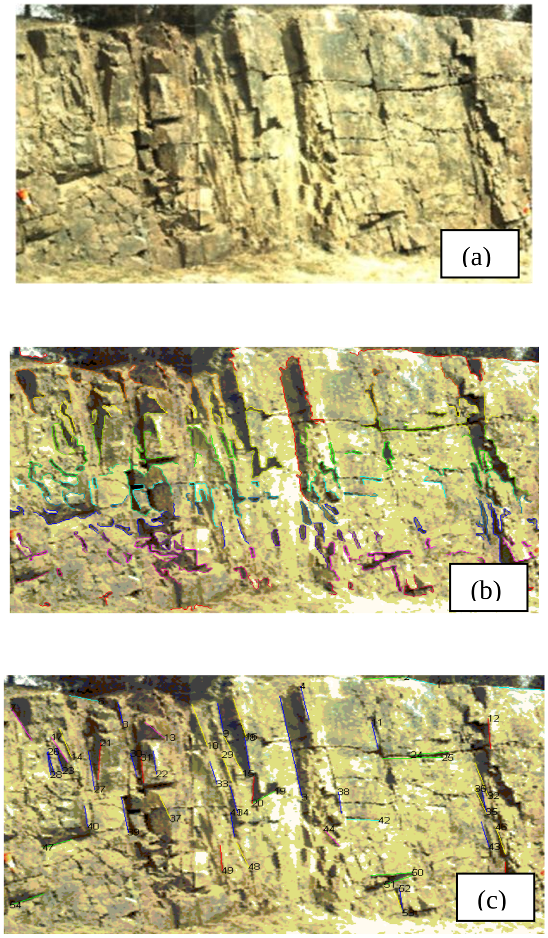
Figure 3.1: Discontinuity facet measurements from LIDAR point cloud data. (a) Point cloud data obtained from the LIDAR. (b) Point cloud data clustered into four colors (green, blue, yellow and red) based on the orientation of the facet. (c) Mean orientations of the four clusters.

Table 1: Mean orientations of clusters from the point cloud data.

Cluster (Color)	Theta Angle (Degree)	Phi Angle (Degree)
Green	189.8	87.58
Blue	288.17	87.9
Yellow	337.68	36.71
Red	188.78	97.18

(Theta and phi angles represent the dip direction and dip respectively)

3.2 Discontinuity Trace Measurements from the Optical Image: 2-D linear traces can be found from the optical image. First, canny edge detection [26] is applied to extract the linear traces components. After the components are extracted, all the co-linear trace components are reconciled by iterative line fitting [27]. The linear traces are then clustered together based on their direction using the k-means algorithm [25]. Figure 3.2 shows the development of discontinuity trace measurements from an optical image. The detected line traces with their orientations and the cluster numbers are listed in Table 2.



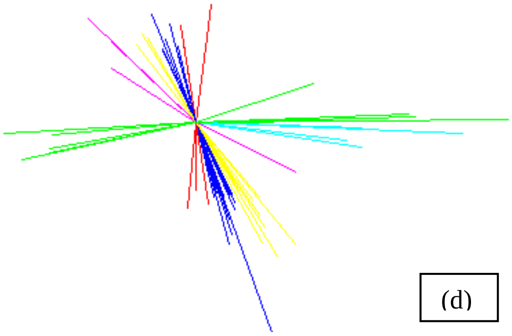


Figure 3.2: Discontinuity Trace Measurements from an Optical Image. (a) Original optical image. (b) Linear trace components detected by canny edge detector (c) Reconciled co-linear trace components using line fitting. (d) Directions of the six clusters of the linear traces. Each color represents a cluster.

Table 2: Mean orientations of clustered linear traces from the optical image.

Cluster (Color)	Angle (Degree)
Red	56.97
Green	165.66
Blue	80.56
Yellow	10.26
Cyan	72.27
Magenta	89

4.0 Results: Results of the developed algorithm look very promising. When the algorithm was run on our current study site, two major facets (green and blue in Fig. 3.0) from the LiDAR data had very close results to measurement made in the field (Table 3). However an expected third orthogonal direction could not be obtained from the LiDAR data. Never the less, it is quite easy to identify it in the 2D line trace analysis.

Table 3: Summary of results from LiDAR data and manual measurement

	Analyses from LiDAR data		Manual measurement	
Cluster (Color)	Theta Angle (Degree)	Phi Angle (Degree)	Theta Angle (Degree)	Phi Angle (Degree)
Green	189.8	87.58	186	88
Blue	288.17	87.9	277	89
Yellow	337.68	36.71	170*	85*
Red	188.78	97.18	203*	82*

5.0 Conclusion: 3-D laser scanning and digital imaging technologies can provide information on discontinuities without having to make physical contact with the rock surface to measure discontinuity properties such as orientation. The technologies provide higher safety and can be used to obtain data on inaccessible rock faces. Also bigger statistical sample is possible and not restricted to only those parts of the rock face that is accessible. The technologies also reduce bias due to humans which is very common when the traditional manual methods are used. Finally, the technologies provide a fast way for data collection and the analysis of discontinuous rock.

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