MULTI-SENSORY DATA INTEGRATION FOR EXTRACTING GEOTECHNICAL PARAMETERS FOR LANDSLIDES HAZARD ASSESSMENT

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ABSTRACT

Geotechnical engineering is a relatively new discipline that has developed rapidly over the past 30 years. It deals with a wide spectrum of natural geological materials ranging from low strength soils to high strength rocks. Earth movements are common in many parts of the world and, as a result, present serious safety and mortality risk to humans in addition to affecting construction activities. Earth movement can be classified into different categories with landslides as being one of those categories. In order to assess the stability of landslides, different geo-technical parameters are required such as the strike and dip of the discontinuity planes in the potential area. Areas affected by landslides are often inaccessible which makes manual compass and inclinometer measurements challenging because of the danger involved in this operation. Preventing large natural landslides is difficult; however some mitigation is possible and can help to minimize the hazards.
Nowadays, 3D modeling of objects can be achieved through either passive or active remote sensing systems. Active sensors, such as Terrestrial Laser Scanning systems (TLS) have been used extensively for quick acquisition of highly accurate three-dimensional point cloud data with high resolution. However, the TLS in some cases has limitations during the data collection due to occlusions, orientation bias and truncation. This research addresses those issues by investigating the possibility of augmenting TLS in the occluded regions through close-range photogrammetry to generate high resolution and dense point cloud using the Semi-Global Matching (SGM) algorithm. By augmenting the two data acquisition methods and registering to a common coordinate system to provide a complete point cloud for the area of interest, any limitations and exposed gaps in the data are filled. Planar segmentation is then carried out to extract the required geotechnical parameters automatically. Four sets of geotechnical parameters have been compared in this research: 1) a set of manual measurements, 2) a set extracted from the TLS data only, 3) a set extracted from the SGM algorithm only, 4) and finally a set extracted from the fused TLS and SGM data. The results showed that the data fusion method provided more accurate results when compared to the results coming from the TLS data and those coming from SGM only. This reveals that the impact of the occluded regions on the calculations of the geotechnical parameters must be considered to achieve the required quality of the estimation process. The proposed method of this research provided high quality measurements for the geotechnical parameters required to assess the landslide hazard, ensured safety, and saved cost and time.

KEYWORDS: discontinuity planes, terrestrial laser scanner, semi-global dense matching, strike and dip, geological hazards.

INTRODUCTION

Landslides are more devastating than most people realize and are often triggered by other natural disasters, such as earthquakes and volcanic eruptions. It is therefore that scientists refer to this as the multi-hazard effect. In the case of a multi-hazard effect even if you manage to survive the initial hazards caused by the natural disaster, another hazard is on its way causing more death and destruction. Geotechnical engineering is a relatively new discipline that has developed rapidly over the past 30 years. It deals with a wide spectrum of natural geological materials, ranging from low strength soils to high strength rocks, associated with many natural hazard incidents such as rock falls, earth flows, mud flows, subsidence, etc. In many parts of the world landslides are common and present serious safety and mortality risks to humans. Prevention of large landslides is difficult, but common sense and good engineering practice can help in minimizing the impacts of such hazards. Due to environmental factors and structural failures, the monitoring of dangerous areas is becoming more important. One of the landslides of the last century occurred in the Ancash region of Peru in 1970 (Harp and Jibson, 1995). Over fifty thousand people lost their lives as a result of this multi-hazard disaster and, in circumstances, death came before burial.

In-situ characterization of rock mass properties is considered as one of the most challenging tasks in geotechnical engineering (Fardin et al., 2004). Existing geological discontinuities, such as faults, joints, bedding planes, and other type of fractures are typically present as surfaces of weakness in any given rock masses (Matthew et al., 2011; Roncella and Forlani, 2005). A rock mass can be seen as a matrix consisting of rock material and rock discontinuities. These discontinuities should be mapped and characterized for their orientation, extensions, and roughness characteristics (ISRM, 1978) because of their major influence on the hydro-mechanical properties of rock mass. These attributes are typically used for the analysis of stability in landslide studies. The orientation of the discontinuity planes is one of the main properties that are needed to be directly determined in the field (Priest, 1993) by characterizing their strike and dip angles (ISRM, 1978). Strike is the direction of the line that is formed by the intersection of the plane of the rock bed with a horizontal surface (relative to north). Dip is the maximum slope of a plane, measured from horizontal surface. Basically, dip is measured as an angle and a direction, and varies from 0^o (horizontal) to 90^o (vertical). The dip direction is always perpendicular to the strike (Figure 1). Traditionally, characterization of the orientation is carried out during field surveys using a geological compass and inclinometer (Figure 2). These traditional methods require direct access to the exposed rock faces. When unstable rock mass conditions are encountered, and no opportunity exists to enter the area of interest, direct contact to the exposed rock faces and collection of data become difficult. This may expose field personnel to hazardous situations because the measurements need to be carried out below steep rock, in a vertical quarry, tunnel, road cuts, etc. and difficult to reach higher parts of steep exposed. Aside from being inaccessible, time consuming, and subjective (Feng, 2001); in-situ measurements, are prone to errors due to sampling difficulties (Fasching, 2001), being cumbersome, and due to the occurrence of instrumental and human errors.

Nowadays, 3D object reconstruction has become a popular area of research (Buckley et al., 2008; Amann et al., 2001). Its applications span many fields such as survey engineering, civil engineering, geological and geotechnical engineering, etc. 3D modeling of objects can be achieved through either passive or active remote sensing systems.

Terrestrial Laser Scanning (TLS) is an example of an active remote sensing system and close-range photogrammetry is a passive remote sensing system. These technologies have been used extensively for the acquisition of highly accurate three-dimensional point cloud data with high resolutions and at very high data-acquisition speed. The increase in quality, availability and affordability of point cloud data has led to the development of many automated point cloud processing software designed specifically for geotechnical applications. This research proposes a new method to generate a high resolution "Digital Surfaces Model (DSM)" in order to extract the discontinuity planes and the computation of their orientations using the multi-sensory data mentioned previously.

TLS appeared at the end of the 1990s (Heritage and Large, 1999) and is currently used in a wide variety of geological applications such as landslide characterization and monitoring (Bauer et al., 2005; Rosser et al., 2005; Lim et al., 2006; Jaboyedoff et al., 2009; Sturzenegger and Stead,2009), structural geological feature extraction (either manual or automated) (Rabbani et al. 2005; Feng and Roshoff 2004; Roncella and Forlani 2005; Sturzenegger and Stead 2009b; Lato et al. 2008), rock mass deformation (Abella´n et al., 2009; Rosser et al., 2005; Donovan and Raza, 2008), monitoring of volcanoes (Hunter et al., 2003; Jones, 2006), earthquake and mining subsidence, quarrying, building reconstruction, and forensics (Paul and Iwan, 2001; Hiatt, 2002; Ono et al., 2000). However, in some cases TLS has limitations during the data collection such as, occlusions, orientation bias, and truncation. This research focusses on the integration of multi-sensory data using TLS and close range photogrammetric data as a proposed solution to address the limitation presented by both methods. To efficiently generate point cloud from close range

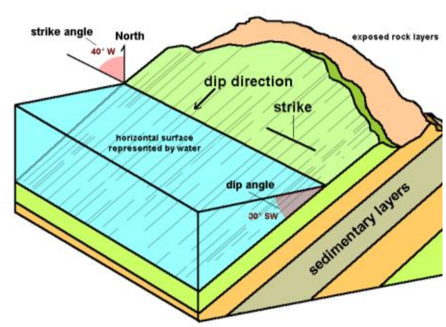

Figure 1. Sketch for dip and strike of a discontinuity plane. (Plummer and McGeary, 1993).

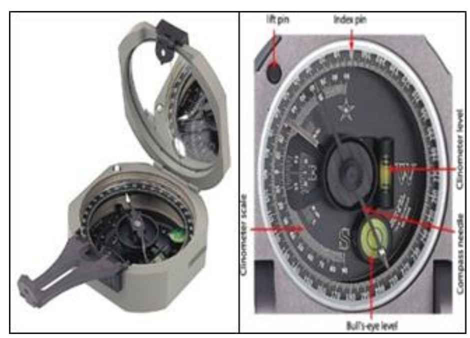

Figure 2. Brunton Geological Compass: Brunton Pocket Transit Conventional Compass Deal (invented in 1894 by Canadian mining engineer D. W. Brunton).

photogrammetry an automatic Semi-Global Dense Matching (SGM) image processing technique has been implemented in order to minimize the amount of field work, thus minimizing time, cost, and to eliminate safety hazards as well as to avoid data acquisition limitations and human errors. The point cloud is generated using the SGM technique would be also useful for filling the gaps in the TLS data resulting from occlusions, orientation bias, and truncation. The integration of multi-sensory data will allow for the accurate identification of the orientation of the discontinuity planes using different data processing techniques. The derived measurements are validated using manual field measurements. This study will provide the means to carry out a comparative analysis between the conventional in-situ approach and the proposed multi-sensory technique in order to mitigate or prevent potential landslide hazards and their associated risks.

METHODOLOGY

This section will discuss the proposed methodologies for processing of the laser scanning data and the point cloud information extracted from the photogrammetric data. The integration of multi-sensory data using TLS and close range photogrammetric data is then utilized to generate a high resolution Digital Surfaces Model (DSM) for the extraction of discontinuity surfaces in order to compute the strike and dip orientations. The procedures listed below aim at activity the research goals : The processing of close ranges photogrammetric data, using Semi-Global Dense matching, and processing of laser scanning data is completed in order to extract discontinuity surfaces.

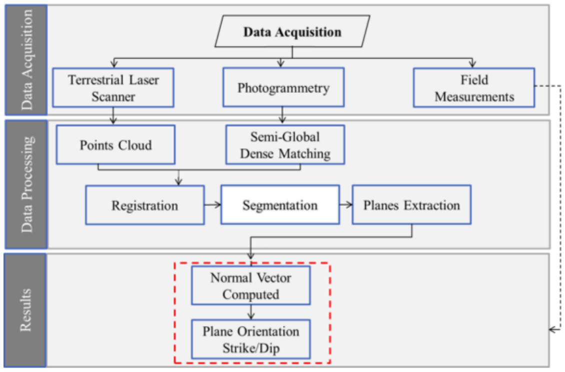

Figure 3. The proposed framework for laser scanning and photogrammetric data processing and integration

- As a prerequisite step prior to the integration procedure, both laser scanning and photogrammetric data should be registered to a common reference frame. This mean the co-registration between different laser scanning viewpoints as well as with the photogrammetric point cloud data is needed.
- Integration of multi- sensory data using TLS and photogrammetric point cloud data is used in order to avoid the limitations from laser scanning occlusions, orientation biases, or truncation, and to facilitate the identification of the discontinuity surfaces.
- In the final step of the processing work flow, parameter-domain clustering segmentation methods are implemented in order to extract the discontinuity planes from the point cloud data. In this case, three sets of discontinuity planes have been extracted from TLS only, SGM only, and after the combination of TLS and SGM.

(Figure 3) illustrates the proposed framework of the implemented methodology in this research work.

SITE DESCRIPTION

A site west of Calgary, Alberta, Canada, along the Trans-Canada Highway towards Banff was selected for geotechnical investigation (Figure 4). The Canadian Rockies in North America are folded and thrust-faulted mountains of mainly sedimentary rock, mostly of parallel northwest/southeast aligned ridges with deep U-shaped valleys and rugged peaks in a region of heavy glaciation. The structure and geology of the study area has been described by Ben Gadd (2009). Coming over the top of the low ridge, we can see that the road cut has exposed rock that is no longer flat-lying. It has been bent by mountain-building processes, indicating that we are now in the foothills of the Rockies. In the cut, sandstone and mudstone beds of the Brazeau Group (young Clastics, late Cretaceous) dip down to the southwest. This dip direction is common in the Canadian Rockies.

Figure 4. Photograph of a rock cut outcrop located roughly 40 km west of Calgary, Alberta along the Trans-Canada Highway to Banff.

DATA COLLECTION

TLS point cloud data acquisition was carried out using a static FARO Focus3D laser scanner. The FARO Focus3D is a high-speed TLS offering the most efficient method for 3D measurement and 3D image documentation. In only a few minutes this 3D laser scanner produces dense point clouds containing millions of points of large scale geometries. TLS datasets collect information in the form of point clouds where each point is referenced with an XYZ coordinate. This scanner has a high resolution digital camera integrated in order to collect true- colour images as additional quantitative information for the TLS scans; by coloring point cloud data with RGB values (Figure 5a) from the digital camera, a supplementary source for data processing. Each point returns laser pulse intensity (with values ranging from 0 and 255) (Figure 5b).

With the increased availability of inexpensive off-the-shelf cameras, close-range photogrammetry has become a viable non-contact alternative used method in this study for complete three-dimensional reconstruction of the area of interest to extract discontinuity orientation. The digital imagery analyzed in this research was acquired using a Canon EOS Rebel T3 digital camera. A total of 15 digital images were collected on July 6, 2013.

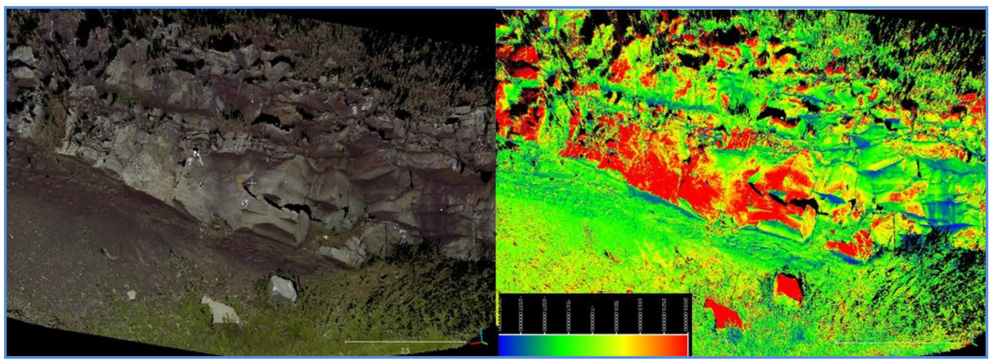

Figure 5. Raw TLS point cloud data of rock outcrop from the viewpoint of the laser scanner, **(a)** point cloud with true color, **(b)** point cloud with intensity

DENSE 3D RECONSTRUCTION USING MULTIPLE IMAGES

In this section, the authors are developing a 3D reconstruction procedure, which utilizes both stereo Semi-Global Dense Matching algorithm and a tracking strategy for multi-view stereo correspondences. To achieve this objective, this section addresses the necessary components of the proposed procedure. An overview of the proposed procedure is given in (Figure 6).

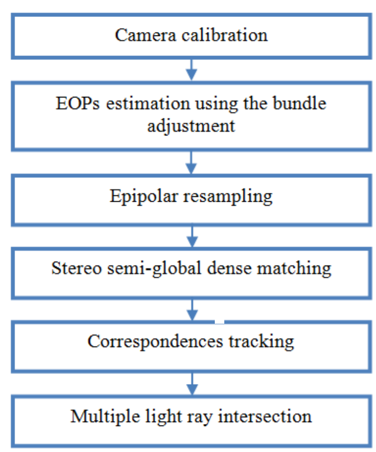

Figure 6. Proposed Dense 3D Reconstruction Procedure

Camera Calibration

The term camera calibration refers to the camera interior orientation and distortion parameters estimation. The proposed dense 3D reconstruction procedure initially involves a camera calibration process through a bundle adjustment process with self-calibration.

The mathematical model for the photogrammetric bundle adjustment is the collinearity equations (Kraus, 1997) (See Equation 2.1).

$$x = x_p - c \cdot \frac{r_{11} \cdot (X - X_0) + r_{21} \cdot (Y - Y_0) + r_{31} \cdot (Z - Z_0)}{r_{13} \cdot (X - X_0) + r_{23} \cdot (Y - Y_0) + r_{33} \cdot (Z - Z_0)} + \Delta x \qquad (2.1)$$
$$y = y_p - c \cdot \frac{r_{12} \cdot (X - X_0) + r_{22} \cdot (Y - Y_0) + r_{32} \cdot (Z - Z_0)}{r_{13} \cdot (X - X_0) + r_{23} \cdot (Y - Y_0) + r_{33} \cdot (Z - Z_0)} + \Delta y$$

Where:

- (x, y) are the observed image coordinates of point P;
- (X, Y, Z) are the coordinates of corresponding object point in the object space;
- r_{11} to r_{33} are the elements of the 3D rotation matrix R, which relates the image coordinate system to the ground coordinate system; three rotation angles ω,φ and κ;
- (X_0, Y_0, Z_0) are the coordinates of camera perspective center in the object space;

- $(\Delta x, \Delta y)$ are the distortion in image space for point P.

The distortion in image space may be divided into radial lens distortion, decentric lens distortion, affine deformation and others. Radial distortion is a type of distortion commonly associated with any lens. Due to the influence of radial distortion, straight lines or other regular structures in the world are often distorted and curved when they are projected onto images. It is particularly visible for areas close to the edge of the image. In this paper, only the radial distortion will be considered, and the mathematical model used is defined as follows (Kraus, 1997)

$$\Delta x = k_1 \cdot (r^2 - r_0^2) \cdot x' + k_2 \cdot (r^4 - r_0^4) \cdot x' \qquad (2.2)$$
$$\Delta y = k_1 \cdot (r^2 - r_0^2) \cdot y' + k_2 \cdot (r^4 - r_0^4) \cdot y'$$

Where:

- k_1 and k_2 are the radial lens distortion parameters;
- r is the radial distance, $r^2 = (x')^2 + (y')^2$, and $x' = x - x_p$, and $y' = y - y_p$, and r_0 is a radial distance with zero radial lens distortion, In this work, r_0 is set to 0.

EOPs Estimation

The EOPs of the involved images are estimated within a free network bundle adjustment process. The tie points of the bundle adjustment process can be extracted either manually or through an automatic feature matching process. In the automatic feature matching process, Scale-Invariant Feature Transform (SIFT) features (Lowe, 2004), which are invariant to image scaling and rotation, are used. Then, the feature correspondences are determined based on the descriptors of the SIFT features.

Epipolar Resampling

By knowing both IOPs and EOPs, the epipolar geometry between each stereo image pair can be reconstructed. The epipolar geometry between two views is essentially the geometry of the intersection of the image planes with the plane which goes through the baseline (the base line is the line joining the two camera) (Hartley & Zisserman, 2000). In terms of a stereo correspondence, the benefit of epipolar geometry is that the search for the corresponding point need not cover the whole image plane, but can be restricted to the corresponding epipolar line.

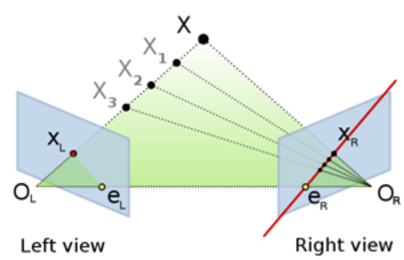

Figure 7. Epipolar Geometry

(Figure 7) Epipolar Geometry; O_L and O_R are the perspective centers of the left and the right views; X_L is one point in the left image, and X_R is the corresponding point on the conjugate epipolar line in the right image; e_L and e_R are the intersection points of the epipolar plane with two image planes (epipoles); X is the point in the object space.

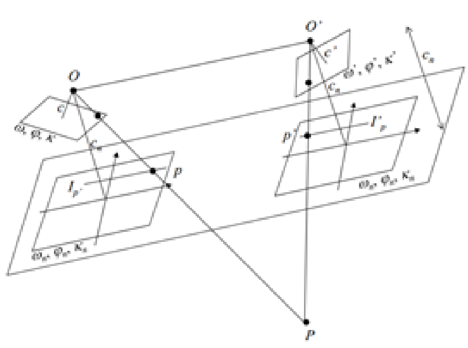

Figure 8. Relationship between the original stereo images and the normalized images (Cho et al., 1993)

In the proposed procedure, epipolar resampling is carried out to enable a much easier feature correspondence search. The objective of epipolar resampling is to remove the y-parallax in each stereo image pair, and generate normalized image pairs, where corresponding feature points have the same row coordinates. The epipolar resampling process introduced in Cho et al. (1993) is adopted in this paper. In this process, the stereo images are projected onto the normalized image plane, where the image rows are parallel to the baseline (see Figure 8).

Stereo Semi-global Dense Matching

In this paper, the stereo semi-global dense matching algorithm is implemented. Semi-Global Matching (Hirschmuller, 2005, 2008; Hirschmüller & Bucher, 2010) successfully combines the concepts of global and local stereo methods for accurate, pixel-wise matching at low runtime. The implemented semi-global matching algorithm minimizes the global energy along different directions (horizontal, vertical, and diagonal directions). The minimum cost path $L_r(x,y,d)$ of pixel (x,y) at disparity d along direction r is defined recursively as in Equation (2.3):

$$\begin{aligned} L_r(x,y,d) = C(x,y,d) + \min(&L_r(x',y',d), \\ &L_r(x',y',d-1) + P1, \\ &L_r(x',y',d+1) + P1, \\ &\min L_r(x',y',i) + P2) \end{aligned} \tag{2.3}$$

Where P1 is a small constant penalty, which is added if the disparitiy change is relatively small (this is, 1 pixel), and the large constant penalty P2 is added if the disparities differ by more than one pixel. Afterwards, the aggregated costs S are summed up over all paths in all directions r (see Equation 2.4). Then, for each pixel, the disparity with the lowest aggregated costs S is selected to be the initial disparity. As a result, semi-global dense matching optimizes the disparity value at each pixel with the optimal paths through the whole image.

$$S(x,y,d) = \sum_r L_r(x,y,d) \tag{2.4}$$

Correspondence Tracking

The proposed correspondence tracking method is described in this section. In Equation 2.5, it obvious that at a constant depth Z, the depth precision σ_Z improves with the increase of the baseline distance B.

$$\sigma_Z = \sqrt{2} \cdot \frac{S}{B/Z} \cdot \sigma_{xy} \tag{2.5}$$

Where:
$s = \frac{Z}{c}$ is the image scale, and σ_{xy} is the image measurement precision.

Equation 2.5 indicates that the large baseline geometry optimizes the intersection accuracy. However, in large baseline scenario, significant relief displacement is usually present, and this causes the difficulty of point matching in the images. On the other hand, although the short baseline scenario has bad intersection accuracy, the matching of short baseline stereo is much easier. That is why a correspondence tracking procedure, which utilizes the advantages of both small baseline stereo and long baseline stereo, is proposed and developed in this research.

The proposed method concatenates the corresponding image points over multiple viewpoints by tracking over disparity images from adjacent image pairs (Figure 9). Similar tracking algorithms are introduced by Pollefeys (2013) and Rumpler et al. (2011).

Multiple Light Ray Intersection

The output of the correspondences tracking procedure is the feature correspondence in multiple images. Then, the 3D object coordinates of the corresponding features are computed in a spatial intersection process using least-squares adjustment (Figure 10). The mathematical model employed for spatial intersection is the collinearity equations.

Two filters have been incorporated in the spatial intersection process. The first one is used to remove blunders or outliers. In this paper, if the average image residuals obtained from the spatial intersection are larger than a certain threshold, the image points are discarded as blunders. The second filter is used to remove points with low intersection precision. In this paper, the second filter is that a tracked point should appeare in at least three images.

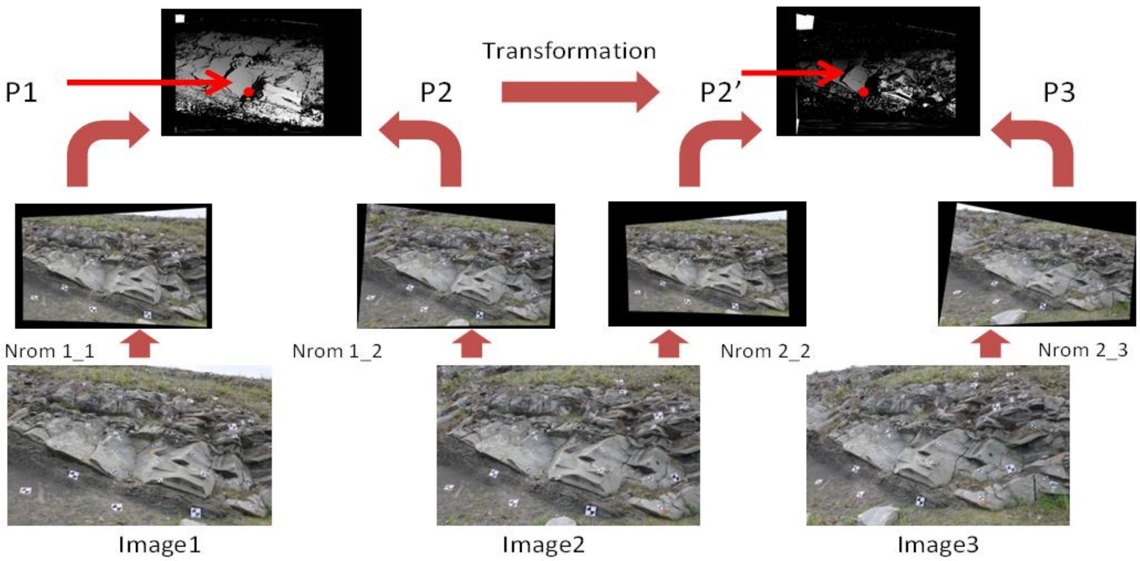

Figure 10. An example of the proposed correspondence tracking procedure

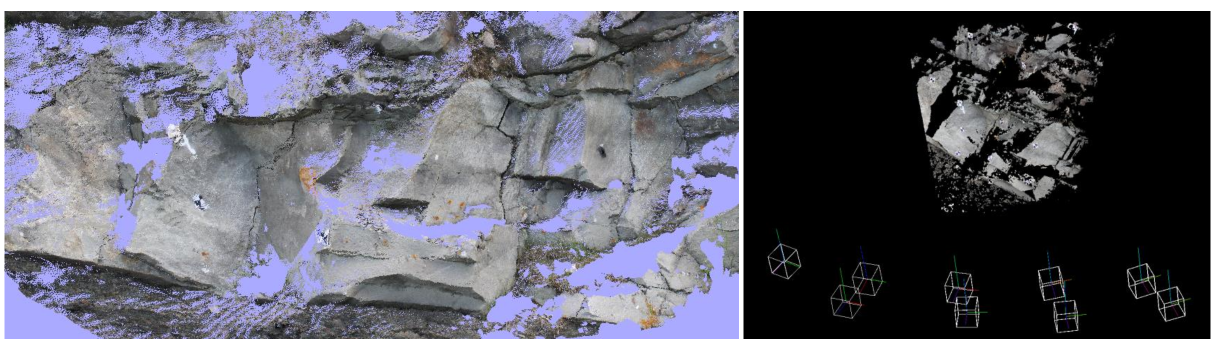

Figure 11. Semi-Global Dense Matching point cloud data of rock outcrop from multiple terrestrial images

POINT CLOUD ALIGNMENT (REGISTRATION METHODS)

In many situations, one laser scan is not sufficient for collecting data in order to cover the entire object of interest from a single viewpoint. Furthermore, discontinuity characterization requires a large area to be captured in order to obtain a statistically significant sample (Sturzenegger et al., 2009). It is also preferable to scan different exposures to avoid orientation biases (ISRM, 1978; Priest, 1993) and occlusions. Hence, several laser scans are needed and each one has its own coordinate system. Another point cloud was generated from terrestrial imagery using semi global dense matching algorithm. This point cloud is used to augment the TLS data and fill in the holes which exist due to occlusions. In order to identify a meaningful 3D model of the rock mass surface, transformation of the

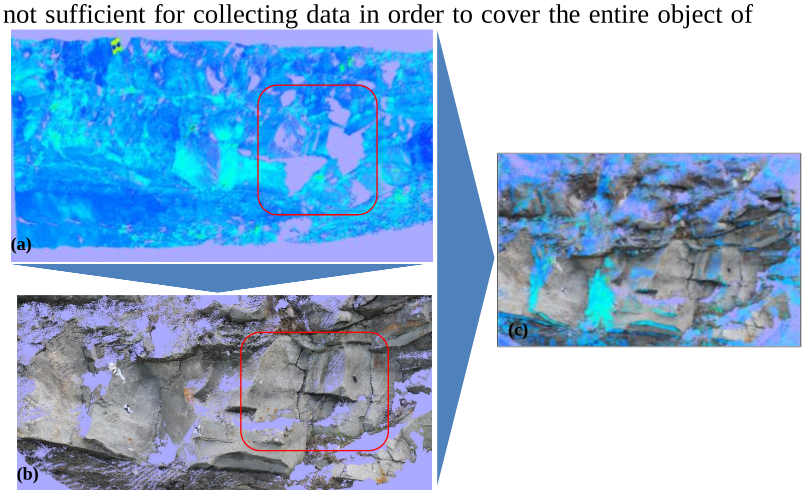

Figure 12. Show (a) TLS point cloud, (b) Semi-Global Dense Matching point cloud, and (c) Combination of both data sets

collected scans as well as the image- based point cloud into a common reference frame coordinate system is necessary (Figure 12). In this research, the Iterative Closest Projected Point method (ICPP) (Al-Durgham et al. (2011), which is a robust registration method and a variant of the ICP method, is considered as both a point-to-point and point-to-plane registration technique, and aims at minimizing the distance between a point in one scan and its projection on the plane defined by the closest three points in the other scan. The ICPP algorithm requires initial alignment of the point clouds with respect to a common coordinate system.

SEGMENTATIONS METHODS

The process of extracting discontinuity planes starts with the identification of planar features in the TLS data, SGM, and combination of both. Points that belong to the same plane can be grouped by a segmentation process. Different planar features can be distinguished by a segmentation process. In order to detect existing planar features and extracting rock mass characterization information from each data set, a novel segmentation approach called Parameter-Domain clustering algorithm, which was presented by Lari et al. (2011), is used. First, the neighborhood of each point is established using an adaptive cylinder in the point cloud, and then the segmentation attributes are computed based on the defined neighborhood of each point. Finally, clusters of points with similar attributes in the scans are represented by the detected peaks in the array of the estimated attributes (Figure 13) (Lari and Habib, 2012).

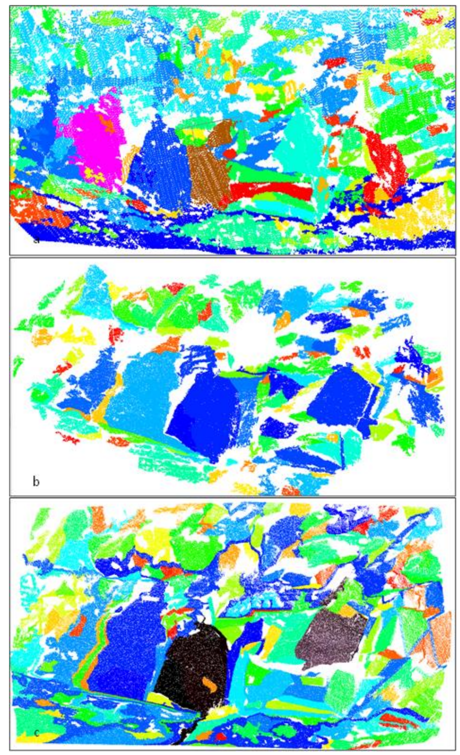

Figure 13. Results of the Parameter-Domain Clustering segmentation method: (a) TLS; (b) SGM; and (c) combination of both data sets

RESULTS AND DISCUSSION

Once the point cloud datasets are segmented using parameter domain clustering segmentation methods and the discontinuity planes have been detected, the orientation for each plane is computed by calculating the normal vector for each plane and converting to geological information, i.e., strike and dip. Large planes based on the number of points clustered or segmented are a good indication of important discontinuity surfaces. Small planes, on the other hand, may not actually be planar surfaces but only a small portion of the surface that happens to be flat. In this case, the surfaces of the smallest planes should be filtered.

Two main prominent discontinuity sets have been identified from each data set (Table 1), which permits the creation of a stereonet based on those discontinuity planes orientations. The average orientations were plotted on a stereonet (Figure 14). Each plane plotted as one point on the stereonet. Stereonet analysis is a statistical approach that relies heavily on grouping clusters of orientations into sets, generally known as joint sets, or families. In Table 1, Summary of the results derived from the geological compass used in the field and extracted planes from TLS, close- range photogrammetry using SGM, and the combination of both data sets.

Table 1. Average strike and dip readings extracted from different data sets

Algorithms	# of Planes Measured	Mean Strike (Degree)	Mean Dip (Degree)	Direction
TLS point cloud	54	265.80	67.5	NW
	216	318.20	51.30	NE
SGM point cloud	22	273.94	72.74	NW
	143	308.14	55.50	NE
Combination of both data sets	70	267.45	65.80	NW
	225	313.21	52.30	NE
Survey Field	32	261.34	69.87	NW
	37	321.70	47.40	NE

Both sets of planes in Table 1 were projected on a stereonet using the software called stereonet (OpenStereo, 2012); these provide an overview and can be used for comparison between the discontinuity orientations that result from each data set. The plane orientations present in Figure 14 are derived from the geological compass used in the field (Figure 14a) extracted from TLS (Figure 14b), SGM (Figure 14c), and the combination of both data sets (Figure 14d).

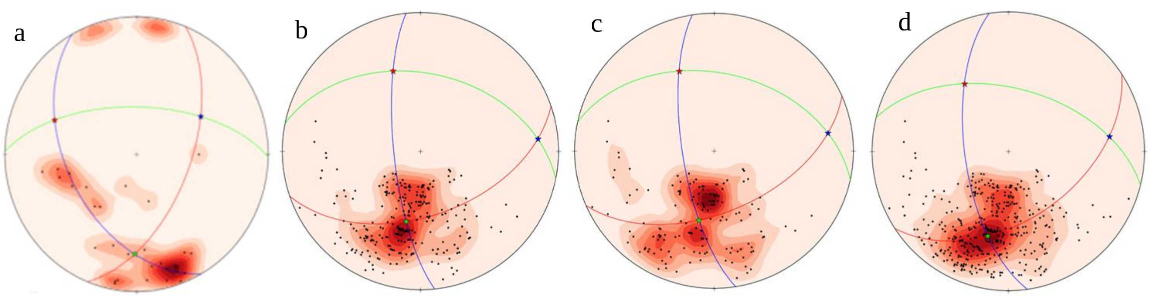

Figure 14. The stereoplots of the discontinuity planes extracted from point cloud. (a) Results of the manual geological survey; (b) Outcome of TLS; (c) SGM; and (d) combination of both data sets

Generally, a good correlation was seen between the measured and extracted orientations. All of the data generated similar results; however, the segmentation processing method gave a powerful option to individually delineate the discontinuity plane sets with high accuracy through a semi-automated process. The TLS and SGM processing option provided excellent visual demonstration of discontinuity configuration compared with using a traditional geological compass. Over 150 structural discontinuity planes were detected in the Brazeau Group (sandstone layers), road cuts have been segmented from the TLS datasets (Figure 14b), and terrestrial images dataset (Figure 14c). Here, the combination of methods is the key for getting the best possible results within a reasonable amount of time, work load, and completeness of rock mass surface. The similarities of all plots are subjective. According to other studies (Herda, 1999; Ewan et al., 1983; ISRM, 1978), the differences between compass measurements and computed discontinuity orientation measurements from the TLS point cloud and SGM are within acceptable limits. All strike directions and dip angles were within a 10^o interval (Table1). The International Society of Rock Mechanics (ISRM) defines 10^o geotechnical parameters applicable for quantitative rock masses analyses, and suggests that a minimum of 150 measurements are needed for a sound statistical analysis (ISRM, 1978). This range of readings comes from (i) determining where the compass can be put in order to obtain the true orientation of the discontinuities; (ii) aligning and levelling the compass. In this work, no significant difference was found between the different dataset. The combination between multi-sensory data is the key for getting the best possible results within a reasonable amount of time, work load and safety. These methods provide more accurate results for discontinuity orientations, compared to compass measurements, which can incur systematic errors from local magnetic attraction, declination, and surface roughness.

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

Different geo-technical parameters are required such as the strike and dip of the discontinuity planes in the area in order to assess landslides stability. Areas affected by landslides are often inaccessible which makes manual compass and inclinometer measurements challenging because of the danger involved in this operation. Preventing large natural landslides is difficult at best; however some mitigation is possible and can help minimize hazards. This paper discusses the use Terrestrial Laser Scanning (TLS) as an example of an active remote sensing system and close-range photogrammetry is a passive remote sensing system. These technologies have been used extensively for the acquisition of highly accurate three-dimensional point cloud data with high resolutions and at very high data-acquisition speed, in order to extract the discontinuity planes and on the other hand to computation of their orientations using the integration multi-sensory data TLS, and SGM.

The integration of multi-sensory data in this research is useful to addresses the limitations issues by investigating the possibility of augmenting TLS in the occluded regions through close-range photogrammetry to generate high resolution and dense point cloud using the Semi-Global Matching (SGM) algorithm. By augmenting the two data acquisition methods and registering data to a common coordinate system to provide a completed point cloud for the area of interest. Four sets of geotechnical parameters have been compared in this research: a set of manual measurements, a set extracted from the TLS data only, a set extracted from the SGM algorithm only, and finally a set extracted from the fused TLS and SGM data. The results showed that the data fusion method provided more accurate results when compared to the results coming from the TLS data and those coming from SGM only. This reveals that the impact of the occluded regions on the calculations of the geotechnical parameters must be considered to achieve the required quality of the estimation process.

The automated procedures (parameter domain clustering) reduce the errors associated with gathering field data by eliminating human bias and standardizing the sampling procedure. These automated methods can also be used to increase the amount of discontinuity information, to further reduce or eliminate safety and access problems. Results for the discontinuity orientation for all planes, using the different procedures applied to a test site, were equivalent or more accurate than traditional geological compass survey, which incurs systematic errors from the local magnetic attraction, declination, and surface roughness. The research could be extended to develop of a program that could automatically extract all discontinuity parameters, such as roughness, volume, density, and spacing, from the point cloud data measured in rock masses. This could also lead to a comprehensive statistical analysis of the discontinuity parameters.

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